Economics of Innovation and New Technology

ISSN: 1043-8599 (Print) 1476-8364 (Online) Journal homepage: www.tandfonline.com/journals/gein20

Digitalisation, institutions and governance, and diffusion: mechanisms and evidence

Vincent Labhard, Jonne Lehtimäki & Claudio Baccianti

To cite this article: Vincent Labhard, Jonne Lehtimäki & Claudio Baccianti (19 Jun 2025): Digitalisation, institutions and governance, and diffusion: mechanisms and evidence, Economics of Innovation and New Technology, DOI: 10.1080/10438599.2025.2517650

To link to this article: https://doi.org/10.1080/10438599.2025.2517650

Published online: 19 Jun 2025.

ECONOMICS OF INNOVATION AND NEW TECHNOLOGY
https://doi.org/10.1080/10438599.2025.2517650

Digitalisation, institutions and governance, and diffusion: mechanisms and evidence

Vincent Labhard[a], Jonne Lehtimäki[b] and Claudio Baccianti[c]

[a]European Central Bank, Frankfurt am Main, Germany; [b]University of Turku, Turku, Finland; [c]Deutsche Bundesbank, Frankfurt am Main, Germany

ABSTRACT
Digitalisation can be described as a sequence of technology and supply shocks which affect the economy through employment and labour markets, productivity and output, and competition and market structure. This paper focuses on how digitalisation – the process of diffusion of digital technologies – is affected by institutions and governance. It discusses a number of theoretical mechanisms and empirical evidence for different sets of European and other countries while also accounting for cross-section dependence that might be caused by technology spillovers. The results indicate that a higher quality of institutions is usually associated with both a greater speed of diffusion and a greater spread of digital technologies. Additionally, some negative effects from high levels of governance are observed. The results also suggest that there are large, policy-relevant differences in the diffusion process depending on the technology, the level of development as well as the state of technological change of a country.

ARTICLE HISTORY
Received 25 December 2023
Accepted 30 May 2025

KEYWORDS
Technology adoption; technology diffusion; digitalisation; institutions; technology spillovers

JEL CLASSIFICATION
E02; O11; O31; O33; O57

1. Introduction

Since the middle of the 20th century, digital technologies have been spreading into almost every aspect of economic activity, transforming production patterns (for example via automation, industry 4.0, the internet of things, digital twins) and consumption patterns (infrastructure, software, platforms). Digital technologies are based on binary-digits (or 'bits') format for storing information, which has facilitated processing, storage and exchange of data, and has led, inter alia, to considerable savings in costs, as described in Goldfarb and Tucker (2019).

The increase in digital technologies – referred to in this paper as digitalisation – is one of the most important transformations affecting microeconomic allocation (relative prices

CONTACT Jonne Lehtimäki jonne.lehtimaki@utu.fi Turun kauppakorkeakoulu, Rehtorinpellonkatu 3, 20500 Turku. Suomi, Finland

*The views expressed in this paper are those of the authors and do not necessarily reflect those of any of the institutions the authors are or have been affiliated to. The work has benefited from comments by colleagues and seminar participants at the Bank of Canada, the European Central Bank, the Federal Reserve Board, the IMF, and the World Bank. In particular, we would like to thank R. Anderton, A. Dieppe, R. Duval, D. Filip, M. Hallward-Driemeier, P. Schulte and R.J. Singh, as well as several anonymous referees for their suggestions.

and preferences as well as the functioning of markets) and macroeconomic outcomes (trends and cycles), alongside changes in integration, geopolitics, demographics and climate. In line with other ongoing structural changes, digitalisation may also have broader consequences on modern economies and societies. As Milkau and Bott (2015) note: 'Digitalisation has not been changing the fundamental laws of economics, but has triggered changes in how agents interact in the market or see intermediaries facilitating this interaction'.

Some of the impacts of digitalisation have been studied in prior research, at least qualitatively.[1] This includes the effects of digitalisation on a macroeconomic level, and in particular the effects on productivity and labour markets.[2] The literature suggests that while new technologies may affect different sectors heterogeneously, they generally lead to productivity gains at the firm level, with more productive firms being, on average, more digital (and vice versa, see for example Gal et al. 2019; OECD 2019).

The productivity-enhancing effect derives from the general-purpose property of digital technologies (Trajtenberg 2018) or those technologies being inventions in the method of inventing (Cockburn, Henderson, and Stern 2018). While there is much support for the idea that digitalisation has productivity-enhancing effects, this idea is by no means uncontested, neither in relation to specific technologies (for example the internet (Gordon 2016)) or regarding digital technologies as such (given digital distraction and addiction).[3]

Nevertheless, at the aggregate level the literature emphasises the so-called productivity puzzle, whereby economy-wide productivity growth is much lower than would perhaps be expected in an era of rapid technological change, and given the firm-level evidence. This suggests that there may also be adverse effects from technology on productivity, even if they may be more difficult to quantify, such as digital and non-digital systems being run in parallel, or distraction and/or addiction effects from digital technology.[4]

The literature on the labour market effects is also ambiguous, because digital technologies may be magnifying and enhancing human capabilities (complementing labour), as argued by Acemoglu, Johnson, and Robinson (2005), Acemoglu (2012) and Acemoglu and Restrepo (2019), or, alternatively, replacing human capabilities (substituting labour) as suggested by Trajtenberg (2018). Acemoglu and Restrepo (2019) also note that digital technologies might displace labour from routine and repetitive work, therefore removing a number of jobs intensive in those tasks. In this way, digital technologies, like other technologies, may also lead to labour market polarisation.

Finally, some attention has also been given to the diffusion of technologies, and comparing the diffusion of digital technologies to the diffusion of other general-purpose technologies. Comin and Hobijn (2004) consider the diffusion of 20 technologies across 23 of the world's leading industrial economies for the period 1788–2001, and find new technologies to have a common trickle-down effect. In a later study, Comin and Hobijn (2010) look at 15 technologies in 166 countries over the last two centuries, and estimate a mean adoption lag of 45 years (less for more recent technologies) after invention. Stokey (2020) contrasts within-country and cross-country adoption patterns, focussing on how costs and the relative price of capital and labour inputs affect the adoption process.

However, the interaction of the diffusion of technologies, and especially digital technologies, with the quality of institutions and governance, has not been addressed in the literature, although this interaction is potentially important, including for policy-making. This paper attempts to fill this gap by describing a number of theoretical mechanisms and providing empirical evidence for the diffusion of digital technologies, and the interplay of the diffusion process with the quality of institutions and governance. The empirical evidence in this paper comes from a large cross-section of 100 countries from all around the world in order to make the assessment more robust and identify potential differences across different sets of countries.[5] Such differences could emerge, for example, for countries at different stages of development if institutions and governance are intrinsically linked to advancement.

One distinctive feature of this paper is that digital technology is measured by means of actual adoption of specific digital technologies, such as the number of devices or subscriptions, which has the advantage of better capturing the actual use of the technologies, as opposed to the potential scope for their use. The approach is taken to avoid a potential issue with data availability faced by most of the preceding literature, which commonly relies on data on Information and Communication Technology (ICT) patents, investment or consumption. While useful inter alia as a cross-check, those alternative measures do not fully capture the actual level of technology they imply (investment, for example, may be more or less efficient). Moreover, those alternative measures do not necessarily reveal sufficiently detailed information about the specific technologies as they are based on statistical categories which have originally been defined with other objectives in mind. To measure diffusion, the focus in this paper is on the extensive margin, such as the number of devices or subscriptions, which has the advantage of better capturing the actual use of the technology, as opposed to the scope for their use. It would be even better to use the intensive margin, the time or intensity of use but such data are not available from the traditional data sources.

While measuring digitalisation via the adoption of specific technologies is a reasonable approach, it also has some limitations. They are mostly related to limited data availability, especially for the most recently adopted digital technologies, including artificial intelligence, internet of things, digital twins and quantum computing. New technologies are challenging to capture, as data is only available for short periods, or are not as easily comparable as in the case of more established technologies. Moreover, this paper restricts itself to traditional data provided by statistical agencies and international organisations, and not the new (and big) data sources that have become available as a result of digitalisation. A final caveat relates to cross-section dependence, which the paper addresses by means of using estimates with standard errors adjusted accordingly.

The remainder of the paper is organised as follows: Section 2 describes the mechanisms at play regarding the process of diffusion of digital technologies, and its interplay with institutions and governance. Section 3 describes the data sources and samples for digital technologies, institutions and governance as well as the variables controlling for other factors that may play a role in the diffusion process. Section 4 describes the methodology for estimating the process of technology diffusion, and how that methodology captures the interaction of the diffusion process with institutions and governance. The empirical evidence is presented and discussed in Section 5, and Section 6 concludes.

2. Theory

This section summaries some of the literature and the theory behind the diffusion process of digital technologies as well as how institutional and governance aspects might affect the process of technology change and how new technology can be adopted for use.

2.1. The diffusion of digital technologies

It has long been acknowledged that technology can take time to diffuse to widespread use, and that heterogeneity of agents is one of the key reasons for this lag (see Young 2010 and references therein to the early models of contagion[6] and social influence and social learning[7] as the source of the heterogeneity and the resulting diffusion patterns).[8] This applies also to digital technologies – not all agents are equally exposed to digital technology (for example due to different educational or professional backgrounds) and not all agents feel the same pressure or face the same learning curve (depending on socio-economic characteristics). The social context and personal preferences are not the same across all agents. In fact, it could be argued that because digital technologies are particular in nature, the diffusion process may simultaneously be different from other technologies as well as be more important for development.

The particularity of digital technologies derives from their general-purpose property – the fact that they do not only offer cost and/or efficiency gains but additionally have many applications, and may be combined with many other (more specific) technologies, for the benefit of further innovation (see Jovanovic and Rousseau 2005; Lipsey, Carlaw, and Bekhar 2005 for an analysis and classification of general-purpose technologies). Therefore, digital technologies are potential catalysts for technological progress and far-reaching effects on the economy in the medium and long term. The potential size of the effects will depend on their diffusion to actual use and, inter alia, on their interaction with institutions and governance.

It has been argued that digital technologies (IT/ICT and the technologies that followed) are, in fact, more powerful than other more traditional technologies, and so the 'digital revolution' or 'fourth industrial revolution' is greater than the preceding industrial revolutions, which were based on analogue technologies such as the steam engine and electricity. Digital technologies are very general as they have applications throughout the economy, in principle for all agents, all activities and all geographies.

While it is true that digital technologies have features which make them more powerful than other technologies, they also have features making them more difficult to fully take advantage of.[9] The first challenge arises from the fact that digital technologies are not as easily accessible as more traditional ones, and notably require more skills to operate. The power switch, for example, is sufficient to use electricity, but this is only the very first step in the use of a digital device. Taking full advantage of digital technologies may also be more difficult in decentralised economies which, therefore, may show 'too little, too late' innovation (Bresnahan and Trajtenberg 1995).

In other words, the diffusion of digital technologies is very specific and depends on a number of other factors that determine how well the technology is integrated into economic processes. One such element is the focus of this paper: the interaction or interplay with institutions and governance.

2.2. The interplay with institutions and governance

Although the terms 'institutions' and 'governance' are sometimes used interchangeably, or as close substitutes, in most cases they refer to different concepts. Institutions, for example, are sometimes considered an aspect of governance, or governance an aspect of institutions. In this paper, institutions are considered to be the structure (the skeleton, or hardware) and governance the way the structure is being run (the muscles, or software), a characterisation that may be reminiscent of Williamson (1998). In this framework, the two concepts are closely connected, intrinsically linked – one does not exist independently of the other, even if they are different aspects of the structure of an economy.

The significance of institutions has been noted in the literature since the seminal work of North (1991) who pointed out that institutions play a notable role in shaping advanced economies and are important, potentially positive or negative, drivers of real economic change, and so should be taken into account when studying related subjects.[10] Another important contribution is by Acemoglu, Johnson, and Robinson (2005) who study the role of institutions from multiple points of view, and consider evidence from history, notably on the reasons for the vast differences in institutions across countries.

The approach taken in this paper is to consider the effects from institutions and governance separately, and whether they depend on the interaction with technological change. Theoretically, this interaction arises as technological change and technology adoption generally have the potential of creating accountability to the stakeholders (e.g. by making agents and actions more traceable), and by providing equal opportunities to market participants and economic actors (for example, in terms of access to information by defining the framework for market transactions).

3. Data

This section describes the data used in this paper, starting with a summary of the data sources, samples and countries. This is followed by the descriptions of the data capturing digital technologies and those capturing institutions and governance. The section also covers other data, notably the variables used in the estimations to control for factors other than institutions and governance that are shaping the diffusion of digital technology. Listings of all the countries and country aggregates as well as all the variables used in the paper can be found in Appendix 1.

3.1. Sources, sample and countries

Neither the quality of institutions and governance or the degree of digitalisation are simple to measure. A general challenge is finding data with sufficient time and cross-section dimensions to conduct meaningful econometric analysis, given that many digital technologies are very recent technological advances, a point also made in Stokey (2020). Another challenge is capturing the different aspects of those technologies (e.g. automation vs. communication) and of the quality of institutions and governance (e.g. accountability, transparency, etc.). A further challenge is capturing the availability as opposed to the actual use in the case of technologies, and the quality (de jure and de facto) of institutions and governance.

To address these challenges as best as possible, data from a large number of sources were considered. In the end, most data were compiled from databases of the World Bank as it is one of only a few available sources that has dedicated and comprehensive databases both for measuring the degree of digitalisation as well as the quality of institutions and governance. Another important factor was the availability of long time and wide cross-section dimensions, with series from that source extending as far back as 1960 and for as many as 253 countries, and the indicators for institutions and governance available as of 1996.

The effective sample used in this paper is 1996–2020 when digital diffusion is measured by the number of internet users, and 1998-2020 in the case of fixed broadband subscriptions. The missing values in the panel were imputed by interpolation, especially in the case of institutions and governance indicators for 1997, 1999 and 2001, as they were published biyearly until 2002.

The full panel consists of 100 countries around the World for which all data used (digitalisation, institutions and governance, and controls) is sufficiently available. Along with the results for the full cross-section, results for the most homogeneous group, 'EU countries', is presented. The choice of EU countries as a separate group of study is due to their codependence through common values and structures as well as, perhaps more importantly, supranational legislation and low trade barriers due to the European single market[11].

3.2. Digital technologies

To measure digitalisation, data were collected from the World Bank's World Development Indicators (WDI) database. Two series, in particular, were considered helpful for capturing the degree of digitalisation. The first is the series 'Individuals using the Internet (per cent of population)', available beginning from 1996, which reflects the necessary condition during the early phases of digitalisation of being able to access and actually using the internet as a basic digital environment. The second series is 'Fixed broadband subscriptions', available for a majority of the countries in the sample from the year 1998, which captures the key precondition for the formation of advanced infrastructure and hence for the current phase of digitalisation.

The series 'Individuals using the Internet (per cent of population)' is compiled from the International Telecommunications Union and its World Telecommunication/ICT Development report and Database, and is defined as individuals who have used the internet in the past three months, via computer, mobile phone, digital television or other device. The quality of this series may vary across countries due to, for example, differences in regulations regarding the cover of data provision and availability. The series also reflect the broadly increased use of mobile phones and the dynamics of easier access to the internet during the studied time period.

The series 'Fixed broadband subscriptions' is from the same source, and covers high-speed access via TCP/IP connections at downstream speed of at least 256 kbits per second, including cable modem, DSL, fiber-to-the-building, satellite broadband and terrestrial fixed wireless broadband. The data are based on surveys carried out by National Statistical Institutes, and potentially suffer from the corresponding drawbacks. Despite best efforts, neither indicator is strictly comparable across all countries, for example, due to differences in the timing of the fiscal year. However, even with these drawbacks, they are two of the few available series with sufficient coverage to examine the effects studied by this paper.

A number of other points are worth noting in this context. First, internet use and broadband subscriptions are important digital technologies, because enabling others (e.g. no e-commerce or e-government without them). Second, while they are enabling,

Table 1. Descriptive statistics of digital technology variables.

Variable	Mean	SDev	Min	10th	90th	Max
EU countries						
Individuals using the internet	53.2	29.9	0.2	6.4	88.1	98.8
Fixed broadband subscriptions	21.3	12.8	0.0	1.4	37.6	48.3
Full cross-section						
Individuals using the internet	36.4	31.5	0.0	0.7	83.4	99.0
Fixed broadband subscriptions	12.3	13.1	0.0	0.1	32.7	48.3

Sources: World Bank, authors' calculations.

Notes: 'Mean' is the arithmetic mean, 'SDev' the standard deviation, 'Min' the minimum, '10th' the 10th, '90th' the 90th percentile, 'Max' the maximum. The sample is 1996–2020 for individuals using the internet and 1998-2020 for fixed broadband subscriptions.

or even a precondition, for other technologies, they say little about the spread of those other technologies. Third, they are capturing the number of users/installations, not how much and what for they are using/being used. The results presented in this paper have to be seen against that background.

The descriptive statistics of the digital technology variables are summarised in Table 1. They suggest that internet use has spread further but also varies more across countries than broadband subscriptions. For both internet users and broadband subscriptions, mean and standard deviation tend to be higher for the EU than the other countries.

A number of other options for indicators of digitalisation were considered as well, but were not used due to short samples or lower country coverage. They included other series from the World Development Indicators, the KOF Information Globalisation Index (Dreher 2006; Gygli et al. 2019), the digitisation index (Katz, Koutroumpis, and Collarda 2014) and the European Commission's Digital Economy and Society Index (DESI) and its international (iDESI) counterpart. The correlations between the series used in the study to proxy different phases of digitalisation and these indeces is generally very high, ranging from 0.7 to 0.9 for individuals using the internet and 0.5 to 0.8 for fixed broadband subscriptions. While these alternative indicators were not used in this study, they might be informative for future work when their sample and coverage are extended, or to study different aspects of the process of digital technological change.

Figures 1 and 2 show the share of countries that have passed a specific threshold of technology adoption (10%) in each year. These thresholds are used in the study to ensure that the adoption of studied technologies has actually begun and to control for the potential of different times of the adoption taking place. The adoption of both technologies studied advanced earlier for the EU countries than the more heterogeneous full cross-section, which is also reflected in the descriptive statistics of Table 1.

3.3. Institutions and governance

The data for institutions and governance were taken from the Worldwide Governance Indicators (WGI) described in Kaufmann, Kraay, and Mastruzzi (2010) and published by the World Bank. This source was chosen due to the advantages of comprehensive databases, and the availability of long time and wide cross-section dimensions, as noted in Section 3.2. Using the World Bank as the source for the indicators on institutions and governance also has the added advantage of the homogeneity of certain data standards and principles across the two data sets.

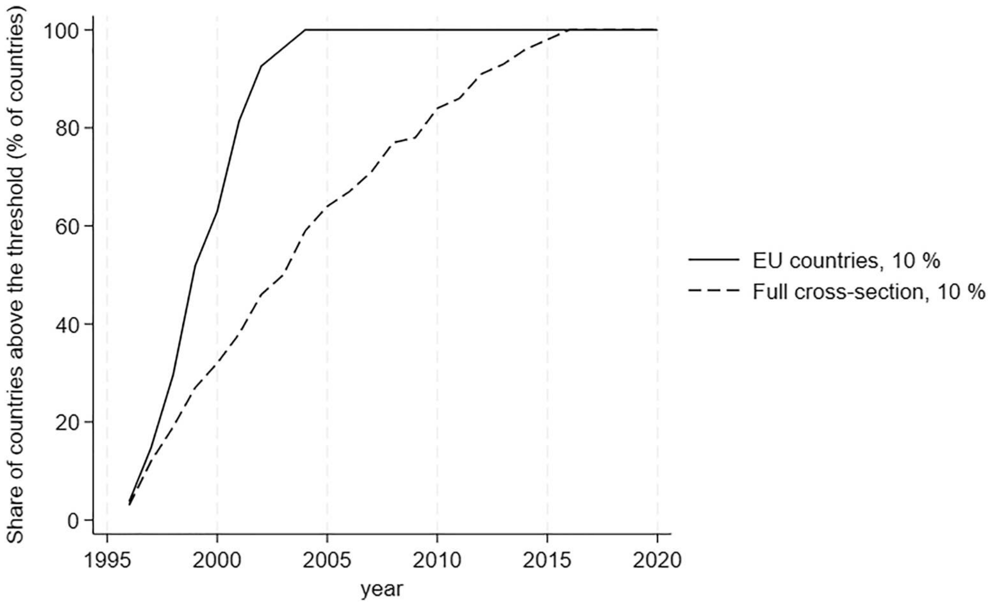

Figure 1. Shares of countries with technology above thresholds, Individuals using the internet.
Sources: World Bank, authors' calculations

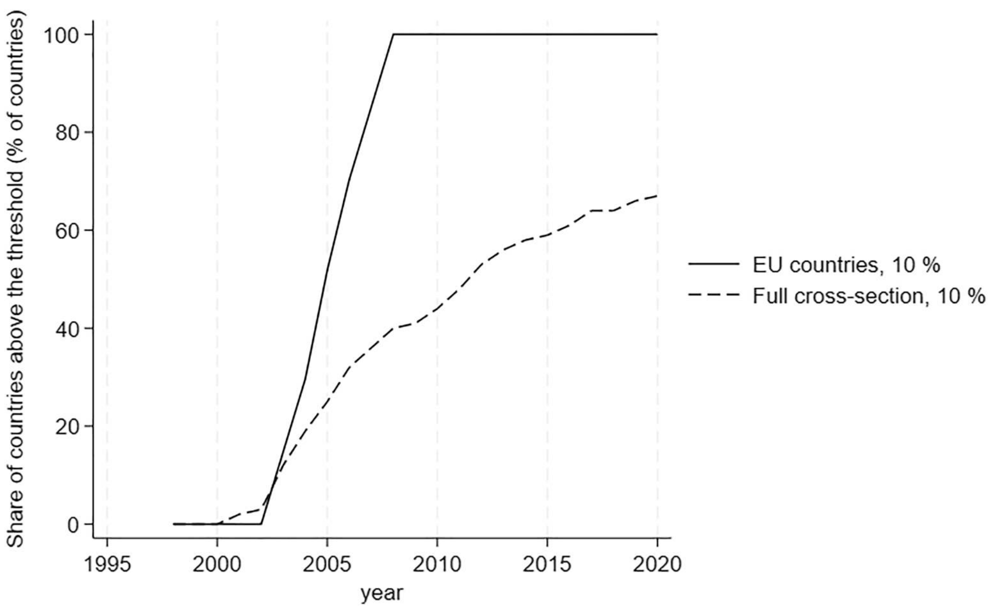

Figure 2. Shares of countries with technology above thresholds, Fixed broadband subscriptions.
Sources: World Bank, authors' calculations.

The WGI consists of six distinct indicators. The 'control of corruption' indicator measures the abuse of public power for private gain and the influence and interference of elites and private interests. The 'government effectiveness' indicator captures the quality of public services, civil service, its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. The 'political stability and absence of violence' indicator measures the likelihood of violence, including terrorism. The 'regulatory quality' indicator measures the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development. The 'rule of law' indicator refers to the rules of a society, including contract enforcement, property rights, police and courts as well as the likelihood of crime and violence. Finally, the 'voice and accountability' indicator relates to the perceived participation in the selection of government, as well as freedom of expression, association and media.

For the approach taken by this paper, the indicators 'government effectiveness', 'political stability and absence of violence' and 'voice and accountability' were considered to capture primarily the institutional aspect (the framework or structure), while the indicators 'regulatory quality', 'rule of law' and 'control of corruption' the governance aspect (how things are run given the framework or structure). Using this division, summary measures were compiled to assess the overall impact and the relative importance of institutional and governance aspects. The indicators were created for the averages across the two sets of indicators and are labelled as 'Institutions' and 'Governance'. This approach is similar to the three-way WGI summary measures proposed by Kaufmann, Kraay, and Mastruzzi (2010) and is expected to capture institutional aspects. However, as noted in the literature, for example by Dellepiane-Avellaneda (2010), one of the challenges of studying such effects is how to distinguish the effects of different institutions. Figure 3 illustrates how the different Worldwide Governance Indicators are related to the summary measures used in this study.

As in the case of digital technologies, a number of alternative data sources were considered for institutions and governance during the study. Notable options were the Fraser Institute Economic Freedom Index (Gwartney et al. 2019) as well as OECD Indicators of Employment Protection Legislation (EPL) and Product Market Regulation (PMR), all of which are, at least indirectly, related to institutions and governance. The other options were not used due to less comprehensive samples and other data issues.

The descriptive statistics for the data on institutions and governance are presented in Table 2. For both composite measures, the maxima are recorded among the EU countries. The mean values are much higher within the EU than outside. The standard deviations are lower within the EU.

3.4. Control variables

In order to properly study the diffusion of digital technology and its interplay with institutions and governance, other factors that might impact on technology diffusion have to be controlled for. This concerns notably the broader state of development of a country and the availability of human capital facilitating the introduction and the use of new technology.

The specific control variables used for this purpose in this paper are: real GDP (per capita), as an indicator of the broader state of development; and human capital, which is proxied with the human education index. The descriptive statistics for the control data are provided in Table 3. For countries outside the EU both variables are somewhat lower but also have higher variance, in particular when it comes to human capital, and this results mostly from the longer tail at the lower end of the distribution.

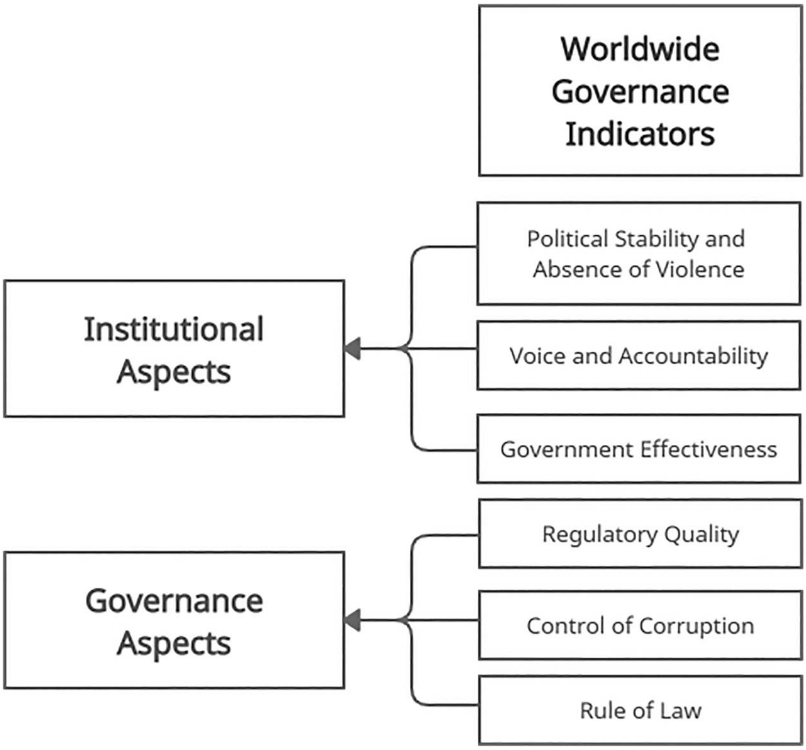

Figure 3. Worldwide Governance Indicators and the summary measures.
Sources: Kaufmann, Kraay, and Mastruzzi (2010), authors.

Some other potential control variables were also considered, but were not used due to lack of general significance or uncertainty over the actual effects on the technology diffusion process as well as to avoid potential overidentification issues. Those other variables include inflation, trade openness, labour force, unemployment and investment.

4. Methodology

4.1. The approach to studying technology diffusion

In order to assess the process of diffusion, this paper uses the contagion model, in other contexts sometimes called the 'epidemic' model of diffusion. As the name suggests, the other contexts are in the medical sciences, specifically epidemiology where it is used to

Table 2. Descriptive statistics of institutions and governance variables.

Variable	Mean	SDev	Min	10th	90th	Max
EU countries						
Institutions	1.012	0.423	−0.095	0.443	1.565	1.858
Governance	1.083	0.610	−0.461	0.259	1.926	2.128
Full cross-section						
Institutions	0.225	0.848	−1.912	−0.807	1.437	1.858
Governance	0.283	0.966	−1.788	−0.819	1.806	2.128

Sources: World Bank, authors' calculations.
Notes: 'Mean' is the arithmetic mean, 'SDev' the standard deviation, 'Min' the minimum, '10th' the 10th, '90th' the 90th percentile, 'Max' the maximum.

Table 3. Descriptive statistics of control variables.

Variable	Unit	Mean	SDev	Min	10th	90th	Max
EU countries							
Real GDP	per capita, log	10.4	0.5	9.2	9.8	10.9	11.7
Human capital	Education Index, [0, 1]	0.80	0.08	0.58	0.69	0.89	0.95
Full cross-section							
Real GDP	per capita, log	9.6	1.0	6.2	8.1	10.8	11.7
Human capital	Education Index, [0, 1]	0.67	0.17	0.18	0.41	0.87	0.95

Sources: World Bank, UNDP, authors' calculations.
Notes: 'Mean' is the arithmetic mean, 'SDev' the standard deviation, 'Min' the minimum, '10th' the 10th, '90th' the 90th percentile, 'Max' the maximum.

predict contagion, endemics and pandemics given certain parameters (such as infection and recovery rates). It is a widely used model in the analysis of technology diffusion in economics (see for example Geroski 2000).[12] The model is based on the logic that exposure or contact to a technology is going to entail adoption of the technology, with the speed of the process and its final point depending on past exposure and a number of other factors.

The epidemic model has interesting features, notably the notion that exposure is a key factor driving diffusion, and so may be sluggish initially, before a critical mass is reached, then accelerating, and finally reaching a plateau, as the maximum reach is attained. However, it does not explicitly quantify the mechanisms contributing to the diffusion dynamics. In this sense, the diffusion model is only a summary model of the diffusion process.

The model has the form:

$$\Delta s_{c,t} = \beta(\tilde{X}_{c,t})[\bar{s}_{c,t}(\bar{X}_{c,t}) - s_{c,t}], \tag{1}$$

a law of motion in which $\Delta s_{c,t}$ is the change in the adoption rate in country c at time t, $\beta(\tilde{X}_{c,t})$ is the speed of diffusion, $s_{c,t}$ is the saturation rate and $\bar{s}_{c,t}(\bar{X}_{c,t})$ is the long-run (saturation level of the) adoption rate. The actual and the long-run saturation rate depend on country characteristics $\tilde{X}_{c,t}$ and $\bar{X}_{c,t}$ respectively. Those sets of country characteristics can be different, as different sets of variables could drive the speed of convergence and the long-run saturation level.

The model in Equation (1) generates an S-shape of (non-linear) adoption process over time that is reflected in the data (see Figures 4 and 5).[13] The speed of adoption picks up in the early stages of adoption and in the later stages falls back as the adoption rate approaches the long-term saturation level. In the model the key role in the diffusion process is the exposure to the technology, which is initially limited, and then increases, up to the point where exposure has no further effects as the technology has already been adopted by most of the agents who are not 'immune' to it.

This pattern of the adoption rate is also consistent with network effects - the fact that the benefits of a technology are higher with a greater spread of that technology. These network effects do not have any obvious analogy in the other contexts in which the model is being used. However, they are important in the context of technology diffusion and support the logic of an S-shaped (non-linear) adoption process over time, and are another reason for the choice of this particular model for the empirical analysis in this paper.

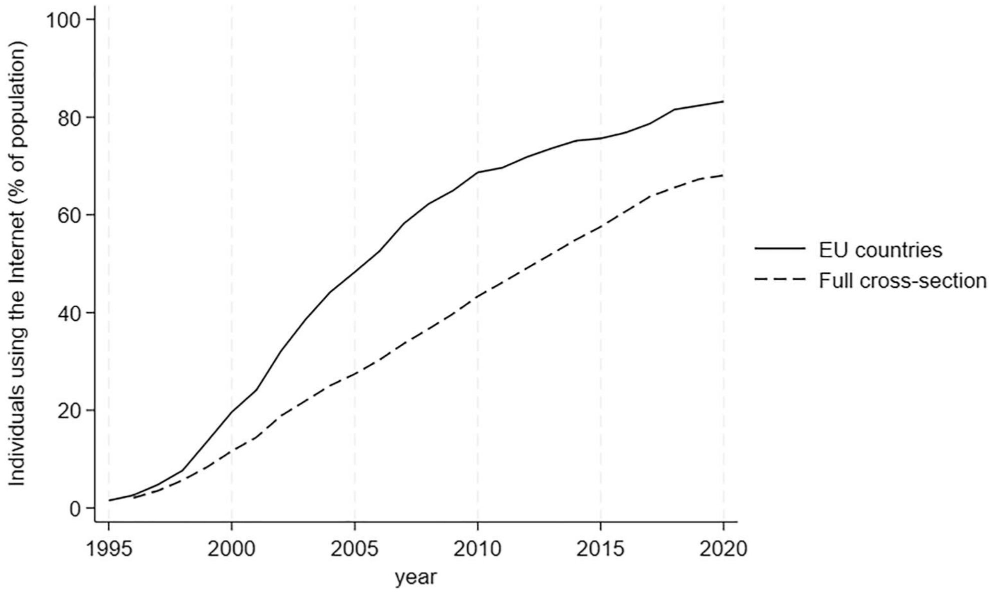

Figure 4. Digital technology adoption, individuals using the internet.
Sources: World Bank, authors' calculations.

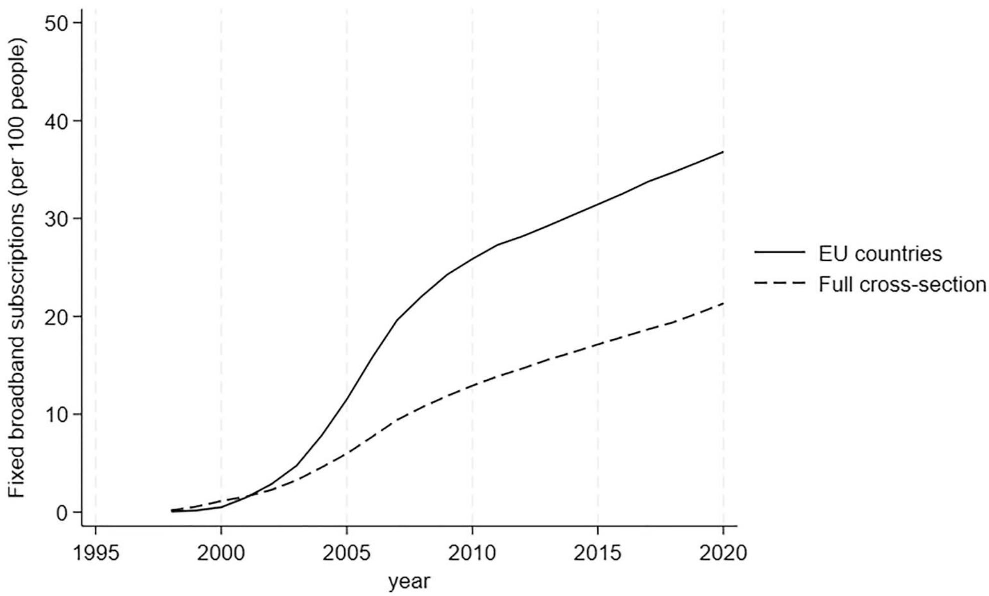

Figure 5. Digital technology adoption, fixed broadband subscriptions.
Sources: World Bank, authors' calculations.

4.2. Empirical implementation

In the empirical implementation, both the speed of technology diffusion and the steady-state adoption rate are allowed to depend on institutions and governance. Results are shown both for a specification in which institutions and governance only affect the steady-state adoption rate, i.e. $\tilde{X}_{c,t} = f(X_{c,t}^{INST})$ and $\bar{X}_{c,t} = f(X_{c,t}^{INST}, X_{c,t}^{DIGI})$, and for a specification in which they affect both the steady-state adoption rate and the speed of diffusion, i.e. $\tilde{X}_{c,t} = f(X_{c,t}^{INST}, X_{c,t}^{DIGI})$ and $\bar{X}_{c,t} = f(X_{c,t}^{INST}, X_{c,t}^{DIGI})$. In contagion model applications, it is also common to control for the first date introduction of the initial adoption of a technology to control for potential variation between countries. As specific times of first adoption are not available, the approach is to study a low level initial threshold, i.e. once the level of adoption exceeds 10%.[14]

In the first case, the estimated equation is:

$$\Delta X_{c,t}^{DIGI} = \beta_1 X_{c,t-1}^{DIGI} + \beta_2 X_{c,t}^{initDIGI} + \beta_3 X_{c,t}^{YSA} + \beta_4 X_{c,t-1}^{INST} + \beta_5 X_{c,t-1}^{C}, \tag{2}$$

where $\Delta X_{c,t}^{DIGI}$ is the change in the adoption rate in country c at time t, $X_{c,t-1}^{DIGI}$ the adoption rate in the previous period, $X_{c,t}^{initDIGI}$ is the year in which the adoption rate passes the low basic threshold, $X_{c,t}^{YSA}$ a variable capturing country-specific years since the adoption rate has passed the threshold, $X_{c,t-1}^{INST}$ is the term capturing institutions and governance aspects and $X_{c,t-1}^{C}$ is the set of control variables, also at time $t-1$. In the second case, the estimated equation is:

$$\Delta X_{c,t}^{DIGI} = \beta_1 X_{c,t-1}^{DIGI} + \beta_2 X_{c,t}^{initDIGI} + \beta_3 X_{c,t}^{YSA} + \beta_4 X_{c,t-1}^{INST} + \beta_5 X_{c,t-1}^{C} + \beta_6 (X_{c,t-1}^{DIGI} x X_{c,t-1}^{INST}) \tag{3}$$

where the terms with coefficients β_1 to β_5 are the same as in Equation (2), and the added term with coefficient β_6 captures the effect of the interaction of digitalisation with institutions and governance on the speed of diffusion.

The linear adoption pattern of years since adoption can be directly interpreted from a policy perspective. The coefficients represent constant marginal effects, allowing policymakers to estimate the expected impact of specific institutional improvements on technology adoption rates. However, the theoretical and empirical literature strongly suggests that technology diffusion typically follows non-linear patterns, with linear models potentially misspecifying the underlying diffusion process.

This aspect is addressed in the third and final case, where Equations (2) and (3) are adjusted to take into account the potential of varying adoption rates and the equations become:

$$\Delta X_{c,t}^{DIGI} = \beta_1 X_{c,t-1}^{DIGI} + \beta_2 \log(X_{c,t}^{YSA}) + \beta_3 X_{c,t-1}^{INST} + \beta_4 X_{c,t-1}^{C} \tag{4}$$

and

$$\Delta X_{c,t}^{DIGI} = \beta_1 X_{c,t-1}^{DIGI} + \beta_2 \log(X_{c,t}^{YSA}) + \beta_3 X_{c,t-1}^{INST} + \beta_4 X_{c,t-1}^{C} + \beta_5 (X_{c,t-1}^{DIGI} x X_{c,t-1}^{INST}), \tag{5}$$

where the years since adoption is logarithmised to allow for non-linear adoption effects beyond the initial level, and the threshold is dropped as the transformation inherently accounts for the different phases of adoption, making a separate threshold parameter redundant as all observations are at or above the threshold.

The non-linear specification in Equations (4) and (5) accounts for the case where the marginal effect of an additional year since initial adoption is likely to be larger in the early stages of diffusion and diminishes over time. Using logarithms effectively compresses later time periods, giving greater weight to the crucial early adoption phase when the foundations of the diffusion process are established. This approach is supported by previous studies such as Comin and Hobijn (2004), which point towards logarithmic time specifications often providing a better fit for long-term diffusion processes.

The control variables in $X^{C}_{c,t-1}$ are the same in all equations. Real GDP per capita is used to control for potential income effects in the diffusion process, and human capital to capture the capability of the population for adopting new technology. The two variables are intended to account for the key economic factors in the process of technological change apart from the institutional and governance aspects under focus in this study.

Turning to the expected signs, the two control variables are likely to have positive signs, suggesting a positive effect on the steady-state diffusion rate in the medium and longer term. Real GDP per capita captures the fact that better-off countries may find it easier to fund investment into digital technologies and/or to facilitate its installation. This should, at least on average, support their spread. Human capital is complementary to new technologies, including digital, and so should also show a positive coefficient. The more human capital is available, the more likely it is that new technologies are explored, evaluated, and, ultimately, adopted.

As for the signs on institutions and governance, the expectation is for a positive effect on the steady-state adoption rate in the medium to long run, i.e. a positive coefficient on the corresponding terms $X^{INST}_{c,t-1}$, and a positive effect on the speed of adoption, i.e. a negative coefficient on the interaction term $(X^{DIGI}_{c,t-1} \times X^{INST}_{c,t-1})$.[15] This is because, as noted in Section 2.2, institutions and governance are considered key elements of the economic framework conditions that support technological advancement and innovation more generally. A negative sign could potentially be possible for institutional environment variables if a higher level of the variable slows down the process of technology adoption.

Before turning to the results, it is worth reiterating that the model described above has one feature that may constitute a caveat in applications to cross-country studies. As noted by Pulkki-Brännström and Stoneman (2013), the epidemic diffusion model effectively describes diffusion as the result of decisions of agents in a specific country and so does not allow for the diffusion in other countries to spill over to that country unless accounted for explicitly, pointing out that such spillovers would likely be positive in the epidemic model. One might even argue that in the context of digital technologies, such cross-country exposure seems particularly relevant and effective, especially in a political and economic union with supranational legislation such as the EU. In other words, not accounting for such spillovers explicitly might lead to the speed and spread of diffusion to be underestimated.

4.3. Technology spillovers, cross-sectional dependence and heteroscedasticity

The potential of cross-section dependence due to spillovers is theoretically expected in a study of technology diffusion for several reasons such as digital technologies inherently creating network effects that cross borders, especially within an integrated system such as the EU common market. When a digital technology becomes widely adopted in one country, it often generates positive externalities for neighbouring countries through knowledge spillovers, shared platforms, and increased compatibility. Multinational corporations also tend to deploy similar technologies across multiple markets simultaneously, creating correlated adoption patterns. Third, many countries, especially within integrated regions like the EU, implement coordinated digital policies, legislation and standards, leading to synchronised technology implementation.

Appendix 3 presents the analysis for the most common methods for studying cross-section dependence and, based on the diagnostics, it appears that at least some level of cross-section dependence can be observed in the sample. To address this potential concern, the estimations are done using Driscoll-Kraay standard errors, which are robust to very general forms of spatial and temporal dependence (Driscoll and Kraay 1998). They are a widely used approach to dealing with potential cross-section dependence and likely provide more realistic standard errors that prevent overestimating the statistical significance of institutional effects.

Additionally, Appendix 4 presents Fixed Effects results with the cross-section weighted Panel Estimated Generalized Least Squares (Panel EGLS) approach, which addresses a different but equally important econometric concern in technology diffusion studies by specifically accounting for country-specific heteroscedasticity and giving appropriate weight to observations based on their error variance structure. Countries differ substantially in their technology infrastructure, economic structure, and population characteristics, all of which can create heterogeneous adoption patterns. This approach also serves as a check for the robustness of the results.

5. Results

This section presents the main results, based on the series 'Individuals using the internet' and 'Fixed broadband subscriptions' as described in Section 3.2 to capture digital technology and the summary measures for 'Institutions' and 'Governance' introduced in Section 3.3. Section 5.1 presents the results for the EU countries and 5.2 for the full cross-section. In both sections, the focus is first on the spread of digital technologies and then on the speed of diffusion.

The effect on the rate of adoption is captured by the coefficients of the lagged dependent variable and, where included, the lagged interaction terms, while the effect on the long-run level of digital adoption is captured by the coefficient on the institutional variables and controls. For the lagged dependent variable and interaction terms, a negative sign means a positive effect on the rate of digital adoption; for the other terms, a positive coefficient means a positive effect on the long-term level of digital adoption.

5.1. EU countries

Table 4 presents the results of the baseline model for EU countries. Institutions are generally insignificant while governance aspects are either insignificant or have highly significant negative effects for both digitalisation variables in the case of the non-linear adoption pattern.

The measures of digital technology (internet use or broadband subscriptions) are significant, and the magnitude of the effect does not depend on the choice of measure for institutions and governance.

The overall fit of the model is very good, and even higher when digital technologies are captured by means of broadband subscriptions. When it comes to the control variables, human capital is significant in a majority of cases, pointing towards an essential role in the

Table 4. Results for EU countries.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Technology								
Internet(−1)	−0.292***	−0.406***	−0.293***	−0.400***				
	(0.017)	(0.070)	(0.017)	(0.071)				
Broadband(−1)					−0.341***	−0.418***	−0.343***	−0.423***
					(0.031)	(0.063)	(0.031)	(0.068)
Years since adoption	0.005***	0.137***	0.004***	0.129***	0.005	0.049*	0.005	0.049*
	(0.001)	(0.061)	(0.001)	(0.065)	(0.005)	(0.024)	(0.005)	(0.027)
Threshold effect	0.292***		0.294***		0.102		0.102	
	(0.045)		(0.045)		(0.062)		(0.063)	
Institutional environment								
Institutions(−1)	0.053	0.017			0.108	0.040		
	(0.047)	(0.050)			(0.145)	(0.041)		
Governance(−1)			−0.042	−0.115***			0.180	−0.102***
			(0.027)	(0.034)			(0.114)	(0.018)
Controls								
Real GDP(−1)	0.023	−0.086	0.079	−0.005	0.094	0.087***	0.023	0.134***
	(0.062)	(0.085)	(0.073)	(0.092)	(0.090)	(0.032)	(0.094)	(0.032)
Human capital(−1)	0.422**	0.486***	0.439**	0.301*	0.798	0.791*	1.037	0.593
	(0.181)	(0.162)	(0.178)	(0.166)	(0.868)	(0.426)	0.859	(0.408)
Constant								
Constant	0.265	1.888	−0.221	1.326	−0.727	−0.294	−0.266	−0.458
	(0.653)	(1.110)	(0.775)	(1.149)	(1.292)	(0.414)	(1.310)	(0.387)
Adoption pattern	linear	log	linear	log	linear	log	linear	log
Sample start	1996	1996	1996	1996	1998	1998	1998	1998
Sample end	2020	2020	2020	2020	2020	2020	2020	2020
N	648	575	648	575	527	419	527	419
F-stat	736.1***	309.9***	885.9***	400.8***	83.5***	158.4***	82.2***	248.1***
Within R^2	0.75	0.73	0.75	0.74	0.82	0.81	0.82	0.82

Notes: Fixed Effect (country) estimates of the change in technology (dependent variable) on the past level of technology, institutional environment and controls. Driscoll-Kraay standard errors in parentheses. *** significant at 1% level, ** significant at 5%, * significant at 10%.

spread of digitalisation. Real GDP per capita is only significant when the diffusion of fixed broadband connections is studied, which could imply that a higher level of economic development is needed to establish more advanced digital structures and connections.

When the interaction terms between digitalisation variables and institutions and governance are introduced in Table 5, the results for institutions suggest that a model taking into account the interaction with digital adoption performs slightly better for EU countries, and the interaction term is statistically significant in the case of internet use with a linear adoption pattern. This suggests that higher quality institutions can accelerate internet adoption, i.e. the first phase of digitalisation, especially in countries with lower initial levels. For fixed broadband use, the interactions are not significant, indicating different dynamics for more advanced technologies in the EU. The negative effects of governance disappear for the non-linear adoption form.

The coefficients of digitalisation are all significant in Tables 4 and 5. The lagged technology variables have moderate negative coefficients, between -0.258 and -0.414 for internet use and -0.331 and -0.423 for broadband use, suggesting a convergence effect where countries with lower initial adoption catch up at a moderate pace.

The variable of years since adoption shows small but significant positive effects in EU countries, suggesting a gradual diffusion of digital technologies over time. The effects of the logarithmic transformation are substantially larger, indicating an accelerating diffusion in the early years followed by a diminishing marginal rate, consistent with theoretical S-shaped diffusion models.

The other factors contributing positively to digital adoption remain similar when the interactions are included with human capital being more important when it comes to the diffusion of internet use and economic development for fixed broadband use. This suggests that education and skills development is important for early adoption of digitalisation and a higher level of economic development for establishing more advanced digital infrastructure and connections.

The results for the Panel EGLS approach in Tables A5 and A6 are very similar, although institutions are statistically significant for two cases in the baseline model, at least at the 10% level, and governance for both studied cases of broadband use. When it comes to the specification with the interaction terms, the results are the same for institutions when it comes to internet use in the linear adoption form but they are also statistically significant in the non-linear form when it comes to broadband use.

The somewhat weak effects of institutional environments could potentially suggest that they are less important for technology diffusion in the relatively homogeneous EU country group, where institutional frameworks have been well-developed for longer.

5.2. Full cross-section

The baseline results for the full cross-section are presented in Table 6. They are generally similar with the EU when it comes to convergence patterns, although the significance of insitutions is subtantially higher for internet use. This emphasises their importance for technology adoption overall for the full panel, suggesting institutions matter more for advancing the diffusion process in diverse economic environments where institutional variations are broader than within the EU. Governance effects in the full cross-section

Table 5. Results for EU countries (with interaction).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Technology								
Internet(−1)	−0.258***	−0.409***	−0.269***	−0.414***				
	(0.022)	(0.098)	(0.023)	(0.085)				
Broadband(−1)					−0.331***	−0.358***	−0.337***	−0.392***
					(0.054)	(0.130)	(0.038)	(0.117)
Years since adoption	0.006***	0.138**	0.006***	0.128*	0.005	0.040	0.005	0.045
	(0.001)	(0.063)	(0.002)	(0.063)	(0.006)	(0.032)	(0.006)	(0.032)
Threshold effect	0.280***		0.280***		0.107		0.108	
	(0.042)		(0.045)		(0.073)		(0.070)	
Institutional environment								
Institutions(−1)	0.152***	0.009			0.126	0.160		
	(0.032)	(0.116)			(0.227)	(0.189)		
Governance(−1)			0.046	−0.164			0.204	−0.032
			(0.044)	(0.097)			(0.178)	(0.039)
Interactions								
Internet(−1) × Institutions(−1)	−0.038***	0.002						
	(0.013)	(0.024)						
Internet(−1) × Governance(−1)			−0.030**	0.011				
			(0.012)	(0.017)				
Broadband(−1) × Institutions(−1)					−0.011	−0.044		
					(0.056)	(0.057)		
Broadband(−1) × Governance(−1)							−0.008	−0.020
							(0.036)	(0.039)
Controls								
Real GDP(−1)	−0.002	−0.085	0.048	0.009	0.072	0.086***	−0.007	0.127***
	(0.068)	(0.078)	(0.080)	(0.090)	(0.154)	(0.028)	(0.152)	(0.024)
Human capital(−1)	0.401**	0.486***	0.394**	0.288	0.733	0.826*	0.966	0.637
	(0.173)	(0.163)	(0.187)	(0.172)	(0.831)	(0.443)	(0.752)	(0.413)
Constant								
Constant	0.466	1.886*	0.082	1.255	−0.465	−0.473	0.077	−0.513
	(0.693)	(1.094)	(0.851)	(1.110)	(1.678)	(0.559)	(1.560)	(0.440)
Adoption pattern	linear	log	linear	log	linear	log	linear	log
Sample start	1996	1996	1996	1996	1998	1998	1998	1998
Sample end	2020	2020	2020	2020	2020	2020	2020	2020
N	648	575	648	575	527	419	527	419
F-stat	1433.9***	405.3***	1556.1***	628.0***	72.7***	225.4***	72.9***	334.3***
Within R^2	0.76	0.73	0.76	0.74	0.82	0.81	0.82	0.82

Notes: Fixed Effect (country) estimates of the change in technology (dependent variable) on the past level of technology, institutional environment, their interactions and controls. Driscoll-Kraay standard errors in parentheses. *** significant at 1% level, ** significant at 5%, * significant at 10%.

Table 6. Results for the full cross-section.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Technology								
Internet(−1)	−0.194***	−0.403***	−0.196***	−0.399***				
	(0.012)	(0.047)	(0.012)	(0.047)				
Broadband(−1)					−0.237***	−0.440***	−0.238***	−0.443***
					(0.024)	(0.035)	(0.024)	(0.033)
Years since adoption	0.002	0.121***	0.001	0.115***	−0.000	0.060***	−0.000	0.063***
	(0.003)	(0.030)	(0.003)	(0.029)	(0.003)	(0.017)	(0.003)	(0.016)
Threshold effect	0.203***		0.204***		−0.162***		−0.170***	
	(0.035)		(0.034)		(0.050)		(0.050)	
Institutional environment								
Institutions(−1)	0.088***	0.044*			0.124	−0.051		
	(0.024)	(0.024)			(0.079)	(0.039)		
Governance(−1)			−0.018	−0.054***			0.094	−0.137***
			(0.029)	(0.018)			(0.093)	(0.022)
Controls								
Real GDP(−1)	0.092	0.113***	0.138*	0.160***	0.490***	0.097**	0.506***	0.147***
	(0.065)	(0.037)	(0.070)	(0.031)	(0.124)	(0.038)	(0.116)	(0.036)
Human capital(−1)	−0.079	0.485***	−0.079	0.409**	0.469	0.529**	0.505	0.381*
	(0.193)	(0.169)	(0.190)	(0.172)	(0.381)	(0.228)	(0.390)	(0.216)
Constant								
Constant	−0.261	−0.134	−0.666	−0.505	−4.474***	−0.094	−4.641***	−0.402
	(0.605)	(0.433)	(0.654)	(0.382)	(1.212)	(0.408)	(1.117)	(0.382)
Adoption pattern	linear	log	linear	log	linear	log	linear	log
Sample start	1996	1996	1996	1996	1998	1998	1998	1998
Sample end	2020	2020	2020	2020	2020	2020	2020	2020
N	2393	1619	2393	1619	1861	886	1861	886
F-stat	243.3***	152.9***	230.3***	146.1***	137.4***	373.2***	136.5***	405.0***
Within R^2	0.57	0.58	0.57	0.58	0.59	0.79	0.59	0.80

Notes: Fixed Effect (country) estimates of the change in technology (dependent variable) on the past level of technology, institutional environment and controls. Driscoll-Kraay standard errors in parentheses. *** significant at 1% level, ** significant at 5%, * significant at 10%.

mirror those in the EU, showing negative impacts on broadband adoption in logarithmic specifications.

The baseline results for the full cross-country sample imply convergence patterns similar to the EU but with notable differences in magnitude. The technology variables show marginally smaller convergence coefficients (−0.194 to −0.403 for internet use, −0.237 to −0.443 for broadband use), suggesting slightly slower convergence across the more diverse global sample. This indicates that catch-up effects may be smaller in the broader international sample.

The control variables act somewhat differently compared to EU countries as economic development is broadly more significant. Human capital is significant for the cases with logarithmic transformations of years since adoption.

The overall fit of the regression is slightly worse compared to the subsample of EU countries. This might be due to the technology change process having progressed, on average, further in the EU. However, the fit still remains very good.

The results with interaction of technology, institutions and governance for the full cross-section are presented in Table 7. The changes to the baseline model as well as the differences to the results for EU countries are quite notable. In all cases for internet use the coefficients for institutions and governance as well as the interaction terms are highly statistically significant and they get expected signs.

Institutional effects become more variable, with institutions having a positive effect on internet use but having weaker effects for broadband use. The interaction terms remain significant for internet use, suggesting that institutional aspects are technology-specific and more important for basic digital technologies. They also indicate that strong institutions are more beneficial for countries with lower initial adoption rates.

The coefficients for governance are somewhat lower than for institutions. They are, however, positive when the interactions are included in the model. Governance shows significant positive effects for internet adoption, suggesting that governance structures can also be beneficial for technology diffusion in the global context.

Institutional effects are more robust for adoption of internet use in the full cross-section, where both direct effects and interactions with technology variables show relatively consistent significance across specifications. The effects become more variable for broadband use, suggesting that institutional quality may matter most during early stages of digital adoption and in more heterogeneous development contexts.

The threshold effects in the full cross-section differ by technology type, showing positive coefficients for internet adoption but negative ones in the baseline model for broadband connections. This indicates fundamentally different diffusion dynamics across technologies, where basic and advanced digital technologies may follow distinct adoption patterns. The logarithmic specifications for adoption patterns reveal stronger convergence effects with technology coefficients ranging from −0.384 to −0.460.

The overall fits of the models are slightly better for the specifications with interaction terms. This observation gives support to the empirical model and the diffusion model of technology adoption as well as for the idea that technologies and institutions are mutually reinforcing.

The Panel EGLS results in Appendix 4 are very consistent with the results in this Section. Table A7 confirms the significant positive effects of institutions wheras governance is broadly negative. The results including the interaction are very similar and confirm the

Table 7. Results for the full cross-section (with interaction).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Technology, lagged								
Internet(−1)	−0.229***	−0.388***	−0.237***	−0.384***				
	(0.010)	(0.042)	(0.010)	(0.042)				
Broadband(−1)					−0.249***	−0.460***	−0.253***	−0.444***
					(0.022)	(0.050)	(0.022)	(0.050)
Years since adoption	0.006***	0.126***	0.007***	0.117***	0.005	0.063***	0.007*	0.063***
	(0.002)	(0.030)	(0.002)	(0.029)	(0.004)	(0.019)	(0.004)	(0.018)
Threshold effect	0.210***		0.205***		−0.045		−0.029	
	(0.027)		(0.026)		(0.047)		(0.041)	
Institutional environment								
Institutions(−1)	0.160***	0.148***			0.589	0.098		
	(0.023)	(0.042)			(0.073)	(0.075)		
Governance(−1)			0.104***	0.070**			0.092	−0.140***
			(0.033)	(0.033)			(0.091)	(0.044)
Interactions								
Internet(−1) × Institutions(−1)	−0.049***	−0.038***						
	(0.008)	(0.010)						
Internet(−1) × Governance(−1)			−0.055***	−0.035***				
			(0.006)	(0.009)				
Broadband(−1) × Institutions(−1)					−0.060***	0.019		
					(0.013)	(0.022)		
Broadband(−1) × Governance(−1)							−0.062***	0.001
							(0.011)	(0.016)
Controls								
Real GDP(−1)	0.096	0.094***	0.116**	0.125***	0.352**	0.103**	0.323**	0.148***
	(0.059)	(0.039)	(0.055)	(0.030)	(0.133)	(0.038)	(0.129)	(0.035)
Human capital(−1)	0.193	0.604***	0.273	0.602***	0.266	0.489*	0.217	0.377*
	(0.209)	(0.149)	(0.226)	(0.152)	(0.407)	(0.244)	(0.380)	(0.213)
Constant								
Constant	−0.363	−0.061	−0.552	−0.337	-2.929**	−0.080	−2.613**	−0.398
	(0.576)	(0.419)	(0.539)	(0.339)	(1.359)	(0.425)	(1.238)	(0.411)
Adoption pattern	linear	log	linear	log	linear	log	linear	log
Sample start	1996	1996	1996	1996	1998	1998	1998	1998
Sample end	2020	2020	2020	2020	2020	2020	2020	2020
N	2393	1619	2393	1619	1861	886	1861	886
F-stat	426.8***	316.9***	454.2***	416.0***	145.9***	493.6***	161.5***	405.0***
Within R^2	0.60	0.59	0.60	0.59	0.61	0.79	0.61	0.80

Notes: Fixed Effect (country) estimates of the change in technology (dependent variable) on the past level of technology, institutional environment, their interactions and controls. Driscoll-Kraay standard errors in parentheses. *** significant at 1% level, ** significant at 5%, * significant at 10%.

broad significance of the interaction between digitalisation and institutional variables, at least for internet use. This points to institutional benefits being the strongest for countries with lower initial adoption levels.

Economic development is consistently more significant for the full cross-section compared to the EU, particularly for broadband adoption. This might imply that economic factors may be more fundamental to technology diffusion globally than within the EU, especially for more advanced digital technologies. Human capital is significant when the adoption pattern is set as non-linear, which points towards educational factors becoming more important in the later stages of the sample.

5.3. Discussion on the results

Both studied samples have at least some level of cross-dependency, resulting from aspects such as technology spillovers across countries, particularly within regions like the EU. Therefore, the approach of using Driscoll-Kraay standard errors seems more prudent with the Panel EGLS approach providing a broad test for robustness of the results as they are mostly in line with the main results while also controlling for country heterogeneity.

The differences between results with and without controlling for cross-dependency potentially imply that digital technologies create strong cross-border externalities that must be properly accounted for in empirical analysis. Both estimation methods confirm threshold effects in technology adoption, supporting the theoretical foundation of S-curve diffusion dynamics. The persistent technology-specific patterns across methodological approaches suggest that targeted policies for different digital technologies remain important regardless of how spillovers are modelled.

When it comes to linear and non-linear adoption, both seem to perform relatively well, capturing similar effects with some notable differences. When comparing the linear and logarithmic specifications across both samples, the higher convergence coefficients in logarithmic models suggest that technology gaps can close more rapidly than linear models would predict and, therefore, it is important to account for the possibility of non-linear dynamics of digital technology diffusion. The non-linear form is also more compatible with the theoretical S-curve of adoption and is slightly more consistently statistically significant in this study. Both forms provide evidence for thresholds representing critical mass points where network effects accelerate adoption or infrastructure sufficiency thresholds that enable wider technology use.

The differences in the results between EU and the full cross-section reveal some potential effects from differences in economic development levels. The full cross-section shows stronger and more consistent institutional effects, suggesting that institutional quality matters for technology diffusion, particularly in developing economies for basic digital technologies, such as internet adoption. This aligns with theories about institutional barriers to technology adoption being more binding in earlier phases of development. Additionally, when it comes to the speed of diffusion, EU countries tend to receive larger negative coefficients for technology variables. This implies faster convergence and more rapid catch-up effects within the more homogeneous group compared to the full global sample.

The interaction terms get higher coefficients and significance in the full cross-section for both estimation approaches, indicating that institutional benefits for technology adoption are higher for countries starting from lower initial adoption levels. It seems that institutional quality matters more for technology diffusion in heterogeneous country samples that include developing economies, where institutional foundations may be more variable and institutions can help through aspects such as reduced transaction costs, improved property rights protection, and enhanced innovation incentives. The negative interaction terms suggest a catch-up mechanism where countries with weaker initial technology adoption benefit more from institutional improvements, possibly because they can benefit more from technology spillovers or leverage existing technologies developed elsewhere.

The results of the study in Sections 5.1 and 5.2 and Appendix 4 are quite consistent across methodologies when it comes to positive institutional effects, negative interaction terms and non-linear diffusion patterns. The negative effects observed in a majority of cases for governance aspects could be indicative of an increasing level of governance potentially having diminishing returns or barriers to adoption and spreading of advanced new technologies. This could happen, for example, in the case of excessive regulatory barriers to innovation and adoption, especially in contexts where governance structures are extensive but not necessarily efficient.

6. Conclusions

This paper has discussed theoretical mechanisms and empirical evidence for the diffusion of digital technology and how it is affected by national institutions and governance based on data on the use of the internet and broadband subscriptions.

The results demonstrate that institutional quality consistently shows positive effects on internet adoption across most specifications, especially for the global sample, while the effects on broadband adoption are more mixed. This technology-specific pattern suggests that institutional reforms may yield greater benefits in the early stages of digital transformation rather than the later ones.

The results also point to a fundamental difference in how institutions and governance affect the introduction of technologies. Advanced institutions can positively affect the speed at which basic means of access to digital technologies are adopted. The process of digitalisation tends to be faster when the quality of institutions and governance is high, and even faster by virtue of the interaction between the level of digitalisation and the quality of institutions and governance.

These observations would lend support to calls for institutions and governance to be designed and managed in line with best international practices, at least when it comes to questions of introducing and adopting new technology. However, policymakers should consider the possibility that fast technology diffusion could lock firms and households into technologies that will be superseded, leading to suboptimal outcomes or potentially lower welfare in the long term (Stoneman 2002).

The significant negative interaction terms between technology variables and institutional measures indicate that countries with lower initial technology adoption benefit more substantially from institutional improvements. This suggests a catch-up effect where high quality institutions can accelerate digital convergence, especially for less digitally advanced countries.

The role of governance is somewhat less clear-cut as more complex regulatory environments appear to slow down technological adoption in many cases, particularly for more sophisticated digital technologies. Regulatory frameworks can, paradoxically, become potential barriers to technological progress if overly complex or rigidly structured.

The results of this study show that the effects of economic development and human capital were somewhat dependent on the studied country group and sample length. Both factors are stronger and more consistently positive in the specification which includes logarithmic specifications of time since adoption, particularly for broadband use. This suggests that the actual process of diffusion might vary due to heterogeneous societal environments. Economic development seems to become increasingly important for more advanced digital technologies, while human capital and institutional quality may be relatively more important for basic digital adoption. It also seems that basic digital technologies have effectively spread to countries around the world, but adoption of more complex technologies has somewhat diverged and their adoption is characterised by slower diffusion.

The methodological comparison between the baseline models with comprehensive controls for technology spillovers and robustness checks reveals how cross-sectional dependence affects the estimation results. The substantially stronger convergence coefficients for the logarithmic approach indicate that properly accounting for adoption patterns and spillover effects is crucial for correctly estimating diffusion speeds and isolating country-specific factors. The findings also highlight potential non-linear temporal dynamics of digital diffusion, as evidenced by the significant coefficients on years since adoption in the logarithmic specifications. This suggests that the diffusion process seems to follow the expected S-shaped curve rather than linear progression, with initial adoption phases potentially requiring different policy approaches than later diffusion stages.

In order to understand the mechanisms and their empirical relevance better, data covering other aspects of the framework conditions would be very desirable. This suggests that traditional data providers should be encouraged to enhance their coverage, and other sources secured that could provide further information and insight, notably big data. Such sources could go some way towards more timely and more granular analysis. To make full use of them, efforts should also be made to upgrade and adapt existing empirical methodologies, and secure new ones, specifically designed for such data.

Finally, the results have some potential policy implications, which should also take into account the differentiated nature of technological adoption as well as the dependencies and spillovers across technologies. For simple digital technologies, policies should focus on maintaining the current momentum of adoption and advancing adoption rates to sufficiently high levels to enable individuals and countries to benefit from the process of digitalisation. For more complex digitalisation infrastructures there is a need for targeted reforms to ensure the streamlining of regulatory processes, providing targeted support and resources in assisting adoption, creating more flexible institutional frameworks and developing specialised capacity-building programmes where adoption rates and infrastructures remain low.

Additionally, the results might imply that institutional quality improvements yield the greatest technology diffusion benefits when initial adoption rates are lower and institutional levels weaker. On the other hand, governance reforms should aim on improving the quality and efficiency of governance rather than only expanding regulatory structures. The differing patterns between internet use and broadband adoption suggest that policies targeting infrastructure-based technologies may require different type of institutional support than those targeting broader technology use. As the process of digitalisation is constantly evolving, this requires a dynamic approach to regulation that can rapidly respond to technological evolution to provide a balanced approach between the protection of property and users' rights on one hand and the promotion of technological advances on the other, not least from a welfare perspective. This has large-scale implications on adoption of new forms of technology, such as artificial intelligence, which require advanced institutions, digital infrastructures and skills.

Notes

1. For a broad summary and references, see for example Anderton et al. (2020) and Anderton and Cette (2021).
2. For a survey, see for example, Degryse (2016), Hüther (2016) or OECD (2019).
3. A related issue, which we do not cover here, is the measurement of productivity. It is discussed in some detail in Anderton and Cette (2021).
4. In parallel, it is still not entirely clear to what extent the measurement of productivity is impaired due to the technological change associated with digitalisation, see for example Anderton et al. (2020) and the references therein.
5. A similar approach is taken to study the effects of institutions and governance in Labhard and Lehtimäki (2022) with a focus on the economic growth effects of digitalisation and Labhard and Lehtimäki (2025) on the diffusion of climate change technology and policies.
6. See for example Bass (1969) and Mahajan and Peterson (1985).
7. See for example Schelling (1971, 1978), Granovetter (1978) and Granovetter and Soong (1988).
8. Some of these points are discussed in a European context in Evangelista, Guerrieri, and Meliciani (2014).
9. As noted by David (1989, 1990) for example, 'computers are not dynamos', have complexities and special attributes, including the challenges related to measurement, which distinguish digital technology from traditional technologies.
10. A comprehensive study into growth effects, including those that might be attributed to institutions, is available in Bassanini, Scarpetta, and Hemmings (2001).
11. For example Lehtimäki and Sondermann (2022).
12. The model has also been applied to other fields in economics, such as economic convergence (alpha convergence, in terms of levels). Alternative approaches have also been taken to study similar dynamics, such as incorporating technology diffusion into a neoclassical growth model (Comin and Hobijn 2010) or using Bayesian hierarchical models to analyse cross-country cross-technology differences (Hoffreumon and Labhard 2022).
13. A technical comparison and analysis of diffusion models and the shapes they generate in the context of technology diffusion can be found in Jaakkola (1996).
14. A threshold of 5% was also studied with broadly similar results.
15. For Equations (2)–(5), in the case of the lagged dependent variable and interaction terms, a negative sign means a positive effect on the rate of digital adoption; in the case of the other terms, a positive coefficient means a positive effect on the long-term level of digital adoption.

Acknowledgments

The views expressed in this paper are those of the authors and do not necessarily reflect those of any of the institutions the authors are or have been affiliated to. The work has benefited from comments by colleagues and seminar participants at the Bank of Canada, the European Central Bank, the Federal Reserve Board, the IMF, and the World Bank. In particular, we would like to thank R. Anderton, A. Dieppe, R. Duval, D. Filip, M. Hallward-Driemeier, P. Schulte and R.J. Singh, as well as three anonymous referees for their thoughts and suggestions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Acemoglu, Daron. 2012. "Introduction to Economic Growth." *Journal of Economic Theory* 147 (2): 545–550. https://doi.org/10.1016/j.jet.2012.01.023.

Acemoglu, Daron, Simon Johnson, and James A. Robinson. 2005. "Institutions as a Fundamental Cause of Long-Run Growth." *Handbook of Economic Growth* 1A:385–472. https://doi.org/10.1016/S1574-0684(05)01006-3.

Acemoglu, Daron, and Pascual Restrepo. 2019. "Automation and New Tasks: How Technology Displaces and Reinstates Labor." *Journal of Economic Perspectives* 33 (2): 3–30. https://doi.org/10.1257/jep.33.2.3.

Anderton, Robert, and Gilbert Cette, eds. 2021. "Digitalisation: Channels, Impacts and Implications for Monetary Policy." *ECB Occasional Paper* no 266.

Anderton, Robert, Valerie Jarvis, Vincent Labhard, Lara Vivian, Julian Morgan, and Filippos Petroulakis. 2020. "Virtually Everywhere? Digitalisation and the Euro Area and EU Economies. Degree, Effects and Key Issues." *ECB Occasional Paper* no 244.

Bass, Frank M. 1969. "A New Product Growth Model for Consumer Durables." *Management Science*15 (5): 215–227. https://doi.org/10.1287/mnsc.15.5.215.

Bassanini, Andrea, Stefano Scarpetta, and Philip Hemmings. 2001. "Economic Growth: The Role of Policies and Institutions. Panel Data Evidence from OECD Countries." *OECD Economics Department Working Paper* no 283.

Bresnahan, Timothy F., and Manuel Trajtenberg. 1995. "General Purpose Technologies." *Journal of Econometrics* 65 (1): 83–108. https://doi.org/10.1016/0304-4076(94)01598-T.

Cockburn, Iain M., Rebecca Henderson, and Scott Stern. 2018. "The Impact of Artificial Intelligence on Innovation." *NBER Working Paper* no 24449.

Comin, Diego, and Bart Hobijn. 2004. "Cross-Country Technology Adoption: Making the Theories Fit the Facts." *Journal of Monetary Economics* 51 (1): 39–83. https://doi.org/10.1016/j.jmoneco.2003.07.003.

Comin, Diego, and Bart Hobijn. 2010. "An Exploration of Technology Diffusion." *American Economic Review* 100 (5): 2031–2059. https://doi.org/10.1257/aer.100.5.2031.

David, Paul A. 1989. "Computer and Dynamo: The Modern Productivity Paradox in a Not-too-Distant Mirror." *Warwick Economics Research Paper* no 339.

David, Paul A. 1990. "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox." *American Economic Review* 80 (2): 355–361.

Degryse, Christophe. 2016. "Digitalisation of the Economy and Its Impact on Labour Markets." *ETUI Research Paper-Working Paper* no 2016.2.

Dellepiane-Avellaneda, Sebastian. 2010. "Good Governance, Institutions and Economic Development: Beyond the Conventional Wisdom." *British Journal of Political Science* 40 (1): 195–224. https://doi.org/10.1017/S0007123409990287.

Dreher, Axel. 2006. "Does Globalization Affect Growth? Evidence from a New Index of Globalization." *Applied Economics* 38 (10): 1091–1110. https://doi.org/10.1080/00036840500392078.

Driscoll, John C., and Aart C. Kraay. 1998. "Consistent Covariance Matrix Estimation with Spatially Dependent Panel Data." *Review of Economics and Statistics* 80 (4): 549–560. https://doi.org/10.1162/003465398557825.

Evangelista, Rinaldo, Paolo Guerrieri, and Valentina Meliciani. 2014. "The Economic Impact of Digital Technologies in Europe." *Economics of Innovation and New Technology* 23 (8): 802–24. https://doi.org/10.1080/10438599.2014.918438.

Gal, Peter, Giuseppe Nicoletti, Stéphane Sorbe, and Christina Timiliotis. 2019. "Digital Dividend: Policies to Harness the Productivity Potential of Digital Technologies." *OECD Economic Policy Papers* no 26.

Geroski, Paul A. 2000. "Models of Technology Diffusion." *Research Policy* 29 (4-5): 603–625. https://doi.org/10.1016/S0048-7333(99)00092-X.

Goldfarb, Avi, and Catherine Tucker. 2019. "Digital Economics." *Journal of Economic Literature* 57 (1): 3–43. https://doi.org/10.1257/jel.20171452.

Gordon, Robert J. 2016. *The Rise and Fall of American Growth*. Princeton, NJ: Princeton University Press.

Granovetter, Mark. 1978. "Threshold Models of Collective Behavior." *American Journal of Sociology* 83 (6): 1420–43. https://doi.org/10.1086/226707.

Granovetter, Mark, and Roland Soong. 1988. "Threshold Models of Diversity: Chinese Restaurants, Residential Segregation, and the Spiral of Silence." *Sociological Methodology* 18:69–104. https://doi.org/10.2307/271045.

Gwartney, James, Robert Lawson, Joshua Hall, Ryan Murphy, Daniel L Bennett, Rosemarie Fike, Fred McMahon, and Boris Nikolaev. 2019. *Economic Freedom of the World: 2019 Annual Report*. Fraser Institute.

Gygli, Savina, Florian Haelg, Niklas Potrafke, and Jan-Egbert Sturm. 2019. "The KOF Globalisation Index – Revisited." *The Review of International Organizations* 14 (3): 543–574. https://doi.org/10.1007/s11558-019-09344-2.

Hoffreumon, Charles, and Vincent Labhard. 2022. "Cross-Country Cross-Technology Digitalisation: A Bayesian Hierarchical Model Perspective." *ECB Working Paper* no 2700.

Hüther, Michael. 2016. "Digitalisation: An Engine for Structural Change – A Challenge for Economic Policy." *IW Policy Paper* no 15/2016E.

Jaakkola, Hannu. 1996. "Comparison and Analysis of Diffusion Models." In *Diffusion and Adoption of Information Technology*, edited by Karlheinz Kautz and Jan Pries-Heje, 65–82. Heidelberg: Springer.

Jovanovic, Boyan, and Peter L. Rousseau. 2005. *General Purpose Technologies*. Amsterdam: Elsevier.

Katz, Raul L., Pantelis Koutroumpis, and Fernando Martin Collarda. 2014. "Using a Digitization Index to Measure the Economic and Social Impact of Digital Agendas." *info* 16:32–44. https://doi.org/10.1108/info-10-2013-0051.

Kaufmann, Daniel, Aart Kraay, and Massimo Mastruzzi. 2010. *Worldwide Governance Indicators*. World Bank Group.

Labhard, Vincent, and Jonne Lehtimäki. 2022. "Digitalisation, Institutions and Governance, and Growth: Mechanisms and Evidence." *ECB Working Paper* No 2735.

Labhard, Vincent, and Jonne Lehtimäki. 2025. "Climate Change Policies and Technologies: Diffusion and Interaction with Institutions and Governance." *ECB Working Paper* No 3027.

Lehtimäki, Jonne, and David Sondermann. 2022. "Baldwin versus Cecchini Revisited: The Growth Impact of the European Single Market." *Empirical Economics* 63 (2): 603–635. https://doi.org/10.1007/s00181-021-02161-w.

Lipsey, Richard, Kenneth I. Carlaw, and Clifford T. Bekhar. 2005. *Economic Transformations: General Purpose Technologies and Long Term Economic Growth*. Oxford: Oxford University Press.

Mahajan, Vijay, and Robert A. Peterson. 1985. *Models for Innovation Diffusion*. Newbury Park, CA: Sage Publications.

Milkau, Udo, and Jürgen Bott. 2015. "Digitalisation in Payments: From Interoperability to Centralised Models?" *Journal of Payments Strategy & Systems* 9 (3): 321–340. https://doi.org/10.69554/KUAW4429.

North, Douglass C. 1991. "Institutions." *Journal of Economic Perspectives* 5 (1): 97–112. https://doi.org/10.1257/jep.5.1.97.

OECD. 2019. "Digitalisation and Productivity: A Story of Complementarities." *OECD Economic Outlook* 1.

Pulkki-Brännström, Anni-Maria, and Paul Stoneman. 2013. "On the Patterns and Determinants of the Global Diffusion of New Technologies." *Research Policy* 42 (10): 1768–1779. https://doi.org/10.1016/j.respol.2013.08.011.

Schelling, Thomas C. 1971. "Dynamic Models of Segregation." *Journal of Mathematical Sociology* 1 (2): 143–86. https://doi.org/10.1080/0022250X.1971.9989794.

Schelling, Thomas C. 1978. *Micromotives and Macrobehavior*. New York City, NY: Norton.

Stokey, Nancy. 2020. "Technology Diffusion." *NBER Working Paper* no 27466.

Stoneman, Paul. 2002. *The Economics of Technological Diffusion*. Hoboken, NJ: John Wiley and Sons Ltd.

Trajtenberg, Manuel. 2018. "AI as the Next GPT: A Political-Economy Perspective." *NBER Working Paper* no 24245.

Williamson, Oliver E. 1998. "The Institutions and Governance of Economic Development and Reform." *American Economic Review* 88 (2): 75–79.

Young, H. Peyton. 2010. "Innovation Diffusion in Heterogeneous Populations: Contagion, Social Influence, and Social Learning." *American Economic Review* 99 (5): 1899–1924. https://doi.org/10.1257/aer.99.5.1899.

Appendices

Appendix 1. Data

Table A1. Countries and country aggregates.

EU countries (27)
Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden
Full cross-section (100)
Albania, Algeria, Argentina, Armenia, Australia, Austria, Azerbaijan, Barbados, Belarus, Belgium, Benin, Bolivia, Brazil, Bulgaria, Cambodia, Cameroon, Canada, Chile, China, Colombia, Costa Rica, Côte d'Ivoire, Croatia, Cyprus, Czech Republic, Denmark, Dominican Republic, Ecuador, Egypt, El Salvador, Estonia, Finland, France, Gabon, Gambia, Georgia, Germany, Ghana, Greece, Hong Kong, Hungary, Iceland, India, Indonesia, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kazakhstan, Kenya, Korea, Kyrgyz Republic, Latvia, Lithuania, Luxembourg, Malaysia, Malta, Mauritania, Mauritius, Mexico, Moldova, Mongolia, Morocco, Mozambique, Nepal, Netherlands, New Zealand, Norway, Pakistan, Panama, Paraguay, Peru, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Senegal, Singapore, Slovak Republic, Slovenia, South Africa, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Tanzania, Thailand, Togo, Tunisia, Turkey, Ukraine, United Kingdom, United States, Uruguay, Vietnam, Zimbabwe

Notes: For the purposes of this paper, 'EU countries' are the EU27.

Appendix 2. Descriptive statistics for WGI summary measures

Table A2. Variables.

Variable/Description (and transformation)	Code	Source
Institutions (average of GE.EST, PS.EST, VA.EST)	–	WB, Authors
Governance (average of CC.EST, RQ.EST, RL.EST)	–	WB, Authors
Fixed broadband subscriptions (per 100 people, in logs)	IT.NET.BBND	WB
Individuals using the Internet (% of population)	IT.NET.USER.ZS	WB
Real GDP per capita (log)	NY.GDP.PCAP.KD	WB
Human capital, Education Index	–	UNDP

Notes: WB stands for World Bank, UNDP for the United Nations Development Programme. In the WGI institutional measures, CC stands for 'Control of Corruption', GE for 'Government Effectiveness, PS for 'Political Stability and Absence of Violence/Terrorism', RL for 'Rule of Law', RQ for 'Regulatory Quality' and VA for 'Voice and Accountability'.

Appendix 3. Tests for cross-section dependence

Table A3. Descriptive statistics for institutional variables.

Variable	Unit	Mean	SDev	Min	10th	90th	Max
EU countries							
Institutions	average of GE, PS, VA	1.022	0.419	−0.095	0.469	1.570	1.858
Governance	average of CC, RQ, RL	1.109	0.614	−0.461	0.270	1.927	2.128
Full cross-section							
Institutions	average of GE, PS, VA	0.234	0.851	−1.912	−0.806	1.440	1.858
Governance	average of CC, RQ, RL	0.295	0.966	−1.788	−0.820	1.806	2.128

Sources: World Bank, authors' calculations.

Notes: 'Mean' is the arithmetic mean, 'SDev' the standard deviation, 'Min' the minimum, '10th' the 10th, '90th' the 90th percentile, 'Max' the maximum. In the WGI institutional measures, CC stands for 'Control of Corruption', GE for 'Government Effectiveness, PS for 'Political Stability and Absence of Violence/Terrorism', RL for 'Rule of Law', RQ for 'Regulatory Quality' and VA for 'Voice and Accountability'.

Appendix 4. Panel EGLS results

Table A4. Tests for cross-section dependence.

	Pesaran CD-statistic	Probability
EU countries		
Individuals using internet	91.5	0.000
Fixed broadband	80.2	0.000
Full cross-section		
Individuals using internet	314.6	0.000
Fixed boadband	262.9	0.000

Notes: Only Pesaran CD-statistics are listed but similar diagnostics were given by Breusch-Pagan LM, Pesaran scaled LM and bias-corrected scaled LM.

Table A5. Results for EU countries.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Technology								
Internet(−1)	−0.272***	−0.381***	−0.274***	−0.377***				
	(0.018)	(0.043)	(0.016)	(0.046)				
Broadband(−1)					−0.350***	−0.385***	−0.349***	−0.383***
					(0.017)	(0.022)	(0.018)	(0.022)
Years since adoption	0.004***	0.121***	0.002**	0.119***	0.004*	0.042**	0.004**	0.036**
	(0.001)	(0.036)	(0.001)	(0.040)	(0.002)	(0.015)	(0.002)	(0.014)
Threshold effect	0.289***		0.294***		0.104***		0.102***	
	(0.035)		(0.035)		(0.027)		(0.029)	
Institutional environment								
Institutions(−1)	0.061*	0.011			−0.013	0.042**		
	(0.036)	(0.039)			(0.065)	(0.019)		
Governance(−1)			−0.024	−0.105***			−0.089**	−0.097***
			(0.033)	(0.035)			(0.032)	(0.019)
Controls								
Real GDP(−1)	0.026	−0.059	0.069	−0.006	0.065*	0.088***	0.096	0.117***
	(0.042)	(0.063)	(0.050)	(0.064)	(0.033)	(0.027)	(0.060)	(0.030)
Human capital(−1)	0.232	0.421***	0.330	0.266*	0.611***	0.576***	0.178	0.444**
	(0.234)	(0.136)	(0.217)	(0.143)	(0.163)	(0.147)	(0.278)	(0.159)
Constant								
Constant	0.317	1.596**	−0.105	1.291	0.311	−0.004	−0.014	−0.263
	(0.405)	(0.768)	(0.509)	(0.779)	(0.610)	(0.367)	(0.656)	(0.341)
Adoption pattern	linear	log	linear	log	linear	log	linear	log
Sample start	1996	1996	1996	1996	1998	1998	1998	1998
Sample end	2020	2020	2020	2020	2020	2020	2020	2020
N	648	575	648	575	527	419	527	419
F-stat	82.5***	58.9***	80.4***	58.9***	230.0***	126.2***	233.8***	128.4***
Adjusted R^2	0.80	0.76	0.80	0.76	0.93	0.90	0.93	0.90

Notes: Fixed Effect (country) estimates of the change in technology (dependent variable) on the past level of technology, institutional environment and controls. White cross-section robust standard errors in parentheses. Adjusted R^2 is cross-section weighted. *** significant at 1% level, ** significant at 5%, * significant at 10%.

Table A6. Results for EU countries (with interaction).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Technology								
Internet(−1)	−0.246***	−0.373***	−0.252***	−0.374***				
	(0.014)	(0.059)	(0.015)	(0.057)				
Broadband(−1)					−0.319***	−0.255***	−0.331***	−0.306***
					(0.014)	(0.041)	(0.011)	(0.039)
Years since adoption	0.004***	0.120***	0.004***	0.119***	0.005*	0.020	0.006**	0.020
	(0.001)	(0.038)	(0.001)	(0.041)	(0.003)	(0.016)	(0.003)	(0.016)
Threshold effect	0.276***		0.275***		0.119***		0.122***	
	(0.029)		(0.030)		(0.035)		(0.039)	
Institutional environment								
Institutions(−1)	0.112***	0.029			0.076	0.293***		
	(0.036)	(0.084)			(0.101)	(0.091)		
Governance(−1)			0.028	−0.091			−0.001	0.051
			(0.031)	(0.082)			(0.066)	(0.067)
Interactions								
Internet(−1) × Institutions(−1)	−0.026***	−0.005						
	(0.006)	(0.016)						
Internet(−1) × Governance(−1)			−0.023***	−0.003				
			(0.005)	(0.014)				
Broadband(−1) × Institutions(−1)					−0.033	−0.087***		
					(0.022)	(0.027)		
Broadband(−1) × Governance(−1)							−0.023	−0.041**
							(0.015)	(0.017)
Controls								
Real GDP(−1)	0.014	−0.061	0.051	−0.010	0.012	0.081**	0.031	0.115***
	(0.070)	(0.058)	(0.067)	(0.059)	(0.059)	(0.032)	(0.065)	(0.029)
Human capital(−1)	0.187	0.421***	0.224	0.266*	0.304	0.673***	0.150	0.572***
	(0.188)	(0.136)	(0.177)	(0.145)	(0.269)	(0.149)	(0.244)	(0.169)
Constant								
Constant	0.440	1.598**	0.134	1.308*	0.581	−0.566	0.593	−0.571
	(0.741)	(0.759)	(0.746)	(0.758)	(0.664)	(0.418)	(0.689)	(0.412)
Adoption pattern	linear	log	linear	log	linear	log	linear	log
Sample start	1996	1996	1996	1996	1998	1998	1998	1998
Sample end	2020	2020	2020	2020	2020	2020	2020	2020
N	648	549	648	549	527	392	527	392
F-stat	80.4***	57.1***	81.4***	56.6***	232.2***	135.0***	226.9***	127.5***
Adjusted R^2	0.80	0.76	0.80	0.76	0.94	0.91	0.93	0.91

Notes: Fixed Effect (country) estimates of the change in technology (dependent variable) on the past level of technology, institutional environment, their interactions and controls. White cross-section robust standard errors in parentheses. Adjusted R^2 is cross-section weighted. *** significant at 1% level, ** significant at 5%, * significant at 10%.

Table A7. Results for full cross-section.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Technology								
Internet(−1)	−0.198***	−0.373***	−0.200***	−0.366***				
	(0.010)	(0.032)	(0.010)	(0.033)				
Broadband(−1)					−0.244***	−0.439***	−0.247***	−0.438***
					(0.010)	(0.011)	(0.011)	(0.013)
Years since adoption	0.001	0.113***	0.000	0.105***	0.001	0.069***	−0.000	0.068***
	(0.001)	(0.022)	(0.001)	(0.022)	(0.002)	(0.004)	(0.002)	(0.005)
Threshold effect	0.215***		0.219***		−0.104***		−0.105***	
	(0.028)		(0.028)		(0.023)		(0.023)	
Institutional environment								
Institutions(−1)	0.069***	0.062***			0.113**	−0.030		
	(0.021)	(0.016)			(0.052)	(0.023)		
Governance(−1)			−0.033	−0.034*			−0.063**	−0.101***
			(0.024)	(0.020)			(0.023)	(0.013)
Controls								
Real GDP(−1)	0.033	0.081**	0.072**	0.111***	0.282***	0.069***	0.383***	0.113***
	(0.034)	(0.029)	(0.034)	(0.030)	(0.042)	(0.024)	(0.064)	(0.027)
Human capital(−1)	−0.154	0.246**	−0.107	0.222*	0.068	0.397***	−0.043	0.321***
	(0.111)	(0.110)	(0.109)	(0.111)	(0.192)	(0.058)	(0.202)	(0.070)
Constant								
Constant	0.366	0.258	−0.014	0.012	−2.190***	0.242	−3.039***	−9.092
	(0.319)	(0.316)	(0.318)	(0.320)	(0.445)	(0.246)	(0.599)	(0.257)
Adoption pattern	linear	log	linear	log	linear	log	linear	log
Sample start	1996	1996	1996	1996	1998	1998	1998	1998
Sample end	2020	2020	2020	2020	2020	2020	2020	2020
N	2393	1689	2393	1689	1861	1861	1861	1861
F-stat	52.9***	40.1***	53.0***	39.8***	84.7***	200.6***	82.8***	162.6***
Adjusted R^2	0.69	0.71	0.70	0.70	0.83	0.96	0.82	0.95

Notes: Notes: Fixed Effect (country) estimates of the change in technology (dependent variable) on the past level of technology, institutional environment and controls. White cross-section robust standard errors in parentheses. Adjusted R^2 is cross-section weighted. *** significant at 1% level, ** significant at 5%, * significant at 10%.

Table A8. Results for full cross-section (with interaction).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Technology, lagged								
Internet(−1)	−0.217***	−0.343***	−0.222***	−0.337***				
	(0.009)	(0.026)	(0.009)	(0.027)				
Broadband(−1)					−0.243***	−0.452***	−0.246***	−0.445***
					(0.008)	(0.027)	(0.008)	(0.020)
Years since adoption	0.004***	0.109***	0.005***	0.098***	0.006***	0.070***	0.007***	0.070***
	(0.001)	(0.020)	(0.001)	(0.020)	(0.002)	(0.009)	(0.002)	(0.007)
Threshold effect	0.228***		0.118***		0.019		0.012	
	(0.028)		(0.030)		(0.019)		(0.017)	
Institutional environment								
Institutions(−1)	0.164***	0.212***			0.144**	−0.067		
	(0.024)	(0.026)			(0.052)	(0.052)		
Governance(−1)			0.118***	0.142***			0.093***	−0.110***
			(0.029)	(0.021)			(0.031)	(0.028)
Interactions								
Internet(−1) × Institutions(−1)	−0.051***	−0.052***						
	(0.005)	(0.007)						
Internet(−1) × Governance(−1)			−0.051***	−0.045***				
			(0.003)	(0.006)				
Broadband(−1) × Institutions(−1)					−0.065***	−0.010		
					(0.006)	(0.013)		
Broadband(−1) × Governance(−1)							−0.058***	0.003
							(0.005)	(0.007)
Controls								
Real GDP(−1)	0.032	0.028	0.052	0.056*	0.137**	0.074***	0.163**	0.114***
	(0.034)	(0.030)	(0.034)	(0.028)	(0.052)	(0.023)	(0.062)	(0.024)
Human capital(−1)	0.145	0.484***	0.276**	0.564***	−0.095	0.384***	−0.094	0.311***
	(0.112)	(0.100)	(0.126)	(0.100)	(0.203)	(0.078)	(0.183)	(0.065)
Constant								
Constant	0.249	0.535*	0.009	0.220	−0.638	0.240	−0.871	−0.069
	(0.336)	(0.310)	(0.335)	(0.301)	(0.598)	(0.270)	(0.631)	(0.264)
Adoption pattern	linear	log	linear	log	linear	log	linear	log
Sample start	1996	1996	1996	1996	1998	1998	1998	1998
Sample end	2020	2020	2020	2020	2020	2020	2020	2020
N	2393	1689	2393	1689	1861	919	1861	919
F-stat	63.9***	45.5***	66.0***	44.6***	129.2***	127.8***	126.9***	161.7***
Adjusted R^2	0.74	0.73	0.74	0.73	0.88	0.94	0.88	0.95

Notes: Fixed Effect (country) estimates of the change in technology (dependent variable) on the past level of technology, institutional environment, their interactions and controls. White cross-section robust standard errors in parentheses. Adjusted R^2 is cross-section weighted. *** significant at 1% level, ** significant at 5%, * significant at 10%.