Title of submission to PLOS journal

Emmanouil Tranos [1] [*]

1 University of Bristol, School of Geographical Sciences, Bristol, UK; The Alan Turing Institute, London, UK

[*] Corresponding author: e.tranos@bristol.ac.uk

Abstract

blah blah

Author summary

blah blah

Introduction

Geographers were always interested in how new technologies and innovations diffuse across space and, importantly, how such spatio-temporal processes can be modelled. The seminal contribution of [1] is illustrative of this early interest. However, the torch of exploring and modelling such processes had been passed to other disciplines such as economics, business studies and sociology well before the 'cultural turn' of economic geography [2]. A potential explanation of lack of studies exploring the diffusion of new and, more specifically, digital technologies across *both* space and time can be attributed to the scarcity of relevant and granular enough data. As [3] highlight, digital activities are hardly ever captured in official data.

This paper aims to reinstate geographers' interest in how new and digital technologies diffuse over space and time. It adopts a geographic standpoint to explore and map the diffusion of web technologies in the UK over space and time. It does so by employing a novel source of big data which captures the active engagement with web technologies during the $1996-2013$ period.

The motivation for this paper lies in the fact that there are various stakeholders who are interested in knowing how new digital technologies diffused over space and time use this information to make predictions regarding the diffusion of related future technologies. As per [4] a variety of actors have a direct interest in gaining such knowledge including network equipment suppliers; network operators, regulatory and local authorities. And despite the spatial heterogeneity of such diffusion mechanisms and the policy relevance, there are very limited attempts in the literature to analyse the diffusion of new digital technologies at a granular level.

the paper answers an empirical question: how did a

[3] Because new digital activities are rarely—if ever—captured in official state data, researchers must rely on information gathered from alternative sources. With this in mind, the overarching aim of this article is outlining an approach for analyzing the "new spaces and geographies" of digital phenomena and practices.

[4] There are numerous agents who would benefit from accurate predictions of introduction times. These include: suppliers of network equipment for production planning; suppliers of mobile phones who need to have inventories of appropriately configured handsets; international network planners who need to provide sufficient bandwidth for communications between different countries; network operators and regulatory authorities.

Classifying adopters of a technology along a time axis was pioneered by Rogers (1962), who categorized adopters into five groups as innovators, early adopters, early majority, late majority and laggards.

An a priori approach groups similar countries into segments, where similarity is defined using economic, social, or political covariates. Examples include Hofstede (2001) and Lee (1990). An a posteriori analysis considers segments based on realized market behaviour, for example see Sood et al. (2009). Some studies investigate changing segment membership over time, see Cannon and Yaprak (2011).

[5] Hägerstrand (1952, 1967) was the first scholar to intensively analyze spatial diffusion pro cesses. Based on the empirical observations of the regional spread of process innovations, he hypothesized that new technology is first implemented in the 'center' – the large agglom erations – and then moves 'down' the spatial hierarchy, the last stop being the 'periphery', i.e. remote and sparsely populated regions. There are at least two factors that may explain this pattern: first, the transfer of tacit knowledge via face-to-face contact and second, the absorptive capacity of a region.

[6] The concept of absorptive capacity has also been applied in the TIS context in terms of the con-struction of capacity needed to transfer and implement a new technology in the receiving country (cf.Van Alphen, 2011), with repercussions for the nature of system functions

[7] larger local technological niches (at least from a demand perspective) are more likely to be formed in urban areas than in rural ones, which is in line with the work of Ha¨gerstrand (1965a,b). However, size is not the only regional characteristic that may matter in this context. Regions also differ in accumulated experiences and the presence of tacit knowledge with respect to products, as well as in actors' propensity share this knowledge among producers (Martin et al., 2019)

To summarize the discussion, first, here the diffusion process is selfperpetuating as initial use stimulates further use. Second, it follows a disequilibrium path as the level of users is always lower than the number of potential users (Stoneman 2002).

The criticisms are mainly based on the fact that although the approach gives an idea of aggregate (industry or household) behaviour, it does not focus on the individual's (firm or household) adoption process

[8] Spatial diffusion is the process by which behavior or characteristics of the landscape change as a result of what happens elsewhere earlier. Spatial diffusion is the spread of the phenomenon, over space and timed, from limited origins

Contagious diffusion=> spatial autocorelation

expansion-type diffusion

The work by the communication sociologist Everett Rogers (1962, 1971, 1983) has emphasized the role of information, communication, formal and informal media, opinion leaders and social networks, and economic and psychological constraints on acceptance. Rogers's work stresses the decision mechanism of the potential adopter; the work of Rogers partitions the adopter's process of choosing to accept a new phenomenon or trait into five stages: stage 1–the potential adopter gains knowledge or awareness of an innovation; stage 2–persuasion is exercised to adopt; stage 3–a decision is made to adopt; stage 4–the decision to adopt is implemented; stage 5–the adopter confirms the decision to adopt. In Rogers's stage theory there may be a substantial time lag between when a potential adopter becomes aware of the new characteristic and when a decision is actually made to adopt.

Hägerstrand considered diffusion to be a fundamental geographic process: Whatever the phenomenon being diffused might be, one may consider it in the context of a larger universal process of spatial diffusion.

[9] Diffusion is a spatial (Hagerstrand, 1967) as well as a temporal process, and historical evidence confirms that technologies diffuse at different times, at different rates, and to different extents in different places, and can be significantly influenced by policies (Victor, 1993).

Lastly, it can be globally optimal for innovative economies to deploy advanced technologies more than what is locally optimal if this enables faster diffusion in less advanced regions that could benefit from the technology.

wilson201281 Early on in their lifecycle, new technologies are crude, imperfect, and expensive (Rosenberg, 1994). New energy technologies are attractive for their ability to perform a particular task or deliver a new or improved energy service (Fouquet, 2010). This is often circumscribed by a particular set of needs in a particular context: a market 'niche'. End-users in niche markets are generally less sensitive to the effective price of the energy service provided or have a higher willingness to pay for its performance advantages (Fouquet, 2010). Thus initially, performance dominates cost competitiveness (Wilson and Grubler, 2011). Market niches afford some protection from competitive pressures, allowing technologies to be tested and improved in applied settings, reducing uncertainties with performance or market demand (Kemp et al., 1998). Costs may only fall substantively after an extended period of commercial experimentation, concurrent with the establishment of an industrial base and characteristic moves towards standardisation and mass production (Grubler, 1998). The influence of accumulating production experience on costs is captured by the concept of learning.

grubler1990rise The scale of spatial innovation diffusion is similar to that of temporal diffusion models: hierarchically decomposed.

[10] Later Hagerstrand conceptualized physical "barrier" effects like lakes or uninhabited areas, which, in addition to distance, act as further retarding effects on diffusion. These are formalized in the form of "zero" or "half" contact multiplicators on the (distance decaying) message flows.

[10] With respect to the formalization of the communication flows Hagerstrand defines a "mean information field" (MIF), in which the probability of communication is a negative function of distance between individuals

[2] Theoretical models disagree as to why firms adopt innovations at different times. Epidemic models emphasize information (Griliches 1957). Certain firms are hypothesized to adopt earlier because they come into contact with, and learn from, adopters of the new technology before others. Economic models, on the other hand, predominantly emphasize firm heterogeneity (Ireland and Stoneman 1986). Firms adopt technologies at different times because they differ with respect to various organizational and environmental variables influencing the economic returns from adoption (Blackman 1999).

Either way, the strong assumption is that developing countries can acquire modern technology innovated in developed economies, often at a fraction of the original research and development (R&D) costs, thereby leapfrogging many decades of technological progress (Teece 2000).

The first involves a country's geographical location. Recent empirical work suggests that diffusion is ‘’geographically localized" (Globerman, Kokko, and Sjo¨holm 2000; Keller 2002; Milner 2003) in that a technology diffuses faster in a country where it is already more widely diffused in neighboring countries. Underlying these regional effects are contagion and contact with prior users or producers of technology.

[11] Rogers (1995) characterized early adopters as knowledgeable risk takers.

Griliches (1957) looked at the rate of return for early adopters and characterized them as profit maximizers. The geographer Hagerstrand (1967) was focusing on the character of early adopters in the transmittal process that produces follow-on participants in the process. Space was treated as a contiguity system with embedded characteristics producing barrier elements to the diffusion process.

[11] REVIEW ON Technological Diffusion

[12] Two main mechanisms are identified in the literature to explain diffusion: (1) epidemic-type dynamics whereby contact with previous adopters stimulates uptake as po tential adopters learn about a new innovation; and (2) economic-type mechanisms whereby potential users adopt a new innovation as it be comesmore profitable, useful, or valuable, with uptake characteristically spreading as costs be come lower, performance improves, or the po tential uses of the innovation grow over time.

To this extent, our results contribute to a growing body of work that has sought to caution against claims about the supposed novelty of the Internet and the suggestion that it is somehow different.

[13] Logistic growth describes an initial period of gradual diffusion as a technology is introduced as a new commercial application, moving then through a rapid, exponential growth phase, before slowing and eventually saturating [14]. The substitution of incumbent technologies by new competitors leads to subsequent decline and eventual obsolescence.

Literature review {#sec2} MAYBE SKIP THIS??

[15] To characterize evolution of the computer industry, we examine the distribution of relative employment across cities in 1977 and how that distribution changes over time to 1992

There is no tendency of relative size distributions of urban computer employment to collapse, go bimodal, or fully spread. Overall computers exhibit some turbulence, with dramatic big winners and losers among cities. In attracting or repelling an industry, urban heterogeneity is important. Large, well educated cities near San Jose have much greater chances of attracting high-tech employment and less of losing it

[7] spatial innovation diffusion By using Bayesian survival models with time-dependent data of wind turbine deployment and firm foundation for 402 German regions between the years 1970 and 2015, we show that the spatial evolution of the German wind energy industry was more strongly influenced by local demand– pull than local supply–push processes.

The industry's initial locations are distributed relatively arbitrarily and unpredictably, as their needs in terms of resources and skills are diverse and distinct from the older existing industries (Boschma and Lambooy, 1999). Consequently, emerging industries are characterized by relatively high degrees of freedom in terms of location. In later extensions of the concept, the assumption of the randomness of locations was revised with greater importance assigned to regional conditions (Boschma and Lambooy, 1999; Fornahl et al., 2012).

[2] analyze whether the rate at which new producer technologies diffuse is significantly influenced by (1) latecomer advantage and (2) engagement with the global economy via trade and foreign investment

Indeed, precisely because of these latecomer advantages, developing countries1 are believed to be well placed to catch up with developed ones (Gerschenkron 1962; Abramovitz 1986).

[5] analyze the spatial diffusion of laser technology research in West Germany from 1960, when this technology began, until 2005.

[12]

[16] We see that the OSN spread almost exclusively from the original location (the capital Budapest, with an order of magnitude more inhabitants than the next size town) to various parts of the country in the early phase of the life-cycle. Later, diffusion became less mono-centric and other towns also emerged as spreaders. Our findings support the idea that spreading initially happens to large distances and becomes more local over time. This is illustrated and discussed later in Figure 2I.

[17]

[9] for energy There is no generally accepted theory that explains diffusion rate heterogeneity across technologies, but several factors are considered important. Greater unit scale and larger market size contribute to slower diffusion. Requirements for interrelated technologies or complex infrastructures also hinder the diffusion process (Grubler, 2012).

Mobile phones benefited from early deployment in recreational boats and automobiles, where the traditional competitor was not a viable option. In the early stages of diffusion, performance is a more important driver of adoption than cost competitiveness. Typically, significant cost reductions only occur once the technology reaches a deployment level capable of supporting standardization and mass production (Wilson, 2012).

[9] Empirical evidence supports the validity of Schmidt's Law over a wide range of technologies, time periods, and geographical contexts. A recent meta-analysis of technology up-scaling found that diffusion accelerated moving from the core to the rim and periphery for technologies as diverse as natural gas power, oil refineries, and automobiles (Wilson, 2009). One historical example that conforms particularly well to Schmidt's Law is the diffusion of coal power in Europe (Grubler, 2012). England emerged as the core region for coal power because it had legal and economic institutions that incentivized scientific pursuits, domestic coal reserves, and a clear industrial motivation to replace water power with coal. ...

[11] model the spatial diffusion of mobile telecommunications in China as well as its determinants. regional socioeconomic characteristics play an important role in determining the timing, speed, and level of mobile telecommunications diffusion in China

[18] explore What determines the duration of formative phases for energy innovations in different markets? We are interested both in initial markets (also: core, lead, first mover, early adopter) where formative phases prepare technologies for mass commercialization, and in follower markets (also: periphery, lag, late adopter) where accelerated formative phases may benefit from diffusion and spillovers.

Materials and Methods

[13] growth function description in p. 86

from R: Asym/(1+exp((xmid-input)/scal)) using the terms from Wilson k/(1 + eˆ(t_0 - t)/scal)

Wilson: k(1 + eˆ-b(t - t_0)) So, scal = - 1/b

The curve is symmetric* around t_0

minimum R2 = 95%, see also [10]

The literature usually uses the saturation level as the asymptote. I am using the total number of websites as we cannot compute a rate.

Moran's I as [11] **TODO** for t_0, diffusion speed

Results

Hexagon density maps: reflect the spatial structure of Britain. Websites are associated in places where people live and work.

TODO maps at the local authority level per firms and discuss patterns

Neighbourhood effect: diffusion proceeds outwards from innovation centers, first "hitting" nearby rather than far-away locations (Grubler 1990)

- Moran's I: for OA and LAD over time **TODO** add 0s
- LISA maps: for OA and LAD over time More and less expected clusters. Different scales show different results
- Website density regressions: for OA and LAD over time **TODO** add 0s Similar pattern

Hierarchy effect: from main centers to secondary ones – central places

- Gini coefficient. Almost perfect polarisation of web adoption in the early stages at a granular level More equally diffused at the Local Authority level Plateau overtime

S-shaped diffusion curves

- S for LADs per firm and OA. **TODO**: OA per firm? fix firms over time.
- Fast and slow LAs map. There is clustering
- **TODo** check s_uk_firm_11
- ranks: there is stability and movement

3.2 Case study approach

Digital technologies and spatial structure: a global view

The impact of ICT on the US and the UK spatial structures

Discussion and conclusions

contrary to results from future studies regarding social media [16], web technologies did not exclusively spread from a central location.

References

1. Hagerstrand T et al. Innovation diffusion as a spatial process. Innovation diffusion as a spatial process. Chicago, USA: Univ. Chicago Press.; 1968;
2. Perkins R, Neumayer E. The international diffusion of new technologies: A multitechnology analysis of latecomer advantage and global economic integration. Annals of the Association of American Geographers. Taylor & Francis; 2005;95: 789–808.

3. Zook M, McCanless M. Mapping the uneven geographies of digital phenomena: The case of blockchain. The Canadian Geographer/Le Géographe canadien. Wiley Online Library; 2022;66: 23–36.
4. Meade N, Islam T. Modelling and forecasting national introduction times for successive generations of mobile telephony. Telecommunications Policy. Elsevier; 2021;45: 102088.
5. Fritsch M, Medrano Echalar LF. New technology in the region–agglomeration and absorptive capacity effects on laser technology research in west germany, 1960–2005. Economics of Innovation and New Technology. Taylor & Francis; 2015;24: 65–94.
6. Bento N, Fontes M. Spatial diffusion and the formation of a technological innovation system in the receiving country: The case of wind energy in portugal. Environmental Innovation and Societal Transitions. Elsevier; 2015;15: 158–179.
7. Bednarz M, Broekel T. Pulled or pushed? The spatial diffusion of wind energy between local demand and supply. Industrial and Corporate Change. Oxford University Press; 2020;29: 893–916.
8. Morrill R, Gaile GL, Thrall GI. Spatial diffusion. Sage Publications; 1988;
9. Leibowicz BD, Krey V, Grubler A. Representing spatial technology diffusion in an energy system optimization model. Technological Forecasting and Social Change. Elsevier; 2016;103: 350–363.
10. Grubler A. The rise and fall of infrastructures: Dynamics of evolution and technological change in transport. Physica-Verlag; 1990.
11. Ding L, Haynes KE, Li H. Modeling the spatial diffusion of mobile telecommunications in china. The Professional Geographer. Taylor & Francis; 2010;62: 248–263.
12. Perkins R, Neumayer E. Is the internet really new after all? The determinants of telecommunications diffusion in historical perspective. The Professional Geographer. Taylor & Francis; 2011;63: 55–72.
13. Wilson C. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. Energy Policy. 2012;50: 81–94. doi:https://doi.org/10.1016/j.enpol.2012.04.077
14. Grübler A, Nakićenović N, Victor DG. Dynamics of energy technologies and global change. Energy policy. Elsevier; 1999;27: 247–280.
15. Beardsell M, Henderson V. Spatial evolution of the computer industry in the USA. European Economic Review. Elsevier; 1999;43: 431–456.
16. Lengyel B, Bokányi E, Di Clemente R, Kertész J, González MC. The role of geography in the complex diffusion of innovations. Scientific reports. Nature Publishing Group; 2020;10: 1–11.
17. Papagiannidis S, Gebka B, Gertner D, Stahl F. Diffusion of web technologies and practices: A longitudinal study. Technological Forecasting and Social Change. 2015;96: 308–321. doi:https://doi.org/10.1016/j.techfore.2015.04.011
18. Bento N, Wilson C, Anadon LD. Time to get ready: Conceptualizing the temporal and spatial dynamics of formative phases for energy technologies. Energy Policy. Elsevier; 2018;119: 282–293.