SQUEEZING SPACE: ICT AND CAPITAL-BIASED TECHNICAL CHANGE

Timothy DeStefano*

Harvard Business School

Richard Kneller

University of Nottingham, GEP, CESIfo

Jonathan Timmis

World Bank, University of Nottingham, CESIfo

Abstract

Historical analysis of past general purpose technologies suggests that multi-factor productivity gains are realised through both labor and capital saving features of these technologies. In this paper, we explore whether ICT leads to capital savings, generated by squeezing a greater amount of economic activity into a smaller amount of space. To do so we use new data on building capital for the UK and cross-space and time variation in broadband connection speeds. We confirm the presence of capital biased technical change and quantify its effects. These results are robust to wide-ranging robustness, falsification and endogeneity bias tests. The capital saving effects of ICT represents an aspect of TFP missing from estimates constructed at both the micro and macro level.

Keywords: ICT; technical change; general purpose technology

JEL codes: E22; L23; O4; R3

* Corresponding author: Timothy DeStefano: Harvard Business School, (e-mail: tdestefano@hbs.edu)
Richard Kneller: University of Nottingham, (e-mail: richard.kneller@nottingham.ac.uk)
Jonathan Timmis: World Bank and University of Nottingham, (e-mail: jonathan.timmis@nottingham.ac.uk)

Acknowledgements: We would like to thank Mary O'Mahony, Irene Bertschek and Jacob Weisdorf for comments along with participants at the ZEW Conference on the economics of ICT, CESIfo conference on Digital Transformation and seminar participants at Loughborough University.

1. Introduction

General purpose technologies (GPTs) make wide-ranging transformations to the economy that often take decades to complete. These transformations help contribute multi factor productivity gains that include those from reducing the amount of capital required for production. The classic example of the capital saving effects of GPTs is provided by Devine (1983) and David (1990,1991), who document how forty years after Edison's invention of the carbon filament incandescent lamp in 1879, electrification led to a transformation from group drive to unit drive transmission within manufacturing. In turn, this affected use of space within factories and began to alter their design, favouring single-story structures with a larger footprint that allowed the free-flow of inputs throughout the plant. These slowly made changes to the shape, layout and the materials used to construct factories reduced the capital requirement of manufacturing firms.[1]

In this paper, we explore whether, as a modern GPT, information and communication technologies (ICT) are also capital saving.[2] David and Wright (2005) compare ICTs against previous GPTs and conjecture that ICT could "yield significant capital-savings by reducing the requirement for commercial office space". In the absence of any formal empirical evidence to date, further support can be found anecdotally through open-plan offices, working from home and hot-desking. These terms suggest increased flexibility in the hours and patterns of work for employees, including in locations away from the office.[3] In turn, they reduce the amount of space firms commit to particular tasks, typically office-based ones, reducing their building capital requirements. These transformations to the workplace were facilitated by the provision of high-speed broadband and related advances in software and hardware applications such as Virtual Private Networks and more recently in cloud computing. Together these have allowed for a greater decoupling of the production, storage, processing and application of information. Such anecdotes suggest that the way ICT is capital saving – allowing more workers to be squeezed into the same space – contrasts with the effects of electricity on the construction of factories where the overall footprint increased.

To provide formal evidence for this type of capital saving we exploit new regional data for the UK on building capital, measured by the area of business properties (meters^2) and intensity with which the capital is used (the average size of business properties and the space, m^2 per employee). From this data

[1] Capital saving is not confined to electricity as a GPT. Acemoglu (2003) writes, while it seems plausible to think of many of the major inventions of the twentieth century, including electricity, new chemicals and plastics, entertainment, and computers, as expanding the set of tasks that labour can perform and the types of goods that labor can produce. Field (1987) writes specifically about the capital saving effects of management and its spread following the invention of the railways. In contrast, some of the early important technological improvements, such as the introduction of coke, the hot blast, and the Bessemer process, can be viewed as capital-augmenting advances, since they reduced the costs of capital and other non-labour inputs.

[2] Whether ICT qualifies as a GPT was originally the subject of some considerable debate, but has now been accepted by many (David, 1990; Bresnahan and Trajtenberg, 1995; David and Wright, 2005; Jovanovic and Rousseau, 2005) if not all (Gordon, 2000, Field, 2006).

[3] Gaining precise statistics on the extent of the use of these types of work practices is difficult. A 2016 study by the UK property company Savills suggests that 73% of UK office workers do so in an open-plan office

we construct a long-difference regression, which captures the long-term effects on building capital for an 18-year period (2000 to 2018) and encompasses slow-moving impacts of GPTs on firm footprint. During this time internet speeds, the network on which these new forms of work practice rely on, grew rapidly. Our treatment exploits regional variation in the way internet speeds have increased across time, from 256kbps to an average in the UK of over 46mbps, but with an interquartile range of between 32 and 57mbps and a maximum of 100mbps, generating time and cross-sectional variation. We use this to answer two principal questions: was ICT associated with changes in the use of building capital consistent with idea that it might be capital saving? And, if so, how large is the effect?

Internet connection speeds within a local area are of course likely to be affected by historical and geographic factors that may similarly affect their suitability as locations for commerce. For example, London has been a center of commerce for several millennia and more recently has received significant investment in the infrastructure to deliver broadband internet. The removal of these time invariant regional factors underpins our use of a long difference strategy. We further augment this by controlling for permanent differences in the growth rate of building capital across regions that are associated with initial conditions, including the size of the agglomeration measured by population. We also control for any effect that faster internet speeds might have on residential property prices, which would indirectly affect commercial property prices (Ahlfeldt et al., 2017).

Our main empirical finding is that ICT has led to capital saving technical change by reducing the building capital requirements needed to produce a given volume of output. Locations with faster broadband connections speeds have been subject to the largest increase in the intensity of building capital use. Therefore, it seems the productivity gains commonly found in the literature from ICT, follow in part from allowing greater economic activity to be squeezed into a smaller amount of space. This effect is economically significant. For every 1mbps increase in broadband speeds, the m^2 area available for commercial rent falls by 0.3%. Given the rapid increase in broadband speeds across the sample period, this equates to a reduction of 14% (m^2) of building capital by 2018. To put this figure in perspective, without this increase in broadband speeds our estimates suggest an additional 72 million m^2 of building capital (compared to a total of 520 million m^2 in 2018) would have been required in the UK over this 18-year period. This is approximately equal to an additional 192,000 business premises, compared to a total stock of 1.46 million[4] in the UK of 2018.

We build the case for a causal interpretation of these estimates through a number of tests. A potential concern with our baseline estimates is the presence of unobservable region-specific changes that may confound our results. We might think of two main types of local confounders that vary in this way. Firstly, the time period that we study coincides with a general increase in the popularity of living in

[4] We include in this figure business premises used as offices, retail or industrial units. We discuss the data in more detail below.

city-centers, in part due to the attraction of fast internet speeds. This increase in new residential properties has affected the competition for land within the city-center, affecting land prices and therefore possibly encouraging some firms to relocate. The increase in the popularity of city-center living is likely to vary across cities according to (but unobservable to the econometrician) amenities and attractiveness. The positive correlation between internet speeds and the popularity of residential city-dwelling, land prices , and the negative correlation between these confounding factors and building capital would indicate that our estimates are likely biased in a negative direction even after first-differencing and we may therefore under-estimate the capital bias effects of ICT. Second, the UK has no national planning laws (Cheshire, 2018). Decisions are instead made by local political committees that are affected by local political changes across time, lobbying and political expediency. This is likely to bias outcomes in an unknown direction.

We confront these points in three main ways. Firstly, we test whether our results are driven by unobservable region specific shocks and apply a falsification test using the average size of residential properties. The shape of residential properties would also be affected by regional shocks, but they should be unaffected by any effects ICT has on allowing production tasks to be squeezed into less space. Continuing to find strong negative effects of ICT for this type of building capital would therefore raise concerns about out interpretation of the results for commercial building capital. For residential properties we find that the correlation between broadband the floorspace of residential properties is in fact positive, although the magnitude of the effect is very small. As a second approach we exploit availability of data on business capital and broadband speeds at a more granular level (at the postcode level) for a sub-set of the time period we study (2010 and 2017). This allows us to control for region specific shocks in a straightforward way (using region fixed effects in our long difference regression) and identify the effects of internet speeds on capital from the within region variation in the internet speed data that we now also have. The estimated effects of increases in broadband speed are again negative in these regressions. Third, we develop an instrumental variable approach that exploits the fact that the internet infrastructure depends on the legacy of the telephone network. We use the postcode-level rollout of high-speed fiber broadband and expected fiber speeds as instruments for reported broadband speeds. These instruments have been previously used by De Stefano et al. (2018). Again, we find that the results for the capital saving effects of ICT are robust.

By allowing a greater amount of economic activity to be concentrated in a smaller amount of space our results have possible economic geography effects. As a final exercise within the paper we make a first pass at examining these. To frame this analysis we draw a second analogy with past GPTs. Prior to the development of electricity and unit drive motors, manufacturing firms were tethered to rivers as a source of power. Their invention allowed a greater freedom in location choices, in principle spreading economic activity. At first glance, recent ICT invention similarly allows greater mobility by lowering the costs of information transmission, a view supported by empirical evidence by Greenstein et al (2018), Kolko (2012), Ioannides et al. (2007) and Sivitanidou (1997). However, our evidence might also be used to suggest that the infrastructure of the internet constrains the location of economic activity reliant on these internet based technologies, akin to the role of rivers before the invention of electricity.[5] As internet speeds have typically grown most quickly in cities in the UK, this would indicate that the capital biased effects of ICT we study have acted as a force towards increased agglomeration.

Our explorative investigations of this point suggest that faster internet speeds are negatively correlated with these measures of economic size, confirming previous evidence that faster communication speeds act to disperse economic activity. In the same regressions we also find that building capital (m^2) per employee is significantly negatively correlated with economic mass, indicating that falls in the amount of space per employee does indeed increase the scale of economic activity that occurs in a region. As far as we are aware, this link between capital saving and economic geography has not previously been explored in the literature.

The paper continues as follows: Section 2, provides a review of the related literature on capital biased technical change and the broader effects of ICT. Section 3, outlines the empirical strategy. Section 4, discusses the data used, along with an explanation regarding the key establishment and broadband variables followed by some descriptive statistics. The empirical results are presented in Section 5, while Section 6 provides various tests for robustness. In Section 7 we explore the economic geography effects of ICT and Section 8 draws some conclusions.

2. Related Literature

The existing empirical and theoretical evidence on capital biased technical change is scattered across several strands of literature. To understand the macroeconomic effects of capital augmenting technical change a natural reference point are theories of economic growth. Here the idea of capital augmenting technical change has traditionally been viewed as relatively unimportant. Such models have at their center the stylised facts of Kaldor and in particular, the relative constancy of factor shares, usually known as the balanced growth path. As discussed by Acemoglu (2003), almost all growth models generate predictions consistent with this balanced growth path by assuming that the elasticity of substitution between capital and labor is equal to one, or by restricting all technical change to be labor augmenting.[6]

[5] Hogendorn and Frischmann (2017) provide a discussion of the mapping between general purpose technologies and infrastructure and whether infrastructures, including the internet, can also be general purpose technologies.

[6] Acemoglu (2003) models these departures from the balanced growth path by allowing for capital augmenting technical change. He shows that as long as the elasticity of substitution between capital and labor is less than 1, the balanced growth path contains only labor-augmenting technical change. More recently Grossman, Helpman,

While factor shares can display a broad constancy over time, in countries such as the US and UK there are periods, sometimes lasting for several decades, in which these ratios are not constant (Acemoglu, 2003; Pikety, 2014; De Loecker and Eeckhout, 2017). Standard versions of these two-factor models of aggregate production suggest that capital saving technical change should be associated with a declining share of capital in income (Barkai, 2016; Barkai and Benzell, 2018) and therefore act as a countervailing effect on the recent falls in the labor share of income found empirically for many countries (Karabarbounis and Neiman, 2013). However, recent work by Barkai (2016) and Barkai and Benzell (2018) has shown that the income share paid to capital has also fallen across time. These models offer little explanation why both the labor and capital share of income may simultaneously decline, such as digital technologies that have both capital and labor saving features (Benzell and Brynjolfsson 2019).

This paper also has a connection with the literature on the production function and estimating rates of capital and labor augmenting technical change at the country level, typically using some form of time trend as a proxy for an aggregate capital stock measure. The earliest example of this is Sato (1970) who derives estimates of factor biased technical change within the production function and discusses its relationship with the elasticity of substitution and factor labor shares. Using data on the US non-farm economy from 1909 to 1960 he finds that technological progress is on the average more labor-saving, growing at a rate about 1/3rd higher than capital-saving technical change. Evidence of capital saving technical progress for the aggregate capital stock is not a ubiquitous outcome in this literature, motivating us to focus on a particular form of capital used in this paper[7].

Our focus on capital augmenting technical change contrasts with the substantial literature that examine more generally the productivity impacts from ICT – that has mostly focused on skill-biased technical change. It has become broadly accepted in this literature that ICT use leads to increased productivity growth (Brynjolfson and Hitt (1996, 2003); Dewan and Min (1997); Black and Lynch (2001, 2004); Bloom et al. (2005, 2014)). There is also evidence these technologies have had strong effects on workers, displaying a strong positive bias towards higher skills and substitution away from lower skilled workers (Akerman et al., 2015). Within this literature there are a small number of papers that have previously examined ICT and capital saving, albeit for a different form of capital. Hubbard (2003) for example finds evidence that the use of on board computers affected capacity utilisation in the trucking industry.[8] According to his estimates about 33 percent of the 10.1% increase in loaded miles per truck between 1992 and 1997 was related to the growing use of on-board computers which enabled better

Oberfield and Sampson (2017) develop a model with human capital accumulation and capital-augmenting technical change that retains a balanced growth path. A further example can be found in Jones (2005) and more recently in Irmen (2017).

[7] For example, Berman (2000) finds evidence using cross-country and industry level data of absolute capital bias from technical change. Antras (2004) finds similar evidence of capital-using for the aggregate capital stock.

[8] Hubbard (2003) does not himself make the link to capital augmenting technical change.

matches between trucks and hauls. An alternative type of ICT is explored by Cramer and Kreuger (2016), who study the capacity utilisation of UberX drivers versus those employed by traditional taxi cab firms. They find that capacity utilization is higher amongst Uber drivers, which is in part determined by the technology that Uber has developed to match drivers and passengers.

Change in the use of space would indicate that this paper also fits with the literature on organisational capital and ICT – but this literature has largely neglected building capital.[9] A commonly held view in this literature is that the productivity effects of ICT are increasing in organisational capital, but also that the costs associated with changes in organisation can be substantial.[10] While it is evident from the discussion of the effects of previous GPTs from Devine (1983) and David (1990, 1991) as well as those of ICT in David and Wright (2005), that capital saving technical change often occurs alongside other organisational changes, it is clear that the mapping between these two concepts is imperfect. Organisational changes may or may not bring about capital saving changes. The possibility that organisational change from ICT might bring about capital saving is rarely discussed in existing literature. Moreover, building capital is often missing from estimates of the total capital stock, or is assumed it to be constant. This suggests that estimates of TFP from the organisational changes brought about by ICT are likely to be under-estimated. Instead the literature has focused on types of organisational changes, such as management hierarchies, that can be more easily quantified.[11]

Finally, this paper relates to a small literature on the economic geography effects of ICT. A well-known study by Kolko (2012) finds a positive relationship between broadband expansion and economic growth in cities, especially in areas with lower population densities. This might be viewed as consistent with the evidence from this paper. Greenstein et al (2018), provides an overview on the effectiveness of digital technology for establishing new partnerships or collaborations across geographic space. Ioannides et al. (2007) take a very different approach to this question, testing directly whether the distribution of the size of cities have become more or less similar over time. They reach the opposite conclusion that ICT leads to a less concentrated distribution of city sizes, suggesting that it acts to disperse economic activity across geography.[2] This approach is close in spirit to work by Sivitanidou (1997) who found that between 1989 and 1994 the office-commercial land value gradients within Los Angeles flattened. This also suggests that the information revolution that occurred

[9] Simple correlations between measures of ICT and productivity are typically larger than those suggested by growth accounting. The explanation that the high magnitudes are due to organizational capital gets some support from Bresnahan, Brynjolfsson, and Hitt (2002) who conducted a survey containing explicit questions on decentralization within firms. Bloom, Sadun, and Van Reenen (2005) find some support for the organizational capital hypothesis as they find much higher returns for the IT in US multinationals compared to non-multinationals than between statistically similar establishments in the UK. Black and Lynch (2001) also find a positive correlation between ICT use and workplace organisation, as do Crespi et al. (2007). Bertschek and Kaiser (2004) find no such relationship.

[10] Yang and Brynjolffson (2001) for example report evidence that the total start-up cost of some types of ICT are five times the cost of the hardware and software licences.

[11] Fabling and Grimes (2016) note that shifts in production towards more ICT-intensive products, while research on the relationship between organisational change and skills include Carolli and Van Reenen (2001, Akerman et al. (2012).

at the end of the 20th century weakened the attractiveness of large business centers to office-commercial activities, resulting in the increasingly dispersed patterns of business locations. We find the opposite for a more recent ICT. We return to this point in the last empirical section of the paper.

3. Empirical Strategy

Our empirical model takes the following form:

$$y_{it} = \alpha + \beta X_{it} - \gamma ICT_{it} + \varepsilon_{it}$$

y_{it} represents our measures of business capital including m^2, the average size of each hereditament and the area per employee in region *i* at time *t* (between 2000 to 2018). ICT_{it}represents the broadband connection speed within the region. If ICT is indeed capital biased with respect to building capital then the estimated coefficient γ is expected to be negative. X_{it} denotes the control variables including measures of the price of building capital (the rateable value in m^2), and the level of output, such that the regression resembles that of a standard factor demand equation. Note that an equation of this type can be derived from the neoclassical model of Jorgenson (1963) in which firms maximize the discounted flow of profits over an infinite horizon with delivery lags and adjustment costs.[12]

A concern with the estimation model is that any naïve estimates of the coefficient on ICT are likely to be biased due to the presence of time invariant confounding factors at the regional level. For example, regions in which there are large agglomerations of businesses are also likely to be large agglomerations of workers and therefore customers of internet providers. To remove the influence of these time invariant regional characteristics we estimate equation (1) in long difference form, such that we now capture the change in business capital over the 18-year period from 2000 to 2018.[13] In the first year of the data, for a majority of firms broadband speeds were constrained by the limits of the copper cabling that make up the telephone network and therefore limited to 256 kbps. The first generation of ADSL broadband only became available to purchase in that year. For this reason, we can measure the change in speeds using the speed available at the end of the sample period (2018).

As a robustness test, the analysis also uses a micro-level dataset containing information about each individual hereditament including their footprint, rateable value, location and so on (the data is available for two years in 2010 and 2017). Employing the data at the micro level allows us to further consider the issue of endogeneity bias by controlling for local authority fixed effects within the long differenced regressions thereby removing any effects from region specific shocks. It also enables us to use an

[12] The literature on estimating factor demand equations for capital is summarised in Chrinko (1993).
[13] A long difference approach of this type is adopted by Brynjolffson and Hitt (2003) when considering the productivity effects of ICT.

instrumental variable approach, where we employ instruments based on the underlying telecommunication network in the UK. See below for further discussions.

4. Data and Summary Statistics

Our measures on the size and number of business properties is from the UK Valuation Office Agency (VOA) administrative database. This newly available dataset provides time series data on the numbers of hereditaments[14], total area of floorspace (thousands m^2) and average rateable values per meter squared for 346 local authorities (equivalent to US counties) in England and Wales from 2000 to 2018. A hereditament in the data is a property on which rates, a local property tax in the UK, may be charged. In general hereditaments are buildings, or premises within buildings, appropriate or used for single occupation. The floorspace is measured in square metres (thousands of) and includes all commercial space. Therefore businesses properties spread across multiple floors have a larger floorspace in our data than a single story business property which has the same land footprint. We combine the data on total area and total hereditaments to calculate area (m^2) per hereditament.

Hereditaments in the data include those that are either occupied or vacant, and therefore differ from data about the birth or death of firms. If a firm death occurs and a new one is born into the same property this does not show up in the data.[15] Changes in the number of hereditaments and floorspace therefore represent increases through newly built properties, or decreases through the demolition of a business property plus any change from say reconfiguring an industrial warehouse property for housing.

The rateable value of property is the value at which a property is expected to be leased for one year.[16] It is based on a range of factors including use, location and age, but a main determinant of is the size (total area) of the property. For many of the more common types of commercial properties, the VOA provides separate data series on retail properties, offices, factories and warehouses and a small miscellaneous group which consists mainly of halls, social clubs, garden centers as well as public buildings such as schools and hospitals.

Information on employment, sales and the number of firms at the local authority level comes from the Business Structural Dataset (BSD). The BSD is generated from the *Inter-Departmental Business Register* (IDBR), which is a live register of data collected by HM Revenue and Customs via VAT and Pay As You Earn (PAYE) records. This dataset contains basic information for almost every firm organization in the UK. Estimations in 2004 for example suggest that the businesses contained in the IDBR represent roughly 99% of all business activity in the country. From this data source we use

[14] A hereditament is defined in the UK according to the answer to the following question: "as a matter of fact and degree, is or will the building, as a building, be ready for occupation, or capable of occupation, for the purposes for which it is intended?" VOA

[15] It follows that we cannot answer questions about changes in the industry of the occupants.

[16] The vacancy of a property also has no impact on rateable value reported in the data, though it can affect the level of rates levied on a property in practice.

information on the precise location of the firm to match this to a local authority and then aggregate across firms. To match types of commercial properties to employment we match descriptions of the types of commercial properties in the VOA with SIC codes.

The data on fixed broadband speed come from the Office of Communication (Ofcom), the regulatory authority for the communication industry in the UK. These are available at the postcode level for 2018.[17] We then aggregate this data to the local authority level to match the data from the VOA on hereditaments and their shape.

In 2000, there were roughly 1.28 million commercial office, retail and industrial properties in England and Wales. By 2018 this had grown by over 13% to 1.46 million properties. Across each local authority this meant that in 2000 there were on an average around 3,700 business premises (of different types), rising to a little under 4,200 by 2018. This rise in the number of hereditaments was faster than the growth in employment (3.2%), such that the average hereditament per employee fell slightly. The total floorspace was 514 million m^2 in 2000, rising to 520 million m^2 in 2018 (an increase of 1.1%).

Summary statistics are displayed in Table 1, where we report means and standard deviations for total area (thousands m^2), the number of business properties (hereditaments), employment, the average size of each business property and the area per employee for the years 2000 and 2018. We report these for all types of properties and for office, retail and industry categories separately.

The average space per hereditament in 2000 was similar in office and retail (248m^2 and 180m^2) than in the industrial sector (694m^2). The average area per employee also differs noticeably across these three categories, with much less space per employee (around 17m^2) for office workers compared to those in retail (155m^2) and industry (290m^2).[18]

The average increase (across local authorities) in the number of business properties, total area and employment between 2000 and 2018 is mostly accounted for by growth in office space. For example, there was a marked increase in the number of office units (56%), in the floor area by (12%) and employment (15%). For retail and industrial units there are some notable differences. The number of retail properties fell by 3.8%, but total space grew by 10%, whereas for industrial units, the number of grew (9.4%) but there were declines in the floorspace (3.4%).[19] Measured in terms of space per employee there is evidence of an overall decline, made up of reduced space per worker in office and retail units, and an increase in industrial units.

[17] Broadband speed data are not available from OFCOM before 2013. For this reason we are unable to estimate a panel regression model.

[18] It is difficult to find accepted industry standards against which to compare these data, although for office the usual guidance is that firms should plan for between 14m2 and 32m2 per employee when choosing a business premises. Our data appear to conform to these generally accepted rules.

[19] This led to declines in the average size of each hereditament overall, and in office and industrial units, but an increase in the average size of retail units.

Table 1: Summary Statistics

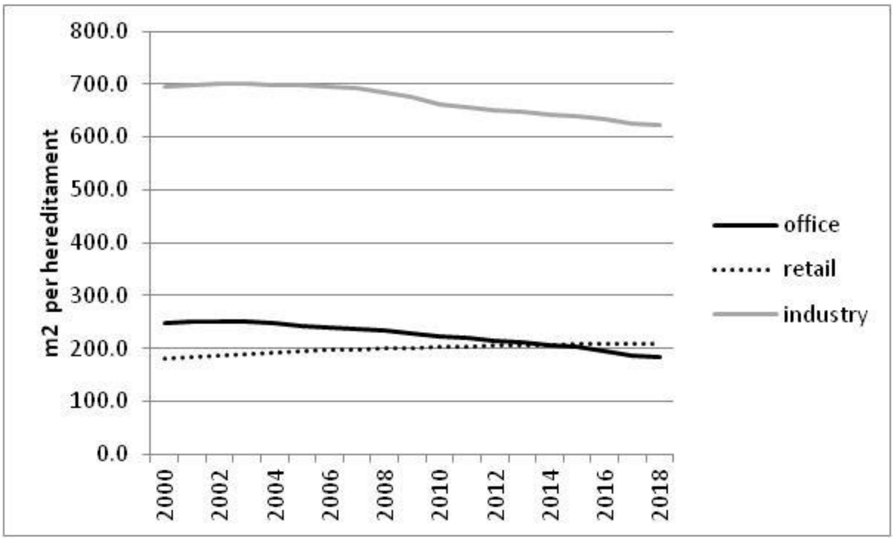
	Year		Commercial Area (thousands m^2)	Hereditaments	Employment	Area per hereditament	Area per employee	Obs
All	2000	Mean	495.2	1233.8	16245.2	374.2	154.2	1038
		Std. Dev.	690.7	1187.2	30948.8	286.0	2077.4	
	2018	Mean	500.84	1403.1	16775.4	337.4	153.8	1038
		Std. Dev.	641.4	1381.8	32571.8	263.7	1853.6	
Office	2000	Mean	229.1	780.4	29312.5	248.7	17.4	346
		Std. Dev.	455.3	1127.5	46408.7	108.2	81	
	2018	Mean	255.7	1218.1	33751.0	182.5	16.9	346
		Std. Dev.	504.7	1758.1	46112.9	70.5	95.6	
Retail	2000	Mean	276.7	1545.9	4339.0	180.1	155.5	346
		Std. Dev.	226.9	1239.0	7031.8	47.3	790	
	2018	Mean	304.6	1486.9	5013.3	208.7	132.9	346
		Std. Dev.	244.1	1209.6	5810.4	55.9	767.6	
Industry	2000	Mean	979.8	1375.0	15084.1	693.6	289.7	346
		Std. Dev.	906.0	1051.8	19001.4	275.9	3507.7	
	2018	Mean	642.2	1504.2	11562.1	621.1	3116.6	346
		Std Dev.	792.4	1064.8	23953.0	282.1	3112.1	

Notes: Data Sources: Area, Hereditaments and Area per hereditament are from UK Valuation Office and are measured at the local authority level. Employment is from the Business Structure Database from the ONS and is aggregated to the local authority level. We report the mean and standard deviation.

We provide further stylised facts about the average size of each hereditament in Figure 1 and the space per employee by type of commercial property in Figures 2 to 4 using the full time series available to us. In so doing we can firstly ensure that the changes summarised in Table 1 are not the consequence of particularly large changes in a single year and second to assess how these measures of capital changed across the business cycle. Comparing the trends for the average size of commercial properties by type suggests rather smooth trends across time (see Figure 1). The general decline in the average size of industrial and office units are evident, while the increase in the average size of retail units is relatively small.

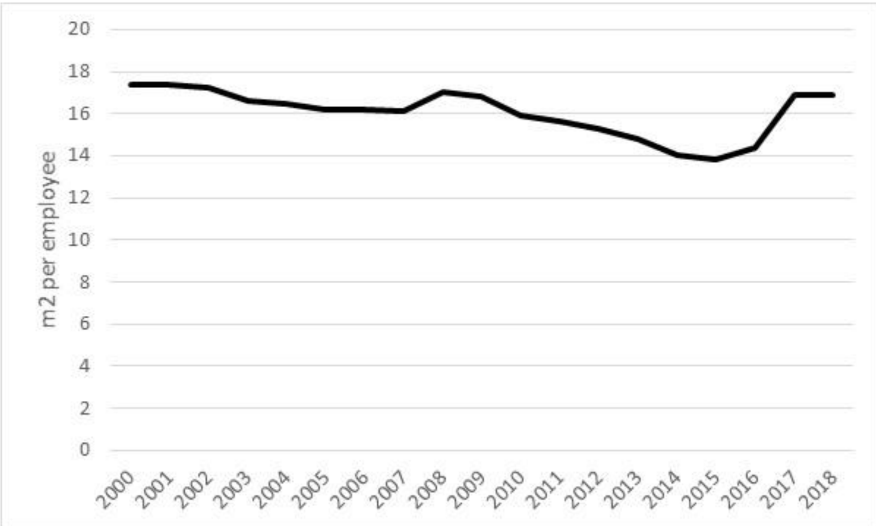
Greater variation across time is found for space per employee. The downward trend in office space per employee apparent in Figure 2 is punctuated by a rise during the years of the global financial crisis and its aftermath followed by a noticeable increase in the last few years of the sample period. This occurs presumably because employment can be adjusted by firms more quickly than commercial office space, where leases might have been signed for several years. For retail units the adjustment in space per employee appears to occur in 2005 to 2009 (see Figure 3). Outside of these years the profile is broadly flat. Finally, for industrial units we again find that most of the downward adjustment occurs in the middle of the sample period, around which there is a mildly increasing trend (see Figure 4).

Figure 1: Average m^2 per hereditament within a local authority by hereditament type, 2000 to 2018



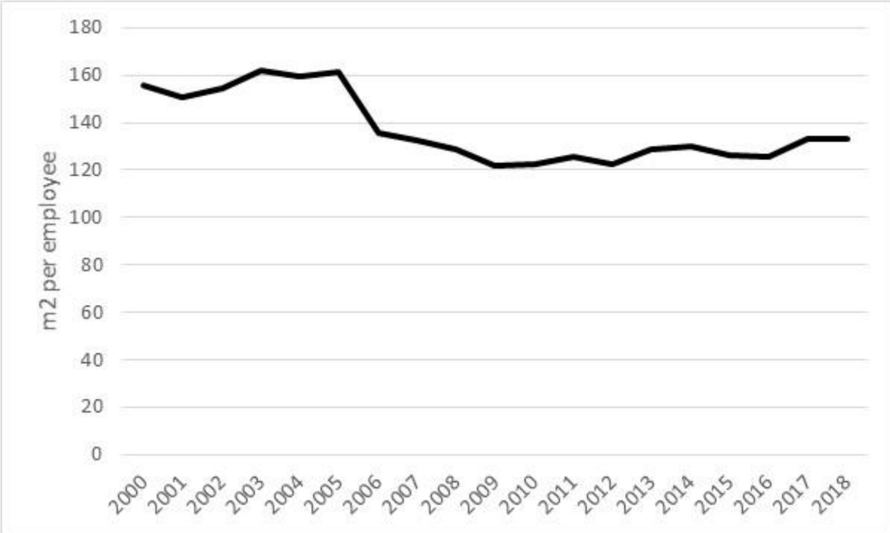
Notes: The average size of hereditaments is constructed as total m^2 by type of business property within a local authority divided by the number of hereditaments.

Figure 2: Office space per employee within a local authority by hereditament type, 2000 and 2018



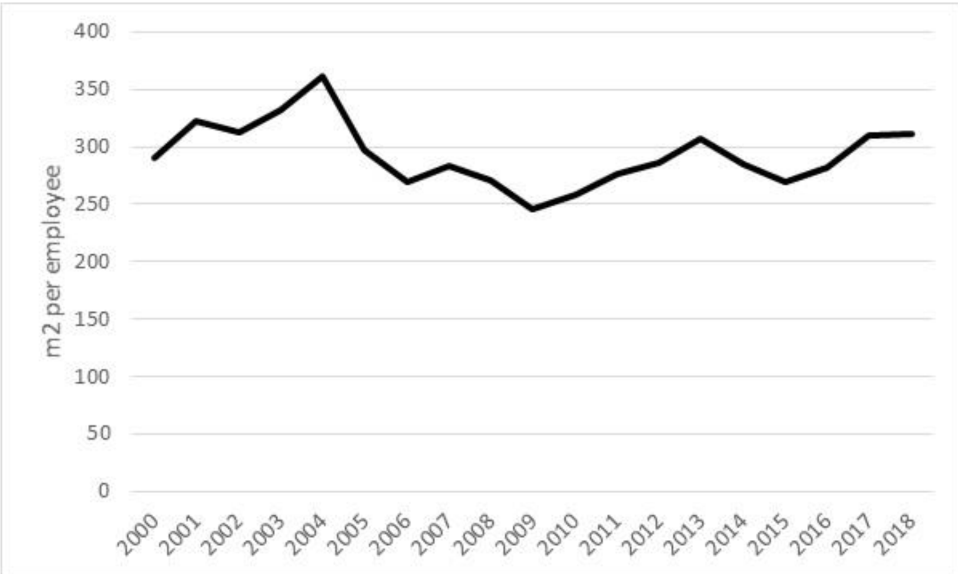
Notes: The average space per employee is constructed as total m^2 of office property within a local authority divided by the employment within the business service sector.

Figure 3: Retail space per employee within a local authority by hereditament type, 2000 and 2018



Notes: The average space per employee is constructed as total m^2 of retail property within a local authority divided by the employment within the retail sector.

Figure 4: Industrial space per employee within a local authority by hereditament type, 2000 and 2018



Notes: The average space per employee is constructed as total m^2 of office property within a local authority divided by the employment within the industrial sector.

5. Regression Results

In Table 2 we estimate a factor demand equation for building capital that controls for broadband speeds alongside the level of output and the price of capital. In regression 1 we begin by estimating a cross-section regression for the level of commercial building using data for 2018. As expected, in this regression we find a strong positive relationship between the available commercial space and output and a negative correlation with prices. We also find that regions with faster broadband speed tend to have larger building capital stocks measured by area.

There are strong reasons to suspect however, that estimated coefficient on broadband speed in regression 1 is unlikely to capture the effects of ICT on building capital owing to omitted variable bias. Business properties and consumers are agglomerated in cities, which are also locations where the volume of demand for broadband services are highest. Cities therefore tend to attract greater broadband investment and therefore have faster broadband speeds on average. The omission of the necessary control variables such as agglomeration in this regression will therefore tend to strongly bias the effect of ICT on capital in a positive direction.

Our first approach to this issue assumes that these confounders are location specific but time invariant. To remove the effect of these regional characteristics, in regression 2 we first difference the data across time. To allow for the possibility that building capital changes take a long time to appear we difference the data from 2000 to 2018, creating a cross section of long-differenced data. The relationship between the total floor area and broadband differs markedly when we account for time invariant regional characteristics in this way. The estimated broadband coefficient is now negative, consistent with an interpretation of capital biased technical change from ICT on building capital.[20] According to these estimates, for every increase in broadband speeds by 1 mbps, business capital fell by 0.3%.

First differencing helps to remove the effect that broadband speed may have on business capital because these speeds are also correlated by time invariant characteristics of a local authority, such as geographic or historical characteristics that make a particular location a more or less attractive place to site a business. In regression 3 we extend this by adding regional characteristics at the initial time period (2000), thereby allow for differences in trends in the level of floorspace associated with these initial conditions. To measure initial regional characteristics we use initial income levels (captured by average wages) and the size of the agglomeration (measured by the working age population).[21] These variables both have statistically significant effects on the change in building capital within a region, with the results suggesting that the smallest changes occurred in initially rich and larger populations. Following evidence from Ahlfeldt et al. (2017) we control the capitalisation of faster broadband speeds in house prices by including the change in house prices over time. The results for this variable suggest find that increases in house prices are associated with declines in the stock of commercial floorspace available, confirming the competing pressures these residential and commercial property play on the demand for

[20] The results for broadband remain robust if we remove the price of capital and/or the sales variable over concerns that their estimated coefficients may suffer from endogeneity bias. In this regression we include initial income, initial population and the change in unemployment to control for region specific shocks. An approach of this type is typical in studies of skill biased technical change from ICT using cost shares or factor demand shares (O'Mahony et al. 2008). It is also robust to the inclusion of non-ICT capital stock to control possible complementarities with floorspace. The result is also robust to the inclusion of the initial price of capital to control for the possibility that broadband and changes to business properties are correlated with initial prices and these affect the rate of change of these variables across time.

[21] Local authorities within the UK have control over local planning applications and therefore the location and size of business properties. To remove the possibility that local differences in the acceptance or rejection of changes to commercial properties can account for our results we add a control for the refusal rate of local planning application following Cheshire. The results are unaffected by the inclusion of this variable.

land. The coefficient on broadband speeds are unaffected by the inclusion of these variables. Moreover, the magnitude of the estimated coefficient on the broadband variable is also unaffected by their inclusion.

Regression 4 considers non-linearities in the effect of broadband speed by using its logged value.[22] This has no effect on the main result. In regressions 5 and 6 we explore the measurement by replacing the broadband speed variable with a measure of broadband or superfast broadband penetration amongst households within the local area. The data on broadband penetration is available only for the years between 2000 and 2012.[23] In both regressions we find that increased broadband use within the region is associated with larger decreases in the available commercial area over this 12 year window.[24]

The evidence presented thus far is consistent with the interpretation that faster broadband connection speeds are associated with capital biased technical change by reducing the building capital required by firms to produce a given level of output. The reliability of this as a causal statement rests on the absence of region specific shocks, such as those to productivity, incomes or prices, which encourage investment in faster broadband speeds within a region along with changes in the shape of commercial properties. We test for this possibility using a falsification test. If these time-varying region-specific shocks are present it seems reasonable to anticipate that they would also be correlated with changes in the shape of other types of property, such as residential property. For example, any unobservable local price or income shocks that make business property more expensive or a region wealthier, should have a similar effect on residential property. Yet, the effects ICT has on allowing production tasks to be squeezed into a smaller amount of space should be absent for residential buildings. Therefore, only in the presence of region specific shocks should we find broadband on the shape of residential buildings.

We explore this point in regression 7 by using data from the ONS on the average size of residential dwellings, including single dwellings, duplexes, town houses and apartments. This data is available annually for the years between 2004 to 2012 and so we use a long differenced regression over those 8-years. The results from regression 7 show that if anything, the average size of residential property *increases* with broadband internet speeds. This result also holds if we focus only on houses and exclude apartments.[25] This result strongly points against the presence of region specific shocks as being a driver

[22] We also used the squared value of broadband speed. This enters the regression with a positive coefficient that is significant at the 5% level. The value of the coefficient implied that the effects of speed on building capital reached their maximum at 72mbps. This speed is at the 99th percentile of the distribution of broadband speeds within our data.

[23] For completeness we repeat regression 4 using the change in building capital between 2000 and 2012. We report this result in Appendix Table A2.

[24] We also considered whether the results are specific to broadband or whether they capture some other feature of ICT by replacing the broadband speed variable with a measure of the number of PCs in 2012. Of interest we find that the estimated relationship of this variable with broadband is positive, although it is not statistically significant. These results remain robust to the inclusion of alternative measures of ICT including ERP, the total number of servers or PC per employee. By themselves none of these control variables are statistically significant.

[25] These results are available on request.

of the results for commercial property elsewhere in the table and further supports our interpretation of those results as the capital saving effects of ICT.

Table 2: OLS results, relationship between broadband speeds and Area (m^2)

Regression No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Dependent variable	**Area (m^2)**	**ΔArea (m^2)**					
	Level	**Long difference**	**Initial Conditions**	**Logged Broadband speed**	**Broadband penetration**	**Superfast Broadband penetration**	**Houses & apartments**
Years	**2018**	**2000-2018**	**2000-2018**	**2000-2018**	**2000-2012**	**2000-2012**	**2004-2012**
Broadband speed$_t$	0.018***						
	(0.003)						
ΔBroadband speed$_t$		-0.003***	-0.003***	-0.114***			0.018***
		(0.001)	(0.001)	(0.024)			(0.010)
ΔBroadband penetration$_t$					-0.507***		
					(0.129)		
ΔSuperfast penetration$_t$						-0.634***	
						(0.183)	
Output$_t$	0.095***						
	(0.031)						
Price of Capital$_t$	-0.595***						
	(0.070)						
ΔOutput$_t$		0.034***	0.032***	0.032***	0.030***	0.031***	
		(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	
ΔPrice of capital$_t$		-0.078*	-0.027	-0.028	0.109***	0.090**	
		(0.046)	(0.046)	(0.045)	(0.039)	(0.039)	
Average Wage$_{t-1}$			-0.153**	-0.153**	0.015	-0.038	0.018
			(0.059)	(0.059)	(0.054)	(0.052)	(0.020)
Working Age Pop$_{t-1}$			-0.045***	-0.044***	-0.044***	-0.038***	0.011***
			(0.011)	(0.011)	(0.010)	(0.010)	(0.003)
ΔHouse Prices$_t$			-0.207***	-0.204***	0.033	0.090	-0.001
			(0.074)	(0.074)	(0.073)	(0.067)	(0.001)
R^2	0.188	0.058	0.092	0.093	0.078	0.072	0.195
Observations	1038	1038	999	999	1005	1005	330

Notes: Regression 1 uses the area (m^2) of commercial properties in 2018 at the UK local authority level and by type of property (office, retail and industrial). Regressions 2-6 uses the change in the area (m^2) of commercial properties between 2000 and 2018 (2012 in regressions 5 and 6) within a UK local authority by property type (office, retail and industrial). Regression 7 uses the change in area (m^2) for residential property between 2004 and 2012. Robust standard errors clustered at the local authority level are presented in parentheses. t-1 refers to the initial year and t to the last year of data available. ** and * indicate significance at the 1%, 5% and 10% level, respectively.

Mechanisms

The mechanism we explore is that broadband technologies allow for more flexible ways of working and have therefore reduced the building capital requirements of the firm. Despite the use of first differencing, the inclusion of initial conditions and a measure of house prices, it remains possible that there are other explanations for the results that we find. In this section we explore these further.

Large agglomerations have larger numbers of business properties and populations. Given that available commercial land is more or less in fixed supply, there is less scope to add new commercial property and/or a greater need to increase its density. We would thus expect that the largest growth in the number of commercial property across time would be concentrated in regions with initially lower stocks. We explore this issue in regressions 8 to 10 in Table 3.

In regression 8 we capture the change in number of commercial properties within local authorities over time.[26] Regression 9 controls for the initial value of the commercial space in the region and regression 10 controls for the average size of hereditaments within the region. All three of these control variables help to explain variations in commercial space. The growth of floorspace also tended to increase more quickly in regions which the initial stock was smaller. Not surprisingly, floorspace was also increasing if the number of hereditaments in the region increased or if their average size increased. In regression 8 and 9 this influences the size of the estimated coefficient of broadband, which falls from 0.114 in regression 4 in Table 2 to 0.076 in regression 8 and 0.072 in regression 9 in Table 3, indicating that these regional factors play some role in explaining the results.

An alternative explanation for the findings would be that broadband rollout coincides with a general upgrading of technology within the firm. These technologies may be labor saving and machines do not have the same need for space as humans. In regression 11 we allow for this possibility by scaling total commercial area by employment to construct a measure of m^2 per employee. If any omitted region characteristics are correlated with the number of businesses in a region then scaling to m^2 per employee will help remove such effects. To reflect the change in the left hand side variable, m^2 per employee, in regression 11 we also divide output by employment levels (labor productivity). In regression 12 we extend this idea and allow for the possibility that changes in building capital are more closely related to changes in employment rather than output. That is, we use the same specification as the baseline model (regression 4), but with the change in employment rather than output as a control variable. A further advantage of adding the change in employment to the regression is that this controls for any effect from ICT on labor augmenting technical change.[27] We find from these results little evidence that this explains

[26] We have also explored whether broadband has affected the number of businesses operating within a region. We find no significant effect of faster broadband speed.

[27] We report estimates of labour augmenting technical change in Table A3. The evidence presented in Table A3 points to a conclusion of no effect. Unfortunately the ONS data do not allow use to separate employment into different types of skills and therefore to consider issues about skill biased technical change.

our findings. The broadband variable remains negative and statistically significant in all of these regressions.

Finally in Table 3 we explore the possibility that our results are explained by small, possibly high-tech firms, self-selecting to areas in which broadband speeds are fastest. We also assess the possibility as to whether these technologies have affected the number of online versus offline transactions, an issue particularly relevant to the retail sector. To control for this we include measures of the change in the average size of the firms within the region and the number of firms (See regressions 13 and 14). We find that building capital is positively affected by the number of firms, but also that the coefficient on the broadband variable is unaffected.

Table 3: OLS results, relationship between broadband speeds and Area (m^2), robustness tests

Regression No.	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Dependent variable	**Δarea (m^2)**	**Δarea (m^2)**	**Δarea (m^2)**	**Δarea (m^2) per employee**	**Δarea (m^2)**	**Δarea (m^2)**	**Δarea (m^2)**
ΔBroadband speed$_t$	-0.076***	-0.072***	-0.109***	-0.226***	-0.116***	-0.115***	-0.122***
	(0.021)	(0.022)	(0.020)	(0.086)	(0.024)	(0.024)	(0.024)
ΔOutput$_t$	0.021***	0.004	0.031***		-0.022	0.056***	0.006
	(0.008)	(0.008)	(0.009)		(0.015)	(0.016)	(0.009)
ΔPrice of capital$_t$	0.062	-0.092**	-0.099**	-0.731***	-0.035	-0.023	-0.022
	(0.042)	(0.043)	(0.041)	(0.122)	(0.045)	(0.046)	(0.045)
Average wage$_{t-1}$	-0.146***	-0.156***	-0.107**	-0.438***	-0.156**	-0.163***	-0.219***
	(0.052)	(0.057)	(0.049)	(0.160)	(0.062)	(0.059)	(0.062)
Working age pop$_{t-1}$	-0.036***	0.014	-0.037***	-0.008	-0.035***	-0.050***	-0.049***
	(0.010)	(0.012)	(0.010)	(0.039)	(0.012)	(0.011)	(0.012)
ΔHouse Prices$_t$	-0.214***	-0.105	-0.127**	-0.056	-0.234***	-0.201***	-0.275***
	(0.064)	(0.070)	(0.063)	(0.183)	(0.075)	(0.073)	(0.074)
ΔHereditaments$_t$	0.384***						
	(0.029)						
Area$_{t-1}$		-0.088***					
		(0.007)					
ΔAve. Hered. Size$_t$			0.338***				
			(0.030)				
ΔLabor Productivity$_t$				0.254***			
				(0.060)			
ΔEmployment$_t$					0.080***		
					(0.017)		
ΔAve. Firm Size$_t$						-0.042**	
						(0.018)	
ΔFirms$_t$							0.234***
							(0.023)
R^2	0.285	0.245	0.231	0.069	0.113	0.099	0.182
Observations	999	999	999	999	999	999	999

Notes: Regression for the change in the area (m^2) of commercial properties (per employee in regression 11) between 2000 and 2018 within a UK local authority by property type (office, retail and industrial). Robust standard errors clustered at the local authority level are presented in parentheses. t-1 refers to the initial year and t to the last year of data available. ** and * indicate significance at the 1%, 5% and 10% level, respectively.

Having ruled out other possible mechanisms as an explanation for these results, we search for further evidence in support of the view that broadband speeds have allowed the adoption of more flexible work practices (See Table 4). We begin by considering the variation across different hereditament types within the data. The description of the capital saving effects of ICT in David and Wright (2005) focuses on offices. While retail and industrial units also contain offices, the effects of ICT on capital saving are less obvious for these types of hereditaments. The sector most obviously affected by the growth of the internet has been the retail sector, with the traditional ‘bricks-and-mortar’ retailers facing an increase in competition from those using e-commerce exclusively or as a hybrid. Hortaçsu and Syverson (2015) detail how retail has been affected by the expansion of warehouses and super-centers as a consequence of e-commerce, which may suggest a similar fall in the footprint. The industrial sector has been affected by the increased use of ‘just-in-time’ technologies, which reduced the need for warehousing, while the offshoring of production has reduced the space needed for machinery as part of production. At the same time, many manufacturing firms have become more service intensive, which typically requires less space.

In regression 15 to 17 of Table 4 we report results using the three types of hereditament in the data, office space (regression 15), retail space (regression 16) and industrial properties (regression 17), separately. The results suggest that there are indeed differences across industries. As expected, ICT exhibits a larger changed on the space requirements for offices compared to industrial space, with rather weak effects found for retail. Each increase in broadband speeds of 1% is associated with a decline in the available commercial m^2 area of office properties by 0.21%, which is more than twice the size of the same change in industrial building capital (0.09%), and more than 5 times the magnitude of the same change for retail (0.04%).

Reductions in the commercial space requirements are likely to come about for a number of different changes, including simply shifting the location of the working environment elsewhere. In regression 18 we add a measure of working from home within the region. This variable differs across regions but not across industries or time (data is for 2012). Despite the imperfections of this measure we find that both broadband internet speeds and working from home help to reduce the commercial area requirements. This is revealing as it suggests that reductions in building capital do not arise from ‘hot-desking’ alone, but are broader than this.

Table 4: OLS results, relationship between broadband speeds and Area (m²), robustness test by hereditament type and working from home

Regression No.	15	16	17	18
Dependent variable		Δarea (m²)		
Hereditament Type	**Office**	**Retail**	**Industrial**	**Office, Retail & Industrial**
Years	**2000-2018**	**2000-2018**	**2000-2018**	**2000-2012**
Broadband Speed$_t$	-0.205***	-0.037*	-0.092***	-0.075***
	(0.052)	(0.020)	(0.035)	(0.027)
ΔOutput$_t$	-0.005	-0.007	0.000	0.032***
	(0.018)	(0.008)	(0.015)	(0.010)
ΔPrice of capital$_t$	0.143*	-0.036	-0.359***	0.096**
	(0.073)	(0.056)	(0.089)	(0.038)
Average wage$_{t-1}$	-0.279**	-0.079*	-0.008	-0.057
	(0.117)	(0.047)	(0.090)	(0.055)
Working age pop$_{t-1}$	-0.042*	0.001	-0.092***	-0.049***
	(0.022)	(0.010)	(0.019)	(0.012)
ΔHouse Prices$_t$	-0.256*	-0.042	-0.360***	0.072
	(0.153)	(0.062)	(0.119)	(0.068)
Working from home$_t$				-0.484**
				(0.237)
R^2	0.144	0.036	0.233	0.071
Observations	333	333	333	990

Notes: Regressions 15-17 use the change in the area (m²) of commercial properties between 2000 and 2018 (2012 in regression 18) within a UK local authority by property type (office, retail and industrial). t-1 refers to the initial year and t to the last year of data available. Robust standard errors clustered at the local authority are presented in parentheses. ** and * indicate significance at the 1%, 5% and 10% level, respectively.

Disaggregated Hereditament Data and Instrumental Variable Estimation

For two years within our data period, 2010 and 2017, the UK Valuation Office have made available micro data on business hereditaments.[28] This includes information about each individual hereditament including their footprint, rateable value, location etc… Using the data at this level of aggregation has both advantages and disadvantages for our question and empirical approach. An advantage is that it allows us to further consider the issue of endogeneity bias by controlling for local authority fixed effects within our long differenced regressions thereby removing any effects from region specific shocks discussed in the previous section. It also allows for the use of an instrumental variable approach as we outline below. The disadvantages of this data is an absence of business identifiers which means it cannot be matched to micro-level employment or output data and that it does not allow for its separation into office, retail and industrial space.

[28] For broadband speed we use the change in the log of broadband speeds measured at the postcode level. These data are from OFCOM as in the main body of the paper, although the earliest year they are available is 2012. The data therefore measures the change in speed over the 5-year period between 2012 and 2017.

The micro data does allow for some additional stylized facts about commercial properties in the UK. Perhaps not surprisingly, the micro data show that changes in the area of commercial properties at the local authority level occur overwhelmingly through the entry and exit margin as new hereditaments are built or older ones are reconfigured for new uses or demolished. Very little adjustment happens in the m^2 of individual hereditaments, such that, in the absence of employment changes, the cross time change in most of the data in most postcodes is zero. To avoid issues about how to deal with the entry and exit of hereditaments and the preponderance of zeros we aggregate to the 7-digit postcode level.[29] At this level there are 133,487 postcodes which contain commercial properties, indicating that we are operating at a much more disaggregated level than the previous regressions. In this way, by first differencing the data we now remove the effect of unobservable time invariant geographic characteristics at the postcode level that might have previously explained our findings. We also include local authority fixed effects to account for differences in trends in business properties at this level.

We report the results for the change in the area of hereditament using the postcode data in Table 5, where we alter the control variables that are included across regressions 19 to 21 in the table. From these results we continue to find evidence that changes in commercial floorspace is negatively correlated with broadband speeds, even when using data across very fine geographies. We also note that the estimated coefficient is similar in magnitude to that for the baseline regressions, indicating that our previous findings were not strongly affected by more finely grained geographic features.

A further advantage of using the micro data is that it allows us to employ the instrumental variables previously used in DeStefano Kneller and Timmis. (2020). The instruments are based on the configuration of the telephone network, which is the infrastructure through which most types of internet are delivered in the UK. Built largely around the start of the 20^{th} century, this network has a tree like structure. Firms and households are connected to aggregators at the street and then local level through fixed wire connections (mostly copper but now also copper and fibre). There local aggregators, known as telephone exchanges, are then connected onto the fibre optic backbone of the network. It is well known that the cable distance from the firm or household to the local telephone exchange, known as local loops, has a strong effect on broadband connections speeds.

To instrument for the average broadband speed we follow DeStefano, Kneller and Timmis. (2020) use information on whether the postcode is attached to a telephone exchange enabled for fibre-broadband and the cable distance of the postcode to the telephone exchange.[30] As in that paper, we anticipate that broadband speeds are likely to be faster if the telephone exchange is enabled for fibre-broadband, but slower the greater the cable distance to the telephone exchange (regressions 22 and 24). The F-stats on these instruments are also very large, suggesting that the instruments are strong. In the second stage

[29] This is the most disaggregated level of postcodes in the UK.
[30] Refer to DeStefano, Kneller and Timmis for empirical evidence on the relevance and validity of these instruments.

results (regressions 23 and 25) we continue to find strong evidence of a negative effect of broadband speeds, consistent with capital biased technical change.

Table 5: OLS and IV results, relationship between broadband speeds and Area (m^2) using disaggregated Hereditaments data

Regression No.	**19**	**20**	**21**	**22**	**23**	**24**	**25**
		OLS		***IV regression***		***IV regression***	
Dependent variable		**Δarea (m^2)**		***ΔBroadband speed***	**Δarea (m^2)**	***ΔBroadband speed***	**Δarea (m^2)**
ΔBroadband speed$_t$	-0.006***	-0.004***	-0.007***		-0.013***		-0.014***
	(0.001)	(0.001)	(0.001)		(0.004)		(0.004)
ΔPrice of capital$_t$	0.811***	0.717***	0.810***		0.801***		0.800***
	(0.006)	(0.007)	(0.006)		(0.007)		(0.007)
ΔHereditament$_t$		0.228***					
		(0.007)					
Floorspace$_{t-1}$			-0.003***				-0.003***
			(0.001)				(0.001)
First Stage IV results							
ΔFibre Availability$_t$				0.388***		0.368***	
				(0.052)		(0.052)	
ΔFibre Availability$_t$				-0.057***		-0.055***	
** Local Loop Length$_i$*				(0.008)		(0.008)	
Local Loop Length$_i$				0.319***		0.309***	
				(0.004)		(0.004)	
ΔPrice of capital$_t$				-0.035***		-0.035***	
				(0.005)		(0.005)	
Floorspace$_{t-1}$						-0.057***	
						(0.002)	
F-stat on excluded instruments					2,781.54		2,781.54
Hansen J statistic p-value					0.84		0.83
Local Authority FEs	Y	Y	Y	Y	Y	Y	Y
Observations	133,487	133,487	133,487	96,996	96,996	96,996	96,996

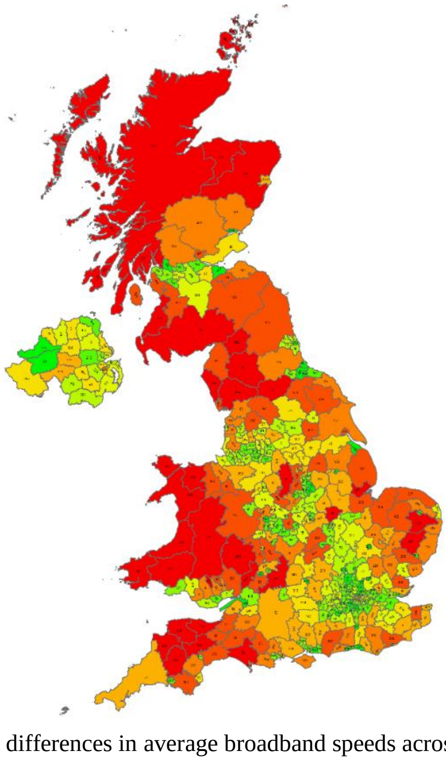
Notes: Regression for the change in the area (m^2) of commercial properties between 2010 and 2017 within a UK postcode. Robust standard errors clustered at the postcode level are presented in parentheses. t-1 refers to the initial year and t to the last year of data available. ** and * indicate significance at the 1%, 5% and 10% level, respectively. Regressions 22 and 24 reflect the first stage and 23 and 25 the second stage of the IV estimates.

6. Relocation and Agglomeration

The negative effect from faster broadband connections on the change in business capital revealed by our estimations implies an impact on the spatial organisation of production. As shown in Figure 5, the fastest broadband speeds in the UK are found in urban agglomerations. This implies that business activity has become more concentrated, which may have occurred in part because firms originally from outside of the region have moved.

That ICT might have led to increased agglomeration through this channel, contrasts with the more general finding in the literature, which is that ICT has led to the dispersion of economic activity. Particularly since communication technology affects the ability to share knowledge and communicate over longer distances. Ioannides et al. (2011) demonstrate that this has led the distribution of city sizes to have become flatter in the UK.

Figure 5 Broadband connection speed by local authority, 2018



Note: The following map illustrates differences in average broadband speeds across local authorities for the year 2018. Local authorities highlighted in green have the fastest average broadband speeds while local authorities highlighted in red have the slowest average broadband speeds.

In this final section of the paper we explore this issue in two alternative ways. Firstly, we allow for the possibility for the shuffling of business properties across space by adding to the regressions on the change in building capital a measure of average broadband speeds in contiguous local authorities. The inclusion of this variables is motivated by Redding and Turner (2015), who discuss the issue in relation to the effect of infrastructure on the reorganisation of production. They simplify the issue and suggest separating regions into three groups; the treated region, who are subject to the benefits of the infrastructure and any displacement effects from elsewhere, untreated regions, who are near treated regions and suffer displacement effects, and a residual group of regions who neither benefit from the infrastructure or displacement effects. Under an assumption that displacement effects are confined to neighbouring regions, the coefficient on the variable measure changes in broadband speed in contiguous regions will be positive, if displacement effects are strong. The results reported in regression 25 suggest that this is not a strong explanation of our results (See Table 6). The coefficient estimate is in fact negative and far from significance as standard levels.

In the final three regressions we measure changes economic activity within the region by the change in the number of firms (regression 26), the change in the level of employment (regression 27) and the change in the level of output (regression 28). Along with some basic controls we include in these regressions the measure of changes in broadband speed along with space per employee. Consistent with evidence from elsewhere in the existing literature that faster broadband speed connections help to disperse economic activity, see regressions 27 and 28 where broadband speed is found to be negatively correlated with changes in employment and output.[31] There is no such effect from broadband on the change in the number of firms (regression 26). Changes in the area per employee also has a negative effect on these measures of economic mass, suggesting that falls in the area allowed for by each employee tends to increase the number of firms, the level of employment and the level of output within a region. This result is consistent with the idea that this form of capital saving technical change increases the agglomeration of economic activity, and this serves to offset the dispersing effects of ICT.

[31] The effects of broadband speed on employment is found to be consistent across different sectors and within the instrumental variable framework, see Table A3 in the Appendix.

Table 6: OLS results, relationship between broadband speeds and relocation and agglomeration

Regression No.	**25**	**26**	**27**	**28**
Dependent variable	**Δarea (m²)**	**ΔNumber of firms**	**ΔEmployment**	**ΔOutput**
ΔBroadband speed$_t$	-0.113***	0.015	-0.108***	-0.128***
	(0.027)	(0.022)	(0.021)	(0.048)
ΔBroadband speed in neighbouring LAs$_t$	-0.027			
	(0.037)			
ΔSpace (m²) per employee$_t$		-0.147***	-0.938***	-0.814***
		(0.015)	(0.012)	(0.030)
ΔEmployment$_t$	0.029***			
	(0.009)			
ΔPrice of capital$_t$	-0.035			
	(0.047)			
Average wage$_{t-1}$	-0.131**	0.247***	-0.149***	-0.208
	(0.064)	(0.062)	(0.053)	(0.127)
Working age pop$_{t-1}$	-0.045***	0.030**	-0.053***	0.04
	(0.012)	(0.015)	(0.011)	(0.028)
ΔHouse Prices$_t$	-0.203***	0.196**	-0.182***	-0.537***
	(0.074)	(0.079)	(0.068)	(0.160)
R^2	0.091	0.124	0.884	0.531
Observations	942	999	999	999

Robust standard errors clustered at the local authority are presented in parentheses. t-1 refers to the initial year and t to the last year of data available. ** and * indicate significance at the 1%, 5% and 10% level, respectively.

7. Conclusion

In this paper we consider whether ICT shares a similar property of past general purpose technologies and has led to capital saving technical change. Exploiting variation in broadband connection speeds across locations and across time and new data on building capital for the UK we find evidence consistent with this hypothesis. Locations with faster broadband connections speeds have been subject to the largest decrease in building capital. This result is robust to considerations of endogeneity bias explained by time invariant regional characteristics and by observable regional characteristics along with those correlated with initial conditions. We also find evidence that this capital biased technical change has mattered more for industries reliant on office and industrial buildings as opposed to retail sectors. The results are also robust to the use of micro data along with an instrumental variable approach exploiting exogenous regional variation in the telephone network on which most broadband internet connection rely.

That ICT leads to capital saving suggests a new interpretation on some important current economic topics. Firstly, standard estimates of total factor productivity often ignore this type of capital, or assume it to be constant. This suggests that estimates of TFP are likely to be over-estimated as they underestimate the growth of capital services from buildings. Using ONS estimates of capital services for non-residential buildings in the UK between 2000 and 2018[32] and applying a back-of the-envelope calculations would suggest an increase of 10% in the productive stock suggested by our econometric estimates. This would imply growth of capital services of 4.02% per annum as compared to official estimates of 3.88%. The decline in TFP over the last decade may therefore be worse than originally feared.

[32] These data are available from https://www.ons.gov.uk/economy/economicoutputandproductivity/output/datasets/capitalservicesestimates

References

Acemoglu, D. (2003). 'Labor- and capital-augmenting technical change' *Journal of the European Economic Association*, Vol. 1 (1), pp-1-37.

Ahlfeldt, Gabriel M., Pantelis Koutroumpis, and Tommaso Valletti. (2017). "Speed 2.0 evaluating access to universal digital highways." Journal of the European Economic Association, Vol. 15(3). 586-625.

Akerman, A., Gaarder, I., and Mogstad, M., (2015). 'The skill complementarity of broadband internet. Quarterly Journal of Economics 130 (4), 1781-1824

Barkai, S., (2016). 'Declining labor and capital shares,' Stigler Center for the Study of the Economy and the State New Working Paper Series, 2016, 2.

Barkai, S., and Benzell, S. G. (2018). '70 Years of US Corporate Profits,' Stigler Center for the Study of the Economy and the State New Working Paper Series, 2018.

Bartel, A, Ichniowski, C. and Shaw. K. (2007). 'How Does Information Technology Affect Productivity? Plant-Level Comparisons of Product Innovation, Process Improvement, and Worker Skills.' *The Quarterly Journal of Economics* 122 (4): 1721–58.

Barkai, S., (2016). 'Declining labor and capital shares,' Stigler Center for the Study of the Economy and the State New Working Paper Series, 2016, 2.

Barkai, S. and Benzell, S. G. (2018). '70 Years of US Corporate Profits,' Stigler Center for the Study of the Economy and the State New Working Paper Series, 2018.

Benzell, S. and Brynjolfsson, E. (2019). 'Digital abundance and scarce genius: implication for wages, interest rates, and growth' NBER Working Paper No. 25585.

Berman, E. (1990). 'Does factor-biased technological change stifle international convergence? Evidence from manufacturing?' NBER Working Paper No. 7694.

Black, S. E. and Lisa M. Lynch. 2001. 'How to compete: The impact of workplace practices and information technology on productivity', The Review of Economic Statistics, Vol. 83(3). 434-445.

Black, S.E. and Lisa M. Lynch. 2004. 'What's driving the new economy?: The benefits of workplace innovation', The Economic Journal, Vol. 114. 97-116.

Bloom, N., Sadun, R. and Van Reenen, J., (2005). 'It ain't what you do it's the way that you do I.T. – testing explanations of productivity growth using U.S. affiliates', Centre for Economic Performance, London School of Economics, September

Bloom, N., Garicano, L., Sadun, R., Van Reenen, J., (2014). 'The distinct effects of information technology and communication technology on firm organization'. *Management Science*, 60, pp. 2859-2885.

Bresnahan, T. F and Trajtenberg, M. (1995). 'General purpose technologies – 'engines of growth? *Journal of Econometrics*, Vol. 2, pp. 83-106.

Bresnahan, T. F., Brynjolfsson, E. and Lorin M. Hitt. 2002. 'Information technology, workplace organization, and the demand for skilled labor: firm-level evidence', Quarterly Journal of Economics, pp. 339-376.

Brynjolfsson, E. and Hitt., L.M. 1996. Productivity, business profitability, and consumer surplus: three different measures of information technology value' MIS Quarterly, Vol. 20(2). 121-142.

Brynjolfsson, E. and Hitt., L.M. 2003. 'Computing productivity: Firm-level evidence', The Review of Economics and Statistics, Vol. 85(4). 793-808.

Brynjolfsson, E., McAfee, A., Sorell, M., Zhu. F. (2008). 'Scale without Mass: Business Process Replication and Industry Dynamics', Harvard Business School Technology & Operations Mgt. Unit Research Paper No. 07-016

Cheshire, P. (2018). 'Broken market or broken policy? The unintended consequences of restrictive planning' *National Institute Economic Review*, Vol. 245 (1), pp.R9-R19.

Chrinko, R. (1993). 'Business fixed investment spending: modelling strategies, empirical results, and policy implications' *Journal of Economic Literature*, Vol. 31(4), pp. 1875-1911.

David, P. A, (1990). "The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox," *American Economic Review*, vol. 80(2), pages 355-61, May

David, P. (1991). "Computer and dynamo: The modern productivity paradox in a not-too-distant mirror". In: Technology and Productivity: The Challenge for Economic Policy. OECD, Paris, pp. 315–347.David, P.A. and Wright, G. (2005). "General Purpose Technologies and Productivity Surges: Historical Reflections on the Future of the ICT Revolution," *Economic History* 0502002, EconWPA.

DeStefano, T., Kneller, R., and J. Timmis. (2020), Cloud computing and firm growth, Discussion paper, 2020/02

Devine, W., Jr.. (1983). 'From Shafts to Wires: Historical Perspective on Electrification,' *Journal of Economic History*, Vol. 43, No. 2, pp. 347-372

Dewan, S. and Chung-ki Min. (1997). 'The substitution of information technology for other factors of production: a firm level analysis', Management Science, Vol. 43(12). 1660-1675.

Fabling, R and Grimes, A. 2016. 'Picking up speed: Does ultrafast broadband increase firm productivity?' MOTU Working Paper 16-22.

Field, A. (1987). 'Modern business enterprise as a capital-saving innovation' *Journal of Economic History*, Vol.XLVII, pp. 473-485.

Field, A. (2006). 'Technical change and U.S. economic growth: the interwar period and the 1990s' in Rhode, P and Toniolo G. eds. "Understanding the 1990s: The economy in long run perspective", Cambridge: Cambridge University Press.

Grossman, G., Helpman, E., Oberfield, E. and Sampson, T. (2017). 'The productivity slowdown and the declining labor share: a neoclassical exploration' NBER Working Paper No. 23853.

Gordon, R. J. 2000. "Does the "New Economy" Measure Up to the Great Inventions of the Past?," *Journal of Economic Perspectives*, Vol. 14(4), pp. 49-74

Greenstein, S., Goldfarb, A. and Forman, C. (2018). 'How Geography Shapes—and Is Shaped by—the Internet', In The New Oxford Handbook of Economic Geography, edited by Gordon Clark, Maryann Feldman, Meric Gertler, and Dariusz Wojcik, 269–285. Oxford: Oxford University Press.

Hogendorn, C., and Frischmann, B. (2017). 'Infrastructure and general purpose technologies: a technology flow framework' Wesleyan Economic Working Papers 2017-001.

Hubbard, T. N. (2003). 'Information, decisions, and productivity: On-board computers and capacity utilization in trucking', *American Economic Review*, Vol. 93(4). pp. 1328-1353.

Ioannides, Y. M. Overman, H. G. Rossi-Hansberg, E. and Schmidheiny, K. (2007) 'The Effect of Information and Communication Technologies on Urban Structure' CEP Discussion Paper 812

Irmen, A. (2017). 'Capital- and labor- saving technical change in an aging economy' *International Economic Review*, Vol. 58, pp. 261-285.

Jorgenson, D. (1971). 'Capital theory and investment behavior' *American Economic Review*, Vol 53(2), pp. 247-259.

Jovanovic, B. and Rousseau, P.L. (2005). 'General purpose technologies' in Aghion, P. and Durlaf, S. (eds.), Handbook of Economic Growth, vol. 1B, Elsevier B.V., Amsterdam, pp. 1181-1224.

Karabarbounis, L., and Neiman, B. (2013). 'The global decline of the labor share,' *The Quarterly Journal of Economics*, Vol. 129 (1), pp. 61–103.

Kolko, J. (2012). 'Broadband and local growth' *Journal of Urban Economics, 71, 100-113.*

Sivitanidou, R. (1997) Are center access advantages weakening? The case of office commercial markets, *Journal of Urban Economics*, 42, pp. 79–97

Data references

Office for National Statistics. Virtual Microdata Laboratory (VML), University of the West of England, Bristol, (2017) Annual Respondents Database X, 1998-2014: Secure Access 4th Edition. Office for National Statistics [original data producer(s)] UK Data Service SN:7989, http://doi.org/10.5255/UKDA-SN-7989-4

Office for National Statistics (2017). Business Structure Database, 1997-2017: Secure Access [data collection] 9th Edition. UK Data Service. SN:6697, http://doi.org/10.5255/UKDA-SN-6697-9

Valuation Office Agency. (2016). Non-domestic rating: business floorspace. https://www.gov.uk/government/statistics/non-domestic-rating-business-floorspace

Appendix

Table A1: Summary Statistics

Variable	mean	sd	Obs.
Floorspace Area	5.68	1.21	1041
ΔArea	0.08	0.212	1141
Broadband Speed	45.93	13.46	1041
ΔOutput	0.40	0.67	1138
ΔPrice of Capital	0.35	0.18	1141
Average Wage$_{t-1}$	5.85	0.13	1026
Working age pop$_{t-1}$	4.33	0.59	1008
ΔHouse Prices	1.09	0.10	1041
ΔEmployment	0.06	0.60	1141
ΔAverage Hered Size	-0.09	0.24	1041
ΔAverage Firm Size	-0.05	0.55	1038
ΔFirms	0.11	0.29	1038
Working from home	0.11	0.04	1020

Notes: Data Sources: Floorspace Area, Hereditaments, Rateable Value (Price of Capital) and Floorspace per hereditament are from UK Valuation Office and are measured at the local authority level. Employment and Number of firms is from the Business Structure Database from the ONS and is aggregated to the local authority level. Broadband Speed is data OFCOM. Working from Home, Average Wage and Working Age Population are from the LFS. House prices are from the ONS.

Table A2: Instrumental variable regressions and falsification test

Regression No.	**1**
Estimation Method	**OLS**
Dependent variable	**Δarea (m^2) 2012**
Hereditament Type	**All**
Broadband speed	-0.041**
	(0.021)
ΔOutput	0.032***
	(0.010)
ΔPrice of capital	0.090**
	(0.039)
Average wage$_{t-1}$	-0.070
	(0.053)
Working age pop$_{t-1}$	-0.045***
	(0.011)
ΔHouse Prices	0.111*
	(0.066)
Observations	990

Notes: Regression for the change in the area (m^2) of commercial properties between 2000 and 2012 within a UK local authority by type (office, retail and industrial). Robust standard errors clustered at the local authority are presented in parentheses. , ** and * indicate significance at the 1%, 5% and 10% level, respectively.

Table A3: Instrumental variable regressions for employment

Regression No.	**1**	**2**	**3**	**4**
Estimation method	**OLS**	**IV**	**OLS**	**IV**
Dependent variable	**ΔEmployment**	**ΔEmployment**	**ΔEmployment**	**ΔEmployment**
Hereditament Type	**All Sectors**	**All Sectors**	**Office & Industrial**	**Office & Industrial**
Broadband speed	-0.006***	-0.009**	-0.005**	-0.009*
	(0.002)	(0.004)	(0.002)	(0.005)
ΔEmployment	0.112***	0.114***	0.110***	0.112***
	(0.020)	(0.020)	(0.020)	(0.020)
ΔPrice of capital	0.027	0.024	0.023	0.02
	(0.020)	(0.020)	(0.020)	(0.020)
Working age pop_{t-1}			-0.003	0.009
			(0.020)	(0.030)
R^2	0.065	0.066	0.063	0.063
F-stat on excluded instruments		391.25		265.04
Observations	934	844	910	820

Notes: Regression for the change in floorspace between 2000 and 2012 within a UK local authority by type (office, retail and industrial). Robust standard errors clustered at the local authority are presented in parentheses. , ** and * indicate significance at the 1%, 5% and 10% level, respectively.