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Broadband and Productivity: Structural Estimates for Germany*

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Abstract

We study the impact of broadband availability on firms' total factor productivity (TFP) using German firm-level data between 2010 and 2015. We adopt a control function approach to causally identify and separately estimate productivity for 46 two-digit manufacturing and service sectors. Over the sample period, broadband availability, measured by 16 Mbps transmission rates, more than doubled in German municipalities. While this increased broadband availability has almost no effect on firms' productivity in manufacturing, it significantly increases TFP in most service sectors. Yet, the size of the effect is heterogenous across industries.

JEL Classification: D24, D22, J24, O14, O22, O33

Keywords: broadband internet, productivity, firm-level data

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1 Introduction

Broadband networks are an essential part of modern economies, just like the energy and the transportation infrastructures. Its importance constantly grew in the last decades due to the increasing degree of digitization of the economy in most of its dimensions, from production processes to distribution, to the success of digital products and services. Such digitization boost could take place, and can continue further, only if the underlying broadband network enables fast transmission of increasingly larger amount of data. Consequently, most countries have embarked on a mission to support the creation and expansion of their broadband networks and to increase access as well as transmission rates. In the European Union (EU), the Commission has set an ambitious target that all Europeans should have broadband access with download rates of at least 30 Mbps and that around half of households should have a broadband connection of 100 Mbps or more (**?**). A similar target was issued by the Federal Communications Commission (FCC) in the United States (US), according to which a broadband infrastructure should be built by 2020 that would enable at least 100 million US households to download at a speed of 100 Mbps (Federal Communications Commission, 2010).

The impact of the expansion of this digital infrastructure on the economy and, more generally, on societies, has been extensively studied by academic research. A large and diverse literature has focused on estimating the effect of broadband infrastructure on several outcomes that ranges from its impact on economic growth (Röller and Waverman, 2001; Czernich et al., 2011), over its effects on labor market outcomes (see for instance Czernich 2014; Forman et al. 2012; Crandall and Lehr 2007), to its impact on various not purely economic outcomes such as, *inter alia*, voting behavior (Falck et al., 2014; Gavazza et al., 2019).

This paper analyzes how the availability of faster broadband affects firms' total factor productivity (TFP). First, we quantify the effect of broadband on TFP by estimating a sector-level production function adopting the framework proposed by Ackerberg et al. 2015 (henceforth ACF). Second, within this framework, we apply a control function approach which allows, under relatively mild assumptions, for a causal interpretation of the estimated links. Finally, we estimate our empirical model using a large panel of German firms, which allows us to estimate the effect of broadband on productivity for 22 two-digit manufacturing industries and 24 two-digit service sectors. This is important because it allows us to capture the substantial heterogeneity across sectors, both in terms of the shape of the production functions and in terms of the impact of broadband infrastructure.

With this study we attempt to overcome some of the limitations of previous analyses, which either focus on labor productivity – thereby mostly treating broadband as standard input factor in the production function – or adopt estimation methods that may raise concerns related to causal interpretation of results. Specifically, due to data limitations, the majority of these studies cannot exploit exclusion restrictions or identification strategies that would allow for a causal interpretation of the estimated effects, although they provide interesting insights on the relationship between broadband availability and productivity. Finally, many studies rely on data for manufacturing firms or, if sufficient observations are available, distinguish only between services and manufacturing without further exploring heterogeneity among the different industries within them.

The richness of the data we use in this study is greatly informative about how broadband affects productivity. Our results show that an increased broadband availability at 16 Mbps transmission speed led to higher TFP in most of the service sectors, but not in most of manufacturing, with some exceptions. According to our estimates, an increase in the average availability of broadband at 16 Mbps by about 40 percent points across municipalities – which corresponds to the growth observed in the period under consideration – causes an increase in productivity of 0.76 to 6.8 percent, depending on the sector. Various robustness checks and additional heterogenous patterns that we observe in the data confirm these findings. For instance, the effects appear to be larger, the better the actual quality of the broadband connection, which we proxy with the distance to the Main Distribution Frame (MDF), which is the node of the network that connects the end user to the internet and it is a crucial determinant of the actual speed.

The remainder of the paper is organized as follows: section 2 presents related studies on the topic of broadband internet and firm productivity. Section 3 discusses the prevailing method in this literature and presents the control function approach applied in our study. The fourth section introduces the data. Section 5 discusses the main results and further robustness checks, while the last section concludes.

2 Literature

Before going into details of the literature, it is important to briefly define what broadband networks are and how they are measured. Whether a network is considered as a broadband network is less a question of its technology (3G to 5G, DSL, cable, fiber to home, fiber to node etc.), but rather the speed with which data are transmitted. There is not, however, a commonly agreed or even stable threshold of a minimum transmission speed that defines broadband. In 2009, the OECD defined networks with transmission volumes of 256 Kbps and above as being broadband (OECD, 2009). At the same time, networks with minimum transmission rates of 1 Mbps were considered broadband by the German Government in their broadband strategy of 2009. These rates were still included in governmental reports concerning broadband coverage in Germany through 2018 (Börnsen, 2012; atene KOM GmbH and WPG, 2018). After 2018, at least in the reporting of the German Government, the lower threshold changed to 16 Mbps (atene KOM GmbH and WPG, 2019). This illustrates that the definition of broadband networks is not univocal and changes over time. Consequently, studies on broadband may differ with respect to the underlying technology and transmission speed, depending on the observation period. However, in the subsequent literature review we include all studies regardless of the specific transmission speed as long as these networks were considered to be broadband within the investigation period.

Few overview studies exist so far. Cardona et al. (2013) provide a compelling overview over 150 studies up until 2013 on the relationship between Information and Communication Technology (ICT), output, and productivity.[1] However, the focus of their literature review is not just on broadband, but rather on all types of ICT assets. In general, they find that economic growth and productivity is enhanced by ICT. It is worth noting that, according to Cardona et al. (2013), those studies focusing on productivity generally treat ICT as an input in a production function. Also Bertschek et al. (2015) provide a comprehensive review of the studies up to 2015 analyzing the effect of broadband networks on economic growth, employment, and productivity. Regarding productivity, Bertschek et al. (2015) conclude that the results in the empirical literature are not unanimous, with a considerable number of studies finding only a weak, if not none, significant impact of broadband adoption on firms productivity.

[1] A further overview is provided by Biagi (2013).

Since Bertschek et al. (2015), further studies have looked into the relationship between broadband networks and firm productivity. For reasons of space, we refrain from presenting them in detail here. A description of each of these studies is provided in Appendix C. In the following, we focus on what conclusions can be drawn from the latest literature, what the essential features of these studies are, what our study does differently in comparison to the these studies and what it adds, to the existing literature.

With regard to the core question of our analysis, i.e. whether and to what extent broadband increases the productivity of firms, the results in the literature to date continue not to be unanimous. First, there are those studies that do not find any statistically significant effect of broadband on productivity, be it labor productivity or TFP. (e.g. Bertschek et al., 2013; Haller and Lyons, 2015; Fabling and Grimes, 2016; De Stefano et al., 2018). Then there are those studies with mixed results (e.g. Hagsten, 2016; Haller and Lyons, 2019). And finally, there are several studies that indeed confirm a statistically significant effect of broadband networks on firm productivity (e.g. Grimes et al., 2012; Bertschek and Niebel, 2016; Hagsten and Sabadash, 2017; Bertschek et al., 2019; Bartelsman et al., 2019).

All but one of these latter studies share the distinct characteristics of using an augmented Cobb-Douglas production functions with labor productivity as dependent variable. It follows that these analyses in essence capture the effect of broadband on the output of firms, because broadband enters the production function like any other input. We discuss this and potential econometric issues of such approach in more detail in section 4.1. We deviate form this strand of the literature by focusing on the direct effect of broadband on TFP. However, in order to link our study to previous analyses and to make its findings more comparable, we also present results based on estimations with broadband as an independent input in an augmented Cobb-Douglas production function with labor productivity as dependent variable.

To date, only very few studies analyze the effect of broadband on TFP. It is worth noting that focusing on direct effect of broadband on TFP does not change the overall picture: two studies find no effect whatsoever (Haller and Lyons, 2015; Fabling and Grimes, 2016), one study has mixed findings (Haller and Lyons, 2019), and one analysis does find a positive effect of broadband on TFP (Grimes et al., 2012). Apart from Grimes et al. (2012), which define TFP as wedge between firm-level labor productivity and industry-level labor productivity, all studies make use of a two-stage approach. In the first stage of this procedure, a Cobb-Douglas production function is estimated. The resulting residuals – which are used to measure TFP –

are used in a second, independent regression as dependent variable. This approach is plagued by econometric issues that we discuss in section 4.1. Our analysis differs from the previous literature by applying a method – the control function approach – that avoids the limitations of this two-stages approach.

An important feature that unifies essentially all papers is the way they deal with the econometric problem of endogeneity and reverse causality of broadband. This issue comes with the fact that firms decide on whether or not to adopt broadband. Following the seminal paper by Falck et al. (2014), the issue is solved by using broadband availability at the regional level as an instrument or a proxy for broadband adoption. We will follow this approach.

With regard to causality, it must be noted that the bulk of the studies cannot claim to capture the causal effect of broadband on productivity. This is usually due to data issues, which often prevent the use of instrumental variables (IVs) or the use of econometric methods that allow for causal inferences. In fact, the estimations are predominantly conducted by means of OLS or similar techniques. Consequently, various authors emphasize that data limitations and econometric issues result in the fact that the "relationships cannot be interpreted as causal" (Bartelsman et al., 2019, pp.38). Exceptions are the studies by Fabling and Grimes (2016) and by Bertschek et al. (2013). The former uses an IV that exploits the introduction of a subsidy scheme for ultra-fast broadband that was imposed by the government of New Zealand. The latter make use of the General Method of Moments (GMM) and uses lagged independent variables within the GMM approach as IVs. In contrast to previous studies, our analysis will apply a control function approach that, under specific assumptions, allows for a causal interpretation of the results. Additionally, we will use external IVs within the control function setting.

A further common characteristic of the literature is the lack of sectoral depth. Most estimations are based on data that are pooled across industry and time. This required previous studies to implicitly or explicitly impose the assumption that broadband affects all firms in the same way and to the same extent, be it a producers of cement or an IT-consulting firms. There are some studies that have sufficiently rich data (Hagsten, 2016; Hagsten and Sabadash, 2017; Bartelsman et al., 2019). But even in these cases, most likely due to remaining data issues, the estimations are not conducted for detailed industries but the analyses only distinguished between manufacturing and services.

One of those studies, Hagsten and Sabadash (2017), finds broadband to have a stronger effect in services. This might be driven by the fact that broadband, at least until the late 2010s, was more important in the production and for the distribution of some services, namely IT-related services, than for the production in some manufacturing industries, say the manufacture of cement or the manufacture of basic metals.[2] This view is supported by the results of Haller and Lyons (2019). Their study focuses on the service sector and is the only one we are aware of that distinguishes between one-digit industries in the analysis. They finds a strong and statistically significant effect of broadband for the ‘Information and communications service´ sector and the ‘Administration and support services´ sector. In contrast, there is no effect in other, less IT-related service sectors.[3]

It follows that, to date, we know very little about the effect of broadband on the productivity of firms in different industries. Our analysis fills this gap by conducting the analysis at the two-digit industry level for 46 sectors that cover most of the business economy. This level of detail has not been provided yet. Hence, this study is the first to capture the heterogeneity among the different industries across the business economy.

We know from other strands in the literature that productivity differs substantially between – and even within – industries (e.g. Corrado et al., 2007; Syverson, 2011; Foster et al., 2016; Bartelsman and Wolf, 2017; Foster et al., 2018). The literature also shows that the relevance of various drivers of productivity, such as R&D, IT and software, organizational capital etc., and their effect on TFP varies substantially between industries (Arrighetti et al., 2014; Ugur et al., 2016; Le Mouel and Schiersch, 2020). We therefore expect that such heterogeneity between industries should also be observed with regard to the effects of broadband. Given the aforementioned discussion, we also expect broadband to increase productivity of firms in service sectors, while we expect only weak or even no effect for most of the manufacturing industries.

[2]It can be expected that this will change over time. If the projected scenarios of industry 4.0 became real, the entire production process of almost all final goods will be directly monitored from the first basic products to the final consumer product. This would require a permanent access to data at all layers of the production process and would entail direct interventions even in the production of the first basic products, such as the forming of metal.

[3]This finding is supported by the results of Maican and Orth (2021). Their study focuses on subsidies for building broadband infrastructure and what incentives and benefits exists for municipalities as well as how it effects hiring in firms and the long-run profits. The study only considers the ‘Information and communication service´ sector. Their model requires several state variables, one of which is productivity. Their estimates show that firms benefit from broadband subsidies in terms of higher TFP.

3 Data and descriptive statistics

The analysis is based on firm-level data from the AFiD-Panel Manufacturing Firms and the AFiD-Panel Service Firms. These datasets contain information on the location of firms, captured by its 9-digit municipality code, on various inputs, and on value added as output.[4] The AFiD-Panel is based on various surveys of the German statistical system.[5] We enrich these datasets with deflator time series for all variables measured in monetary units, as well as depreciation rates for capital. These time series are provided by the Statistical Office at the two-digit industry level. The depreciation rates are used to estimate capital stocks by means of the perpetual inventory method (PIM). Data on the population and size of each municipality are provided by the Federal Office for Building and Regional Planning and merged to the data using the unique 9-digit geo-code. Finally, broadband availability at the municipality level comes from the Federal Government's Broadband Atlas[6] of the German Federal Ministry of Transport and Digital Infrastructure. The available data cover the 2010 to 2015 period.

The data at hand contain information on broadband availability at 16 Mbps transmission speed by municipality and year. The data cover about 8000 municipalities in seven West-German federal states and represent a snapshot at the end of each year.[7] While the analysis is not based on observations for all of Germany, the dataset covers the majority of the economically relevant regions, which produced about 80 percent of the German GDP in the observation period.

These datasets are used in a number of previous studies, although not in the combined form as in this study, and are presented in detail therein, which is why we abstain from repeating a detailed discussion here.[8] Instead, we first focus on describing the variation in the broadband data and then discuss the main statistics for the variables relevant for the production function aggregated at the level of one-digit industries.

Figure 1 depicts the average percentage coverage with 16 Mbps transmission speed in

[4]The 9-digit geo-code is not part of the AFiD-Panel Service Firms. It is obtained from the AFiD-Panel Company Register and separately added to the data in the data preparation process.

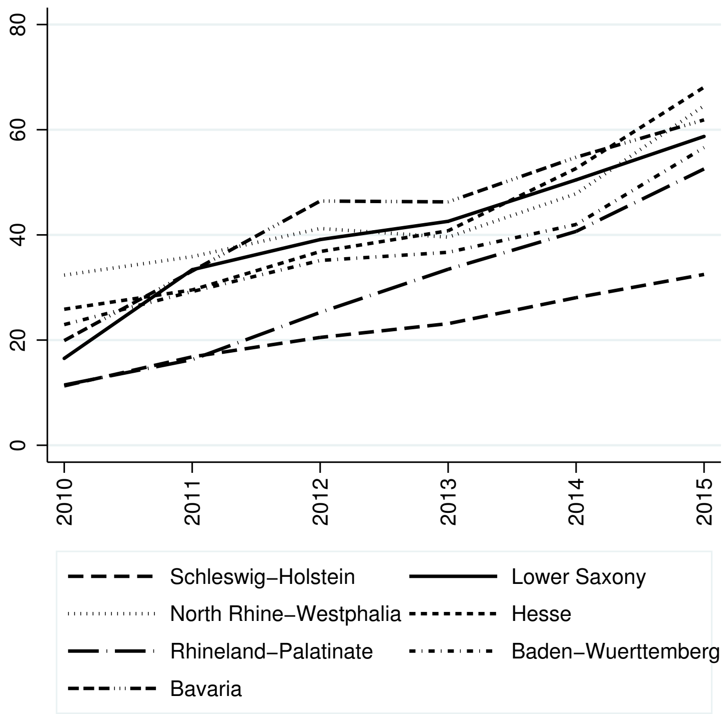
[5]Responsible for most of the surveys are the Statistical Offices of the Federal States, not the Federal Statistical Office. The State Statistical offices also retain ownership of the data.

[6]https://www.bmvi.de/DE/Themen/Digitales/Breitbandausbau/Breitbandatlas-Karte/start.html

[7]These states are: Schleswig-Holstein, Lower-Saxony, North Rhine-Westphalia, Hesse, Rhineland-Palatinate, Baden-Wuerttemberg, and Bavaria. See Duso et al. (2021) for a discussion of the data.

[8]Interested readers are referred to Le Mouel and Schiersch (2020), Gornig and Schiersch (2019), Richter and Schiersch (2017), Falck et al. (2014) , Koch (2007), and Fritsch et al. (2004).

Figure 1: Average availability of 16 Mbps transmission in percent, municipality level

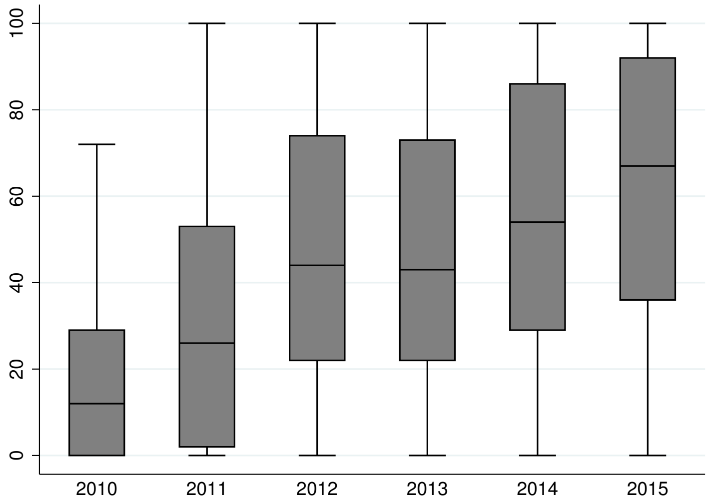


municipalities for each Federal State over time. In 2010, average availability was at 11 percent in municipalities within the state of Schleswig-Holstein and 32 percent in North Rhine-Westphalia. By 2015, it had tripled to 32 and doubled to 64 percent in these two states, respectively. While the trend is positive in all federal states, there appears to be quite some variation between the states.

Moreover, there is not only substantial variation over time and states, but also within states. This is evident from Figure 2, which depicts the distribution of broadband speeds across municipalities for the federal state of Bavaria by means of box plots. Similar graphs for the remaining states are shown in Appendix B. First, the figure reveals that variation across municipalities is substantial, as boxes are large and whiskers range from zero to 100 percent for most years. Furthermore, the size of the boxes increase between the start and the end of the observation period. Hence, despite the fact that the mean and median coverage of 16 Mbps transmission speed increases over time, the variation remains large throughout the observation period.

We interpret the low coverage of 16 Mbps at the beginning of the sample period, its constant increase over time, and the remaining high share of municipalities with little to no coverage,

Figure 2: Boxplot of broadband coverage in Bavarian municipality in percent over time



as an expression of the roll-out phase of high-speed broadband internet in the concerned regions. According to the literature, the effects of broadband networks are better captured in the early stages of new technologies and speeds. Therefore, we assume that our data cover the period in which changes in broadband coverage has actually affected businesses.

Because of the matching of different databases and due to the regional and time restrictions resulting from the broadband data, the final firm-level dataset contains about 455,000 observations, covering 46 two-digit industries.[9] Table 1 reports the mean and the standard deviation of the main production function variables and other important control variables by one-digit industries.

As can be expected, the average value added of manufacturing firms is larger than that of service firms. Manufacturing firms are also larger in terms of employment and capital. Also in line with expectations, manufacturing firms require significantly more material inputs than service firms. The average gross wages are largest in the Manufacturing sector (C) and in Information and communication services (J). Regarding population density, it seems that service firms, especially in the Information and communication services (J) and in Professional, scientific and technical activities services (M), are more often located in densely populated

[9]Note that the analysis must comply with the strict privacy policy requirements of the German Statistical Offices. This includes issues such as dominance as well as the number of observations per year and cell etc. As a result, the following industries had to be dropped as part of the data preparation process in order to be in line with the privacy policy requirements: the entire Mining industry (B5-B9), the Manufacturing of tobacco products (C12), and the Manufacturing of refined petroleum products (C19). Further, we define outliers for our analysis as those observations at the two-digit industry and year level with labor productivities, capital labor ratios, or capital productivities that are above the 99.5 percentile or below the 0.5 percentile.

Table 1: Mean of production variables

Variable	Manufacturing (C)	Transport (H)	Information serv. (J)	Prof. services (M)	Admin. services (N)	Repair services (S)
Value Added	28.422	4.728	8.57	2.29	3.336	.614
	(289.575)	(51.358)	(121.052)	(18.253)	(24.991)	(2.495)
Employment†	317.686	69.871	71.745	28.471	97.675	12.621
	(2400.326)	(596.602)	(476.764)	(208.799)	(612.586)	(39.754)
Capital	57.222	30.103	17.809	2.553	7.377	.288
	(547.025)	(1142.207)	(413.464)	(47.209)	(96.826)	(.902)
Material	45.62	7.204	11.161	2.324	2.719	.726
	(592.467)	(78.296)	(185.361)	(82.93)	(42.974)	(4.845)
Wages	46.087	26.723	47.031	34.744	24.526	18.578
	(15.883)	(31.426)	(38.729)	(48.335)	(28.295)	(15.774)
Population density	242.469	333.441	592.954	531.318	428.19	306.717
	(561.026)	(735.063)	(1085.041)	(1016.68)	(870.056)	(723.965)
N	71948	64017	50516	169341	93104	6470

Standard deviation in parentheses. Monetary values in million €. †: head-count number of employees

areas as compared to manufacturing firms. The patterns observed in Table 1 match those that can be found in previous studies with the respective administrative firm-level dataset and covering the whole Germany (e.g. Le Mouel and Schiersch, 2020; Gornig and Schiersch, 2019). Hence, our restriction on observations from the seven West-German Federal States – which is determined by the broadband data – does not substantially affect the structure of the sample.

4 Method

As discussed in section 2, most studies use labor productivity as the dependent variable in the analyses. Studies assessing the effect of broadband on TFP generally apply a two-stage approach in which a Cobb-Douglas production function is estimated in the first stage. The results are used to compute TFP. These TFP values are then used in the second stage to estimate the effect of broadband on productivity. Regardless of whether labor productivity or TFP is the dependent variable, most studies make use of OLS. Below, we first present and discuss the standard models used so far in the literature. Subsequently, we present the econometric method that is applied in the second phase of the analysis to derive the main results of this study.

4.1 The standard approaches

Equation 1 shows a standard estimation equation that is predominantly used within the literature on productivity and broadband. It is an augmented Cobb-Douglas production function in logs with labor productivity (lp_{it}) as the dependent variable, with y_{it} as value added, while labor (l_{it}) and capital (k_{it}) are the standard production inputs.[10] Broadband (b_{it}) is added as main variable of interest.[11] The matrix $X_{k,it}$ contains k control variables. In our analysis, it encompasses year dummies, federal state dummies, and population density. Population density is included to control for a higher productivity of firms in urban (more densely populated) areas compared to rural (less densely populated) areas due to positive agglomeration effects (e.g. Gornig and Schiersch, 2019). It is also well known that broadband availability is generally higher in agglomeration areas. Hence, population density is needed to avoid spurious correlations between the output and broadband availability.

$$lp_{it} = y_{it} - l_{it} = \beta_0 + (\beta_l - 1)l_{it} + \beta_k k_{it} + \beta_b b_{it} + \boldsymbol{X_{k,it}\beta_k} + \varepsilon_{it} \tag{1}$$

The first part of our analysis consists of estimating equation 1 by means of OLS. This pursues two goals. First, it makes our analysis more directly comparable to the existing literature. Second, it provides a first impression on the correlation between broadband and labor productivity – or better said – output, conditional on controlling for some observables.

Yet, estimating equation 1 by means of OLS has a number of issues. First, and foremost, OLS estimates are expected to deliver biased and inconsistent estimates of the causal relationships of interest. A second, more conceptual issue is the fact that broadband enters the function like any other normal input. This implies that it can be used to substitute labor or capital, with a substitution elasticity of one. While there might be some substitutability in terms of software or services that might be outsourced, broadband as an infrastructure itself can hardly substitute inputs required in the production process. Third, due to its functional form, equation 1 does not allow valid conclusions about the effect of broadband on the productivity of firms but only whether broadband has an positive effect on output.[12] Of

[10] By imposing the strong assumption of constant returns to scale, $(\beta_l - 1)l_{it}$ would drop out and capital (k_{it}) would be replaced by capital intensity ($k_{it} - l_{it}$)

[11] Note that equation 1 would be enhanced to include material if a sales- or gross output production function is estimated.

[12] By simple rearranging of the production function, it can be easily shown that all coefficients –with the exception of the labor coefficient– measure the output elasticity of the respective inputs and remain unchanged regardless of whether the dependent variable is labor productivity or value added (or sales etc.). Thus, any

course, if broadband is indeed part of a function that governs TFP, the coefficient of broadband might show up positive and significant when estimating equation 1 because the variable might capture some of the variation that is due to variation in TFP. Yet, this remains speculative as the modelled relationship is one between output and broadband, not that between broadband and productivity.

Some studies address the second and third issue by applying a two-stage approach as outlined in equations 2a and 2b.

$$y_{it} = f(l_{it}, k_{it}; \boldsymbol{\beta}) + \boldsymbol{X_{k,it}\beta_k} + \underbrace{\varepsilon_{it}}_{(\omega_{it}, \epsilon_{it})} \tag{2a}$$

$$\omega_{it} = g(b_{it}, ...) \tag{2b}$$

The first stage consists of estimating equation 2a. It does not need to be a value added production function, as in the present example, but it could be a sales- or gross output production function instead. The TFP estimate from the first stage enters equation 2b as a dependent variable, which is used in the second step to evaluate the effect of broadband on productivity.

The main econometric issue of this approach is the well known simultaneity and endogeneity issue of production function estimations first emphasized by Marschak and Andrews Jr. (1944). This issue stems from the fact that firms take into account their productivity in choosing the inputs. Yet, TFP is an unobserved variable in all firm-level datasets. Consequently, ω_{it} is part of the residual (ε_{it}) in any estimation of equation 2a. This causes correlation between the input variables and the error term, which violates the necessary exogeneity assumption and lead to biased output elasticities for labor and capital, and, consequently, leads to biased TFP, which are then used in Eq. 2b. Furthermore, in this two-stage approach, the dependent variable in equation 2b is rather $\hat{\varepsilon}_{it}$ than $\hat{\omega}_{it}$.

An additional issue with this approach is the use of identical – or functionally dependent – control variables in both stages. Not uncommon is the use of labor in the first stage and the second stage. This is problematic because the exogeneity assumption must be imposed in the first stage on all variables in order to obtain unbiased coefficients, which are then

significant positive coefficient of an exogenous variable, e.g. broadband, is not capturing the "effect" on "productivity" but its output enhancing effect.

used to calculate TFP. However, this initial assumption is almost taken to absurdity if the second equation (equation 2b) postulates the exact opposite. Namely, that the TFP, which is part of the error term in equation 2a, is driven by the same variable that is assumed to be uncorrelated with that very error term. This problem applies to all variables that are used in both stages. Classic candidates are labor or a labor related variable, such as size-class dummies, which are used to capture the difference between small and large firms or variables that capture differences due to regions or industries.

4.2 The control function approach

We address the three listed issues –that is the difficulty of claiming causality in the standard approaches, the required focus on the direct effect of broadband on productivity instead of its output enhancing effect, and the econometric issues associated with production function estimations– by applying the ACF approach (Ackerberg et al., 2015) in the second and main part of our estimation strategy. The control function approach builds on the seminal studies of Olley and Pakes (1996) and Levinsohn and Petrin (2003). In what follows, we will briefly outline the necessary assumptions and steps of this method.

The starting point is a production function in logs with value added as dependent variable as depicted in equation 2a. As discussed above, the observed error term (ε_{it}) contains the true i.i.d. error (ϵ_{it}) and the unobserved TFP (ω_{it}). Since the seminal paper of Levinsohn and Petrin (2003), it is assumed that an intermediate demand function ($m_{it} = h_t(\omega_{it}, ...)$) with a number of distinct characteristics exists. These are, *inter alia*, that the intermediary input (m_{it}) is a fully flexible input, that the function is strictly monotonic in ω_{it}, and that ω_{it} is the only unobserved state variable.[13] Based on these assumptions, h_t is invertible, leading to $\omega_{it} = h_t^{-1}(m_{it}, ...)$. Besides the intermediate inputs, $h_t^{-1}(...)$ also contains the state variables capital and labor as well as other (observed) variables that are relevant to the development of TFP.[14] In our application, broadband (b_{it}) is also included in h_t^{-1}. This function is substituted into equation 2a, this way controlling for the unobserved TFP.

[13] See Olley and Pakes (1996) and Levinsohn and Petrin (2003) for further assumptions.

[14] Ackerberg et al. (2015) provides a detailed discussion for the necessity of including labor in the control function. See De Loecker and Warzynski (2012) for a discussion of further variables that need to be included in the first stage control function.

$$y_{it} = \underbrace{f(l_{it}, k_{it}; \boldsymbol{\beta}) + \overbrace{h_{it}^{-1}(m_{it}, l_{it}, k_{it}, b_{it})}^{\omega_{it}}}_{\phi_{it}} + \boldsymbol{X_{k,it}\beta_k} + \epsilon_{it} \tag{3}$$

Equation 3 is estimated in a first step by means of OLS. The aim of this step is to break the correlation between production inputs and the error term ε_{it} by controlling for productivity with the help of the proxy function h_t^{-1}. Put differently, the error term ε_{it} is split into the i.i.d. error term ϵ_{it} and the TFP, which is a part of ϕ_{it}. The functional form of h_{it}^{-1} is unknown and is approximated by a second-order polynomial in the estimation. However, because labor and capital are part of both functions, the output elasticities of labor and capital are not identified in this first step.[15]

A second step is required in order to obtain consistent estimates for all relevant variables. This step builds upon the function that describes TFP. Throughout the literature, it is assumed that the development of productivity is best described by a first-order Markov process:

$$\omega_{it} = E[\omega_{it}|I_{it-1}, b_{it}] + \xi_{it} = g(\omega_{it-1}, b_{it}; \boldsymbol{\gamma}) + \xi_{it} \tag{4}$$

Hence, the productivity in period t is determined by the expected productivity, given the past experiences summarized in the information set I_{it-1}, an exogenous variable that affects productivity – broadband in this analysis – and a random shock to productivity ξ_{it}. The estimation equation (equation 5) is derived by substituting the TFP in equation 4 with the functional relationship established in equation 3, i.e. $\omega_{it} = \phi_{it} - f(l_{it}, k_{it}; \boldsymbol{\beta})$. The remaining unobservable is ϕ_{it}, which is replaced by the estimates obtained from the first stage. Note that by estimating equation 5, both the production function coefficients ($\boldsymbol{\beta}$) and the coefficients of the law of motion ($\boldsymbol{\gamma}$) are estimated simultaneously. Also note that, in line with the literature, we use lagged values instead of contemporaneous values for our broadband measure, in order to mitigate potential endogeneity concerns due to two-way causality. We further discuss this assumption in one of the robustness checks in section 5.3.

$$\hat{\phi}_{it} = f(l_{it}, k_{it}; \boldsymbol{\beta}) + g\left(\hat{\phi}_{it-1} - f(l_{it-1}, k_{it-1}; \boldsymbol{\beta}), b_{it-1}; \boldsymbol{\gamma}\right) + \xi_{it} \tag{5}$$

In the econometric estimations, $g(\cdot)$ is assumed to be a simple linear function and $f(\cdot)$ to

[15]See Ackerberg et al. (2015) for an extensive discussion on this issue.

be a Cobb-Douglas production function. The estimation of Eq.5 is conducted by means of the General Methods of Moments (GMM). Orthogonality between the random shock ξ_{it} and the instruments applied in the GMM process is needed to recover consistent coefficients. This is ensured by using timing assumptions regarding the decision making and implementation process within firms. We follow the entire literature that, starting with Olley and Pakes (1996), assumes orthogonality between the capital stock and the shock to productivity in t. This is based on the perception that investments that are conducted in t are decided upon in $t-1$, once ω_{it-1} has been observed by the firm. In case of markets with strict employment protection legislation (EPL), labor is not very flexible and, thus, concurrent labor is uncorrelated with the shock to productivity (Ackerberg et al., 2015). According to the OECD, the German labor market is especially rigid, which is why $E[\xi_{it}|l_{it}] = 0$ is expected to likely hold (OECD, 2015). Finally, once-lagged broadband is orthogonal to ξ_{it} by definition. Hence, the following moment condition apply: $E[\xi_{it}|\boldsymbol{z_{it}}]$ with $\boldsymbol{z_{it}} = \{l_{it}, k_{it}, b_{jt-1}\}$.

Our empirical analysis consists of three steps. First, we estimate equation 1 by means of OLS to compare with the previous literature. Second, we estimate the production function by means of the outlined structural approach in order to recover the causal effect of broadband on TFP. Finally, we present various extensions and robustness checks to check the sensitivity of our main findings.

5 Results

5.1 Conditional correlation analysis

As first step of the analysis, we estimate equation 1 by OLS, following the previous literature. We use the one-year lagged broadband availability at 16 Mbps as the main variable of interest. Additional control variables are state dummies, year dummies, and population density.[16]Dummies for two-digit industries are also included in the estimations run at the one-digit industry level. Standard errors are clustered at the company level.

Table 2 shows the estimation results for one-digit industries. Labor and capital have the expected coefficints, and the same holds for population density. The availability of 16 Mbps transmission speed does not have a statistically significant effect for 'Manufacturing' (C)

[16]Note that we could not use municipality dummies to control for municipality fixed effects, because the number of municipalities turned out to be too large in most estimations, leading to $k > n$.

and ‘Repair services’ (S), but the coefficients are significant for ‘Transport services’ (H), the ‘Information and communication services’ (J), ´Professional services’ (M) and ‘Administrative services’ (N). The latter three are also considered to be knowledge intensive services. Hence, the OLS estimations are in line with the limited evidence in previous studies that IT-related services benefit the strongest from broadband availability.

Table 2: OLS results, 16Mbit, 1-digit industries

Variable	Manufacturing (C)	Transport (H)	Information (J)	Prof. services (M)	Admin. services (N)	Repair services (S)
Labor	-.276*	-.407*	-.246*	-.242*	-.431*	-.182*
	(0.0086)	(0.0134)	(0.0135)	(0.0089)	(0.0073)	(0.0311)
Capital	0.347*	0.395*	0.238*	0.237*	0.291*	0.226*
	(0.0071)	(0.0123)	(0.0114)	(0.0074)	(0.0078)	(0.0284)
Population density	0.032*	-.005	0.0673*	0.0643*	0.0374*	0.0094
	(0.004)	(0.0071)	(0.0101)	(0.005)	(0.0068)	(0.0206)
Broadband_{t-1}	0.0001	0.0007*	0.0021*	0.0007*	0.001*	0
	(0.0001)	(0.0003)	(0.0004)	(0.0002)	(0.0002)	(0.0007)
Year	yes	yes	yes	yes	yes	yes
State	yes	yes	yes	yes	yes	yes
Constant	6.118*	5.831*	7.916*	7.959*	7.397*	8.085*
	(0.0841)	(0.161)	(0.138)	(0.0855)	(0.124)	(0.306)
R-squared	0.925	0.809	0.839	0.834	0.819	0.817
N	31,269	20,647	17,456	47,631	29,180	1,775

Standard deviation in parentheses. Standard errors are clustered at the firm level. * p<0.01

The effect is found to be strongest for Information and communication services (J) with a coefficient of 0.0021. To evaluate the economic relevance of this seemingly small number, we make use of the average change of 16 Mbps availability during the observation period, which grew by about 38 percentage points. On average, this increased the output of firms in this sector by 8 percent over the entire sample period, or roughly 1.5 percent per year.[17] Yet, the estimates also imply that the effect was considerably smaller in the remaining service sectors. For instance, it was only 0.4 percent for ‘Administrative and support services’ (N). Also note that these findings cannot be interpreted as causal since, in our production functions setting

[17]This follows from the fact that the broadband variable is not in logs, but ranges from 0 to 100. The effect of a one percent increase in a covariate in any log-level estimations is given by $\%\Delta y = 100 * \beta$. Thus, a ten percent increase in broadband availability increases productivity by 2.1% given a beta of 0.0021. It follows that the average increase in 16 Mbps availability productivity of 38 percentage points over the course of the observation period is correlated with an increase in productivity in ‘Information and communication services’ (J) by about 8%.

with potentially endogenous inputs, OLS cannot provide consistent estimates.

To further address the heterogeneity between sectors, the estimations are also conducted separately for each two-digit industries. The respective estimation results are shown in Tables A.2 and A.3 in the Appendix. These results illustrate that the magnitude of the effect largely differs across industries and also in comparison to the elasticities presented in Table 2. Furthermore, it is only for a few two-digit service sectors in 'Information and communication services' (J) and 'Professional, scientific and technical activities services' (M) that we estimate statistically significant coefficients at the 1 percent level. Broadband is significant only at the 10 percent level in the other two-digit services in these sectors. This supports our expectation that the effect should be heterogeneous across industries as industries differ substantially with respect to the production technology and, therefore, also with respect to how broadband can improve the efficiency of the production process.

5.2 Structural approach

Table 3 reports the results of the estimations of equation 2a and equation 2b by means of the above outlined control function approach. It contains both the output elasticities from the production function and the coefficients of the law of motion, which are jointly estimated. Note that, within the applied method, the variation that is due to regional differences, time differences, and population density is filtered out after the first stage of the process (see section 4.2). Furthermore, we follow the literature and include average wages in h_t^{-1} as an additional control variable.

The coefficients of labor and capital show the expected signs and reasonable magnitudes, which reassures on the quality of our specification. The coefficient estimate for broadband is not found to be significantly different from zero for 'Repair services' (S), but it is significant for the remaining one-digit sectors. Apart from the significant coefficient for manufacturing, the results of the control function approach mimic those obtained with the OLS estimates. However, the effects are smaller, especially in 'Information and communication services' (J). The OLS estimates are expected to be larger for several reasons. First, while the coefficients in Table 3 show the direct effect of broadband on TFP, OLS estimates capture the output enhancing effects of broadband. This could be larger, for example, due to the use of additional sales channels and internet marketing. Second, TFP has a high degree of persistence. Indeed, one-year-lagged TFP explains most of the variation of TFP, which is perfectly in line with the theoretical considerations behind the control function approaches. In contrast, past productivity is ignored in the OLS estimations shown in Table 2, which can cause an upward bias.

A further note on the coefficient of one-year-lagged TFP: it is largest in manufacturing, indicating that TFP in service sectors is not as path dependent as in manufacturing. Nevertheless, as one would expect, the today's productivity of a firm is mainly its productivity of the last period, with minor changes due to own efforts (Doraszelski and Jaumandreu, 2013), infrastructural changes such as the availability of broadband, policy changes, and unexpected shocks. This holds for all firms in all sectors. Put differently, productivity is mostly path-dependent and not very erratic, something that the estimation results confirm.

Table 3: Control function estimation results, 16Mbit, 1-digit industries

Variable	Manufacturing (C)	Transport (H)	Information (J)	Prof. services (M)	Admin. services (N)	Repair services (S)
	production function $f(\cdot)$ – output elasticities ($\hat{\beta}$)					
Labor	0.771*	0.5346*	0.777*	0.7102*	0.665*	0.6533*
	(0.013)	(0.0145)	(0.0189)	(0.009)	(0.01)	(0.062)
Capital	0.2929*	0.4833*	0.244*	0.3117*	0.237*	0.3485*
	(0.0106)	(0.0137)	(0.0164)	(0.0085)	(0.0097)	(0.0447)
	law of motion $g(\cdot)$ – elasticities regarding TFP ($\hat{\gamma}$)					
TFP_{t-1}	0.954*	0.878*	0.896*	0.892*	0.902*	0.884*
	(0.0016)	(0.0033)	(0.0032)	(0.0021)	(0.0025)	(0.0112)
Broadband_{t-1}	0.0001*	0.0003*	0.0005*	0.0004*	0.0003*	0.0001
	(0.0000)	(0.0001)	(0.0001)	(0.0000)	(0.0000)	(0.0001)
Constant	0.352*	0.691*	0.869*	0.757*	0.816*	0.834*
	(0.0119)	(0.0186)	(0.0262)	(0.0145)	(0.0203)	(0.0793)
R-squared	0.917	0.778	0.831	0.809	0.827	0.78
N	31268	20647	17456	47631	29180	1775

Standard deviation in parentheses. Population density, federal states dummies and year dummies are controlled for in the first stage. The Hansen test has p-value of about 99 percent in all industries, indicating that there no endogeneity issue with the instruments. Significance levels: * $p<0.01$.

As noted in section 5.1, there are considerable differences within one-digit sectors. Therefore, all estimates are also conducted separately for each two-digit industry. Figure 3 shows the coefficient estimates for broadband availability, which are depicted as dots. The whiskers represent the 99% confidence intervals. Black is used for significant coefficients and gray for insignificant results.[18] Lastly, the names of the two-digit sectors are shortened for the shake of space. The sector codes in parentheses are in accordance with the ISIC Rev.4 classification.[19]

Figure 3 reveals that broadband does not have a significant effect on TFP in most two-digit Manufacturing industries (C). Hence, while Table 3 would suggest that broadband has some effect on TFP in manufacturing, the more disaggregated analysis demonstrates that such a conclusion overstates the actual effect of broadband. In fact, it seems that broadband availability does not significantly increase TFP in most industrial sectors. In this respect, our results confirm previous studies, according to which broadband has no or only very limited effect on the output or productivity of manufacturing firms. It further emphasizes the need to capture the heterogeneity within sectors when assessing the effect of broadband.

In Transport service (H), broadband does not have a statistically significant effect for 'Land transport and transport via pipelines' (H49). Although significant, the results for 'Air transport' (H51) should be taken with caution, as the number of observations is quite low and the standard errors are large.

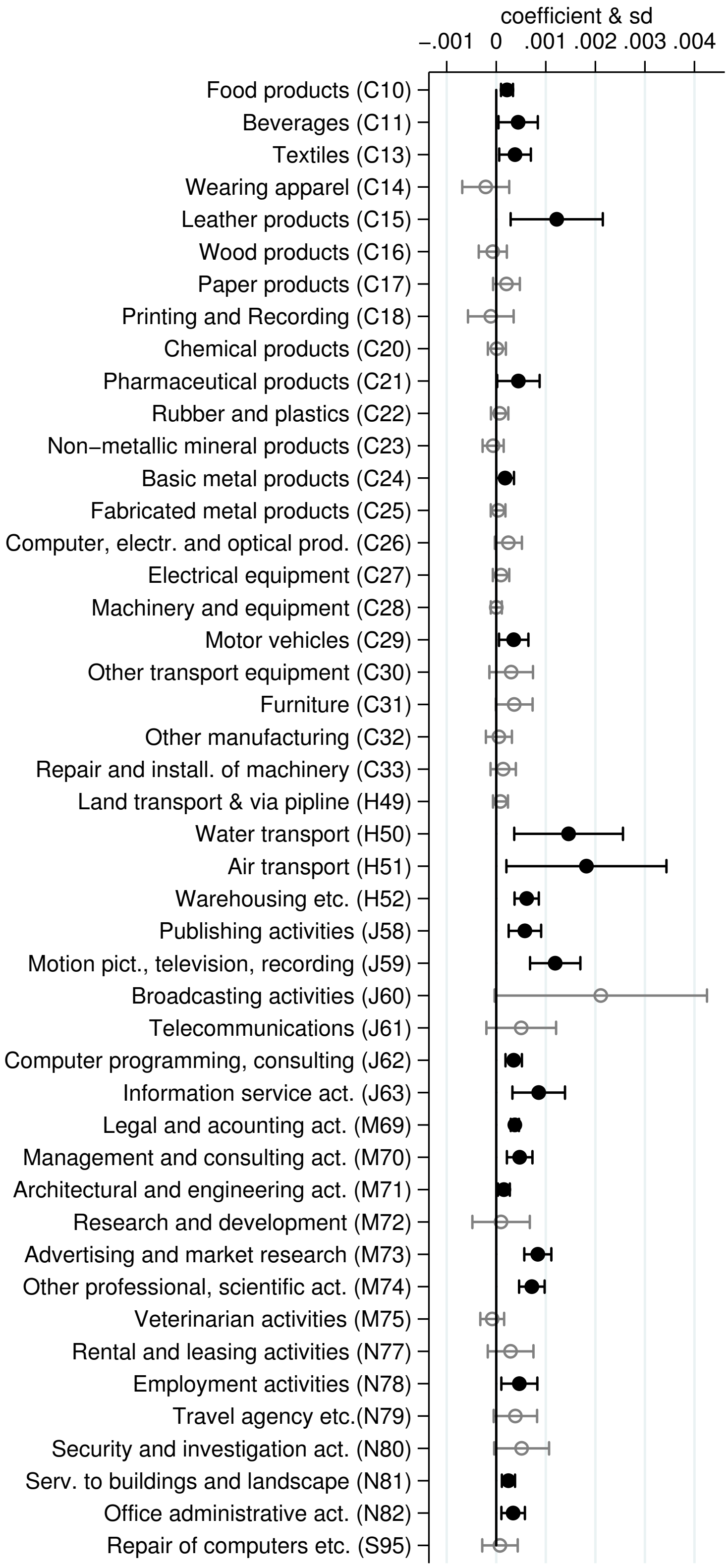
Broadband significantly increases productivity in four out of six two-digit sectors within the 'Information and communications services' (J). While the effect is strongest for 'Programming and broadcasting activities' (J60), it remains insignificant due to the large standard error. This might be driven by the low number of observations for this sector. The same holds for 'Telecommunications services' (J61). Overall, however, the results for the two-digit industries are in line with the expectation that such services should gain from broadband availability - not only merely through increased output but also in terms of productivity.

Apart from the 'Research and development services' (M72) as well as the 'Veterinarian activities' (M75), broadband availability is also found to significantly increase the productivity in all remaining sectors of the 'Professional, scientific and technical activities services' (M). The strongest effect within this service industry is found for 'Advertising and market research' (M73). Lastly, greater broadband availability positively and significantly affects half of all the services considered to be 'Administrative and support service activities' (N).

[18]Tables A.4 and A.5 in the Appendix contains the coefficients and the standard deviation for broadband and all main variables.

[19]The full list of all sectors is provided in Table A.1 in the Appendix.

Figure 3: Coefficients and standard deviation for once-lagged 16 Mbps broadband availability, control function estimations, two-digit industries



Overall, the results for two-digit sectors confirm our expectation that a growing broadband availability positively affects the productivity of firms in most service sectors, while there is not a statistically significant effect for most manufacturing industries.

However, the effect of higher broadband availability seems rather limited economically. The significant coefficient estimates range from around 0.0002 to 0.0018. Using the change in average broadband availability in the dataset (see section 5.1), this corresponds to an increase in productivity of 0.76 percent to 6.84 percent between 2010 and 2015.

Putting these results in the larger perspective of aggregate productivity growth, the modest effect estimated in our analysis is less surprising, as the estimated aggregate TFP growth for the respective one-digit sectors is also not very strong. According to the EUKLEMS database, between 2010 and 2015, TFP increased in 'Manufacturing' (C) by 7.1 percent, in 'Information and communication services' (J) by 17 percent, and in Business services by only 0.1 percent.[20]

5.3 Robustness

This section presents further analyses that are performed to assess the robustness of the results presented so far. First, we address the potential endogeneity of broadband by using instrumental variables (IVs) such as a municipality's geographic conformation or the availability of broadband in other regions. Second, we refine our measure of broadband availability based on the quality of the transmission. Due to the physical characteristics of the "last mile" – that is the part of the network between the Main Distribution Frame (MDF) and the final user – the quality of the broadband signal quickly decays with distance. Thus, we test whether broadband has a stronger impact the smaller the distance to the MDF. Third, we repeat our analysis using the contemporaneous rather than the lagged broadband variable, which allows us to save several firm-year observations and, at least partially, mitigate potential selection issues due to specific firms not being included in our analysis. Fourth, instead of using broadband availability, we use a variable measuring broadband adoption that is available for a small sub-sample of our data. This aims at testing whether the municipality-related broadband variable used in the main analysis is able to capture the TFP variation due to broadband and not merely the variation of other omitted variables at municipality level.

[20]Note that no detailed TFP estimates are provided for the 'Professional, scientific and technical activities' (M) and the 'Administrative and support service activities' (N), but only the TFP for the combined sectors. https://euklems.eu/download/ Further note that the TFP in EUKLEMS is derived by means of the growth accounting method. The results are not one to one comparable with estimations based on econometric methods, be it OLS or control function approaches.

5.3.1 IV

Our main specification applies a control function approach that allows to address the issue of input endogeneity. Moreover, broadband availabilty within a municipality enters the law of motion of productivity lagged one year to mitigate potential endogeneity concerns due to reverse causality. Yet, one could claim that lagging is not sufficient. In order to address remaining concerns and reinforce the causal interpretation of the link between broadband and TFP, we propose to use several IVs for broadband availability. The first instrument that we propose is the broadband availability in the neighboring municipalities of the focal municipality. This follows the idea that it is more likely that broadband providers expand broadband within a municipality if the respective infrastructure in already in place in the surrounding communities (*relevance*). At the same time, broadband availability in neighboring communities should not affect the productivity of firms in the municipality under consideration (*exclusion*). With a similar argument, we propose a second instrument that measures the average distance to the MDF in neighboring municipalities.

The remaining two instruments exploit information on the municipality's geographic conformation. Based on the procedure proposed by Riley et al. (1999), we calculate an index for the ruggedness of the terrain for each municipality.[21] Ruggedness can be considered a relevant instrument because a municipality's terrain conformation has a direct impact on the costs – and therefore on the likelihood – of building or expanding the broadband network (*relevance*). At the same time the terrain should have little to no impact on production technology and the efficiency with which a firm utilizes it (*exclusion*). Finally, we also use the average ruggedness of the neighboring municipalities as an additional instrument.

For applying the IVs within our control function setting, we build on the empirical original production function framework developed by Olley and Pakes (1996). Their framework consists of three instead of two steps. The step in between aims at addressing the selection issue that potentially biases the estimation results. This selection issue stems from the fact that a firm survival probability is likely to be correlated to their capital stock and productivity. Thus, the second step of Olley and Pakes (1996) consists of estimating a function explaining

[21] In a first step, the difference in elevation between a each cell (200m grid) and the eight cells immediately surrounding it is calculated. Subsequently, each of the eight elevation difference values are squared to make them all positive and average of the squares is computed for each cell. The topographic ruggedness index is then derived by taking the square root of this average. Finally, we calculate the average ruggedness at the level of the municipality averaging the ruggedness of all pixel in that municipality.

the probability of firm survival. The predicted probabilities from this estimation are then used as an instrument in the estimation of the law of motion of productivity in the third and final stage. While the seminal study of Levinsohn and Petrin (2003) showed that, in many applications, selection is not a serious issue, the Olley and Pakes (1996) approach can serve as a blueprint for how to incorporate IV estimations into a control function approach. Consequently, we enhance the procedure used so far to account for an IV estimation after the first step. In this estimation, which resemble a standard 2SLS procedure, broadband is the dependent and all exogenous variables in our model as well as the IVs serve as explanatory variables. We predict broadband availability based on this regression and the predicted values are used in the final step of the estimation instead of the observed broadband availability.

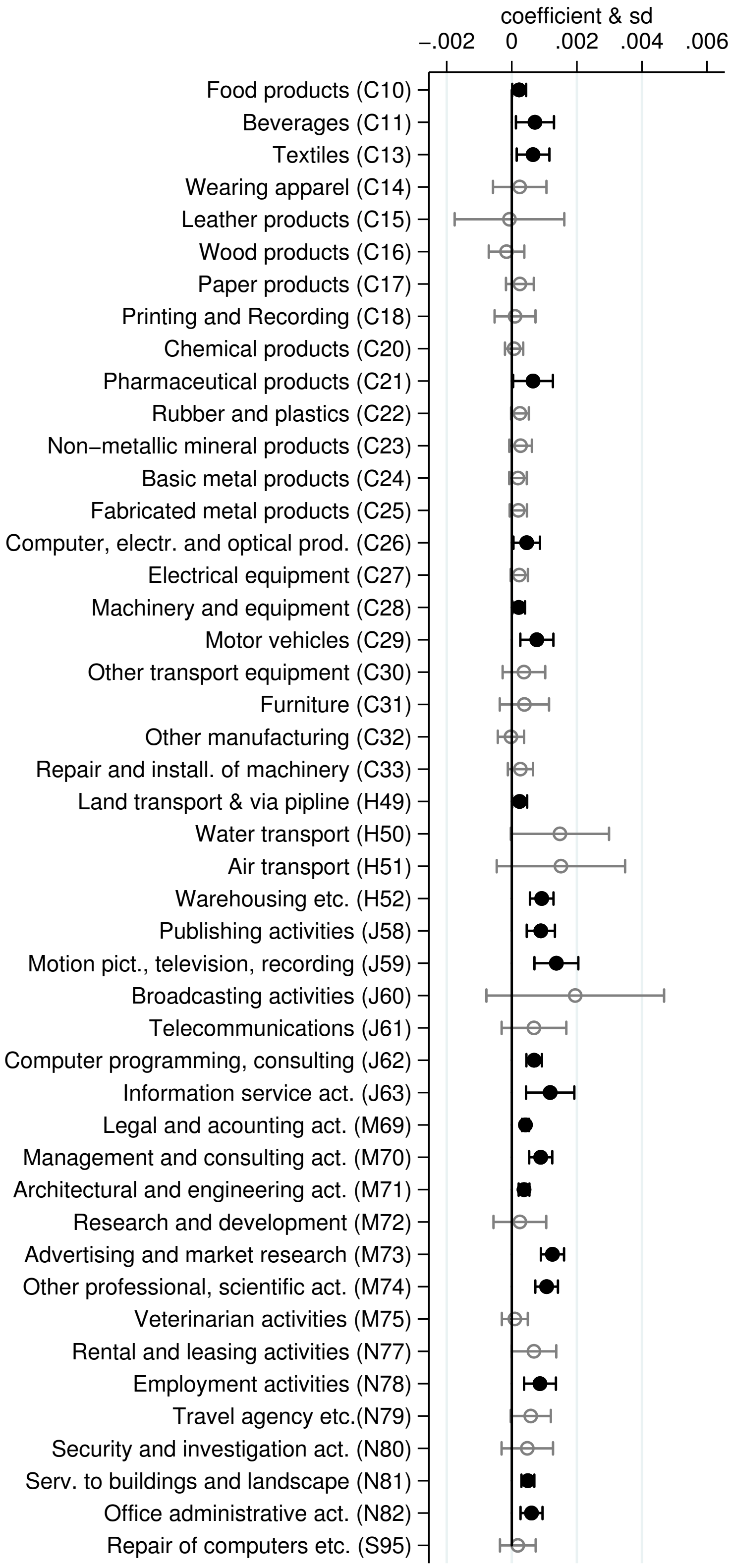
Figure 4 depicts the results of this robustness check.[22] Most importantly, the results based on the instrumented broadband variable hardly differ qualitatively from the results of the main specification as depicted in Figure 3. For almost all industries for which we estimate a significant positive coefficient for broadband in the main specification, we also estimate a significant positive coefficient when the broadband variable is instrumented. Moreover, for all industries, for which we did not estimate a significant coefficient for broadband in the main specification, we do not estimate a significant effect in this robustness check. The IV approach therefore supports our main findings.

Of the few differences that we observe, the first is little surprising: The point estimates and standard deviations are often of slightly larger in magnitude when instrumenting broadband. However, these differences are not large enough to conclude that the estimates from the two approaches significantly differ.[23] That said, there are four industries, for which the standard errors increase, causing the coefficients to be no longer significant at the 1 percent level. In the case of 'Air transport' (H51) and 'Water transport' (H50), the already large standard error observed in Figure 3 increase further.

[22]The full estimation results of the third step are shown in Tables A.8 and A.9. The relevant coefficients for the IV variables from the new second step, the IV regressions, and the results from the corresponding tests are reported in Tables A.6 and A.7. The under-identification test as well as the test for weak instruments confirm that the IV estimations are not suffering from either of these potential problems. The R^2 ranges from 0.24 to 0.54 in manufacturing and is between 0.36 and 0.71 in services. With regard to the individual IVs, it should be noted that average neighboring broadband is always highly significant. In many cases, this is also true for ruggedness. The average distance to the MDF in neighboring municipalities is less often significant. The same is true for the ruggedness in neighboring communities. Note that the coefficients for ruggedness are negative as a flat area has a low index value while the value is larger the more hilly the terrain.

[23]For a direct comparison see Figure B.2.

Figure 4: Coefficients and standard deviation for instrumented 16 Mbps broadband availability, control function estimations, two-digit industries



Note, however, that the coefficients are still significant at the 5 percent level. This is not the case for the manufacturing sectors 'Basic metals' (C24) and 'Producers of leather products' (C15). A final difference between the main results and the results of this robustness check is the significance of broadband in the 'Computer and electric products industry' (C26), for which the coefficient estimate is now significant at the 1 percent level, while in the main specification it is only significant at the 5 percent level.

5.3.2 Distance to MDF

By using regional broadband availability, all firms located in a given municipality face the same kind of broadband shock. Thus, one might be concerned that this variable captures other systematic shocks or policies at the municipality level, which might be correlated to broadband availability rather than the true effect of broadband internet. To control for some of these potential municipality-related shocks, we include population density as well as federal state dummies in our analysis. The former is correlated with broadband availability, as density is an important driver of broadband investment (Duso et al., 2021). Thus, it might not only capture difference across municipalities due to agglomeration economies, but also changes at the municipality level that affect all firms operating in the municipality simultaneously. Furthermore, by using Federal state dummies, we control for shocks at the state level as well as different policy settings that might affect firms.

Yet, to further address the remaining measurement issues with the broadband variable, we follow the existing literature and use a technical particularity of the German broadband network (Falck et al., 2014). The copper lines of the German telephone network are the base on which the digital network – starting with transmissions speeds below 1 Mbps– was built upon. The Main Distribution Frame (MDF) is an important part of this network. From here, the cooper lines go to the service area interfaces and further to the final users. In the opposite direction, the MDFs are the entrance point (and end point) to the so called "backbone" – the main distribution network that allows for the transfer of large data volumes – mostly through fiber cables.[24] In contrast to the lines of the backbone, the material properties of copper lead to a loss of data that gets larger, the longer the distance to the MDF. Because of this peculiar technological reason, one critical threshold for this data quality decay is 4,200

[24]Often, the DSL-Multiplexer, which essential for the transmission of large volumes of data, is included in the MDF.

meters.[25]

Our data contain information on the distance between the MDF and the midpoint of a municipality.[26] Thus, we create two dummies taking the value of one if this distance is larger or smaller than 4,200 meter. These dummies are interacted with the broadband availability at 16 Mbps transmission speed. Put differently, one variable captures the impact of broadband availability *in range* of 4,200 meters from the MDF and the other one *out of range*. If the availability variable is actually measuring the extent of broadband infrastructure, we would expect that it has the strongest impact on TFP *in range*. In the most extreme case, we would not expect broadband availability *out of range* to have a significant impact on productivity. This heterogenous effect would not be expected if the availability variable is a proxy for other municipality related shocks or policies that should not be affected by the distance to the MDF.

With respect to manufacturing, the results in Figure 5 are in line with our expectations.[27] Apart from the 'Chemical industry' (C21), for all two-digit industries for which we estimate positive significant coefficients in the main analysis we also estimate significant effects in this robustness check. In addition, broadband availability becomes significant for producers of 'Computer, electronic and optical products' (C26). Furthermore, in 18 of the 22 industry sectors in manufacturing, the coefficient estimates for broadband availability out of the 4,200 meters range are not significantly different from zero. Most point estimates are also very close to zero. These results are in line with expectations.[28]

[25] According to Falck et al. (2021, p.8): "The threshold value of 4,200 meters is a consequence of the DSL provision policy of the German telecommunication carrier, Deutsche Telekom, which marketed DSL subscriptions at the lowest downstream data transfer rate of 384 kbit/s only if the line loss was less than 55 decibel (dB). Since the copper cables connecting a household with the MDF usually had a diameter of 0.4 mm, a line loss of 55dB was typically reached at about 4,200 meters. As the actual line loss depends on other factors as well, the 4,200-meter threshold is only a fuzzy threshold (Falck et al., 2014). This fuzziness in the technological threshold of DSL availability is substantially more severe in other countries, effectively limiting the use of the threshold identification to Germany."

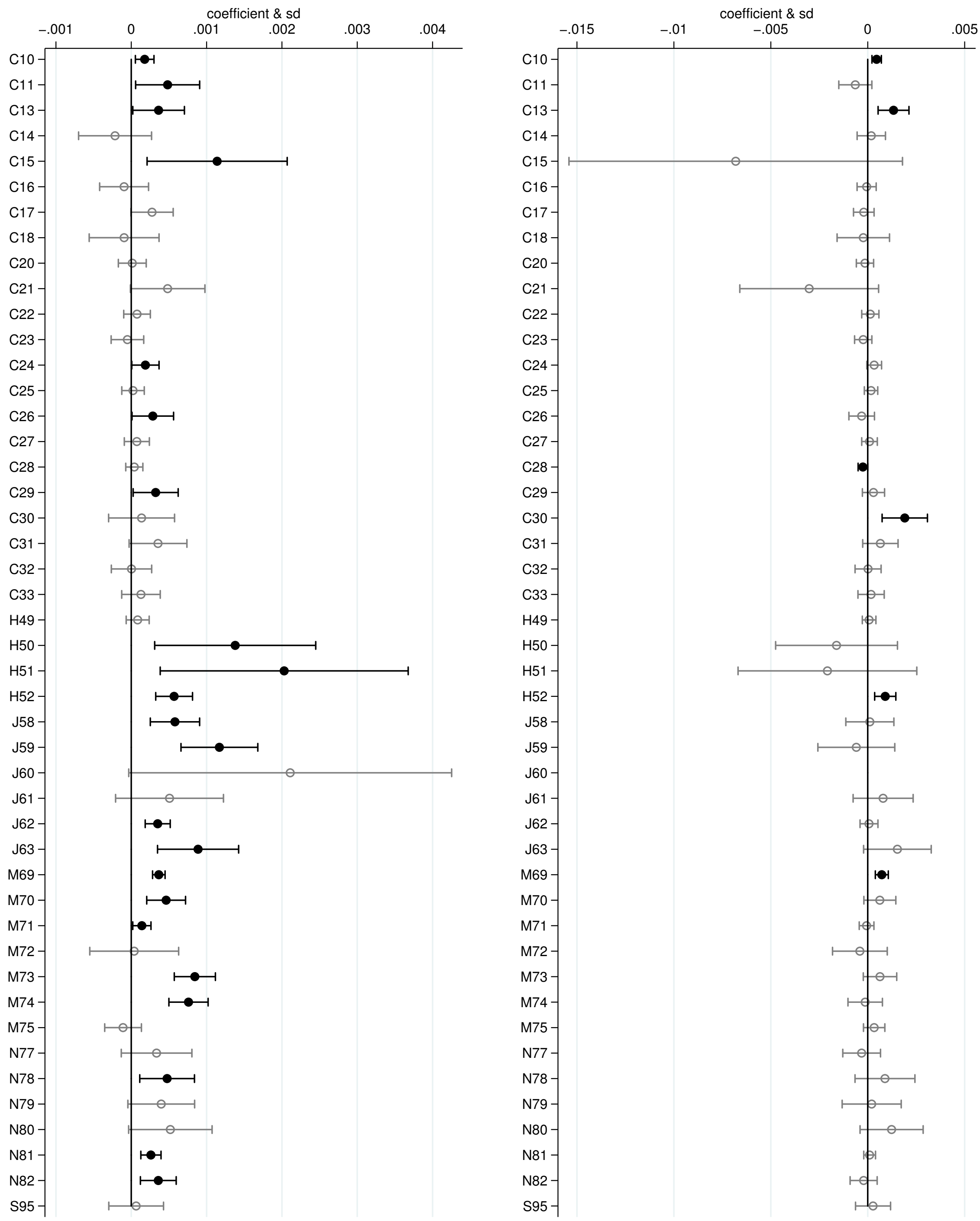
[26] See Falck et al. (2014) on the issues that come with using a distance that is measured between the midpoint of a municipality and the MDF.

[27] The full estimation results are shown in Tables A.12 and A.13.

[28] Note that we, unfortunately, cannot calculate the true distance between the location of a given firm and the closest MDF. Therefore, the dummies used in this robustness check are only a proxy. It might be that some firms located in a municipality whose center is quite far from the MDF are actually closer to the MDF than the center itself. Therefore, there might be some measurement error underlying that can help explaining why some of the coefficient estimates do not behave exactly as we expected.

Figure 5: Effect of Broadband within a certain distance of an MDF

(a) Location within 4200 m from MDF (b) Location beyond 4200 m from MDF



The results for services are even more in line with our expectations. First, for all services sectors in which we estimated broadband to significantly increase TFP in our main specification, the coefficient estimates for broadband availability within the range of 4200m from an MDF are also significant. Second, broadband availability *out of range* does not have a significant effect on TFP in 22 out of the 24 service sectors. All together, we take these additional results as strong evidence that the measure of broadband availability used in this study well captures the role of broadband availability rather than other omitted municipality characteristics.

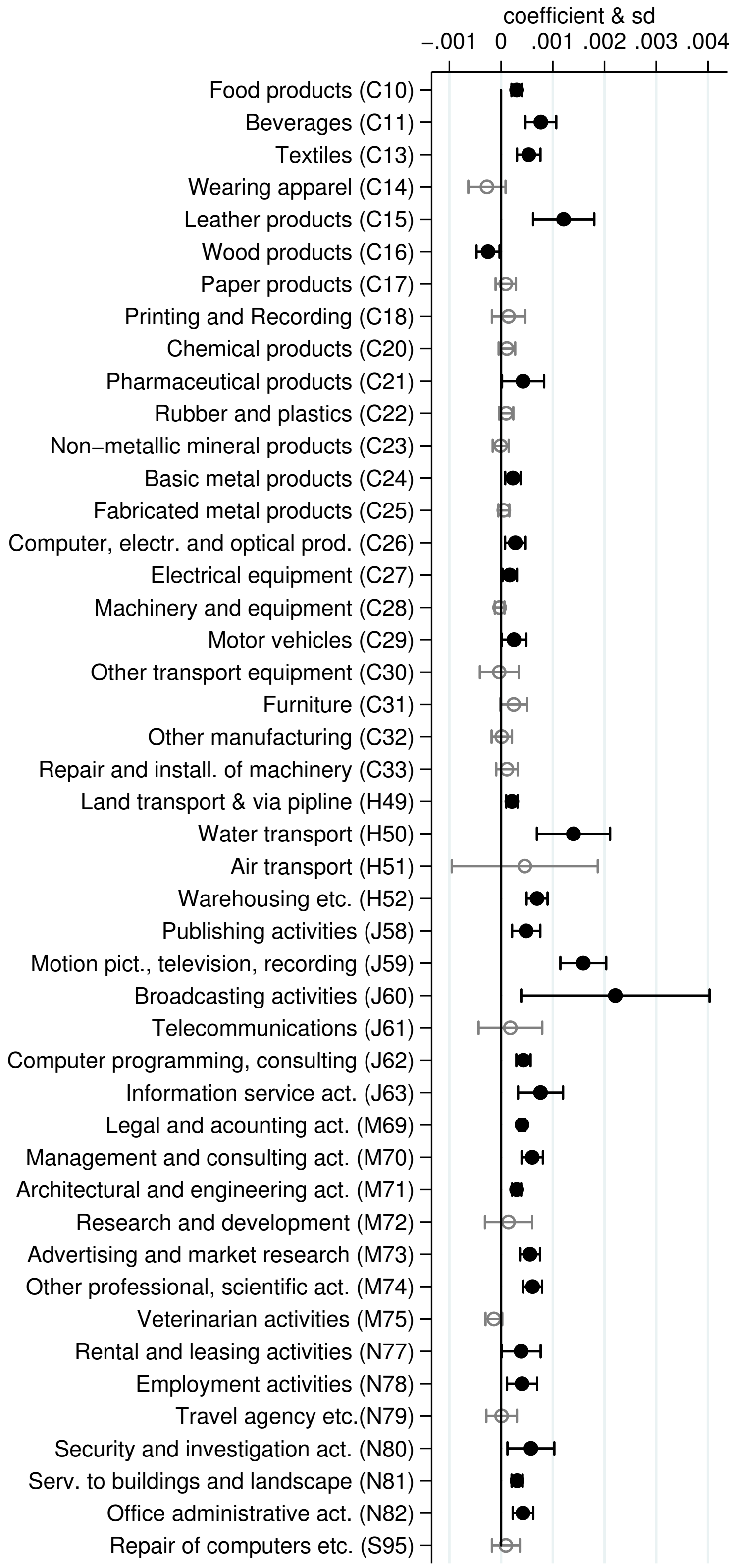
5.3.3 Potential selection effect

At various points in the discussion of the main results, we refer to the low number of observations available in some sectors. This is driven by the fact that three consecutive firm observations are needed for the estimation. The reason for this is the use of the one-year-lagged broadband variable within the control function approach. As shown in equation 5, $\hat{\phi}_{it-1}$ and $\hat{\phi}_{it}$ are required in the estimation. $\hat{\phi}_{it}$ is calculated after the first stage, in which one-year-lagged broadband (i.e. b_{t-1}) is used in the second-order polynomial that approximates h_t^{-1}. Consequently, two consecutive observations are needed to derive $\hat{\phi}_{it}$ and three consecutive observations to estimate equation 5, as this requires not only $\hat{\phi}_{it}$ but also $\hat{\phi}_{it-1}$.

This might raise concerns regarding potential selection issues because only well performing firms that survive at least three consecutive years might remain in the final estimation sample. In order to address such concerns, the analysis is repeated using the broadband availability without a time lag. This allows us to keep in the sample also all those firms that manage to survive only two consecutive years. Figure 6 reports the results of these estimations.[29] Within Manufacturing (C), all industries for which we obtained significant coefficient estimates in the main specification also show significant estimates when using broadband availability in t. In addition, broadband is found to be significant in three additional industries.

[29] The full estimation results are shown in Tables A.10 and A.11.

Figure 6: Coefficients and standard deviation for contemporaneous 16 Mbps broadband availability, control function estimations, two-digit industries



In ‘Transport services’ (H), the slightly larger number of observations for ‘Air transport’ (H51) makes the coefficient estimates for broadband to become no longer significantly different from zero. Thus, it seems that the caution expressed when discussing the main result for ‘Air service’ (H51) in section 5.2 is appropriate. The remaining transport services for which we obtained significant estimates in the main analysis show again significant coefficients in this robustness check. Within ‘Information and communication services’ (J), the coefficient estimate for broadband in ‘Programming and broadcasting activities’ (J60) becomes significant, although the standard error remains quite large. Because the number of observations remains extremely low, this result should still be taken with caution.

In contrast, the coefficient of broadband in ‘Telecommunications services’ (J61) stays insignificant. The results for the remaining sectors within ‘Information and communication services’ (J) confirm the previous findings. With regard to the sectors in ‘Professional, scientific and technical activities services’ (M), there are no major differences to the main results from section 5.2. Lastly, the robustness checks confirm the significance of broadband in the various sectors of ‘Administrative and support service activities’ (N).

In sum, the findings in section 5.2 do not seem to be driven by a selection effect that might come from the use of firms with at least three consecutive observations.

5.3.4 Alternative broadband variable

As described in section 2, many studies that aim to analyze the effect of firms’ broadband adoption on their performance make use of regional broadband data as an instrument or a proxy for adoption to overcome the potential endogeneity of adoption decisions due to self-selection issues and two-way causality. The main idea behind this choice is that, to be adopted, broadband must first be available. Yet, availability is less likely to be correlated with the i.i.d productivity shock.

As a robustness check, we propose to use data on the adoption and use of broadband technology that is available for a small sub-sample of the firms used in our analysis.[30] This variable has two great advantages. First, the positive productivity effects of broadband are

[30] The analysis is based on an additional administrative dataset, the ICT-survey of the Federal Statistical Office, that can be matched to the AFiD-Panel through a unique firm identifier. A categorical variable captures the contractually stipulated data transmission speed for each firm. It covers five different speeds: less than 2 Mbps, 2 Mbps up to below 10 Mbps, 10 Mbps up to below 30 Mbps, 30 Mbps up to below 100 Mbps, and more than 100 Mbps. These categories are translated into four dummy variables with the lowest transmission speed being the reference category.

mainly expected through its usage and are not merely due to its availability. Second, the variable measuring broadband usage is no longer municipality-specific but firm-specific.

Yet, apart from the self-selection issues discussed above, this variable has also some additional disadvantage. First, only a subset of the 10,000 annually surveyed firms belong to the economic sectors that are covered by the two AFiD-Panels. Second, most of the firms are only surveyed once. Third, the overlap between the surveys in the AFiD-Panel and the ICT-survey is far from perfect. As a result, the number of available observations drops to about 8,400 for the service sector and to about 7,500 for manufacturing for the entire observation period of 6 years. Because most firms are only surveyed once, the control function approach that was applied in section 5.2 cannot be used here, as it would require at least three consecutive observations for each firm. This would reduce the total number of observations to about 260 for manufacturing and about 300 for services. To avoid this selection issue, we perform this robustness check by using the contemporaneous – instead of one-year-lagged – speed dummies and estimating our model by simple OLS. The estimation is carried out for the aggregated manufacturing sector and service sector with dummies for the two-digit industries.

Nonetheless, if the results of this robustness check are in line with those obtained in the main specification and the effective adoption of broadband turns out to positively affecting firms' productivity (or better said, output), this should give us more confidence that the results in the main analysis based on broadband availability are not purely driven by variation of an unobserved and, therefore, omitted variable at the municipality level.

Table 4 shows the output elasticities of the four broadband dummies for manufacturing and services.[31] In general, the results support our main findings as they show that broadband is positively correlated with the output of a firm. Of course, the estimation setting does not allow for concluding that broadband adoption causally leads to higher outputs and that this is due to an increase in the TFP. However, if the main results are driven by unknown municipality characteristics, meaning that broadband availability is actually irrelevant for firms, then we should not find positive results here.

Because of the econometric issues of this OLS estimation and the additional specific issues of a broadband adoption variable, the magnitude of the point estimates should not be over interpreted. With this caveat in mind, it is interesting to note that the magnitude of the coefficients increase with increasing broadband transmission speed. This is what we would

[31] The full results are presented in Table A.14 in Appendix A.

expect, given that 100 Mbps allows for using more applications and business models than does 1 Mbps.

Table 4: OLS results, four speed dummies

Industry	2 Mbps to 10 Mbps	10 Mbps to 30 Mbps	30 Mbps to 100 Mbps	more than 100 Mbps	R-squared	N
Manufacturing	0.0811*	0.0875*	0.137*	0.142*	0.93	7532
	(0.0248)	(0.0252)	(0.0265)	(0.0283)		
Service	0.0464	0.0592	0.118*	0.189*	0.854	8409
	(0.0422)	(0.042)	(0.0429)	(0.0441)		

Standard deviation in parentheses. Standard errors are clustered at the firm level. Less than 2 Mbps as reference category. * p<0.01

6 Concluding remarks

This study aims to estimate the causal effect of broadband availability on firms' TFP. The analysis is based on about 455,000 observations of German firms across 46 two-digit industries. The observation period is 2010 to 2015, a time during which the average availability broadband at 16 Mbps transmission speed increased from about 17 percent to 55 percent in those municipalities for which data are available. The results of the analysis reveal that this increase had almost no effect on the productivity of most manufacturing firms. In contrast, across the majority of the service sectors, firm TFP increased as a result of the growing broadband availability. The results further reveal, however, that better broadband is not a golden bullet to solve productivity issues, as the estimated effects are moderate. They range from 0.76 percent to 6.84 percent for the entire 6 year period.

Substantial efforts have been made in the literature to assess the relationship between broadband networks and productivity. Our study adds new insights to it. We start discussing the prevailing two-stage approach used in previous studies on the effect of broadband on TFP and argue that this approach is plagued by econometric issues. By adopting a control function approach, we address several of these issues. This allows for a causal interpretation of the estimated links under relatively mild assumptions. We provide several additional pieces of evidence to further support the causality of our findings. Lastly, to the best of our knowledge, our is the first study that actually addresses the large heterogeneity of the impact of broadband infrastructure between industries within broader sectors. We show that a significant effect at the one-digit industry level, which is the most common aggregation level used in the literature, can lead to false conclusions since it masks the fact that several –in some cases most– of the industries within this one digit sector do not actually benefit from broadband.

Although we think that our study provides an important and novel contribution, the analysis is not without limitations. In particular, more can be done to model the heterogeneous response to broadband availability among firms within an industry: which firms profited the most and why? One first important dimension that we only touched upon in one of the robustness checks is related to the quality of the broadband transmission. The lack of geo-coded data of the precise location of the firm and the MDF and, thus, the availability and quality of broadband at that specific location would be needed to better assess this issue. Second, firms' complementary investments, especially in intangible assets and hardware along with their interplay with the evolution of the broadband network, are not considered in the analysis. Yet, they might be very important for understanding which firms profit the most in terms of enhanced productivity. Finally, while the entire literature applies a Cobb-Douglas production function, as we do in this study, this functional form assumption is relatively restrictive and could be dropped in favor of a more flexible form, for instance a translog function. Future research should address these issues.

In closing, it is worth stressing that our findings might have important policy implications. On the one hand, they provide causal evidence in support to those popular policies aiming at improving a country's digital infrastructure. Indeed, the availability of broadband internet seem to have significant positive productivity effects for several firms in many (service) industries. On the other hand, however, our results also send a cautious message. First, improving the broadband infrastructure – even when this improvement is substantial as in the sample period we consider – has only a moderate positive impact on productivity. Second, these moderate benefits are heterogenous and only accrue to some firms. In particular, the finding that manufacturing firms do not seem to benefit from improved broadband availability suggests that, in these sectors, other policies might be needed. One of the reasons why broadband availability is not improving productivity could simply be that the demand – not the supply – for high bandwidths is still limited among many companies because their production technology is not yet enough digitized. While the existence of broadband infrastructure is a sort of necessary condition, complementary capabilities are needed to fully appropriate the benefits of digitization. Policies supporting the transition to a more digitized production process might be therefore more appropriate and effective to improve the productivity of such firms.

This debate seems particularly timely at the beginning of the 2020's, when the policy discussion is centered on public policies in support of the so-called gigabit fibre networks as well as the support for 5G and 6G mobile networks. Building on our results, it is likely that these support plans could have substantial productivity effects. However, they can be expected to mostly benefit some (service) sectors and, within those sectors, those innovative companies that already digitized a large part of their production process. These patterns could have two further consequences. They could be a booster for speeding up the overall digitization process, especially in more traditional industrial sectors, by providing an incentive to invest in new, digitized production processes: the industry 4.0 scenarios. Yet, the unequal ability by firms to internalize the benefits of improved digital infrastructure could even exacerbate the productivity gap between highly innovative and digitized firms (sometimes called the super-star firms) and the less advanced firms and sectors in the economy. As stressed by an increasing literature, this could have an impact on concentration trends with more general, and not only positive, macroeconomic implications (e.g. Autor et al., 2020; De Loecker et al., 2020; Eeckhout, 2021)

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A Tables

Table A.1: 2-digit industry classification

ISIC Rev.4		Code	Description
Manufacturing		C10	Food Products
		C11	Beverages
		C13	Textiles
		C14	Wearing apparel
		C15	Leather and related products
		C16	Wood and of products of wood and cork, except furniture
		C17	Paper and paper products
		C18	Printing and reproduction of recorded media
		C20	Chemicals and chemical products
		C21	Basic pharmaceutical products and pharmaceutical preparations
		C22	Rubber and plastics products
		C23	Other non-metallic mineral products
		C24	Basic metals
		C25	Fabricated metal products, except machinery and equipment
		C26	Computer, electronic and optical products
		C27	Electrical equipment
		C28	Machinery and equipment n.e.c.
		C29	Motor vehicles, trailers and semi-trailers
		C30	Other transport equipment
		C31	Furniture
		C32	Other manufacturing
		C33	Repair and installation of machinery and equipment
Transport	& Logistics	H49	Land transport and transport via pipelines
		H50	Water transport
		H51	Air transport
		H52	Warehousing and support activities for transportation
		H53	Postal and courier activities
Information &	Communications	J58	Publishing activities
		J59	Motion picture, video and television program production, music recording
		J60	Programming and broadcasting activities
		J61	Telecommunications
		J62	Computer programming, consultancy and related activities
		J63	Information service activities
Professional, scientific	& technical activities	M69	Legal and accounting activities
		M70	Activities of head offices; management consultancy activities
		M71	Architectural and engineering activities; technical testing and analysis
		M72	Scientific research and development
		M73	Advertising and market research
		M74	Other professional, scientific and technical activities
		M75	Veterinary activities
Administrative &	support activities	N77	Rental and leasing activities
		N78	Employment activities
		N79	Travel agency, tour operator, reservation service and related activities
		N80	Security and investigation activities
		N81	Services to buildings and landscape activities
		N82	Office administrative, office support and other business support activities
		S95	Repair of computers and personal and household goods

Table A.2: OLS results, two-digit manufacturing industries

Ind.	Labor	Capital	Popul. density	Broad-band $_{t-1}$	Year, State dummies	Constant	R^2	N
C10	-.583*	0.598*	0.012	0.073	yes	3.671*	0.888	3,974
	(0.019)	(0.016)	(0.011)	(0.041)		(0.197)		
C11	-.179*	0.269*	-.003	0.166	yes	7.806*	0.783	546
	(0.102)	(0.071)	(0.046)	(0.174)		(0.917)		
C13	-.163*	0.262*	-.01	0.15	yes	7.012*	0.891	682
	(0.062)	(0.048)	(0.026)	(0.102)		(0.58)		
C14	-.309*	0.462*	0.064	0.063	yes	4.016*	0.847	500
	(0.121)	(0.102)	(0.049)	(0.142)		(1.064)		
C15	-.208*	0.438*	0.032	0.482	yes	4.283*	0.889	224
	(0.157)	(0.133)	(0.075)	(0.201)		(1.386)		
C16	-.173*	0.248*	0.031	-.06	yes	7.659*	0.908	664
	(0.047)	(0.04)	(0.023)	(0.073)		(0.485)		
C17	-.351*	0.431*	0.009	0.023	yes	5.357*	0.925	948
	(0.051)	(0.041)	(0.021)	(0.074)		(0.461)		
C18	-.197*	0.27*	0.09*	-.019	yes	6.886*	0.871	575
	(0.051)	(0.042)	(0.03)	(0.102)		(0.529)		
C20	-.376*	0.428*	0.051*	-.055	yes	5.694*	0.907	1,997
	(0.04)	(0.035)	(0.02)	(0.065)		(0.429)		
C21	-.171*	0.268*	0.078	0.073	yes	6.833*	0.913	424
	(0.088)	(0.079)	(0.057)	(0.157)		(0.935)		
C22	-.293*	0.378*	0.042*	0.014	yes	5.815*	0.955	1,578
	(0.028)	(0.024)	(0.014)	(0.047)		(0.306)		
C23	-.355*	0.407*	0.053*	-.088	yes	5.567*	0.919	1,526
	(0.037)	(0.03)	(0.017)	(0.057)		(0.361)		
C24	-.235*	0.299*	0	-.004	yes	7.455*	0.942	1,596
	(0.038)	(0.032)	(0.017)	(0.059)		(0.408)		
C25	-.189*	0.27*	0.036*	-.014	yes	7.24*	0.942	3,631
	(0.017)	(0.014)	(0.008)	(0.03)		(0.17)		
C26	-.018*	0.125*	0.079*	-.014	yes	8.948*	0.912	1,356
	(0.041)	(0.037)	(0.022)	(0.079)		(0.452)		
C27	-.147*	0.237*	0.044*	-.016	yes	7.877*	0.936	2,099
	(0.033)	(0.028)	(0.016)	(0.057)		(0.31)		
C28	-.083*	0.173*	0.032*	-.041	yes	8.559*	0.947	4,334
	(0.02)	(0.018)	(0.009)	(0.029)		(0.194)		
C29	-.174*	0.256*	0.04	0.025	yes	7.343*	0.952	1,238
	(0.048)	(0.041)	(0.022)	(0.074)		(0.444)		
C30	-.051*	0.156	0.01	0.088	yes	8.415*	0.928	459
	(0.075)	(0.07)	(0.037)	(0.126)		(0.83)		
C31	-.208*	0.294*	0.004	0.08	yes	7.075*	0.940	678
	(0.058)	(0.045)	(0.02)	(0.078)		(0.48)		
C32	-.2*	0.313*	0.053*	-.021	yes	6.619*	0.927	1,124
	(0.051)	(0.037)	(0.018)	(0.071)		(0.397)		
C33	-.073*	0.162*	0.03	-.009	yes	8.623*	0.939	1,116
	(0.029)	(0.026)	(0.016)	(0.057)		(0.308)		

Standard deviation in parentheses. Standard errors are clustered at the firm level. * p<0.01

Table A.3: OLS results, two-digit service sectors

Ind.	Labor	Capital	Popul. density	Broad-band $_{t-1}$	Year, State dummies	Constant	R^2	N
H49	-.469*	0.505*	-.027*	0.02	yes	4.505*	0.823	14,570
	(0.016)	(0.014)	(0.008)	(0.029)		(0.176)		
H50	-.258*	0.123	0.196*	0.35	yes	9.764*	0.590	787
	(0.068)	(0.089)	(0.058)	(0.247)		(1.284)		
H51	-.228*	0.302*	-.015	0.472	yes	6.762*	0.840	276
	(0.092)	(0.081)	(0.108)	(0.348)		(1.206)		
H52	-.348*	0.221*	0.047*	0.162	yes	8.363*	0.773	5,014
	(0.024)	(0.022)	(0.017)	(0.063)		(0.304)		
J58	-.414*	0.346*	0.113*	0.252	yes	7.147*	0.776	3,539
	(0.039)	(0.031)	(0.027)	(0.101)		(0.346)		
J59	-.524*	0.344*	0.139*	0.65*	yes	5.809*	0.659	2,159
	(0.045)	(0.048)	(0.038)	(0.13)		(0.619)		
J60	-.52*	0.616*	-.007	0.926	yes	2.851	0.913	219
	(0.116)	(0.093)	(0.106)	(0.366)		(1.22)		
J61	-.291*	0.366*	0.042	0.203	yes	5.906*	0.888	818
	(0.05)	(0.04)	(0.051)	(0.158)		(0.534)		
J62	-.075*	0.114*	0.031*	0.068	yes	9.647*	0.890	8,954
	(0.013)	(0.011)	(0.01)	(0.036)		(0.121)		
J63	-.29*	0.287*	0.026	0.099	yes	7.603*	0.833	1,767
	(0.035)	(0.028)	(0.036)	(0.121)		(0.346)		
M69	-.21*	0.275*	0.104*	0.109*	yes	7.495*	0.873	14,737
	(0.015)	(0.015)	(0.007)	(0.024)		(0.159)		
M70	-.247*	0.207*	0.098*	-.017	yes	8.481*	0.793	6,400
	(0.02)	(0.016)	(0.018)	(0.065)		(0.21)		
M71	-.212*	0.231*	0.048*	-.013	yes	8.359*	0.854	11,671
	(0.013)	(0.012)	(0.009)	(0.031)		(0.134)		
M72	-.113*	0.125*	-.068	-.112	yes	9.63*	0.785	1,233
	(0.043)	(0.034)	(0.046)	(0.137)		(0.464)		
M73	-.362*	0.215*	0.111*	0.132	yes	8.659*	0.732	5,468
	(0.027)	(0.019)	(0.019)	(0.068)		(0.204)		
M74	-.291*	0.305*	0.046*	0.081	yes	7.283*	0.778	4,387
	(0.024)	(0.02)	(0.017)	(0.065)		(0.225)		
M75	-.316*	0.25*	-.039*	-.042	yes	8.295*	0.776	3,735
	(0.026)	(0.02)	(0.011)	(0.041)		(0.216)		
N77	-.585*	0.512*	0.043	0.178	yes	4.549*	0.597	2,875
	(0.037)	(0.037)	(0.036)	(0.117)		(0.552)		
N78	-.275*	0.161*	0.043*	0.055	yes	9.224*	0.840	4,468
	(0.014)	(0.013)	(0.015)	(0.05)		(0.167)		
N79	-.174*	0.146*	0.068*	0.1	yes	9.074*	0.766	2,276
	(0.034)	(0.028)	(0.023)	(0.08)		(0.328)		
N80	-.319*	0.275*	0.001	0.094	yes	7.81*	0.858	1,214
	(0.035)	(0.034)	(0.033)	(0.1)		(0.38)		
N81	-.471*	0.279*	0.019*	0.054	yes	7.93*	0.875	12,362
	(0.007)	(0.009)	(0.007)	(0.025)		(0.116)		
N82	-.397*	0.285*	0.098*	0.125	yes	7.312*	0.784	5,985
	(0.016)	(0.014)	(0.016)	(0.059)		(0.187)		
S95	-.182*	0.226*	0.009	-.002	yes	8.18*	0.817	1,775
	(0.031)	(0.028)	(0.021)	(0.072)		(0.304)		

Standard deviation in parentheses. Standard errors are clustered at the firm level. * $p<0.01$

Table A.4: ACF results, two-digit manufacturing industries, broadband from $t-1$

	production funct. $f(\cdot)$		law of motion $g(\cdot)$			
Ind.	Labor	Capital	TFP_{t-1}	Broad band$_{t-1}$	Constant	N
C10	0.5159*	0.4531*	0.954*	0.0002*	0.272*	3974
	(0.0304)	(0.0247)	(0.0038)	(0.0000)	(0.0215)	
C11	0.7934*	0.4148*	0.949*	0.0004*	0.279*	546
	(0.1209)	(0.1005)	(0.0115)	(0.0002)	(0.0641)	
C13	0.9002*	0.1718	0.961*	0.0004*	0.313*	682
	(0.0923)	(0.0725)	(0.0118)	(0.0001)	(0.0951)	
C14	0.5271*	0.2232	0.983*	-.0002	0.175	500
	(0.1343)	(0.3737)	(0.0081)	(0.0002)	(0.0762)	
C15	0.8435*	0.4091	0.927*	0.0012*	0.288	224
	(0.1403)	(0.1358)	(0.0288)	(0.0004)	(0.113)	
C16	0.7673*	0.2698*	0.912*	-.0001	0.68*	664
	(0.0589)	(0.0462)	(0.0134)	(0.0001)	(0.103)	
C17	0.6432*	0.4195*	0.922*	0.0002	0.462*	948
	(0.0672)	(0.0448)	(0.0133)	(0.0001)	(0.0774)	
C18	0.7688*	0.2882*	0.933*	-.0001	0.488*	575
	(0.0845)	(0.0686)	(0.0169)	(0.0002)	(0.119)	
C20	0.6924*	0.3893*	0.967*	0	0.227*	1997
	(0.0552)	(0.0533)	(0.0065)	(0.0001)	(0.0404)	
C21	0.6554*	0.37*	0.883*	0.0004*	0.716*	424
	(0.0743)	(0.0626)	(0.0172)	(0.0002)	(0.104)	
C22	0.7595*	0.3056*	0.927*	0.0001	0.539*	1578
	(0.0342)	(0.0294)	(0.0079)	(0.0001)	(0.0559)	
C23	0.9233*	0.1897*	0.944*	-.0001	0.468*	1526
	(0.0555)	(0.0467)	(0.0085)	(0.0001)	(0.0692)	
C24	0.8067*	0.2706*	0.89*	0.0002*	0.85*	1596
	(0.0326)	(0.0273)	(0.0095)	(0.0001)	(0.0734)	
C25	0.7827*	0.2739*	0.891*	0	0.829*	3630
	(0.0224)	(0.0174)	(0.0071)	(0.0001)	(0.0532)	
C26	0.9392*	0.167*	0.926*	0.0002	0.644*	1356
	(0.0562)	(0.0485)	(0.0095)	(0.0001)	(0.0809)	
C27	0.7987*	0.2335*	0.972*	0.0001	0.243*	2099
	(0.0479)	(0.0347)	(0.0061)	(0.0001)	(0.0498)	
C28	0.8903*	0.1897*	0.928*	0	0.641*	4334
	(0.0249)	(0.0206)	(0.0058)	(0.0000)	(0.0504)	
C29	0.7805*	0.3072*	0.909*	0.0004*	0.626*	1238
	(0.0588)	(0.047)	(0.0126)	(0.0001)	(0.0858)	
C30	0.8298*	0.2258	0.913*	0.0003	0.713*	459
	(0.0953)	(0.0804)	(0.0196)	(0.0002)	(0.157)	
C31	0.7782*	0.2683*	0.873*	0.0004	0.971*	678
	(0.059)	(0.0456)	(0.0187)	(0.0001)	(0.143)	
C32	0.7734*	0.3754*	0.947*	0.0001	0.323*	1124
	(0.076)	(0.0601)	(0.0099)	(0.0001)	(0.0578)	
C33	0.8867*	0.2184*	0.882*	0.0001	0.968*	1116
	(0.0383)	(0.0359)	(0.0118)	(0.0001)	(0.096)	

Standard deviation in parentheses. Variation due to population density, federal states and years is controlled for in the first stage. The Hansen test has p-value of about
99 percent in all industries, indicating that there no endogeneity issue with the instruments.
Significance levels: * $p<0.01$.

Table A.5: ACF results, two-digit service sectors, broadband from $t-1$

	production funct. $f(\cdot)$		law of motion $g(\cdot)$			
Ind.	Labor	Capital	TFP_{t-1}	Broad band_{t-1}	Constant	N
H49	0.5251*	0.5219*	0.851*	0.0001	0.655*	14570
	(0.0141)	(0.0129)	(0.0041)	(0.0001)	(0.0181)	
H50	0.6906*	0.1543	0.904*	0.0015*	0.891*	787
	(0.0819)	(0.1228)	(0.0169)	(0.0004)	(0.162)	
H51	0.6353*	0.392*	0.836*	0.0018*	0.946*	276
	(0.1124)	(0.1116)	(0.0271)	(0.0006)	(0.164)	
H52	0.5947*	0.2843*	0.868*	0.0006*	1.043*	5014
	(0.0386)	(0.0359)	(0.0077)	(0.0001)	(0.0615)	
J58	0.5057*	0.4448*	0.891*	0.0006*	0.682*	3539
	(0.0342)	(0.0331)	(0.0068)	(0.0001)	(0.0431)	
J59	0.4917*	0.4034*	0.921*	0.0012*	0.459*	2159
	(0.0433)	(0.0559)	(0.0081)	(0.0002)	(0.048)	
J60	0.4356*	0.718*	0.834*	0.0021	0.26*	219
	(0.1156)	(0.1198)	(0.0303)	(0.0008)	(0.0815)	
J61	0.516*	0.5868*	0.935*	0.0005	0.229*	818
	(0.1176)	(0.1152)	(0.0134)	(0.0003)	(0.0502)	
J62	0.8919*	0.1513*	0.835*	0.0004*	1.535*	8954
	(0.0164)	(0.0134)	(0.0057)	(0.0001)	(0.0534)	
J63	0.7398*	0.2921*	0.82*	0.0009*	1.425*	1767
	(0.0294)	(0.0227)	(0.0116)	(0.0002)	(0.0929)	
M69	0.7087*	0.3801*	0.86*	0.0004*	0.891*	14737
	(0.0119)	(0.0117)	(0.004)	(0.0000)	(0.0256)	
M70	0.7253*	0.2633*	0.887*	0.0005*	0.925*	6400
	(0.0239)	(0.0246)	(0.006)	(0.0001)	(0.05)	
M71	0.7378*	0.2967*	0.84*	0.0002*	1.246*	11671
	(0.0132)	(0.012)	(0.005)	(0.0000)	(0.0391)	
M72	0.7664*	0.3047*	0.903*	0.0001	0.71*	1233
	(0.0828)	(0.0863)	(0.0125)	(0.0002)	(0.091)	
M73	0.6124*	0.2739*	0.868*	0.0008*	1.07*	5468
	(0.0208)	(0.021)	(0.0065)	(0.0001)	(0.0534)	
M74	0.6458*	0.3749*	0.814*	0.0007*	1.215*	4387
	(0.0202)	(0.0174)	(0.0081)	(0.0001)	(0.0536)	
M75	0.6207*	0.3092*	0.772*	-.0001	1.752*	3735
	(0.0228)	(0.0175)	(0.0106)	(0.0001)	(0.0815)	
N77	0.267*	0.6369*	0.925*	0.0003	0.244*	2875
	(0.0549)	(0.059)	(0.0071)	(0.0002)	(0.0218)	
N78	0.7098*	0.1858*	0.761*	0.0005*	2.21*	4468
	(0.0162)	(0.0157)	(0.0098)	(0.0001)	(0.0912)	
N79	0.803*	0.1782*	0.714*	0.0004	2.482*	2276
	(0.023)	(0.0187)	(0.0134)	(0.0002)	(0.116)	
N80	0.7506*	0.1675	0.87*	0.0005	1.158*	1214
	(0.043)	(0.0531)	(0.0125)	(0.0002)	(0.113)	
N81	0.5351*	0.3301*	0.872*	0.0002*	0.946*	12362
	(0.0098)	(0.0108)	(0.0041)	(0.0001)	(0.0305)	
N82	0.5867*	0.3508*	0.904*	0.0003*	0.688*	5985
	(0.0206)	(0.0193)	(0.0053)	(0.0001)	(0.038)	
S95	0.6533*	0.3485*	0.884*	0.0001	0.834*	1775
	(0.062)	(0.0447)	(0.0112)	(0.0001)	(0.0793)	

Standard deviation in parentheses. Variation due to population density, federal states and years is controlled for in the first stage. The Hansen test has p-value of about
99 percent in all industries, indicating that there no endogeneity issue with the instruments.
Significance levels: * $p<0.01$.

Table A.6: IV regression results, two-digit manufacturing industries

Ind.	neighb. Broad-band$_{t-1}$	neighb. Distance to MDF$_{t-1}$	rugged-ness$_{t-1}$	neighb. rugged-ness$_{t-1}$	R^2	N	value F-Test	p-value F-Test	p-value under-identific. test	p-value weak instrum. test
C10	0.519***	0.000302	-0.0732*	0.0349	0.323	3,971	143,8	0	0	0
	(0.0259)	(0.000537)	(0.0441)	(0.0461)						
C11	0.604***	-0.00135	-0.217**	0.141	0.462	546	52,2	0	0	0
	(0.0601)	(0.00164)	(0.0916)	(0.101)						
C13	0.575***	-0.00105	0.00363	0.0935	0.402	678	44,15	0	0	0
	(0.0561)	(0.00115)	(0.0833)	(0.0850)						
C14	0.483***	0.000758	-0.0650	0.0237	0.335	500	23,98	0	0	0
	(0.0726)	(0.00152)	(0.107)	(0.114)						
C15	0.290***	0.00433	0.0480	0.194	0.302	224	9,07	0	0	0
	(0.107)	(0.00267)	(0.354)	(0.374)						
C16	0.577***	0.000823	-0.133	0.0971	0.271	664	15,93	0	0	0
	(0.0599)	(0.00134)	(0.0823)	(0.0902)						
C17	0.631***	-0.00275**	-0.153***	0.180***	0.406	948	45,03	0	0	0
	(0.0524)	(0.00113)	(0.0555)	(0.0668)						
C18	0.485***	-0.000692	0.0701	-0.0619	0.538	575	68,8	0	0	0
	(0.0579)	(0.00169)	(0.113)	(0.124)						
C20	0.490***	0.00332***	0.0528	-0.103*	0.430	1,993	118,07	0	0	0
	(0.0338)	(0.000915)	(0.0537)	(0.0593)						
C21	0.392***	0.000712	-0.312***	0.0948	0.494	424	49,61	0	0	0
	(0.0631)	(0.00150)	(0.0993)	(0.125)						
C22	0.600***	0.00107	-0.0192	0.0609	0.428	1,577	81,7	0	0	0
	(0.0362)	(0.000834)	(0.0542)	(0.0598)						
C23	0.575***	-0.00250***	-0.0789	0.0562	0.378	1,526	70,09	0	0	0
	(0.0407)	(0.000891)	(0.0509)	(0.0610)						
C24	0.480***	0.00287***	-0.115***	-0.00649	0.440	1,596	94,24	0	0	0
	(0.0458)	(0.000957)	(0.0347)	(0.0420)						
C25	0.528***	0.000126	0.00136	-0.0512	0.315	3,630	120,74	0	0	0
	(0.0283)	(0.000653)	(0.0337)	(0.0385)						
C26	0.636***	0.00157	0.113**	-0.0933	0.472	1,355	119,38	0	0	0
	(0.0455)	(0.00106)	(0.0523)	(0.0609)						
C27	0.443***	0.000407	-0.119**	0.119**	0.402	2,099	119,44	0	0	0
	(0.0338)	(0.000753)	(0.0475)	(0.0523)						
C28	0.529***	2.21e-05	-0.0525	-0.0149	0.343	4,332	168,57	0	0	0
	(0.0249)	(0.000566)	(0.0333)	(0.0377)						
C29	0.476***	2.81e-05	-0.0515	0.00295	0.347	1,238	52	0	0	0
	(0.0413)	(0.00104)	(0.0682)	(0.0832)						
C30	0.619***	0.00166	-0.235*	0.0327	0.465	459	42,77	0	0	0
	(0.0678)	(0.00200)	(0.127)	(0.151)						
C31	0.542***	0.00335***	-0.220**	0.171	0.242	678	15,97	0	0	0
	(0.0633)	(0.00129)	(0.100)	(0.114)						
C32	0.534***	-0.000300	0.0536	-0.0711	0.430	1,124	66,69	0	0	0
	(0.0481)	(0.00117)	(0.0770)	(0.0790)						
C33	0.544***	0.000993	-0.0417	0.0529	0.442	1,116	91,88	0	0	0
	(0.0501)	(0.00107)	(0.0946)	(0.104)						

Standard deviation in parentheses. Robust standard errors. * p<0.001 ** p<0.05 *p<0.1
Labor, capital, year dummies, population density and state dummies are also included in the regressions.

Table A.7: IV regression results, two-digit service sectors

Ind.	neighb. Broad-band$_{t-1}$	neighb. Distance to MDF$_{t-1}$	rugged-ness$_{t-1}$	neighb. rugged-ness$_{t-1}$	R^2	N	value F-Test	p-value F-Test	p-value under-identific. test	p-value weak instrum. test
H49	0.529***	0.000279	-0.0457**	0.00968	0.431	14,554	889,28	0	0	0
	(0.0134)	(0.000298)	(0.0202)	(0.0226)						
H50	0.364***	9.18e-05	-0.109	0.229**	0.555	777	68	0	0	0
	(0.0598)	(0.00123)	(0.0770)	(0.115)						
H51	0.430***	-0.00159	-0.432**	0.354*	0.713	272	52,59	0	0	0
	(0.110)	(0.00227)	(0.168)	(0.193)						
H52	0.458***	-0.000204	-0.0594	-0.0420	0.473	5,011	293,07	0	0	0
	(0.0236)	(0.000493)	(0.0382)	(0.0403)						
J58	0.471***	0.00138*	0.0114	-0.0662	0.571	3,535	306,15	0	0	0
	(0.0243)	(0.000743)	(0.0394)	(0.0443)						
J59	0.495***	0.00121	-0.256***	0.136*	0.602	2,150	122,07	0	0	0
	(0.0319)	(0.000956)	(0.0588)	(0.0702)						
J60	0.561***	-0.00182	-0.0622	-0.0919	0.625	219	23,31	0	0	0
	(0.117)	(0.00409)	(0.186)	(0.193)						
J61	0.418***	0.00612***	-0.123	-0.0590	0.516	818	51,55	0	0	0
	(0.0588)	(0.00164)	(0.165)	(0.172)						
J62	0.460***	0.00292***	-0.196***	0.0725**	0.498	8,947	623,98	0	0	0
	(0.0168)	(0.000495)	(0.0328)	(0.0359)						
J63	0.441***	0.00356***	-0.0259	-0.109	0.524	1,767	148,06	0	0	0
	(0.0423)	(0.00118)	(0.0678)	(0.0849)						
L68	0.474***	0.00125**	-0.0678	-0.00936	0.547	6,320	638,09	0	0	0
	(0.0200)	(0.000488)	(0.0419)	(0.0416)						
M69	0.493***	0.000314	-0.0661***	0.0134	0.611	14,714	1649,98	0	0	0
	(0.0126)	(0.000298)	(0.0222)	(0.0230)						
M70	0.374***	0.00123**	-0.0338	-0.136***	0.545	6,395	503,51	0	0	0
	(0.0218)	(0.000575)	(0.0367)	(0.0448)						
M71	0.503***	0.00119***	-0.0711***	0.0171	0.531	11,663	1095,45	0	0	0
	(0.0144)	(0.000391)	(0.0245)	(0.0257)						
M72	0.443***	0.00391***	-0.151*	-0.117	0.506	1,233	82,86	0	0	0
	(0.0415)	(0.00133)	(0.0786)	(0.0766)						
M73	0.476***	0.00274***	-0.0910**	0.0234	0.612	5,468	456,45	0	0	0
	(0.0240)	(0.000707)	(0.0425)	(0.0453)						
M74	0.439***	0.00182**	-0.0571	-0.00138	0.568	4,382	347,25	0	0	0
	(0.0252)	(0.000728)	(0.0392)	(0.0451)						
M75	0.531***	0.00111**	-0.0986**	0.0766	0.364	3,724	145,94	0	0	0
	(0.0251)	(0.000556)	(0.0410)	(0.0467)						
N77	0.571***	0.00162**	-0.180***	0.0964*	0.470	2,874	170,88	0	0	0
	(0.0269)	(0.000698)	(0.0538)	(0.0559)						
N78	0.505***	-0.000335	-0.0757*	0.0153	0.558	4,466	478,39	0	0	0
	(0.0241)	(0.000619)	(0.0401)	(0.0460)						
N79	0.450***	0.000847	0.00410	0.0162	0.512	2,274	189,35	0	0	0
	(0.0340)	(0.000824)	(0.0490)	(0.0581)						
N80	0.579***	0.00153	-0.161**	0.125	0.494	1,214	80,31	0	0	0
	(0.0473)	(0.00116)	(0.0671)	(0.0776)						
N81	0.504***	0.000915**	0.00153	-0.0420	0.450	12,354	800,51	0	0	0
	(0.0148)	(0.000355)	(0.0237)	(0.0257)						
N82	0.541***	0.00282***	-0.0270	-0.0174	0.508	5,977	401,79	0	0	0
	(0.0213)	(0.000593)	(0.0400)	(0.0430)						
S95	0.621***	0.000797	-0.194***	0.111	0.433	1,772	100,93	0	0	0
	(0.0398)	(0.000883)	(0.0578)	(0.0712)						

Standard deviation in parentheses. Robust standard errors. * p<0.001 ** p<0.05 *p<0.1

Labor, capital, year dummies, population density and state dummies are also included in the regressions.

Table A.8: ACF results, two-digit manufacturing industries, instrumented broadband variable

	production funct. $f(\cdot)$		law of motion $g(\cdot)$			
Ind.	Labor	Capital	TFP_{t-1}	Broad band$_{t-1}$	Constant	N
C10	0.5157*	0.4516*	0.954*	0.0002*	0.269*	3971
	(0.0307)	(0.025)	(0.0038)	(0.0001)	(0.0216)	
C11	0.8034*	0.4046*	0.948*	0.0007*	0.276*	546
	(0.1175)	(0.0978)	(0.0116)	(0.0002)	(0.0662)	
C13	0.881*	0.1758	0.962*	0.0007*	0.291*	678
	(0.0944)	(0.0741)	(0.0116)	(0.0002)	(0.0935)	
C14	0.5316*	0.1935	0.982*	0.0002	0.17	500
	(0.1347)	(0.3896)	(0.0079)	(0.0003)	(0.0774)	
C15	0.8496*	0.3717	0.953*	-.0001	0.265	224
	(0.1607)	(0.1797)	(0.0288)	(0.0007)	(0.132)	
C16	0.7712*	0.2663*	0.912*	-.0002	0.689*	664
	(0.0596)	(0.0469)	(0.0134)	(0.0002)	(0.104)	
C17	0.6422*	0.4207*	0.922*	0.0002	0.46*	948
	(0.0672)	(0.045)	(0.0133)	(0.0002)	(0.0773)	
C18	0.7706*	0.2817*	0.93*	0.0001	0.499*	575
	(0.0832)	(0.0673)	(0.0169)	(0.0002)	(0.12)	
C20	0.6924*	0.3849*	0.967*	0.0001	0.227*	1993
	(0.0551)	(0.0547)	(0.0066)	(0.0001)	(0.0408)	
C21	0.6741*	0.3503*	0.882*	0.0007*	0.737*	424
	(0.0765)	(0.0672)	(0.0173)	(0.0002)	(0.109)	
C22	0.7559*	0.3086*	0.924*	0.0003	0.551*	1577
	(0.0335)	(0.0288)	(0.0081)	(0.0001)	(0.0564)	
C23	0.9098*	0.1914*	0.942*	0.0003	0.473*	1526
	(0.0542)	(0.0459)	(0.0086)	(0.0001)	(0.0697)	
C24	0.8066*	0.2705*	0.89*	0.0002	0.853*	1596
	(0.0331)	(0.0278)	(0.0096)	(0.0001)	(0.0736)	
C25	0.783*	0.2747*	0.89*	0.0002	0.827*	3630
	(0.0222)	(0.0173)	(0.0071)	(0.0001)	(0.0531)	
C26	0.9415*	0.1602*	0.922*	0.0005*	0.671*	1355
	(0.0553)	(0.0477)	(0.0097)	(0.0002)	(0.0826)	
C27	0.7974*	0.2334*	0.97*	0.0002	0.251*	2099
	(0.047)	(0.0339)	(0.0062)	(0.0001)	(0.05)	
C28	0.8867*	0.189*	0.925*	0.0002*	0.649*	4332
	(0.0244)	(0.0202)	(0.0059)	(0.0001)	(0.0502)	
C29	0.7675*	0.3036*	0.906*	0.0008*	0.643*	1238
	(0.0584)	(0.0457)	(0.0128)	(0.0002)	(0.0871)	
C30	0.8274*	0.2241	0.914*	0.0004	0.707*	459
	(0.0958)	(0.0817)	(0.0197)	(0.0003)	(0.157)	
C31	0.7786*	0.2679*	0.874*	0.0004	0.964*	678
	(0.0593)	(0.0456)	(0.0188)	(0.0003)	(0.143)	
C32	0.7727*	0.3762*	0.948*	0	0.324*	1124
	(0.0764)	(0.0605)	(0.01)	(0.0002)	(0.0576)	
C33	0.8852*	0.2157*	0.88*	0.0003	0.982*	1116
	(0.0377)	(0.0356)	(0.0119)	(0.0001)	(0.0967)	

Standard deviation in parentheses. Variation due to population density, federal states and years is controlled for in the first stage. The Hansen test has p-value of about
99 percent in all industries, indicating that there no endogeneity issue with the instruments.
Significance levels: * $p<0.01$.

Table A.9: ACF results, two-digit service sectors, instrumented broadband variable

Ind.	production funct. $f(\cdot)$ Labor	Capital	law of motion $g(\cdot)$ TFP_{t-1}	Broad band$_{t-1}$	Constant	N
H49	0.5224*	0.5234*	0.851*	0.0002*	0.617*	14554
	(0.0142)	(0.013)	(0.0041)	(0.0001)	(0.0176)	
H50	0.6858*	0.1493	0.909*	0.0015	0.849*	777
	(0.0821)	(0.1305)	(0.0173)	(0.0006)	(0.164)	
H51	0.6438*	0.3906*	0.84*	0.0015	0.933*	272
	(0.1246)	(0.1183)	(0.0277)	(0.0008)	(0.167)	
H52	0.5941*	0.2828*	0.867*	0.0009*	1.035*	5011
	(0.0379)	(0.0355)	(0.0078)	(0.0001)	(0.0612)	
J58	0.5042*	0.4407*	0.89*	0.0009*	0.678*	3535
	(0.0338)	(0.0326)	(0.0068)	(0.0002)	(0.0434)	
J59	0.4916*	0.4047*	0.922*	0.0014*	0.428*	2150
	(0.0436)	(0.0566)	(0.0083)	(0.0003)	(0.0464)	
J60	0.4353*	0.7237*	0.84*	0.0019	0.245*	219
	(0.1171)	(0.1306)	(0.0303)	(0.0011)	(0.0928)	
J61	0.5136*	0.5792*	0.934*	0.0007	0.228*	818
	(0.1162)	(0.1204)	(0.0136)	(0.0004)	(0.0529)	
J62	0.8883*	0.1491*	0.832*	0.0007*	1.573*	8947
	(0.0161)	(0.0131)	(0.0058)	(0.0001)	(0.0542)	
J63	0.7369*	0.289*	0.818*	0.0012*	1.428*	1767
	(0.0294)	(0.0228)	(0.0117)	(0.0003)	(0.0934)	
M69	0.7077*	0.3798*	0.86*	0.0004*	0.888*	14714
	(0.0119)	(0.0118)	(0.004)	(0.0000)	(0.0256)	
M70	0.7174*	0.2644*	0.883*	0.0009*	0.938*	6395
	(0.0236)	(0.0238)	(0.0061)	(0.0001)	(0.0504)	
M71	0.7324*	0.2987*	0.839*	0.0004*	1.262*	11663
	(0.0131)	(0.0118)	(0.005)	(0.0001)	(0.0395)	
M72	0.7642*	0.3046*	0.902*	0.0002	0.703*	1233
	(0.0829)	(0.086)	(0.0124)	(0.0003)	(0.0911)	
M73	0.6053*	0.2711*	0.863*	0.0013*	1.088*	5468
	(0.0204)	(0.0203)	(0.0066)	(0.0001)	(0.0537)	
M74	0.6438*	0.3761*	0.808*	0.0011*	1.229*	4382
	(0.02)	(0.017)	(0.0082)	(0.0001)	(0.0537)	
M75	0.6168*	0.3101*	0.773*	0.0001	1.78*	3724
	(0.0236)	(0.0177)	(0.0106)	(0.0002)	(0.0836)	
N77	0.2664*	0.6242*	0.923*	0.0007	0.272*	2874
	(0.054)	(0.0582)	(0.0072)	(0.0003)	(0.026)	
N78	0.7095*	0.1838*	0.758*	0.0009*	2.238*	4466
	(0.016)	(0.0156)	(0.0099)	(0.0002)	(0.092)	
N79	0.8016*	0.1788*	0.714*	0.0006	2.514*	2274
	(0.0228)	(0.0185)	(0.0134)	(0.0002)	(0.118)	
N80	0.7514*	0.1679	0.871*	0.0005	1.156*	1214
	(0.0439)	(0.0539)	(0.0126)	(0.0003)	(0.113)	
N81	0.5276*	0.332*	0.871*	0.0005*	0.937*	12354
	(0.0101)	(0.0108)	(0.0042)	(0.0001)	(0.0304)	
N82	0.5841*	0.348*	0.902*	0.0006*	0.693*	5977
	(0.0202)	(0.0189)	(0.0054)	(0.0001)	(0.0383)	
S95	0.6509*	0.3492*	0.884*	0.0002	0.83*	1772
	(0.062)	(0.0445)	(0.0112)	(0.0002)	(0.0791)	

Standard deviation in parentheses. Variation due to population density, federal states and years is controlled for in the first stage. The Hansen test has p-value of about 99 percent in all industries, indicating that there no endogeneity issue with the instruments. Significance levels: * p<0.01.

Table A.10: ACF results, two-digit manufacturing industries, broadband in t

	production funct. $f(\cdot)$		law of motion $g(\cdot)$			
Ind.	Labor	Capital	TFP_{t-1}	Broad band$_t$	Constant	N
C10	0.4936*	0.4848*	0.947*	0.0003*	0.279*	6083
	(0.0233)	(0.0197)	(0.0033)	(0.0000)	(0.0172)	
C11	0.7813*	0.3544*	0.91*	0.0008*	0.579*	853
	(0.0647)	(0.0498)	(0.0107)	(0.0001)	(0.0712)	
C13	0.8666*	0.1191	0.947*	0.0005*	0.493*	1128
	(0.0569)	(0.0553)	(0.008)	(0.0001)	(0.0751)	
C14	0.6575*	0.2568	0.983*	-.0003	0.162	734
	(0.1278)	(0.2217)	(0.0078)	(0.0001)	(0.0655)	
C15	0.9447*	0.3331	0.939*	0.0012*	0.285*	329
	(0.1108)	(0.1292)	(0.0175)	(0.0002)	(0.0851)	
C16	0.742*	0.2954*	0.914*	-.0003*	0.646*	1182
	(0.0506)	(0.0396)	(0.0113)	(0.0001)	(0.0827)	
C17	0.5758*	0.4692*	0.921*	0.0001	0.43*	1505
	(0.0509)	(0.0349)	(0.0098)	(0.0001)	(0.0519)	
C18	0.7961*	0.2638*	0.917*	0.0001	0.609*	1055
	(0.0556)	(0.0477)	(0.0125)	(0.0001)	(0.0931)	
C20	0.6742*	0.3715*	0.94*	0.0001	0.417*	2908
	(0.0398)	(0.0382)	(0.0056)	(0.0001)	(0.0376)	
C21	0.6974*	0.3611*	0.851*	0.0004*	0.932*	621
	(0.0593)	(0.0495)	(0.0161)	(0.0002)	(0.0992)	
C22	0.7284*	0.3394*	0.918*	0.0001	0.564*	2842
	(0.0275)	(0.0232)	(0.0067)	(0.0001)	(0.0446)	
C23	0.7634*	0.2887*	0.937*	0	0.465*	2365
	(0.0387)	(0.0321)	(0.007)	(0.0001)	(0.0508)	
C24	0.7627*	0.2939*	0.87*	0.0002*	1*	2272
	(0.025)	(0.0211)	(0.0078)	(0.0001)	(0.0598)	
C25	0.7624*	0.2846*	0.879*	0.0001	0.914*	6501
	(0.0181)	(0.0138)	(0.0054)	(0.0000)	(0.0403)	
C26	0.8933*	0.2047*	0.919*	0.0003*	0.666*	2219
	(0.0467)	(0.0404)	(0.0072)	(0.0001)	(0.0584)	
C27	0.8088*	0.2362*	0.94*	0.0002*	0.501*	3418
	(0.0317)	(0.0233)	(0.0055)	(0.0001)	(0.0445)	
C28	0.8582*	0.2188*	0.894*	0	0.9*	7412
	(0.0183)	(0.0154)	(0.0048)	(0.0000)	(0.0399)	
C29	0.73*	0.3509*	0.886*	0.0002*	0.754*	1921
	(0.0462)	(0.0379)	(0.0103)	(0.0001)	(0.0663)	
C30	0.7732*	0.3056*	0.908*	0	0.673*	636
	(0.0944)	(0.0813)	(0.0162)	(0.0001)	(0.114)	
C31	0.7324*	0.3242*	0.862*	0.0002	0.96*	1181
	(0.0454)	(0.0352)	(0.0144)	(0.0001)	(0.1)	
C32	0.7375*	0.386*	0.95*	0	0.304*	1860
	(0.0626)	(0.0482)	(0.0079)	(0.0001)	(0.0463)	
C33	0.9164*	0.1675*	0.87*	0.0001	1.151*	1756
	(0.027)	(0.0254)	(0.0097)	(0.0001)	(0.0854)	

Standard deviation in parentheses. Variation due to population density, federal states and years is controlled for in the first stage. The Hansen test has p-value of about
99 percent in all industries, indicating that there no endogeneity issue with the instruments.
Significance levels: * p<0.01.

Table A.11: ACF results, two-digit service sectors, broadband in t

	production funct. $f(\cdot)$		law of motion $g(\cdot)$			
Ind.	Labor	Capital	TFP_{t-1}	Broad band$_t$	Constant	N
H49	0.4585*	0.5788*	0.837*	0.0002*	0.606*	26529
	(0.0094)	(0.009)	(0.003)	(0.0000)	(0.0115)	
H50	0.5873*	0.3747*	0.921*	0.0014*	0.469*	1435
	(0.0584)	(0.1127)	(0.0109)	(0.0003)	(0.07)	
H51	0.7312*	0.338*	0.864*	0.0005	0.88*	449
	(0.0994)	(0.0971)	(0.0219)	(0.0005)	(0.146)	
H52	0.6368*	0.2807*	0.807*	0.0007*	1.506*	8929
	(0.0192)	(0.019)	(0.006)	(0.0001)	(0.047)	
J58	0.4822*	0.479*	0.904*	0.0005*	0.554*	5605
	(0.0272)	(0.0272)	(0.0051)	(0.0001)	(0.0299)	
J59	0.464*	0.5064*	0.896*	0.0016*	0.454*	3580
	(0.0354)	(0.0456)	(0.0065)	(0.0002)	(0.0298)	
J60	0.3569	0.6199*	0.915*	0.0022*	0.211*	355
	(0.1533)	(0.1326)	(0.021)	(0.0007)	(0.0773)	
J61	0.5295*	0.6207*	0.908*	0.0002	0.247*	1390
	(0.0917)	(0.0901)	(0.0098)	(0.0002)	(0.0295)	
J62	0.871*	0.2019*	0.829*	0.0004*	1.488*	16161
	(0.0124)	(0.011)	(0.0043)	(0.0001)	(0.0374)	
J63	0.693*	0.3511*	0.83*	0.0008*	1.178*	3047
	(0.0247)	(0.0212)	(0.0091)	(0.0002)	(0.0639)	
M69	0.7028*	0.4296*	0.831*	0.0004*	0.919*	31500
	(0.0076)	(0.0078)	(0.0028)	(0.0000)	(0.0154)	
M70	0.7044*	0.3046*	0.871*	0.0006*	0.991*	12874
	(0.0153)	(0.0155)	(0.0043)	(0.0001)	(0.0332)	
M71	0.7219*	0.3195*	0.829*	0.0003*	1.308*	23253
	(0.0081)	(0.0078)	(0.0036)	(0.0000)	(0.0272)	
M72	0.7682*	0.2674*	0.878*	0.0001	0.965*	2044
	(0.0405)	(0.0372)	(0.0097)	(0.0002)	(0.0765)	
M73	0.6137*	0.3223*	0.889*	0.0006*	0.826*	9869
	(0.0166)	(0.0171)	(0.0043)	(0.0001)	(0.0328)	
M74	0.5473*	0.4535*	0.855*	0.0006*	0.838*	8160
	(0.0207)	(0.0165)	(0.0055)	(0.0001)	(0.032)	
M75	0.5445*	0.4157*	0.81*	-.0001	1.267*	6909
	(0.0181)	(0.015)	(0.0071)	(0.0001)	(0.0469)	
N77	0.2644*	0.7234*	0.9*	0.0004*	0.156*	5122
	(0.0401)	(0.0488)	(0.0053)	(0.0001)	(0.0113)	
N78	0.7029*	0.2194*	0.738*	0.0004*	2.356*	7487
	(0.0119)	(0.0124)	(0.0076)	(0.0001)	(0.0683)	
N79	0.721*	0.2816*	0.797*	0	1.586*	4207
	(0.0225)	(0.0198)	(0.009)	(0.0001)	(0.0695)	
N80	0.6333*	0.3536*	0.867*	0.0006*	0.891*	2109
	(0.0317)	(0.0383)	(0.0099)	(0.0002)	(0.0675)	
N81	0.507*	0.3568*	0.837*	0.0003*	1.156*	23906
	(0.0068)	(0.0073)	(0.0032)	(0.0000)	(0.0226)	
N82	0.556*	0.3837*	0.89*	0.0004*	0.75*	10760
	(0.0156)	(0.0148)	(0.004)	(0.0001)	(0.0276)	
S95	0.6771*	0.323*	0.881*	0.0001	0.888*	3323
	(0.0403)	(0.0266)	(0.0086)	(0.0001)	(0.0633)	

Standard deviation in parentheses. Variation due to population density, federal states and years is controlled for in the first stage. The Hansen test has p-value of about
99 percent in all industries, indicating that there no endogeneity issue with the instruments.
Significance levels: * p<0.01.

Table A.12: ACF results, two-digit manufacturing industries, broadband from $t-1$, in and out of range of 4200 m to MDF

	production funct. $f(\cdot)$		law of motion $g(\cdot)$				
Ind.	Labor	Capital	TFP_{t-1}	in range	out of range	Constant	N
C10	0.5188*	0.4565*	0.954*	0.0002*	0.0005*	0.267*	3974
	(0.0305)	(0.0247)	(0.0039)	(0.0000)	(0.0001)	(0.0213)	
C11	0.7808*	0.42*	0.943*	0.0005*	-.0006	0.32*	546
	(0.1172)	(0.0945)	(0.012)	(0.0002)	(0.0003)	(0.0692)	
C13	0.9335*	0.1597	0.963*	0.0004*	0.0013*	0.304*	682
	(0.0962)	(0.0767)	(0.0127)	(0.0001)	(0.0003)	(0.105)	
C14	0.5396*	0.121	0.986*	-.0002	0.0002	0.164	500
	(0.1367)	(0.5138)	(0.007)	(0.0002)	(0.0003)	(0.077)	
C15	0.8437*	0.3941	0.92*	0.0011*	-.0068	0.342*	224
	(0.1383)	(0.1326)	(0.0296)	(0.0004)	(0.0033)	(0.123)	
C16	0.7833*	0.2565*	0.907*	-.0001	-.0001	0.732*	664
	(0.0598)	(0.0464)	(0.0144)	(0.0001)	(0.0002)	(0.111)	
C17	0.6166*	0.4356*	0.916*	0.0003	-.0002	0.486*	948
	(0.067)	(0.045)	(0.0133)	(0.0001)	(0.0002)	(0.0758)	
C18	0.771*	0.2848*	0.932*	-.0001	-.0002	0.511*	575
	(0.0833)	(0.0677)	(0.017)	(0.0002)	(0.0005)	(0.123)	
C20	0.6885*	0.3977*	0.965*	0	-.0001	0.231*	1997
	(0.0557)	(0.0538)	(0.0066)	(0.0001)	(0.0002)	(0.04)	
C21	0.6892*	0.3569*	0.845*	0.0005	-.003	0.979*	424
	(0.0635)	(0.0556)	(0.0205)	(0.0002)	(0.0014)	(0.129)	
C22	0.7588*	0.3055*	0.926*	0.0001	0.0001	0.542*	1578
	(0.0341)	(0.0295)	(0.0079)	(0.0001)	(0.0002)	(0.056)	
C23	0.9112*	0.1987*	0.945*	-.0001	-.0002	0.453*	1526
	(0.0567)	(0.0473)	(0.0085)	(0.0001)	(0.0002)	(0.0688)	
C24	0.8055*	0.271*	0.89*	0.0002*	0.0003	0.854*	1596
	(0.0325)	(0.0273)	(0.0094)	(0.0001)	(0.0001)	(0.0725)	
C25	0.7801*	0.2753*	0.892*	0	0.0002	0.824*	3630
	(0.0226)	(0.0175)	(0.007)	(0.0001)	(0.0001)	(0.0529)	
C26	0.9276*	0.1743*	0.922*	0.0003*	-.0003	0.674*	1356
	(0.0555)	(0.0476)	(0.0095)	(0.0001)	(0.0003)	(0.0808)	
C27	0.7994*	0.2305*	0.972*	0.0001	0.0001	0.247*	2099
	(0.0477)	(0.0348)	(0.006)	(0.0001)	(0.0002)	(0.0499)	
C28	0.8954*	0.1831*	0.926*	0	-.0002*	0.661*	4334
	(0.0249)	(0.0207)	(0.0058)	(0.0000)	(0.0001)	(0.0511)	
C29	0.7825*	0.3078*	0.911*	0.0003*	0.0003	0.614*	1238
	(0.0592)	(0.0475)	(0.0125)	(0.0001)	(0.0002)	(0.0846)	
C30	0.8679*	0.2193	0.906*	0.0001	0.0019*	0.76*	459
	(0.0888)	(0.0756)	(0.0197)	(0.0002)	(0.0005)	(0.156)	
C31	0.7639*	0.2799*	0.871*	0.0004	0.0007	0.974*	678
	(0.0599)	(0.0461)	(0.0186)	(0.0001)	(0.0004)	(0.141)	
C32	0.7634*	0.3805*	0.943*	0	0	0.345*	1124
	(0.0742)	(0.0583)	(0.01)	(0.0001)	(0.0003)	(0.058)	
C33	0.889*	0.219*	0.884*	0.0001	0.0002	0.946*	1116
	(0.0388)	(0.0366)	(0.0118)	(0.0001)	(0.0003)	(0.0953)	

Standard deviation in parentheses. Variation due to population density, federal states and years is controlled for in the first stage. The Hansen test has p-value of about
99 percent in all industries, indicating that there no endogeneity issue with the instruments.
Significance levels: * p<0.01.

Table A.13: ACF results, two-digit service sectors, broadband from $t-1$, in and out of range of 4200 m to MDF

	production funct. $f(\cdot)$		law of motion $g(\cdot)$				
Ind.	Labor	Capital	TFP_{t-1}	in range	out of range	Constant	N
H49	0.5252*	0.5214*	0.85*	0.0001	0.0001	0.659*	14570
	(0.0141)	(0.0129)	(0.0041)	(0.0001)	(0.0001)	(0.0182)	
H50	0.6925*	0.1543	0.909*	0.0014*	-.0016	0.856*	787
	(0.0823)	(0.1235)	(0.0166)	(0.0004)	(0.0012)	(0.159)	
H51	0.6269*	0.4027*	0.836*	0.002*	-.0021	0.938*	276
	(0.1135)	(0.1126)	(0.0273)	(0.0006)	(0.0018)	(0.165)	
H52	0.5913*	0.288*	0.871*	0.0006*	0.0009*	1.011*	5014
	(0.039)	(0.0364)	(0.0077)	(0.0001)	(0.0002)	(0.0606)	
J58	0.5068*	0.4479*	0.893*	0.0006*	0.0001	0.671*	3539
	(0.0343)	(0.0334)	(0.0068)	(0.0001)	(0.0005)	(0.0428)	
J59	0.4972*	0.4073*	0.92*	0.0012*	-.0006	0.462*	2159
	(0.0433)	(0.0559)	(0.0081)	(0.0002)	(0.0008)	(0.0476)	
J60	0.4356*	0.718*	0.834*	0.0021	0.	0.26*	219
	(0.1156)	(0.1198)	(0.0303)	(0.0008)	(0.)	(0.0815)	
J61	0.5151*	0.5965*	0.937*	0.0005	0.0008	0.186*	818
	(0.1203)	(0.1216)	(0.0132)	(0.0003)	(0.0006)	(0.0431)	
J62	0.8911*	0.151*	0.835*	0.0004*	0.0001	1.538*	8954
	(0.0164)	(0.0134)	(0.0057)	(0.0001)	(0.0002)	(0.0534)	
J63	0.7381*	0.294*	0.814*	0.0009*	0.0015	1.462*	1767
	(0.029)	(0.0225)	(0.0117)	(0.0002)	(0.0007)	(0.094)	
M69	0.709*	0.3791*	0.861*	0.0004*	0.0007*	0.891*	14737
	(0.012)	(0.0118)	(0.004)	(0.0000)	(0.0001)	(0.0256)	
M70	0.7247*	0.2637*	0.888*	0.0005*	0.0006	0.909*	6400
	(0.024)	(0.0248)	(0.006)	(0.0001)	(0.0003)	(0.0499)	
M71	0.739*	0.2949*	0.839*	0.0001*	-.0001	1.26*	11671
	(0.0132)	(0.012)	(0.005)	(0.0000)	(0.0001)	(0.0393)	
M72	0.7564*	0.3225*	0.906*	0	-.0004	0.658*	1233
	(0.0863)	(0.0921)	(0.0124)	(0.0002)	(0.0005)	(0.0871)	
M73	0.6159*	0.2726*	0.866*	0.0008*	0.0006	1.091*	5468
	(0.0205)	(0.0209)	(0.0065)	(0.0001)	(0.0003)	(0.0536)	
M74	0.6478*	0.3749*	0.809*	0.0008*	-.0001	1.249*	4387
	(0.02)	(0.0172)	(0.0082)	(0.0001)	(0.0003)	(0.0541)	
M75	0.6237*	0.3064*	0.77*	-.0001	0.0003	1.78*	3735
	(0.0231)	(0.0176)	(0.0106)	(0.0001)	(0.0002)	(0.082)	
N77	0.2637*	0.6353*	0.923*	0.0003	-.0003	0.251*	2875
	(0.0544)	(0.0581)	(0.0071)	(0.0002)	(0.0004)	(0.0221)	
N78	0.7096*	0.1862*	0.762*	0.0005*	0.0009	2.209*	4468
	(0.0162)	(0.0158)	(0.0098)	(0.0001)	(0.0006)	(0.0912)	
N79	0.8042*	0.1777*	0.705*	0.0004	0.0002	2.559*	2276
	(0.0223)	(0.0181)	(0.0134)	(0.0002)	(0.0006)	(0.116)	
N80	0.7563*	0.163	0.871*	0.0005	0.0012	1.144*	1214
	(0.0443)	(0.0535)	(0.0125)	(0.0002)	(0.0006)	(0.112)	
N81	0.5339*	0.3314*	0.872*	0.0003*	0.0001	0.946*	12362
	(0.0099)	(0.0109)	(0.0042)	(0.0001)	(0.0001)	(0.0305)	
N82	0.5871*	0.3493*	0.904*	0.0004*	-.0002	0.694*	5985
	(0.0204)	(0.0192)	(0.0053)	(0.0001)	(0.0003)	(0.0382)	
S95	0.6504*	0.3494*	0.892*	0.0001	0.0003	0.776*	1775
	(0.0646)	(0.0469)	(0.0113)	(0.0001)	(0.0004)	(0.0798)	

Standard deviation in parentheses. Variation due to population density, federal states and years is controlled for in the first stage. The Hansen test has p-value of about 99 percent in all industries, indicating that there no endogeneity issue with the instruments. Significance levels: * $p<0.01$.

Table A.14: OLS results, four speed dummies

Variables	Manufacturing	Services
Labor	0.75*	0.759*
	(0.0144)	(0.0134)
Capital	0.319*	0.258*
	(0.0116)	(0.0117)
Population density	0.0273*	0.0743*
	(0.0057)	(0.0099)
2 Mbps to 10 Mbps	0.0811*	0.0464
	(0.0248)	(0.0422)
10 Mbps to 30 Mbps	0.0875*	0.0592
	(0.0252)	(0.042)
30 Mbps to 100 Mbps	0.137*	0.118*
	(0.0265)	(0.0429)
more than 100 Mbps	0.142*	0.189*
	(0.0283)	(0.0441)
Constant	6.438*	8.004*
	(0.144)	(0.339)
Ind., year, regional dummies	yes	yes
R^2	0.93	0.854
N	7532	8409

Standard deviation in parentheses. Standard errors are clustered at the firm level. Less than 2 Mbps as reference category. * p<0.01

B Figures

Figure B.1: Boxplot of broadband coverage in municipality over time

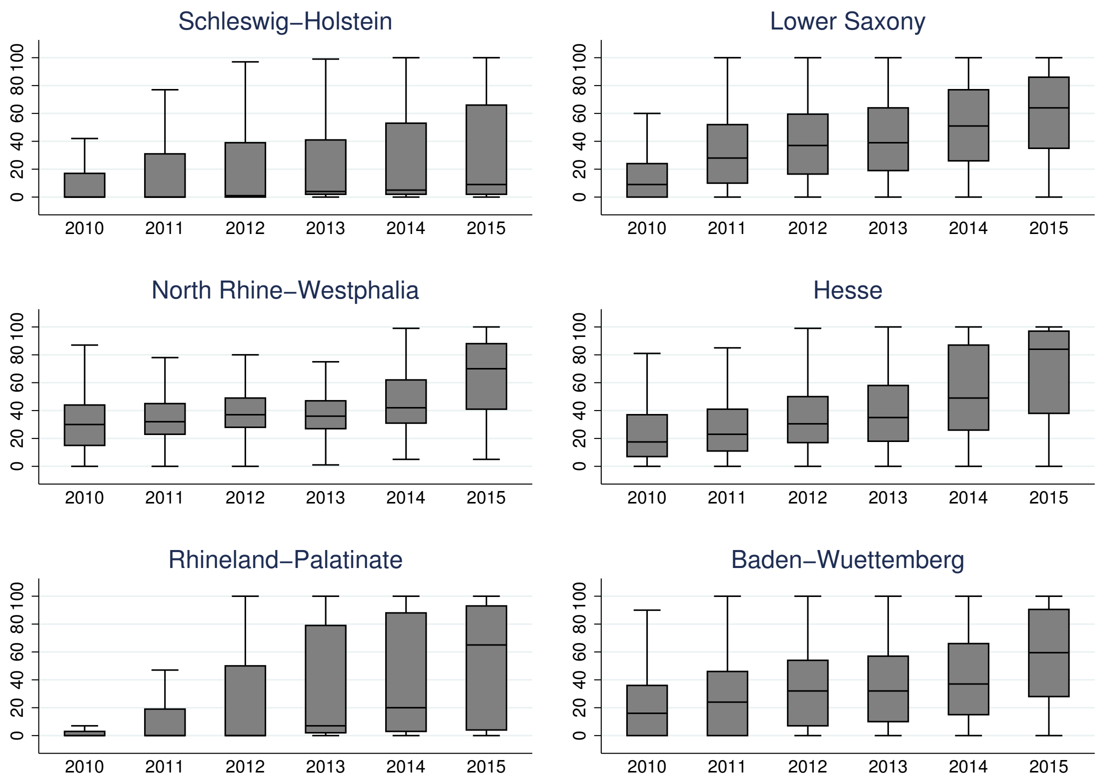
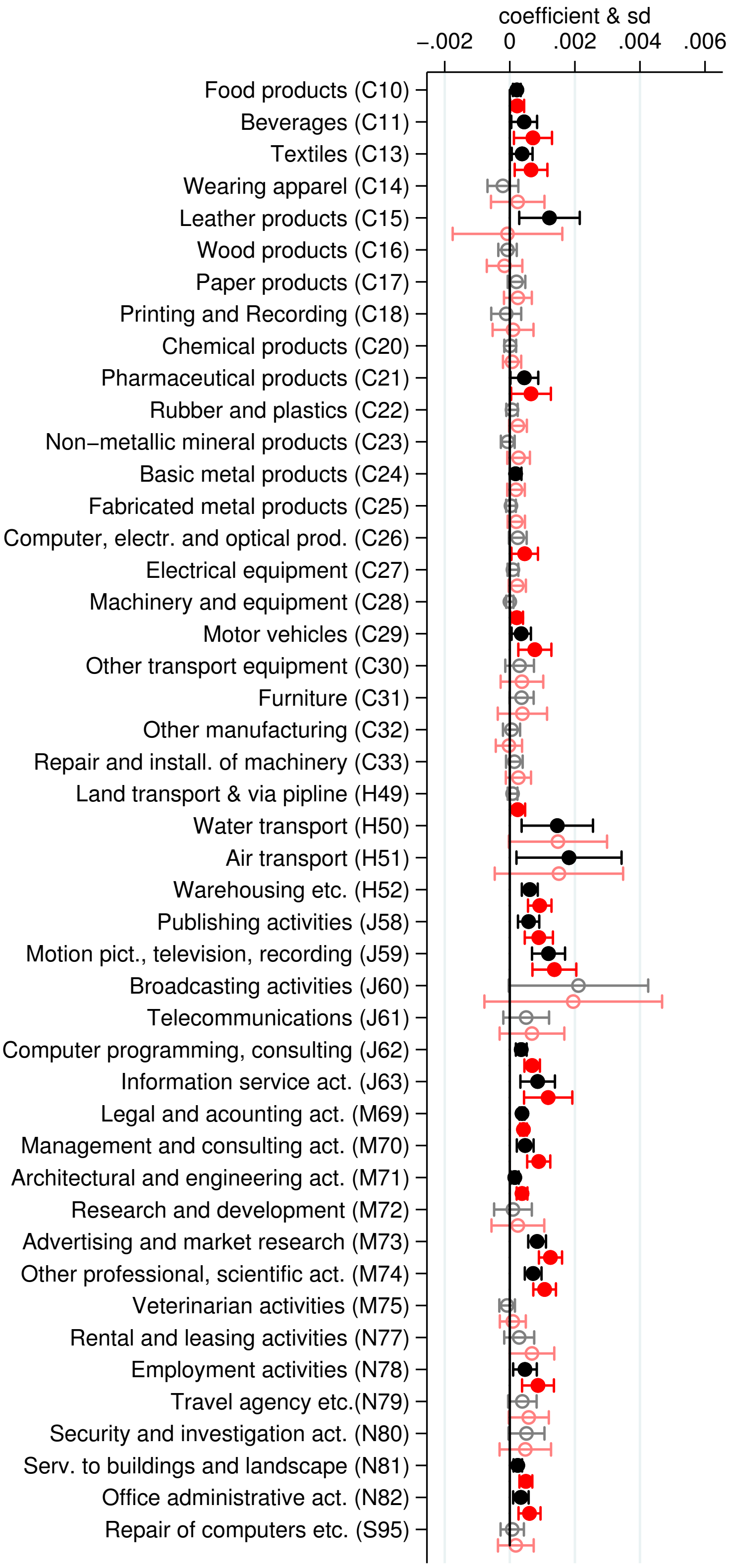


Figure B.2: Coefficients and s.e. for main specification and for instrumented 16 Mbps broadband availability, two-digit industries



Black and gray for main specification, red and light red for IV estimates; gray and light red when coefficients are not significantly different from zero.

C Extended literature review

Haller and Lyons (2015) investigates the relationship between broadband adoption and its effect on productivity based on a dataset of Irish manufacturing firms. Their dataset covers the 2002 to 2009 period and contains 8,023 observations. The authors use a two-step approach, with the first step estimating the TFP of firms by assuming a Cobb-Douglas sales production function and by applying OLS. The second stage regresses broadband –the adoption of DSL in their specific case– and other covariates on TFP levels and TFP growth rates obtained from the first step, applying a fixed effect estimation. Reverse causality and the endogeneity issue that comes with the fact that firms decide on broadband adoption is addressed by using broadband availability at the regional level. Robustness checks include the use of labor productivity as well as a TFP superlative index as dependent variable. Furthermore, different transmission speeds are considered. Although mostly positive, the coefficients for the different broadband variables are never significantly different from zero in each and every specification. Consequently, Haller and Lyons (2015) conclude that broadband adoption has no statistically verifiable effect on the level or development of firm productivity.

Fabling and Grimes (2016) come to a similar conclusion while focusing on Ultra-Fast Broadband (UFB). Their analysis uses data from 2,031 firms located in New Zealand covering the 2010 to 2012 period. The IV approach makes use of a governmental program (RBI) that aimed at providing schools and hospitals with access to modern digital infrastructure. As explicitly stated within the program, fiber connections are provided "to schools and hospitals, as well as businesses and households [that] are located on new fibre routes" (New Zealand Government, 2011, pp.4440). Thus, the expansion of the network was not aimed at supporting companies, but firms could benefit if they were located within a reasonable distance of the built infrastructure. The study takes advantage of this fact and uses the proximity to schools as an instrument. It analyzes the impact of UBF on employment, labor productivity, and TFP. TFP is obtained in a first step from industry-specific Cobb-Douglas gross output production functions. Regardless of the chosen specification in the second stage, the analysis finds no significant effect of UFB on TFP for five out of six specifications, with the same holding for labor productivity. However, exploiting further responses in their survey data, Fabling and Grimes (2016) find positive and significant effects on both productivity measures when investment in organizational changes and broadband are interacted. Yet, because of remaining econometric issues, the author emphasizes that this relationship cannot be considered causal beyond any doubt and, thus, the results must be considered cautiously.

In an earlier study, Grimes et al. (2012) came to a different finding when analyzing the impact of broadband adoption by New Zealand companies on their labor productivity. Focusing on 2006 and based on a sample of 6,060 observations, it uses a Propensity Score Matching (PSM) to identify firm characteristics that determine the use of broadband. Broadband users and non-users with similar characteristics are matched and the treatment effect of broadband adoption is estimated by looking at the differences in performance between the two groups. The firm specific deviation from the average industry labor productivity is considered identical to the firm specific TFP and serves as dependent variable. The authors also use a parametric IV approach as a robustness check. The results indicate that productivity increases by up to ten percent if firms switch from narrow-band telecommunications networks to broadband. The results are even higher in the IV estimation. The difference to the aforementioned study might point to the fact that broadband adoption mostly had an impact in the early days of the broadband roll-out.

Bertschek et al. (2013) analyze the causal effect of broadband networks on labor productivity and innovation based on a sample German firms covering the 2001 to 2003 period and containing 849 to 985 observations. The main source of data for the study is the ZEW ICT survey. Broadband is included as an input into a Cobb-Douglas sales production function along with tangible capital, ICT capital, and further controls. Endogeneity that stems from the fact that broadband adoption can be part of the firms' strategy is tackled by using geographical broadband availability at the postal code level as a proxy. The well known issue of endogeneity regarding all remaining production inputs (Marschak and Andrews Jr., 1944) is addressed by using lagged inputs as instruments. The estimation is conducted by means of OLS and the General Method of Moments (GMM). The latter is used to obtain causal and unbiased effects. Although broadband has a weakly significant effect in some OLS specifications, this effect is insignificantly different from zero once all relevant control variables are added. GMM estimates confirm this finding. Interestingly though, the effect of broadband on innovation is significantly positive across a large number of different specifications. Hence, while Bertschek et al. (2013) is another study that cannot confirm statistically significant direct effects of broadband internet on productivity, it finds evidence for its positive effect on innovation. In a way, this supports the claim that broadband fosters innovation - at least in the roll-out phase - and through this channel it might also influence productivity indirectly.

In an additional analysis, Bertschek and Niebel (2016) focus on the effect of mobile broadband internet on labor productivity. The 2004 wave of the ZEW ICT survey serves as main firm-level database, as it contains information on the use of mobile internet in firms. The final dataset contains 2,143 observations. The estimation equation is a Cobb-Douglas sales production function with additional controls, of which one is the share of workers with access to mobile internet. This function is rearranged such that labor productivity is the dependent variable of this production function. The analysis is conducted using OLS and 2SLS. To overcome the endogeneity issue, mobile internet access is instrumented with the average mobile internet use in each of the 51 industries. A further instrument is the number of years the interviewee has owned a smart phone. Regardless of the specifications, mobile internet always turns out to significantly improve labor productivity.

Bertschek et al. (2019) analyze whether ICT-intensive firms were more resilient during the 2008 and 2009 crisis in terms of their labor productivity development than less ICT-intensive firms. The Micro Moments Database, created in the ESSLait project, serves as data source for the analysis.[32] The final dataset covers 12 countries[33] and contains micro-aggregated industry data for 7 industries.[34] The data are pooled over time. ICT-intensity is defined as a dummy variable that takes the value of one if more than 40 percent of workers have access to broadband. A crisis dummy and its interaction with the ICT dummy are used in a Cobb-Douglas gross-output production function that is estimated by means of OLS. The coefficients of the respective dummies are significant in all specifications. Accordingly, labor productivity of non-ICT-intensive firms dropped during the crisis, while it stayed fairly stable, if not increased modestly, in ICT-intensive firms, depending on the econometric specification. The results are confirmed in a specification with productivity growth rates as dependent variable. Additional robustness checks reveal that the positive results of ICT-intensive firms are mainly driven by the service industries in the dataset. Note that Bertschek et al. (2019) also address the relationship between innovation and ICT-intensity, finding that it is positive and significant. Although causality cannot be claimed, this supports the view that broadband positively affects productivity through its positive effect on innovations.

[32] For more information on this database see https://ec.europa.eu/eurostat/cros/content/esslait_en and Hagsten (2015); Bartelsman et al. (2018).

[33] The MMD covers 14 countries in total.

[34] When analyzing the effect of ICT-intensity on innovation, the dataset shrinks to 10 countries because product- and process-innovation are not available for Germany and the UK.

Bartelsman et al. (2019) investigate how the use of broadband by firms, measured as proportion of employees connected to broadband, affects their labor productivity and their innovation activities. While Bertschek et al. (2019) use the aggregated data of the MMD, Bartelsman et al. (2019) make use of the underlying micro-data, which they access individually for each country and then applying the identical estimation code.[35] For the analysis, broadband and four innovation variables are included as additional inputs into an augmented Cobb-Douglas value added production function. Besides product- and process-innovation, the additional innovation variables cover organizational innovations and marketing innovations. The estimations are conducted both with and without broadband, while the innovation variables always appear in the production function. Data are pooled over time, but estimations are conducted separately for manufacturing and service firms as well as separately for each country. The observation period is 2002 to 2010. The results of the OLS regressions confirm a positive and significant effect of product innovations on productivity in both manufacturing and service in most countries. However, very few positive and significant effects are found for the remaining three innovation variables in most countries. Once broadband is added to the estimation, the magnitude of the coefficient of product innovations drops considerably and, more importantly, becomes insignificant in many countries. In contrast, broadband affects the productivity of firms significantly. The magnitude of the effect is found to be larger than that of product innovations. Robustness checks include the use of a gross output production function, the aggregation of innovation variables and the removal of outliers. The main results of the analysis are confirmed by these robustness checks. The authors conclude that broadband is more relevant for productivity than innovation. However, as econometric issues are evident, the authors also emphasize that the "relationships cannot be interpreted as causal" (Bartelsman et al., 2019, pp.38).

Hagsten (2016) also make use of national firm-level statistics of 14 European countries that cover the 2001 to 2010 period. About 390,000 observations are available for analysis. These are again the national micro-level data that are used to build the Micro Moments Database in the course of the ESSLait project. The estimation equation is an augmented Cobb-Douglas value added production function with broadband as an additional input. Broadband is measured as proportion of broadband connected employees. The estimation equation of Bartelsman et al. (2019) and Hagsten (2016) differ in two ways. Firstly, Bartelsman et al. (2019)

[35] This is known as Distributed Microdata Approach (DMD) (Hagsten, 2015; Bartelsman et al., 2018).

uses innovation variables, which are missing in Hagsten (2016). Secondly, Hagsten (2016) includes labor costs that are supposed to capture the quality of labor. This variable is also interacted with broadband. Estimations are conducted by means of OLS, separately for service and manufacturing firms in each country, with the data being pooled over time. The study finds a positive and significant relationship between labor productivity and the share of broadband connected employees in most countries for both the services and manufacturing industries. For some countries, however, the coefficient is also negative and significant. When the interaction variable of broadband and labor costs is included, estimation results become inconclusive with a negative and significant coefficients for broadband and the interaction term in many countries.

Hagsten and Sabadash (2017) emphasize the importance of appropriate ICT skills in a firms' workforce and of the ICT-relevant organizational capital that is needed to reap the benefits of ICT investments. However, due to the lack of better data, the authors assume that, "those forms of intangible organizational capital that are related to firms' decisions to engage ICT in production will be captured by an ICT-intensity variable" (Hagsten and Sabadash, 2017, pp.375), which turns out to be the percentage of broadband connected employees. For analyzing the effect on labor productivity, an augmented value added Cobb-Douglas production function is used that encompasses additional inputs such as the broadband variable and the share of employees with ICT-skills as well as the share of generally educated employees. Apart from these two variables, the estimation equation resembles those used in Hagsten (2016) and Bartelsman et al. (2019). The micro-data of the ESSLait project serve as base of data.[36] Initially, data are pooled over time and industries and estimations conducted by means of OLS, with additional dummies capturing time and industry effects. Both skill variables are positive and significant in all estimations. The coefficients change only very modestly once broadband is added. The coefficient of broadband is also found to be positive and significant, but the magnitude is smaller than that of the two human capital variables. This general finding is confirmed when the production function is estimated in first differences instead of levels as part of the robustness checks. When explaining the differences between service and manufacturing, the effect of broadband is found to be significant and stronger in services in all countries. However, due to a number of data issues that constrain the authors

[36]Unlike Bartelsman et al. (2019) and Hagsten (2016), the dataset covers only 6 countries and the 2001 to 2009 period. This might be driven by the fact that the study, although published latter than Hagsten (2016), is from an early stage of the ESSLait project.

from using more rigorous econometric methods, the authors state that "no general conclusion [can be] drawn on the possible causality" (Hagsten and Sabadash, 2017, p.384) from their results.

De Stefano et al. (2018) make use of a regional peculiarity – the so called digital divide– to assess whether broadband infrastructure affects firm performance by means of a fuzzy regression discontinuity (FRD) design. Due to historical developments, a large part of telecommunication infrastructure in the surrounding areas of Kingston-upon-Hull, UK, is owned and operated by Kingston Communications (KC). The rest is owned and managed by British Telecom (BT), a national telecommunication oligopolist. The analysis covers the 2000 to 2005 period, with KC providing broadband service (ADSL) from 2000 onwards, while BT doing so starting in 2005. Put differently, while one firm had access to ADSL, another firm had no access, although located in the same street - just, on the other side. The analysis takes advantage of this historically driven randomness. Because the difference in access to broadband existed for 5 years, any effects that broadband might have, even if delayed, should become identifiable. When using OLS, significant effects of broadband adoption are found for the various outcome variables, of which one is labor productivity. However, once the FRD is applied, no significant effect for any of the dependent variables is found. This result is supported by various robustness checks. Hence, De Stefano et al. (2018) expand the list of those studies that reinforces doubts on whether broadband networks can actually increase productivity.

Some of the evidence presented so far suggests that service firms might benefit more than manufacturing companies from broadband Internet. We are only aware of the study by Haller and Lyons (2019) that explicitly analyses the effect of broadband networks on service firms' productivity.[37] It includes all service sectors from Wholesale and Retail Trade (sector G, according to ISIC Rev.4) to Repair Services (sector S95 in ISIC 4). The dataset covers the 2006 to 2012 period and contains about 48,000 observation, of which about 40 percent are from Wholesale and Retail Trade firms. A Cobb-Douglas sales production function is estimated by means of OLS in the first stage of the analysis to obtain firm specific TFP.[38]

[37] Tranos and Mack (2017) focus on broadband and business services in a regional context. They show that broadband availability is supporting the growth of knowledge intensive business services in terms of number of firms. However, productivity is not considered.

[38] While the authors are aware of the simultaneity issue and discuss the reasons that prevent them from using more appropriate methods like control function approaches of Olley and Pakes (1996) and Levinsohn and Petrin (2003) or the method of Wooldridge (2009), another pressing issue is not discussed: intermediate inputs are missing in the estimation, although they are required when estimating a sales- or gross-output

The second stage uses a fixed effect regression with broadband availability at the postal code level and additional controls as regressors. To address the issue of endogeneity and reverse causality, the author use regional broadband availability instead of firm specific broadband adoption. Note, however, that labor is also included as explanatory variable in the second stage, which raises identification issue regarding the first stage estimation. When pooling all service sectors, the contemporaneous level of DSL availability has a positive but only weakly significant effect on TFP and labor productivity. Once lagged DSL variables are used, the coefficient for broadband is no longer significantly different from zero, regardless of whether the dependent variable is TFP or labor productivity. Estimations for individual service sectors show that broadband has a statistically significant effect on productivity in the Information and communications services sector and the Administration and support services sector. Interestingly, no effect is found in the Profession, scientific and technical services sector, which encompasses a large part of what is considered knowledge intensive service industries. A number of robustness checks, which include the splitting of the sample in large and small firms, or domestic and foreign companies etc., mostly confirm the main results. A final interesting finding is the negative and significant coefficient for broadband in estimations for ICT-using small firms. Hence, Haller and Lyons (2019) is yet another study with ambiguous findings for the relationship between broadband and productivity.

production function.