The Role of Key Regions in Spatial Development

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Abstract

We discuss the role of key regions in spatial development. Local productivity shocks can affect the entire economy as they expand via tight connections in the domestic production network and influence the geographical allocation of labor. In particular, we identify the set of key regions with the highest potential to affect aggregate productivity, output, and welfare. Key regions are central locations with strong spatial linkages in the production network but are not too large and congested so they can still attract additional labor in response to positive productivity shocks without local rents and input costs rising too much. Using a spatial equilibrium model and data from German districts, we find that a relatively modest development of productivity in key regions lowered German output and welfare growth by a factor of two from 2010 to 2015.

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1 Introduction

Large cities constitute the economic centers of each economy attracting the most productive workers and firms. This goes along with considerable differences in income per capita between cities and rural areas in many countries. In Germany, for example, productive cities like Munich and Hamburg have more than twice the income per capita than rural areas and smaller cities. At the same time, however, small towns and cities often host important suppliers providing specialized materials, components, and services to the rest of the economy.

A larger presence of highly specialized intermediate goods suppliers allows local firms to concentrate on what they are relatively good at producing without having to devote resources to other functions. As this represents an important source of competitive advantage, this increases local income and productivity levels and provides incentives for firms and workers to agglomerate in or close to geographical areas with stronger input-output linkages between highly specialized firms (Krugman and Venables, 1995, Moretti, 2011). If the strength of input-output linkages and with it the productivity of firms and workers varies considerably across space, the aggregate economy can, in general, be stimulated by facilitating local productivity and expanding employment in so-called key economic regions via spatial development policies, for example in the form of public investments, subsidies, or enterprise zones.[1] Moreover, recent research suggests that local shocks hitting important suppliers can amplify via tight connections in the network of input-output and trade linkages (e.g., Adao et al., 2019) with the potential to affect the entire economy (Gabaix, 2011; Carvalho, 2014). This suggests that spatial development is particularly promising in areas with existing clusters of specialized intermediate goods suppliers and strong input-output linkages such that local productivity shocks in a particular sector there spread through the wider economy (Redding and Rossi-Hansberg, 2017). We argue that while positive local productivity growth and economic development are beneficial for the local economy, it may be less so for the aggregate when it diverts economic activity away from key economic regions (Kline and Moretti, 2014; Hsieh and Moretti, 2019). In Germany, the government redistributes substantial public resources across regions and creates a variety of spatial development policies in the form of public investments and subsidies. A remarkable total amount of 65.7 billion euro worth of transfers are shifted across regions and around 1.5 billion euro are spent on spatially targeted development policies per year (Henkel et al., 2019). Given all these big efforts we do not know, however, where are the best places to promote spatial development if the government wants to maximize aggregate productivity, output, and welfare?

In this paper, we identify the key regions with the highest potential to affect the German economy. Specifically, we follow Caliendo et al. (2018) and quantify a spatial variant of a general equilibrium model to analyze the long-term aggregate changes in total factor productivity (TFP), real gross domestic product (real GDP), and welfare allowing for the endogenous reallocation of labor and adjustment of prices in response to local productivity growth. We employ a unique dataset on interregional trade relations and input-output linkages between sectors while taking any initial differences in size and economic importance between regions into account. In a counterfactual analysis, we then simulate how aggregate economic activity and the distribution of workers and income across space would change in response to a spatial development policy measured by an exogenous increase in local productivity in all tradable and non-tradable sectors of a region. We repeat this exercise for all regions and compare the aggregate effects.

The main finding of the analysis is that the growth rate of aggregate productivity, output, and welfare is not necessarily maximized by concentrating local productivity growth in the most productive regions. In other words, given the current production structure in Germany, the most productive cities do not serve as the key regions in spatial development. If the government wants to maximize aggregate economic outcome, when allocating local productivity growth across regions, it should target central, but less congested regions in the vicinity of large cities.

[1] See Neumark and Simpson (2015) for a comprehensive survey.

The regional allocation of local productivity growth via spatial development policies affects the aggregate economy through a complex mechanism. Any increase in a region's local productivity raises local wages and employment but is not restricted to the affected region or sector as it is transmitted to other regions and sectors via spatial links (measured by input-output and trade linkages) in the economy. Changes in relative prices affect trade patterns and the real income of workers in each region. This provides incentives for workers to migrate between regions, which further affects the level of productivity, real income, and welfare. Local rents, however, increase in response to an influx of labor, as some local production factors, like land and existing structures (machinery, equipment, etc.), are in fixed supply. Higher nominal wages and rental prices lead to higher local input costs acting as a congestion force and constraining the potential of further economic growth. If the most productive cities are not too congested, then less productive regions are not the best places for spatial development programs. In this case, increasing productivity in the largest and most productive cities is good for economic growth due to strong spatial links and the high presence of important suppliers there. But if the less congested and productive regions are still relatively central in the domestic production network, then it pays off to concentrate local productivity growth in initially smaller regions.

Further, we quantify the aggregate effects based on observed local productivity changes in Germany. While cities like Berlin and Munich (Frankfurt am Main and Cologne) had a major impact on aggregate output (welfare) growth between 2010 and 2015, the key regions contributed significantly less due to relatively low local productivity growth there. We interpret this as a sign of a (relatively) poor performance of the German economy compared to its potential optimum, in terms of both real GDP and welfare. In Germany, highly productive cities attracted the largest share of employment between 2010 and 2015, while productivity and employment growth in less congested key regions with strong spatial linkages was less pronounced. To quantify the magnitude of this finding we consider what would have happened if the key regions in Germany had experienced the highest observed local productivity changes. When we assign local productivity changes according to each region's theoretical potential to affect the aggregate economy we find growth rates of aggregate productivity, output, and welfare that are twice as large as in a baseline scenario that accounts for the actual observed productivity changes. We conclude that a low economic performance of the key regions of an economy and too much concentration of economic activity in already congested areas can have sizeable implications for aggregate growth. In our case, a relatively low local productivity growth in key regions lowered German output and welfare growth by a factor of two from 2010 to 2015.

Our paper relates to various strands of literature. First, we build on the general idea of the literature on the macroeconomic importance of local shocks in production networks, where local shocks do not necessarily wash out and potentially affect the aggregate economy when they hit an important supplier.[2] We demonstrate how local shocks propagate through the entire production network via input-output and trade linkages. Similar to this strand of literature so-called "cascade effects" in the production network have the potential to amplify the impact of initial small local shocks.[3] Our paper builds on this general idea showing that local productivity shocks in more central but less congested regions have the largest potential to affect the aggregate economy and to attract economic activity in the long-run. We differ from this work by highlighting how the aggregate effects of local productivity changes depend on the mobility of labor across regions and sectors. Second, we build on the work that uses quantitative general equilibrium models with labor mobility to analyze the spatial distribution of economic activity within countries.[4] An important aspect of these models is that they account in their analysis of the aggregate impact of a local TFP shock for all spillover effects, through

[2]See, for example, Horvath (1998, 2000); Baqaee (2005); Baqaee and Farhi (2019); Di Giovanni and Levchenko (2010); Gabaix (2011); La'O and Bigio (2016).

[3]See, for example, Acemoglu et al. (2012), Acemoglu et al. (2015) and Acemoglu et al. (2016).

[4]See Redding and Rossi-Hansberg (2017) for a recent survey.

spatial linkages and the mobility of labor, to all other regions. We follow Caliendo et al. (2018) who introduce the detailed structure of trade and input-output networks as spatial linkages into a quantitative economic geography model to analyze the impact of regional and sectoral productivity changes across US federal states. Our focus is to analyze, in the spirit of Rahman (1963), how to allocate local productivity growth via spatial development policies across regions to maximize aggregate economic outcomes. To our knowledge, this is the first paper to identify the key regions of the German economy while simultaneously accounting for the disaggregated production structure.

The paper is organized as follows. Section 2 describes the model and discusses the model-induced channels. Section 3 presents the data and the calibration of the model to the data. In Section 4, we identify the key regions for the aggregate economy. Finally, we evaluate the impact of observed local productivity changes on the aggregate economy. Section 5 concludes.

2 A spatial model with input-output linkages

We use a spatial general equilibrium model with input-output linkages (see, e.g., Caliendo et al., 2018). Consider an economy with N regions (indexed by i, n) and J sectors or goods (indexed by j, k). Production takes place under conditions of perfect competition and constant returns to scale. The economy is populated by a mass of $\bar{L}$ workers, who are mobile across regions and sectors. Each region is endowed with a limited amount of a geographically immobile factor comprising land and structures, which is mobile across sectors. In each region and sector representative firms use labor L_n^j and land and structures H_n^j to produce intermediate goods q_n^j. Productivity levels differ across firms, sectors, and regions.

Intermediate goods from a given sector j may be either shipped between any two regions i and n at iceberg trade costs $\kappa_{ni}^j \geq 1$, or non traded with $\kappa_{ni}^j = \infty$ for all $i \neq n$. Intra-regional trade costs, κ_{ii}^j, are normalized to unity. Firms in region n and sector j use the intermediate goods to produce non-traded final goods Q_n^j. Further, final goods of each sector are either consumed by representative agents or enter again the production process of intermediate goods in all industries as additional material inputs.

2.1 Preferences

In each region n, consumers derive utility from the consumption of final domestic goods c_n^j and supply inelastically one unit of labor. Workers generate income I_n from wages w_n and the returns from land and structures, r_n. Local governments partly own the local factor land and structures and collect a share $(1-\iota_n)$ of region n's local rents. The local government redistributes the corresponding revenues to residents in a lump-sum fashion. The remaining fraction of the rents of the local factor ι_n goes into a national portfolio and all workers of the economy receive the same proportion of its returns. The preferences of workers are represented by a utility function of Cobb-Douglas type, where the consumption shares $\sum_{j=1}^J \alpha^j = 1$ vary across sectors. To maximize utility the budget-constrained representative workers choose consumption bundles c_n^j at prices P_n^j in all sectors $j \in \{1, ..., J\}$ according to:

$$U_n \equiv \max_{\{c_n^j\}_{j=1}^J} \prod_{j=1}^J (c_n^j)^{\alpha^j} \quad \text{subject to} \quad \sum_{j=1}^J P_n^j c_n^j = I_n, \tag{1}$$

where $I_n = w_n + (1-\iota_n) r_n H_n / L_n + (\sum_{i=1}^N \iota_i r_i H_i / \sum_{i=1}^N L_i) L_n$ is the per capita income of agents in region n and P_n^j denotes the price of a sector $j's$ output in region n. $P_n = \prod_{j=1}^J (P_n^j/\alpha^j)^{\alpha^j}$ denotes the region-specific price index.

2.2 Production technology

Representative firms produce a continuum of varieties with constant returns to scale technologies. In any region n and sector j representative firms use labor as well as land and structures, and potentially final goods from any other sector k as 'material' inputs.

Productivity. Firms of any region n and sector j differ in their idiosyncratic productivity level $z_n^j > 0$. Across all goods, sectors, and regions the idiosyncratic productivity levels are independently drawn from a Fréchet distribution such that the joint density function is given by:

$$\phi^j(z^j) = \exp\left\{ -\sum_{i=1}^{N} \left(z_n^j\right)^{-\theta^j} \right\}, \tag{2}$$

with productivity draws $z^j = (z_1^j, \ldots, z_N^j)$, a location parameter of 1 and sector-specific shape parameters $\theta^j > 1$. The shape parameter, θ^j, captures the extent of sector-specific heterogeneity in technological know-how across varieties and is assumed to be constant across goods and regions. A larger θ^j implies less variability across goods and regions. Production depends also on the non-random fundamental productivity level T_n^j. The level of fundamental productivity aims to capture factors that affect the productivity of all firms in a given region and sector. For example, local climate, infrastructure, and regulation.[5]

Intermediate goods. The production function for the intermediate good $q_n^j(z_n^j)$ in region n and sector j is Cobb-Douglas:

$$q_n^j(z_n^j) = z_n^j \left[T_n^j \left[h_n^j(z_n^j)\right]^{\beta_n} \left[l_n^j(z_n^j)\right]^{1-\beta_n} \right]^{\gamma_n^j} \prod_{k=1}^{J} \left[M_n^{jk}(z_n^j) \right]^{\gamma_n^{jk}}, \tag{3}$$

where $h_n^j(\cdot)$ and $l_n^j(\cdot)$ reflect the demand for land and labor, respectively, β_n is the share of land and structures in value-added, $M_n^{jk}(\cdot)$ is the demand for final goods from sector k used in the intermediate goods production of sector j (materials), γ_n^j denotes the share of value-added in gross output and γ_n^{jk} represents the share of sector j goods spent on materials from sector k. Because of constant returns to scale, it must hold $\gamma_n^j = 1 - \sum_{k=1}^{J} \gamma_n^{jk}$.

Market structure. Markets are assumed to be perfectly competitive. There is free entry of firms implying zero profits. The cost of the input bundle required to produce intermediate goods in region n and sector j is given by:

$$x_n^j = B_n^j \left[r_n^{\beta_n} w_n^{1-\beta_n} \right]^{\gamma_n^j} \prod_{k=1}^{J} \left[P_n^k \right]^{\gamma_n^{jk}}, \tag{4}$$

with the region-sector-specific scaling factor $B_n^j = [\gamma_n^j (1-\beta_n)^{1-\beta_n} \beta_n^{\beta_n}]^{-\gamma_n^j} \prod_{k=1}^{j} [\gamma_n^{jk}]^{-\gamma_n^{jk}}$, and P_n^k is the price index for intermediate goods in region n and sector k. Assuming constant returns to scale, the unit cost is $x_n^j / (z_n^j [T_n^j]^{\gamma_n^j})$. Firms in region n and sector j will set their prices according to their unit costs.

Interregional trade. Intermediate goods trade between any regions n and i within a given sector j is costly. Trade costs $\kappa_{ni}^j \geq 1$ are of the iceberg type. Hence, $\kappa_{ni}^j \geq 1$ units of an

[5] Alternatively, to model region-sector-specific productivity differences we could set the location parameter of the joint density function to $(T_n^j)^{\beta_n}$. This, however, would imply a disproportional increase of real GDP in response to fundamental productivity shocks.

intermediate good must be shipped from location i to location $n \neq i$ in sector j for one unit to arrive. Perfect competition together with constant returns to scale imply that agents in each region n aim to minimize the cost of acquiring a specific intermediate good in sector j. The trade cost-adjusted price p_n^j across all potential source regions is given by:

$$p_n^j(z_n^j) = \min_i \left\{ \frac{\kappa_{ni}^j x_i^j}{z_i^j} (T_i^j)^{-\gamma_i^j}, \right\} \tag{5}$$

with the input costs x_i^j, trade costs κ_{ni}^j, and the two productivity terms T_i^j and z_i^j, scaled by the share of value-added in gross output γ_i^j. The price of a tradable sector $j's$ output in region n is given by:

$$P_n^j = \Gamma(\varphi_n^j)^{1-\eta_n^j} \left(\sum_i \left(x_i^j \kappa_{ni}^j \right)^{-\theta^j} \left(T_i^j \right)^{\theta^j \gamma_i^j} \right)^{-1/\theta^j}, \tag{6}$$

where $\Gamma(\varphi_n^j)$ evaluates a Gamma function at $\varphi_n^j = 1 + (1 - \eta_n^j)/\theta^j$.[6] The price of a non-tradable sector $j's$ output in region n is given by:

$$P_n^j = \Gamma(\varphi_n^j)^{1-\eta_n^j} x_n^j [T_n^j]^{-\gamma_n^j}. \tag{7}$$

In line with Alvarez and Lucas (2007), the expenditure share π_{ni}^j of region n on products from region i in sector j can be written as:

$$\pi_{ni}^j = \frac{X_{ni}^j}{\sum_{i=1}^N X_{ni}^j} = \frac{\left[\kappa_{ni}^j x_i^j (T_i^j)^{-\gamma_i^j} \right]^{-\theta^j}}{\sum_{i=1}^N [\kappa_{ni}^j x_i^j]^{-\theta^j} (T_i^j)^{\gamma_i^j \theta^j}}, \tag{8}$$

where the shape parameters $\theta^j > 1$ can be interpreted as the sector-specific trade elasticity.

Final Goods. Denote by $\tilde{q}_n^j(z^j)$ the quantity demanded of intermediates with productivity draws $z^j = (z_1^j, \ldots, z_N^j)$. Final goods in region n and sector j, Q_n^j, are produced using a 'Constant Elasticity of Substitution' (CES) production function that aggregates a continuum of varieties:

$$Q_n^j = \left(\int \tilde{q}_n^j(z^j)^{1-1/\eta_n^j} \phi^j(z^j) dz^j \right)^{\frac{\eta_n^j}{\eta_n^j - 1}}, \tag{9}$$

where η_n^j denotes the elasticity of substitution across varieties. For non-traded goods, only the region-sector-specific density function $\phi_n^j(z_n^j)$ is relevant because interregional trade is ruled out by construction.

2.3 Equilibrium

A competitive equilibrium in this economy is defined by the following conditions:

1. **Labor market clearing.** This implies

$$L_n = \sum_{j=1}^J L_n^j = \sum_{j=1}^J \int_0^\infty l_n^j(z) \phi_n^j(z) dz \qquad \forall n = 1, \ldots, N. \tag{10}$$

   On the aggregate level, $\sum_{n=1}^N L_n = \bar{L}$, where total labor is normalized to one. Profit maximization together with labor market clearing yields $r_n H_n(1 - \beta_n) = \beta_n w_n L_n$.

[6] $\Gamma(\cdot)$ denotes the gamma function, i.e., $\Gamma(t) = \int_0^\infty u^{t-1} \exp(-u) du$.

2. **Land and structures market clearing.** This implies

$$H_n = \sum_{j=1}^{J} H_n^j = \sum_{j=1}^{J} \int_0^\infty h_n^j(z)\phi_n^j(z)dz \qquad \forall n = 1, \ldots, N. \tag{11}$$

3. **Final goods market clearing.** In equilibrium all final goods Q_n^j are used for consumption and intermediate goods production, so

$$Q_n^j = L_n c_n^j + \sum_{k=1}^{J} M_n^{kj} = L_n c_n^j + \sum_{k=1}^{J} \int_0^\infty M_n^{kj}(z)\phi_n^k(z)dz. \tag{12}$$

Moreover, in equilibrium, the value of the final good j in region n sold to all destinations is equal to

$$X_n^j = \sum_{k=1}^{J} \gamma_n^{kj} \sum_i \pi_{in}^k X_i^k + \alpha^j I_n L_n, \tag{13}$$

4. **Intermediate goods market clearing.** In equilibrium, total expenditures on intermediates purchased from other regions must equal total revenue from intermediates sold to other regions plus the net receipts from the national portfolio.

$$\sum_{j=1}^{J} \sum_{i=1}^{N} \pi_{ni}^j X_n^j + \Gamma_n = \sum_{j=1}^{J} \sum_{i=1}^{N} \pi_{in}^j X_i^j. \tag{14}$$

The difference between contributions and receipts from the national portfolio generates trade imbalances for region n given by:

$$\Gamma_n = \iota_n r_n H_n - \frac{\sum_{i=1}^{N} \iota_i r_i H_i}{\sum_{i=1}^{N} L_i} L_n. \tag{15}$$

This redistribution mechanism endogenizes trade surpluses and deficits in the model and aims to closely match trade imbalances Γ_n between regions observed in the data. A region n that is a net contributor to the national portfolio runs a trade surplus, while a net recipient runs a trade deficit.

5. **Utility equalization.** Finally, free mobility of labor implies that agents must be indifferent about living in any region n.

$$v_n = \frac{I_n}{P_n} = U \;\; \forall n \in N. \tag{16}$$

The free mobility condition of labor together with labour market clearing, and $\omega_n = [r_n/\beta_n]^{\beta_n}[w_n/(1-\beta_n)]^{1-\beta_n}$, and $u_n = \iota_n r_n H_n / L_n - \chi$ leads in equilibrium to the labor demand equation:

$$L_n = \frac{H_n \left[\frac{\omega_n}{P_n U + u_n}\right]^{1/\beta_n}}{\sum_i H_i \left[\frac{\omega_i}{P_i U + u_i}\right]^{1/\beta_i}} L, \tag{17}$$

where, $\chi = \sum_i \iota_i r_i H_i / \sum_i L_i$ denotes the per capita receipts from the national portfolio.[7]

[7] We present the equilibrium conditions in changes as well as the different steps of the solution mechanism in Appendix A.

2.4 How changes in local productivity affect the spatial economy

In this section, we present the intuition of how changes in local productivity affect the spatial economy. From the structure of the model we derive analytic expressions for relative changes, $\hat{x} = x'/x$, in measured TFP, real GDP, and welfare, where x' denotes the new value. Input-output and trade linkages define how changes in local productivity diffuse across sectors and regions. The mobility of labor across regions and sectors as well as transfers of rental income across regions serve as additional adjustment channels. Derivations are in Appendix B.

The structure of the model allows us to relate changes in measured productivity, $\hat{A}_n^j$, to fundamental productivity changes, $\hat{T}_n^j$, according to the following log-linear relationship:

$$\ln\left(\hat{A}_n^j\right) = \ln\left(\frac{\hat{x}_n^j}{\hat{P}_n^j}\right) = \ln\left(\frac{\left[\hat{T}_n^j\right]^{\gamma_n^j}}{\left[\hat{\pi}_{nn}^j\right]^{1/\theta^j}}\right). \tag{18}$$

The share of value-added in gross output, γ_n^j, adjustments of the home expenditure share, $\hat{\pi}_{nn}^j$, together with the trade elasticity, θ^j, scale changes in fundamental productivity.[8] For the growth of real GDP, we have:

$$\ln\left(\widehat{\mathrm{GDP}}_n^j\right) = \ln\left(\hat{A}_n^j\right) + \ln\left(\hat{L}_n^j\right) + \ln\left(\frac{\hat{w}_n}{\hat{x}_n^j}\right). \tag{19}$$

In addition to changes in measured productivity, $\hat{A}_n^j$, changes in labor, $\hat{L}_n^j$, and nominal wages relative to input costs, $\hat{w}_n/\hat{x}_n^j$, are important drivers for changes in real GDP. The change in welfare is given by:

$$\ln\left(\hat{U}\right) = \sum_{j=1}^{J} \alpha^j \left(\ln\left(\hat{A}_n^j\right) + \ln\left(\bar{\omega}_n \frac{\hat{w}_n}{\hat{x}_n^j} + (1-\bar{\omega}_n)\frac{\hat{\chi}}{\hat{x}_n^j}\right)\right), \tag{20}$$

with $\bar{\omega}_n = (1-\beta_n\iota_n)w_n/\left[(1-\beta_n\iota_n)w_n + (1-\beta_n)\chi\right]$. Hence, changes in measured TFP, nominal wages relative to input costs, and receipts per capita from the national portfolio relative to input costs, $\hat{\chi}/\hat{x}_n^j$, are important drivers for changes in welfare.

Input-output linkages. In region n and sector j, final goods of any other sector k may serve as potential additional input in the production of intermediate goods. These input-output linkages determine how changes in fundamental productivity in any region-sector pair n, j diffuse to other region-sector pairs $n, k \neq j$. The first component of the numerator in equation (18) highlights the importance of the input-output linkages for changes in measured TFP. The direct effect of fundamental productivity changes, $\hat{T}_n^j$, is scaled down by the share of value-added in gross output, γ_n^j. When input-output linkages are present the share of value-added is less than one, $\gamma_n^j < 1$, and the direct effect is less than proportional. The rationale is that production in sector j then uses materials from other sectors $k \neq j$, which did not experience productivity improvements. Without any linkages between sectors $\gamma_n^j = 1$, a rise in fundamental productivity T_n^j would lead, everything else equal, to a proportional rise in measured productivity $\hat{A}_n^j$.

Trade linkages. Intermediate goods are traded within sectors across regions. In the Ricardian setting at hand, regions produce and export more intermediate goods in sectors in which they

[8] Note that the share of value-added in output, γ_n^j, is a mirror image of the share of sector j goods spent on materials from sector k. Constant returns to scale in the intermediate goods production ensures that $\gamma_n^j = 1 - \sum_{k=1}^{J} \gamma_n^{jk}$.

are relatively more productive. The relative level of fundamental productivity determines the comparative advantage in producing and exporting of each region with each sector. A positive fundamental productivity shock in region n and sector j increases the comparative advantage of all firms in region n and sector j. This affects relative prices and shifts expenditure towards output produced in region n and sector j.

To be more precise. Given initial factor prices w_n and r_n, a rise in fundamental productivity in region n and sector j lowers the unit costs of intermediate goods production. As a result, input costs x_n^j and the local price index P_n^j decline. In response, the home expenditure share $\hat{\pi}_{nn}^j > 1$ in region n and sector j increases. In other words, region n gets less open than before, $\hat{\pi}_{nn}^j > 1$, and region n tends to produce a larger, but on average less productive subset of varieties in sector j. At the same time all other regions reduce their home expenditure shares $\hat{\pi}_{ii}^j < 1$, for $i \neq n$ and all k, as they now import more intermediates from sector j in region n. Now, the varieties of intermediate goods still produced in all other region-sector pairs i, j for $i \neq n$, have relatively higher idiosyncratic productivities, which increases measured TFP in those regions. This is the so-called 'selection effect'.[9]

The sector-specific trade elasticity θ^j represents the variability of technology levels across goods and regions and therefore governs the comparative advantage within sectors. The parameter θ^j scales the change in trade-relationships between regions within sectors, captured by the change in home expenditure shares $\hat{\pi}_{nn}^j$. As the trade elasticity θ^j increases (smaller dispersion in idiosyncratic productivity levels within sector j), the term $[\hat{\pi}_{nn}^j]^{1/\theta^j}$ in equation (18) approaches one and changes in fundamental productivity $\hat{T}_n^j$ crowd out the 'selection effect' in determining changes in measured productivity. In other words, with higher trade elasticities θ^j the 'selection effect' gets less important.

In sum, trade linkages ensure that productivity shocks propagate across regions and sectors, which affects the selection of firms and the average productivity of the firms that survive on the market (see, e.g., Finicelli et al., 2013, Costinot et al., 2012). The denominator of the second term on the right-hand side of equation (18) exactly accounts for this trade-driven selection. As a result, the change in measured TFP, $\hat{A}_n^j$, in region n and sector j is lower than the change in fundamental productivity, $\hat{T}_n^j$.

Factor reallocation and input costs. Equations (19) and (20) demonstrate that the same factors that contribute to changes in measured TFP also affect changes in real GDP and welfare. The reallocation of labor across regions and sectors and changes in relative factor prices, inputs costs, and receipts from the national portfolio in response to fundamental productivity changes further influence the change in real GDP and welfare. The second term on the right-hand side of equation (19) shows that an increase in labor proportionally increases real GDP. The intuition is simple. Because of constant returns to scale in production and perfect competition, the price index decreases and nominal wages $\hat{w}_n > 1$ increase in response to productivity improvements. Rising nominal wages attract labor $\hat{L}_n > 1$ from other regions and sectors, which contributes to the growth of local real GDP and acts as an additional agglomeration force.

In each location, however, land and structures H_n are fixed in supply and local rents r_n rise proportionally with an increase of nominal wages w_n and labor L_n, $w_n L_n = [\beta_n/(1-\beta_n)] r_n H_n$. From equation (4) it gets evident that input costs x_n^j increase with rising wages and local rents (depending on the strength of input-output linkages). When input costs increase more than nominal wages, this will work against the positive selection and labor reallocation effects. Hence, the term $(\hat{w}_n/\hat{x}_n^j)$ in equations (19) and (20) shows that an increase of fundamental productivity that positively affects the growth of real GDP and welfare can be counterbalanced by a higher increase of input costs relative to nominal wages, which represents a congestion force in the model.

[9]For further information see Levchenko and Zhang (2016), Tombe and Zhu (2019), Eaton and Kortum (2012) and Costinot and Rodríguez-Clare (2014).

Regional transfers of local rents. A smaller increase of per capita receipts from the national portfolio relative to an increase of input costs works as an additional congestion force. The transfers from the national portfolio aim to capture trade imbalances between regions and influence factor reallocation (and therefore real GDP) and local welfare. The third term on the right-hand side of equation (20) shows that given fixed contribution shares ι_n the relative value of receipts per capita from the national portfolio, $\chi = \sum_i \iota_i r_i H_i / \sum_i L_i$, mechanically decreases with an increase of input costs x_n^j in response to a local productivity shock. Regions without positive productivity developments, however, benefit from higher per capita receipts from the national portfolio without having to bear the burden of rising input cost, which works as an agglomeration force for these regions.

In equilibrium, congestion forces from rising input costs and declining relative receipts per capita from the national portfolio counterbalance the positive agglomeration force from rising nominal wages and prevent all workers from residing in the most productive place. Note that in contrast to costly trade the transfers between regions are not subject to any frictions. Income transfers between regions, therefore, play a key role in aggregate welfare. Local factor price changes affect the income of all agents in the economy via linkages from the national portfolio. This generates inefficiencies in the model as mobile workers impose externalities on the local rents received by other agents.

Summary. The previously described channels suggest that local fundamental productivity growth leads to higher measured productivity, output, and welfare. Local productivity growth attracts additional workers depending on the relative strength of local agglomeration and congestion forces. Agglomeration forces are larger for regions with stronger trade and input-output linkages. As such, central regions with strong spatial linkages in the production network can source inputs at lower costs, thus generating a competitive advantage and leading to lower trade costs. Positive local productivity growth further strengthens this competitive advantage providing an incentive of workers to agglomerate in this region. Areas that lack abundant land and structures display a large degree of initial congestion (indicated by high input costs), making it difficult to attract additional labor in response to positive local productivity growth. As such, initially less congested regions can attract a larger share of employment making it more attractive to allocate local productivity growth in initially smaller regions. An additional argument relates to net contributions towards the national portfolio. While being a net recipient may appear well for local consumption, being a net donor serves as an additional congestion force and prevents labor to migrate to the most productive (donor) regions.

In reality, all these channels work together and the aggregate implications of local productivity growth depend on the actual strength of relative agglomeration and dispersion forces for all regions. We, therefore, calibrate the model for the German economy accounting for the linkages between sectors and regions, interregional transfers and labor mobility. In a counterfactual analysis, we then analyze the impact of spatial development, measured by positive local productivity growth, on the aggregate economy.

3 Quantification

To be able to analyze the impact of local productivity changes, we start with the quantification of the model and briefly describe the data and discuss our parameter choice. Next, we empirically identify the central locations with the strongest spatial links in the domestic production network.

3.1 Data

Quantifying the model requires data on sector-specific output and input-output linkages, sector-region-specific value-added, inter-regional bilateral trade flows per sector, as well as data on employment and wage income per region and sector. Our calibration of the model is for 2010, as it is the most recent year for which all relevant information is available. In our analysis, we aggregate sectors at the 1-digit level represented by the ISIC Revision 4 classification and distinguish between $J = 7$ industries. Four tradable sectors and three non-tradable sectors.[10] The tradable sectors are Agriculture, Mining, Manufacturing and Retail trade. The non-tradable sectors include Construction and Financial Services and the Public sector including public administration. At the regional level, our unit of observation are the 402 German administrative districts (Kreise and kreisfreie Städte). This geographic unit represents the third level of administrative division called the Nomenclature of Territorial Units for Statistics (NUTS-3). NUTS-3 regions are administrative districts whose average population usually ranges between 150,000 and 800,000 people.

Data for employment and wage income for every district are readily available from Eurostat (Eurostat, 2016) and the INKAR Database (NUTS-3 level, see INKAR, 2016). We normalize employment, to sum up to one. We use the information on sector-specific output and input-output linkages from the World Input-Output Tables (WIOD, see Timmer et al., 2015). We allocate sector-specific output across regions according to region-specific employment shares. Information on sector-region specific value-added comes from Eurostat.

We use information on interregional trade flows from the Forecast of Nationwide Transport Relations in Germany 2030 (Verkehrsverflechtungsprognose 2030, henceforth VVP) provided by the Clearing House of Transport Data at the Institute of Transport Research of the German Aerospace Center (see Schubert et al., 2014).[11] The data contain bilateral trade volumes in metric tons at the product level by transport mode (road, rail, water) that went through German territory in 2010. We aggregate trade flows to the $N = 402$ German administrative districts and across transport modes at the 1-digit level of the ISIC Revision 4 classification. Moreover, our theoretical model requires trade *values* rather than *volumes*, so we convert the data by using appropriate unit values. We match aggregate trade flows in metric tons to output per region and sector in millions of euro and calculate the corresponding unit values. This procedure is convenient for two reasons: First, we can derive region-sector-specific unit values based on actual output data.[12] Second, using the unit values per region-sector pair together with information on region-sector-specific trade volumes from VVP we can match region-sector-specific gross output.

3.2 Parameter choices

In this subsection we discuss the choice of parameters that we hold constant across our counterfactual simulations. We choose values for $\{\alpha^j, \beta_n, \gamma_n^j, \gamma_n^{jk}, \iota_n\}$ to match observable data. We calculate the consumption share α^j as the total expenditure of sector j goods, adjusted by the intermediate goods expenditure and divided by the total final absorption. Since we use two input factors, we must identify the share of labor $(1 - \beta_n)$ in the production function. For this purpose we divide the sum of labor income $w_n L_n$ by region n's value-added. Similarly, we compute the share of value-added in gross output γ_n^j as the ratio of value-added over gross output, VA_n^j / Y_n^j. Next, we use the γ_n^j's to determine the share of sector j goods used in sector k and region n, γ_n^{jk}. Taking national input-output shares γ^{jk}, we notice that $\gamma_n^{jk} = (1 - \gamma_n^j)\gamma^{jk}$.[13] Once we have identified the share of labor $(1 - \beta_n)$ in the production function, we can calculate local rents per capita from the internal structure of the model using data on nominal wage income. Recall that the rents from land and structures can be expressed as $r_n H_n = \beta_n V A_n$,

[10] Table C1 in Appendix C presents a summary of all data sources and Table C2 in Appendix C lists the different sectors.

[11] The data can downloaded from http://daten.clearingstelle-verkehr.de/276/. It is similar to the US commodity flow survey.

[12] The derived unit values highly correlate with alternative unit values calculated using the ratio of values and quantities based on trade data from COMTRADE.

[13] To see this, recall that $\sum_k \gamma_n^{jk} = 1 - \gamma_n^j$ and that on the national level $\sum_k \gamma^{jk} = 1$.

where $VA_n = 1/(1-\beta_n)w_n L_n$. Hence, using data on nominal wage income and the parameter β_n we can solve for the respective local rents. Hence, rents per capita are higher in cities with higher nominal wage levels, like Munich (Landeshauptstadt) or Wolfsburg (kreisfreie Stadt). Local rents per capita vary significantly across regions with $14,280$ euro in Eisenach and $41,782$ euro in Wolfsburg. To determine the fraction of rents contributed to the national portfolio we match the trade imbalances $\Gamma_n^M = \iota_n r_n H_n - (\sum_{i=1}^N \iota_i r_i H_i / \sum_i L_i) L_n$ in the model to the observed imbalances Γ_n^D in the data. We search for the respective contribution shares ι_n that minimize the sum of squared residuals $\sum_{i=1}^N (\Gamma_n^M - \Gamma_n^D)^2$ subject to the constraint $\iota_n \in [0,1]$. The predicted imbalances perform quite well to match the observed trade imbalances (although not perfectly). Moreover, regions with a trade surplus are net contributors to the national portfolio, while regions with trade deficits are net recipients (see Figure C1 in Appendix C).

The trade elasticity θ^j plays a crucial role in the impact of trade costs. We borrow elasticities from Caliendo et al. (2018) and map their values into our sectors. Table C3 in Appendix C displays the respective values. In the last step, we calculate a baseline counterfactual economy and remove any remaining unexplained differences between trade imbalances in the model and the data. With this procedure, differences between Γ_n^M and Γ_n^D, which the estimation procedure of ι_n was not able to account for, vanish. The new equilibrium serves as our starting point from which all other counterfactual simulations are conducted. To achieve this perfect fit of the model to the data, we allow for adjustments in trade costs κ_{ni}^j and productivity T_n^j levels. This procedure has the advantage that we do not need to alter any official statistical data but only ex-ante unobservable variables. We consider this procedure an appropriate alternative to Caliendo et al. (2018) who change the distribution of economic activity across space to calculate a baseline counterfactual economy, as they let observed wages w_n and labor shares L_n adjust endogenously.[14]

3.3 Centrality of regions and sectors

We follow the literature on network analysis and define regions as central, when all its trading partners have high import shares from that region and when neighboring regions in the network are themselves well connected. To be more precise, to highlight the importance of the strength of spatial links in the economy, we transfer the concept of 'eigenvector centrality' to the German trade network in 2010 and follow Carvalho (2014) to calculate the Katz-Bonacich eigenvalue centrality measure. The 'centrality' measure captures the argument that more centrally located regions have the comparative advantage in producing and exporting goods to surrounding regions, and therefore stronger spatial links. According to our model, more central regions either have higher productivity levels T_n^j, lower trade costs κ_{in}^j, or a higher share of value-added in gross output γ_n^j (see equation (8) on the expenditure share π_{in}^j, that translates into the centrality measure). To calculate the centrality measure for each region $n \in N$, $c_n > 0$, we add to some baseline centrality level across all regions, $\eta = 0.5/N$, the weighted sum of the centrality weights of each regions trading partners, where we use the import shares, $\pi_{in} = \sum_j \pi_{in}^j$ for all region pairs i, n as weights: $c_n = \lambda \sum_i \pi_{in} c_i + \eta$, with $\lambda = 0.5$.[15] The vector of centralities is given by $c = \eta(I - \lambda \Pi)^{-1}\mathbf{1}$, where Π, is the import share matrix, and $\mathbf{1}$ is a vector of ones.

We find that regions differ significantly with respect to their network centrality.[16] The

[14] Our procedure leaves us with minor changes for trade costs between -1.81 percent and $+1.93$ percent, while changes in productivity are more pronounced. For the model imbalances to match the data, we need sizeable changes in productivity. For example, Potsdam (kreisfreie Stadt)'s productivity must increase by 9.80 percent while Altenburger Land's productivity must decline by 9.37 percent.

[15] The literature on network analysis documents several concepts to measure the connectedness and relative importance of different nodes within networks. See, for example, Carvalho (2014), Bonacich (1972) and Ballester et al. (2006). Moreover, Carvalho (2014) gives a nice survey and describes different measures in the context of production networks with input-output linkages. For our purpose the concept of 'eigenvector centrality' is the most suitable measure, as it allows us to analyze the existing domestic trade network in Germany.

[16] See Figure E1 in Appendix E. The qualitative results are robust to the choice of η and λ. Both measures are

most central regions are big and productive cities, like Munich (Landeshauptstadt), Berlin and Hamburg, with respective centrality measures of 0.681, 0.631 and 0.517 (in hundreds). Regions like Bremerhaven (kreisfreie Stadt, 0.181) and Emden (kreisfreie Stadt, 0.183) (in hundreds) feature the lowest centrality measures. Table 1 explores how the 'centrality measure' relates to other economic characteristic on the regional level. It shows that, for example, more central regions in the trade network are more employment-intensive, more engaged in the manufacturing sector, and more important for the overall production process as measured by their value-added and gross output shares.

To determine the relative importance of sectors in the aggregate economy, we also calculate centrality measures for each sector based on the national input-output shares γ^{jk}. The Financial 24.68, Wholesale 18.84, and Manufacturing sector 17.03 (in hundreds) are the most central sectors in the network, while Agriculture 7.96, Mining/Quarrying, Electricity, Gas, Water Supply 11.10, Construction 10.09, and Public Administration, Defense, Social Security, Human Health 10.30 are less central on the aggregate level. Note, however, that the relative importance of the different sectors varies across regions as represented by the region-specific expenditure shares for materials from other sectors γ_n^{jk} in our model.

As some regions and sectors are more central than others in terms of their relative connectivity within the domestic production network, we would expect that they are also relatively more important in transmitting local productivity growth and determining aggregate economic activity. Hence, in our analysis, we will refer to the concept of centrality as one important statistic in determining the propagation of local productivity shocks.

Table 1: Centrality Distribution with Other Variables in 2010

	Quartiles of Centrality			
	1	2	3	4
Share of Total (in percent)				
Employment	0.10	0.16	0.23	0.51
Manufacturing	0.21	0.23	0.25	0.26
Value-added	0.09	0.14	0.22	0.55
Gross output	0.11	0.16	0.23	0.50

Notes: We split regions into quartiles of the centrality measure. For each quartile, we then calculate the average across sectors and regions for the respective characteristics. We calculate these numbers for the year 2010.

4 The impact of local productivity changes

In this section, we use the model from Section 2 to analyze the impact of local productivity changes in Germany. The section is composed of two parts. First, we identify the places — so-called key regions — with the highest potential to affect the German economy in terms of aggregate TFP, real GDP, and welfare. Second, we examine the impact of observed local productivity changes and evaluate the economic performance of those key regions between 2010 and 2015.

the same for all regions and thus do not change their ordering.

4.1 Identifying key regions

The goal of this subsection is to identify the key regions for the aggregate economy. To do so, we consider a productivity shock of 10 percent, $\hat{T}_n^j = 1.10$, for all sectors j within a given region n and solve for the new equilibrium. We repeat this exercise for all $n \in N$ regions and calculate the aggregate changes in TFP, output, and welfare.

To calculate changes in measured TFP on either the region, sector, or aggregate level, we use gross output shares. Respective changes in measured TFP on the national level, for example, are simply weighted averages of disaggregated changes in measured TFP for each region-sector pair (n, j):

$$\widehat{A} = \sum_{j=1}^{J} \sum_{n=1}^{N} \frac{Y_n^j}{\sum_{j=1}^{J} \sum_{n=1}^{N} Y_n^j} \hat{A}_n^j, \tag{21}$$

where $Y_n^j = w_n L_n^j / \gamma_n^j (1 - \beta_n)$ is equilibrium gross output (see Appendix D for details).

Real GDP is a value-added measure so we use value-added shares as weights. Hence, aggregate change in real GDP is given by:

$$\widehat{\text{GDP}} = \sum_{j=1}^{J} \sum_{n=1}^{N} \frac{w_n L_n^j + r_n H_n}{\sum_{j=1}^{J} \sum_{n=1}^{N} (w_n L_n^j + r_n H_n)} \widehat{\text{GDP}}_n^j. \tag{22}$$

The literature on the macroeconomic consequences of microeconomic shocks has identified so-called "Domar weights" in a perfectly competitive economy as a sufficient statistic to understand the first-order impact of local shocks on the aggregate economy (see, e.g., Domar, 1961 and Hulten, 1978). In other words, for efficient economies, the sales share or Domar weight Y_n/Y is a sufficient statistic to evaluate the first-order effects of disaggregated productivity shocks to aggregate welfare and real GDP. In this sense, to a first-order, the input-output and trade linkages, as well as the reallocation of labor across sectors and regions are not relevant for the impact of disaggregated productivity shocks on the aggregate economy (see Baqaee and Farhi, 2019). To account for the heterogeneity in the initial economic importance of different regions and sectors, we calculate aggregate elasticities and normalize the aggregate TFP change by each region's output share, the aggregate real GDP change by each region's wage income share $w_n L_n / wL$ and the change in welfare by the labor share L_n/L. This ensures that the aggregate elasticities do not vary systematically with the respective shares. We will see that the input-output and trade linkages, as well as the reallocation of labor across sectors, play dominant roles for the respective results.[17] To make the identical shock comparable across the different regions we multiply all values by the size of the fundamental productivity shock.[18] The aggregate elasticities are given by:

$$\text{TFP}^{\text{elas.}} = \frac{dA}{dT_n} \left(\frac{Y_n}{Y} \right)^{-1}; \ \text{GDP}^{\text{elas.}} = \frac{dGDP}{dT_n} \left(\frac{w_n L_n}{wL} \right)^{-1}; \ \text{Welfare}^{\text{elas.}} = \frac{dU}{dT_n} \left(\frac{L_n}{L} \right)^{-1}. \tag{23}$$

We find that locations differ significantly in terms of their aggregate elasticities. Figure 1 presents the geographic distribution of the aggregate elasticities.[19] In general, regions in the western and southern parts of Germany exhibit the highest aggregate elasticities. Surprisingly,

[17] We restrict our analysis to identify the key regions, because of the relatively high level of sectoral aggregation in our data.

[18] The actual shock size is only of minor interest. We conduct various robustness checks and vary the shock size with smaller values of $\{2, 4, 6\}$ percent as well as negative values $\{-10\}$ percent. The qualitative implications do not change. For the negative productivity change, the rank correlation compared to the positive counterpart varies between 0.88 (welfare) and 0.99 (TFP).

[19] Table E1 in Appendix E provides a list of the 15 top and bottom regions concerning the aggregate elasticities.

for aggregate output and welfare we do not identify the biggest and most productive cities, but smaller regions in their surroundings as key for the aggregate economy. Hence, regions that are geographically close and well connected to highly productive cities have on average a larger impact on the aggregate economy. The intuition is, that these less congested regions can attract a larger share of workers in response to positive productivity shocks. They can grow and reap the benefits of rising nominal wages without increasing local rents and input costs, which is the congestion force in the model, too much. This suggests that the big cities like Munich, Berlin, and Hamburg are already relatively congested and cannot attract additional employment without rising local rents significantly.

Figure 2 also documents that regions with higher elasticities are on average more central in the domestic production network. This means that local productivity shocks in central regions spill over to many other locations. However, the biggest and most central regions only have an average aggregate elasticity. Furthermore, we find that key regions in terms of aggregate welfare are net contributors to the national portfolio. They contribute more to the national portfolio than they receive on average. Hence, these regions attract a large share of labor in response to positive productivity shocks, while in the meantime redistributing a larger share of their higher income to the rest of the economy.

Summary. To sum up, regions differ concerning their aggregate TFP, real GDP and welfare elasticities. Depending on the specific aggregate measures of TFP, output, or welfare, we identify different regions as the main important players for the aggregate economy. In the case of Germany, concentrating local productivity growth in the biggest and most productive cities does not maximize aggregate output and welfare. Spatial development policies that affect local productivity growth exhibit larger aggregate effects in smaller regions in the surroundings of big cities. The key regions in spatial development have relatively strong spatial linkages and are less congested to attract a larger share of workers in response to positive productivity growth.[20]

4.2 Evaluating changes in local productivity

To identify local productivity changes per region and sector, we employ standard growth accounting techniques. We use the model structure and regional data on wages, employment, and prices to calculate the local productivity change $\hat{T}_n^j$ between 2010 and 2015. We assume a constant production structure, perfect competition under constant returns to scale, market clearing, and cost minimization. Intuitively, we measure the growth of real output relative to changes in input factors and costs. We proceed in three steps: i) using the structure of the model we organize official statistical data in an internally consistent way to recover the changes in input costs, ii) using the changes in input costs together with observed changes in real output, employment and wages we calculate the measured TFP model counterpart, and iii) using the changes in measured TFP we calculate the model-based changes in fundamental productivity. As data on actual changes of TFP and detailed changes in input costs are not readily available, we manipulate equation (19) to calculate the measured TFP model counterpart using observed data on real output, employment, and wages:

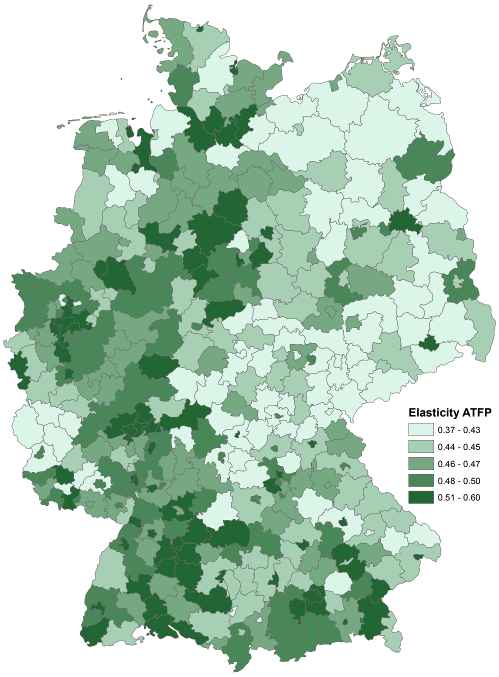
$$\ln(\hat{A}_n^j) = \ln(\widehat{\mathrm{GDP}}_n^j) - \ln(\hat{L}_n^j) - \ln(\hat{w}_n^j / \hat{x}_n^j). \tag{24}$$

We normalize the data to have a mean of one. From a theoretical point of view, a change in measured TFP depends on several factors. First, a change in real output leads, everything else equal, to a one-by-one change in measured productivity. Second, when output increases at

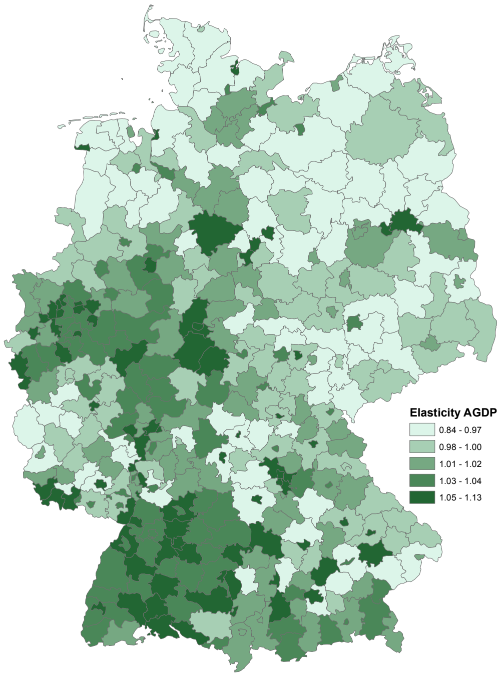
[20] In Appendix F, we decompose the aggregate effect into a direct effect and a spillover effect. We show that spillover effects in all other regions not directly affected by productivity changes are highly important to explain the aggregate results.

Figure 1: Aggregate Elasticities, by Region

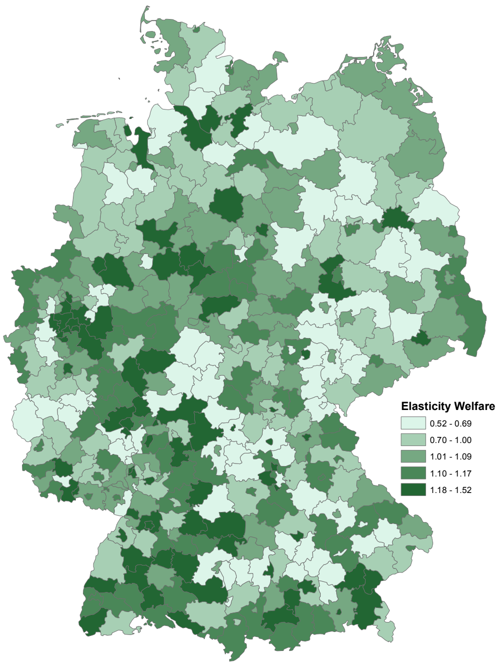
(a) Aggregate TFP Elasticities



(b) Aggregate GDP Elasticities



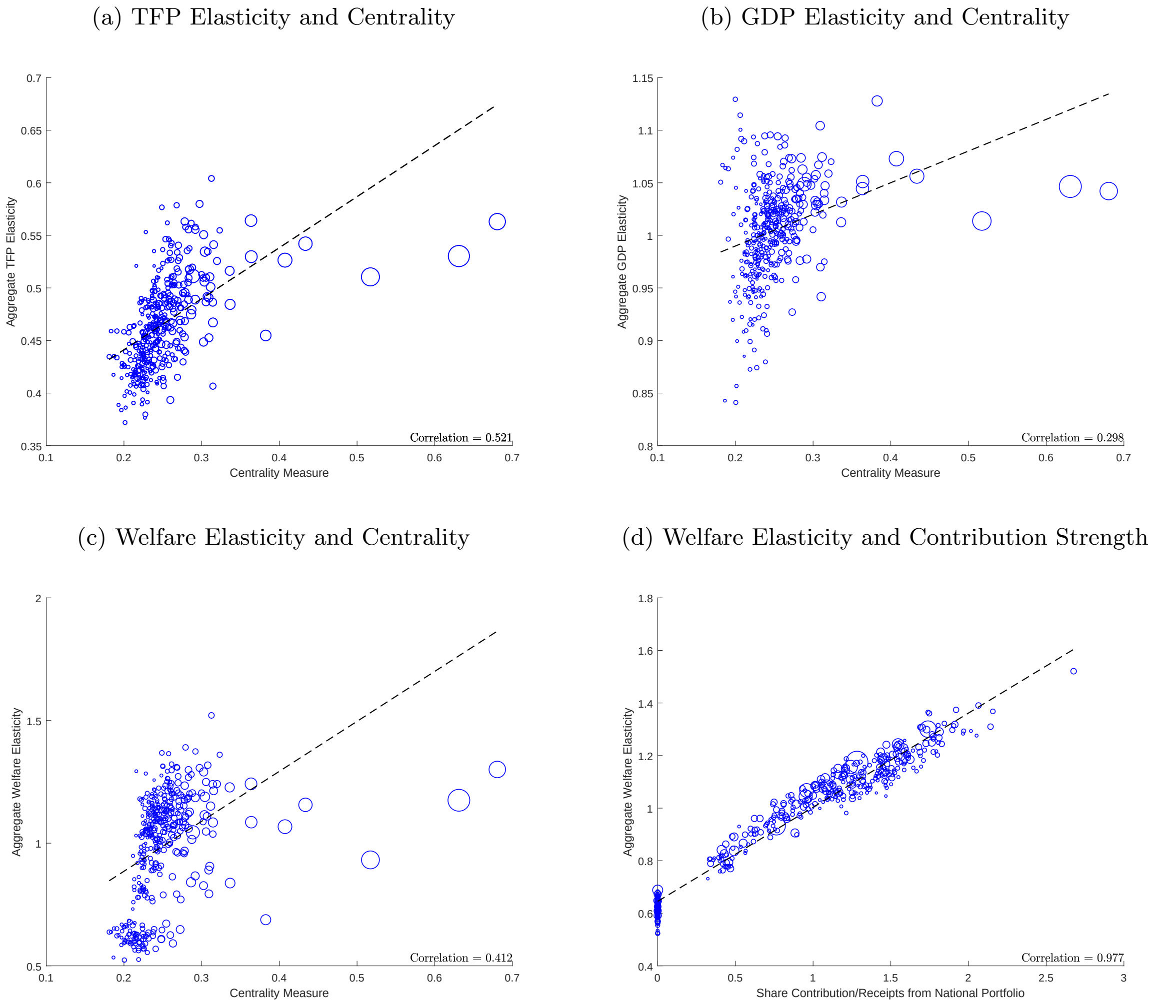
(c) Aggregate Welfare Elasticities



Notes: This figure plots the aggregate TFP, real GDP, and welfare elasticities of a 10 percent fundamental productivity shock to all sectors in a given region. Darker shading indicates higher values.

a lower rate than employment, the net effect on productivity is negative. Third, when wages increase at a higher rate than input costs, this too lowers measured productivity. We calculate

Figure 2: Influence Factors for Aggregate Elasticities



Notes: Panel (a) plots the relationship between the centrality measure and aggregate TFP elasticities. The size of the marker is proportional to the initial output share of each region. Panel (b) shows the relationship between the centrality measure and aggregate GDP elasticities. The size of the marker is proportional to the initial value-added share of each region. Panel (c) displays the relationship between the centrality measure and aggregate welfare elasticities. Panel (d) plots the strength of contributions to the national portfolio (i.e., the ratio of contributions to receipts from the national portfolio) against the aggregate welfare elasticity. In both cases, the size of the marker is proportional to the initial employment share of each region.

the region-sector specific wage changes $\hat{w}_n^j$ as a composite measure consisting of the change in nominal wages $\hat{w}_n$ per region, and sector-specific wage changes $\hat{w}^j$ from official statistical data. As we lack data on detailed changes in input costs, we solve for the corresponding changes using data on changes in prices, employment, and wages between 2010 and 2015. To compute $\hat{x}_n^j$, we use the information on changes in employment, wages and the relevant parameters on the share of value-added in gross output, γ_n^j and γ_n^{jk}, and the wage share in the production of value-added, β_n. We quantify the change in input costs according to:

$$\ln(\hat{x}_n^j) = \gamma_n^j \left[\ln(\hat{w}_n) + \beta_n \ln(\hat{L}_n)\right] + \ln\left[\prod_{k=1}^{J} (\hat{P}_n^j)^{\gamma_n^{jk}}\right]. \tag{25}$$

To proxy the changes in input costs, we need information on price changes $\hat{P}_n^j$, for which

— to the best of our knowledge — no region-sector specific official statistical data are available. Therefore, we use an iterative algorithm over the changes, which minimizes the squared deviation of the weighted sum of region-sector TFP across both regions and sectors from the aggregate change in measured TFP, where the weights are equal to the value of gross output shares. As starting values for the changes in region-sector specific intermediate goods prices, $\hat{P}_n^j$, we calculate the product of sector-specific price changes from WIOD and region-specific price changes from Eurostat. This procedure matches the sector-specific increases of measured multifactor productivity in Germany between 2010 and 2015 from the EU KLEMS Productivity and Growth Accounts (see Ark and Jäger, 2017).[21] As a result, we get the change in measured TFP per region-sector pair defined as $\hat{A}_n^j = A_n^{j,2015}/A_n^{j,2010}$, where the gross output share weighted sum over regions n and sectors j exactly matches the aggregate change in measured productivity.[22] In the next step, we use equation (18) to calculate the model-based changes in fundamental productivity, $\hat{T}_n^j$, in region n and sector j using the changes in measured TFP:

$$\hat{T}_n^j = \hat{A}_n^{j^{1/\gamma_n^j}}, \tag{26}$$

where we abstract from trade and selection effects, i.e., any changes in the home intermediate expenditure shares, $\hat{\pi}_{nn}^j$.[23] Further, to analyze whether a region or sector experiences a rise or decline in TFP between 2010 and 2015, we either aggregate the corresponding region-sector specific measurements to the regional, $\hat{T}_n$, or sectoral, $\hat{T}^j$, level using regional or sectoral GDP shares as weights.

Table 2 displays the productivity changes per sector. The Manufacturing and Wholesale, as well as the non-tradable sectors Construction and Financial/Insurance Activities, developed positively concerning fundamental TFP between 2010 and 2015. The growth factors range between 1.076 and 1.157. The sectors with fundamental productivity losses are Agriculture and the Public sector, for which we observe growth factors of 0.707 and 0.925, respectively. While there are no empirical counterparts for our calculated fundamental productivity changes, we can compare the underlying changes in measured TFP $\hat{A}^{j,model}$ to their empirical equivalent $\hat{A}^{j,data}$ coming from the EU KLEMS Productivity and Growth Accounts. According to columns (3) and (4) of Table 2, the model-induced growth factors in measured TFP match closely to the data for all sectors, except for Mining/Quarrying (1.125 versus 1.020) and Construction (1.120 versus 1.035). These differences can be justified threefold. First, our model includes an imperfect measure for capital by including the input factor *land and structures*. Second, we could only approximate the changes in input costs, $\hat{P}_n^j$. In particular, for the Construction sector, there has been a substantial increase in the input prices $\hat{P}_n^j$ in recent years, which are not fully captured by our routine. Finally, there are also slight methodological differences in quantifying total factor productivity.[24] Overall, we are, however, confident to provide reasonable numbers for disaggregated changes in fundamental TFP, as we correctly predict the sign of all changes in measured TFP.

Figure 3 displays the geographical distribution of fundamental productivity changes $\hat{T}_n$. Regions in the northeast of Germany exhibit larger values indicating a catch-up process between 2010 and 2015. Note, however, that this catch-up process is not only due to a positive real GDP growth, but also comes from employment losses in the northeast of Germany between 2010 and 2015.[25]

[21]The data can be downloaded from http://www.euklems.net/.

[22]In Appendix G we describe the specific procedure in more detail.

[23] To account for extreme values that arise in the case of small value-added shares, we winsorize the respective values at the 10 percent and 90 percent percentiles.

[24] For example, there are different measures for TFP. Based on value-added per hour worked or value-added per person employed. Ademmer et al. (2017) provide a more detailed overview of this topic.

[25]Figure G1 in Appendix G displays the changes in fundamental productivity for the Agriculture and Manufacturing sector per region. The plots for the remaining sectors are available upon request.

Table 2: Sectoral Productivity Changes, 2010−2015

Sector (Tradable, Non-tradable)	Model		Data
	$\hat{T}^j$	$\hat{A}^j$	$\hat{A}^j$
Agriculture, Forestry, Fishing	0.707	0.784	0.780
Mining/Quarrying, Electricity, Gas, Water Supply	1.159	1.125	1.020
Manufacturing	1.076	1.062	1.060
Wholesale	1.131	1.104	1.120
Construction	1.157	1.120	1.035
Financial and Insurance Activities	1.057	1.045	1.030
Public Administration, Defense, Social Security, Health	0.925	0.978	0.999

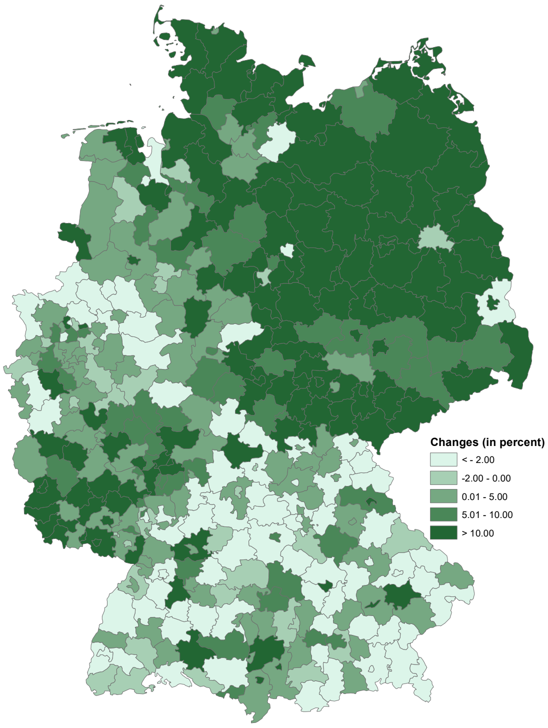
Notes: This table displays the per-sector growth factors (values > 1 indicate positive growth) of fundamental productivity changes $\hat{T}^j$ (model) and measured TFP changes $\hat{A}^j$ (model and data) from 2010 to 2015. The data comes from the EU KLEMS Productivity and Growth Accounts.

To further pin down the realized patterns, we estimate the elasticities of local productivity changes concerning the employment shares and the centrality of regions in 2010 from a simple 'Ordinary Least Squares' (OLS) regression. Panel (a) and Panel (b) of Figure 4 indicate a smaller productivity increase in already agglomerated and centrally located areas showing a negative relationship between initial employment shares as well as the centrality measure and local productivity changes. In other words, although we observe a concentration of labor in the largest cities and most central locations, the increase of local productivity was less pronounced in these areas between 2010 and 2015. In the following analysis, we will quantify the implied aggregate effects of these patterns of local productivity changes using the structure of the model.

After having identified the key regions and their observed changes in local productivity, we aim to evaluate their actual performance. To quantify the impact of local productivity changes on the development of the German economy between 2010 and 2015, we simulate a baseline scenario (accounting for all observed local productivity changes) and compare the outcome to various counterfactual scenarios where we abstract from local productivity changes in a given region (or group of regions). For the relevant location, we set $\hat{T}_n^j = 1$ for all sectors, while accounting for the productivity changes of all other regions. This allows us to quantify the marginal (or cumulative) effect of observed local productivity changes on aggregate TFP, real GDP, and welfare. Whenever abstracting from observed local productivity changes leads to declines in the outcome variables (relative to the baseline scenario), we infer that the region positively contributed to the development of the aggregate economy between 2010 and 2015.[26] If, on the other hand, abstracting from local productivity changes does not substantially change the outcome variables, or worse, rises aggregate TFP, real GDP or welfare, we conclude that a region has not developed according to its potential. A rise in either of the outcome variables even means that without the observed local productivity changes, the aggregate economy would have performed better. However, this is only possible if the region's actual contribution to the aggregate change was negative. In our counterfactual analysis where we account for all observed local productivity changes, the aggregate implications are not clear ex-ante. When productivity in hundreds of cities and regions changes simultaneously, some places will attract economic activity at the expense of others. Even when local productivity increases significantly for a single region, it may be harmful to the economy as a whole, as it diverts economic activity

[26]Note, that this exercise does not allow us to evaluate whether key regions developed according to their potential in absolute terms. All we can determine is if locations with the highest potential contributed more to the aggregate than locations with a lower potential.

Figure 3: Geographical Distribution of Local Productivity Changes, 2010−2015

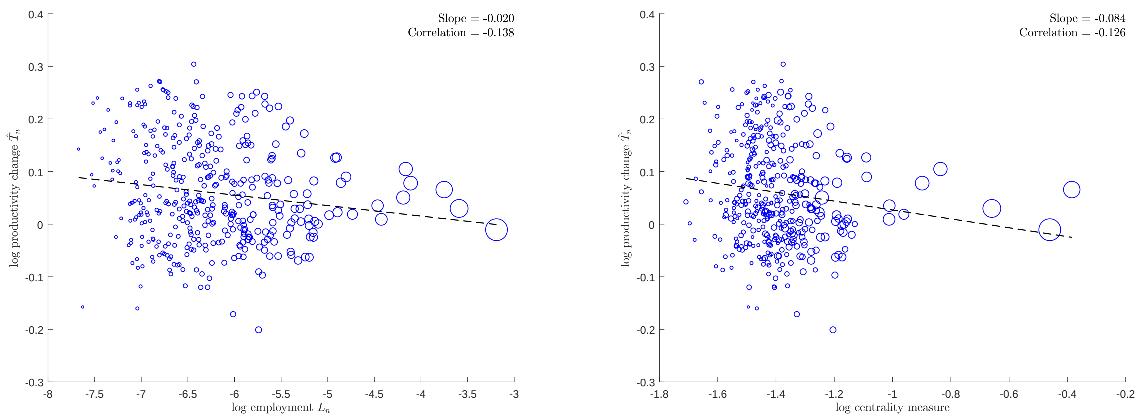


Notes: This figure plots the geographical distribution of fundamental productivity changes, $\hat{T}_n$ (in percent). A darker shading indicates higher values.

Figure 4: Local Productivity Changes, 2010−2015

(a) Did larger regions get more productive?

(b) Did central regions get more productive?



Notes: Panel (a) plots the relationship between initial employment shares and local productivity changes. Panel (b) the relationship between the centrality measure and local productivity changes. The size of the marker is proportional to the regional employment growth between 2010 and 2015.

away from key regions with a higher aggregate elasticity.

In the baseline scenario, aggregate TFP increases by 4.15 percent, aggregate real GDP by 9.81 percent, and the gain in welfare amounts to 5.92 percent. As a welcome side effect, the resulting changes fit quite well to observed aggregate changes for the German economy as published by the OECD, where Germany experienced an increase of multifactor productivity by 4.39 percent (which implies a compound annual growth rate of $1.0439^{1/5} = 1.0086$, that is 0.86 percent per year), and an increase of real GDP by 8.90 percent (i.e., 1.72 percent per year) from 2010 to 2015.[27] In the following exercise, we normalize the baseline scenario to zero and report relative deviations from this baseline case in percentage points.

Figure 5 displays the results for aggregate TFP, real GDP, and welfare. Abstracting from the observed productivity changes step-by-step from the upper end to the lower end of the aggregate elasticity distribution affects the aggregate measures with varying impact. When we suppress the productivity changes for all regions between 2010 and 2015, we trivially lose the entire gains of the benchmark scenario. The left y-axis depicts the cumulative effect of jointly abstracting from productivity changes for a group of regions $\{1, \ldots, i\}$ ranked by their respective elasticity distribution. For example, if we evaluate the top 10 regions with the highest values in the respective aggregate elasticity distribution — displayed by the value on the x-axis — we abstract from the observed productivity changes in all sectors of this subset of regions while accounting for the observed productivity changes of the remaining $N - 10$ regions. Similarly, on the right y-axis, we display the marginal effect of observed productivity changes. Here, we abstract from the observed productivity changes of one single region, while accounting for all the other $N - 1$ observed productivity changes.

TFP. According to Panel (a) in Figure 5, the key regions in terms of aggregate TFP indeed experienced productivity gains and contributed significantly to the increase of aggregate TFP between 2010 and 2015. The top 10 percent of locations account for 18 percent of the entire aggregate productivity gains, calculated as the respective 0.75 percentage points reduction relative to the overall effect of 4.15 percentage points (left axis). This corresponds to abstracting from the productivity gains associated with the top 40 key regions, among them are cities like Ludwigshafen am Rhein (kreisfreie Stadt), Wiesbaden (kreisfreie Stadt), Leverkusen (kreisfreie Stadt), but also Munich (Landeshauptstadt). These key regions also have relatively high marginal effects concerning aggregate TFP (right axis). Specifically, when we abstract from the productivity changes of Munich (Landeshauptstadt) aggregate TFP drops by 0.14 percentage points, for Frankfurt am Main (kreisfreie Stadt) by 0.13 percentage points and for Wiesbaden (Landeshauptstadt) by 0.05 percentage points, relative to the benchmark scenario. For some regions we find positive marginal effects indicating actual negative local productivity growth. Examples are Göttingen (Landkreis, 0.20 percentage points) and Rhein-Neckar-Kreis (Landkreis, 0.02 percentage points).

Real GDP. Panel (b) of Figure 5 displays the effects on aggregate output. We observe only minor changes in aggregate real GDP relative to the baseline scenario when we abstract from the observed productivity changes of the key regions with the highest aggregate GDP elasticities. The cumulative effect for the first 40 regions, i.e., the top percentile of locations in the aggregate real GDP elasticity distribution, accounts for 14.68 percent of the overall effect. For the group of top five key regions, the increment is, however, rather small and sometimes positive. This corresponds to minor or even negative productivity changes for Salzgitter (kreisfreie Stadt), Landshut (Landkreis) and Aschaffenburg (Landkreis). Only when we abstract from the observed local productivity changes of central locations, like Ingolstadt (kreisfreie Stadt), and big cities like Frankfurt am Main (kreisfreie Stadt), Berlin and Hamburg, the cumulative effect gets larger culminating in a real GDP drop by 9.81 percentage points when we abstract from all observed productivity changes (left axis).

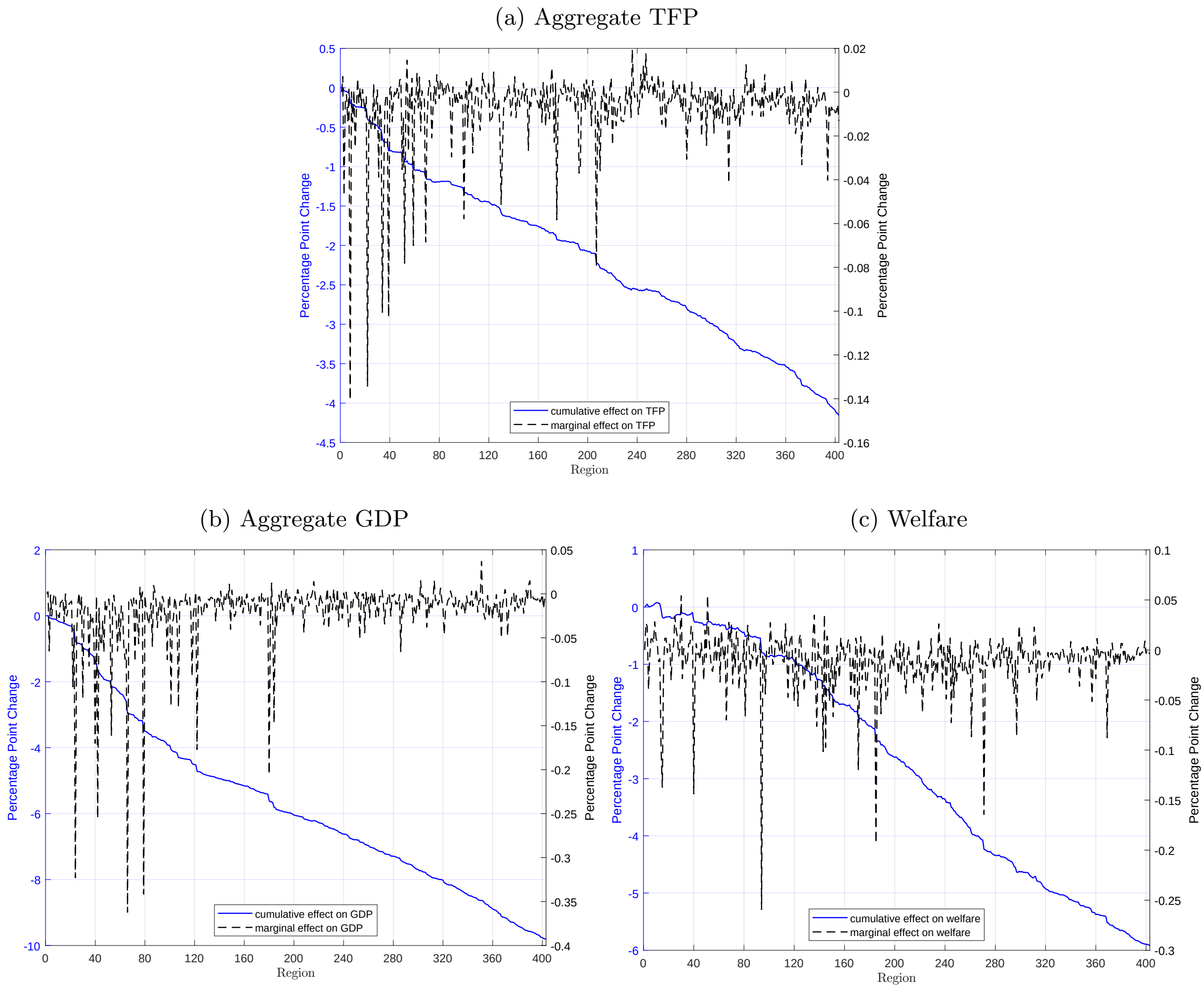
We find the highest marginal effects for the biggest cities Berlin and Munich (Landeshauptstadt), whose development — if neutralized — would lower aggregate real GDP by 0.36 percentage points and 0.34 percentage points, respectively. For the five key regions, however, the marginal effects are significantly lower, and at most 0.07 percentage points. Hence, the biggest

[27] The data can be downloaded from `https://data.oecd.org/lprdty/multifactor-productivity.htm`.

contribution to the change in national output between 2010 and 2015 does not come from the key regions at the upper end of the aggregate real GDP elasticity distribution, indicating that the German economy remained under its potential between 2010 and 2015.

Welfare. The results for aggregate welfare are quite similar. Panel (c) of Figure 5 shows that locations with the highest welfare elasticities experienced declines in fundamental productivity between 2010 and 2015. The cumulative effect of abstracting from the productivity changes of the top percentile of locations in the aggregate welfare elasticity distribution translates into a welfare drop of only 4 percent. More interestingly, for the top 10 regions, we do not find an effect when we abstract from their observed productivity changes. Only when we abstract from the observed positive productivity changes of the large cities, like Munich (Landeshauptstadt), Stuttgart (Stadtkreis) and Frankfurt am Main (kreisfreie Stadt), the cumulative effect turns negative.

Figure 5: Marginal and cumulative impact of local productivity changes



Notes: This figure plots the impact of local productivity changes between 2010 and 2015. The baseline accounts for the complete set of productivity changes and is normalized to zero. The horizontal axis depicts the respective regions (across all sectors) ranked according to their respective aggregate elasticities. Panel (a) shows the implications for aggregate TFP, Panel (b) for real GDP, and Panel (c) for welfare. The marginal effects of abstracting from productivity changes of single regions are depicted as a dashed (black) line. The cumulative effect of abstracting from productivity changes of a group of regions is shown as the solid (blue) line. The baseline scenario, where we account for all local productivity changes between 2010 and 2015, is normalized to zero.

We find the largest marginal effects for the cities Frankfurt am Main (kreisfreie Stadt, 0.26 percentage points) and Cologne (0.19 percentage points). On the other hand, according to the model welfare would have increased by up to 0.06 percentage points if Göttingen would not have developed as quantified. In line with the findings for real GDP, the biggest contribution to the change in welfare between 2010 and 2015 comes from the productivity improvements of regions with intermediate aggregate welfare elasticities. This points to the rather poor performance of the German economy in terms of social welfare between 2010 and 2015.

4.3 Optimal development of the economy

Given the observed local productivity changes, we examine how far the German economy remained below its potential optimum by assuming that the key regions experienced the highest productivity gains. The counterfactual exercise is as follows. We assign the observed local productivity changes between 2010 and 2015 according to the previously determined ranking of aggregate elasticities. This means we attribute the largest improvements in fundamental productivity $\hat{T}_n$ between 2010 and 2015 to the key region in the respective TFP, real GDP, or welfare elasticity distribution. Within each sector, the top key region is assigned the highest productivity change and the region with the lowest elasticity the lowest productivity change. This counterfactual allows us to define the potential optimum of the aggregate economy, given the calculated local productivity changes between 2010 and 2015.

What would have happened if the key regions developed according to the highest local productivity changes? Table 3 shows a large difference between the potential optimum and our baseline results. We find that aggregate TFP, real GDP, and welfare changes would be around twofold of the development in our baseline scenario. This indicates an undesirable development of local productivity changes in Germany between 2010 and 2015. We also find that the highest potential can be attributed to the key locations in terms of aggregate TFP. In other words, had key TFP regions also experienced the highest observed productivity gains, aggregate TFP would have increased by 9.43 percent (i.e., an annual compound growth rate of 1.82 percent), output by 19.21 percent (i.e., around 3.58 percent per year), and welfare by 18.13 percent (i.e., around 3.39 percent per year) within the five-year interval.

Table 3: Aggregate Effect of Local Productivity Changes

	Aggregate Change (in percent)		
	TFP	Real GDP	Welfare
Baseline	4.15	9.81	5.92
Assigning local productivity changes according to aggregate			
TFP elasticity	9.43	19.21	18.13
Real GDP elasticity	8.80	18.39	15.24
Welfare elasticity	7.06	15.02	14.79

Notes: This table displays the impact of local productivity changes between 2010 and 2015 on aggregate TFP, real GDP, and welfare (in percent). Row (1) displays the results for the baseline scenario in which each region and sector is assigned its actual productivity change. Rows (3) to (5) show cases in which the respective key regions of the TFP, real GDP, and welfare elasticity distributions are assigned the highest observed fundamental productivity changes.

Summary. Key regions in terms of aggregate TFP constitute the set of regions that experienced the largest increase in productivity between 2010 and 2015. However, regions with the highest potential to increase aggregate output and welfare experienced only modest fundamental productivity growth on average. We interpret this as a sign of a (relatively) poor performance of the German economy compared to its potential optimum, in terms of both real GDP and welfare. The relatively low local productivity changes in key regions lowered German output and welfare growth by a factor of two from 2010 to 2015.[28]

5 Conclusion

In this paper, we analyze the optimal regional allocation of spatial development policies if the government wants to maximize aggregate productivity, output, and welfare. We calibrate a general equilibrium model using disaggregated German data on input-output linkages and interregional trade to capture the complex links between sectors and regions while accounting for the endogenous reallocation of labor and adjustment of prices in response to local productivity growth.

Our main finding is that given the current structure of the German production network local productivity growth in the most productive regions, like Munich and Hamburg, does not maximize the outcome of the aggregate economy as they are already too congested. Whether conducting spatial development policies in less productive regions gives higher aggregate growth rates than in the most productive cities depends on the strength of spatial links and the degree of congestion. In the case of Germany, less productive, central regions with strong spatial links that are not too congested are key in spatial development. Moreover, we find that depending on the primary policy goal of either increasing aggregate productivity, output, or welfare, the government should target a different set of regions.

Further, we explore whether the key regions, i.e., those locations with the highest potential to affect the aggregate economy, have also contributed the most to the development of the aggregate economy in recent years. Our calculations of the observed local productivity changes in Germany between 2010 and 2015 indicate a (relatively) poor performance of the German economy compared to its potential optimum, in terms of both output and welfare. While highly productive cities, like Berlin and Munich (Frankfurt am Main and Cologne), attracted the largest share of employment and had a major impact on aggregate output (welfare) growth, the initially less congested key regions with strong spatial linkages contributed significantly less due to relatively low productivity growth there. The relatively low economic performance of the key regions in Germany and the rising concentration of employment in the already congested cities had sizeable implications for aggregate growth. In particular, we calculate that the relatively low local productivity growth in key regions lowered German output and welfare growth by a factor of two from 2010 to 2015.

Overall, we provide a tool to identify the key regions in spatial development while accounting for the complex production structure. We acknowledge, however, that it remains difficult for

[28] We repeat our exercise for the set of German NUTS-2 regions to infer the importance of the geographical unit for our results. In general, we find similar qualitative patterns. The aggregate elasticities and the importance of the influence factors are similar to the NUTS-3 case. The results are available upon request. For aggregate TFP the five key regions constitute one-third of the aggregate effect. Similarly, for aggregate GDP we find that the key regions indeed experienced productivity gains. The largest contribution to aggregate real GDP comes from regions in the middle of the aggregate elasticity distribution. For welfare, the findings on the NUTS-2 regions are even more pronounced. The results show that key regions in terms of welfare experienced big losses. The findings, however, differ concerning the effect size. For GDP we estimate an aggregate change of 6.03 percentage points between 2010 and 2015 (9.81 percentage points for NUTS-3), 1.26 percentage points for TFP (4.15 percentage points for NUTS-3) and 1.55 percentage points for welfare (5.92 percentage points for NUTS-3). Hence, the granularity of the regional dimension and with it the degree of factor reallocation across regions matters for the quantitative results. The difference can be explained by taking averages when aggregating to the NUTS-2 level and by a smaller degree of labor mobility across regions. So our analysis shows that the patterns are similar but it is essential to analyze the spillover effects on a rather disaggregated level.

policymakers to identify the key regions and sectors before they become too large and congested. Even if it were clear ex-ante which regions and sectors had the highest potential to positively affect the aggregate economy, it would still be difficult to pick the right policy instruments to push local productivity within those regions and sectors. Finally, it remains to be said that spatial development policies are probably not the best way to deal with the problem of congestion. The first-best policy is to address the market failures directly, which hamper investments in existing local structures that drive up local rents and limit the growth of the most productive regions.

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Appendix A Equilibrium conditions and solution algorithm

Equilibrium in changes. We briefly describe the equilibrium conditions in relative terms and the solution mechanism for the equilibrium expressed in changes. Similar to the main text, we define the change of a variable $\hat{y} \equiv y'/y$. Using the free mobility condition $U = (r_n H_n/L_n + w_n - s_n)/P_n$ and the equilibrium condition on input costs, $r_n \frac{H_n}{L_n} = \frac{\beta_n}{1-\beta_n} w_n$, we can rewrite labor demand L_n as

$$L_n = H_n \left(\frac{\omega_n}{P_n U + s_n} \right)^{1/\beta_n} \tag{A.1}$$

where $s_n = S_n/L_n$ is the per capita imbalance. In relative terms, the change in labor yields:

$$\hat{L}_n = \left(\hat{\omega}_n \frac{P_n U + s_n}{P'_n U' + s'_n} \right)^{1/\beta_n}. \tag{A.2}$$

A little algebra yields:

$$\frac{P'_n U' + s'_n}{P_n U + s_n} = \varphi_n \hat{P}_n \hat{U} + (1 - \varphi_n) \hat{s}_n, \tag{A.3}$$

where we define $\varphi_n \equiv 1/\left(1 + \frac{s_n}{P_n U}\right)$. Hence, for the change in labor, L_n we obtain:

$$\hat{L}_n = \left(\frac{\hat{\omega}_n}{\varphi_n \hat{P}_n \hat{U} + (1 - \psi) \hat{s}_n} \right)^{1/\beta_n}. \tag{A.4}$$

We can use this relationship to derive an expression for the change in indirect utility. Starting with the free mobility condition

$$U = \frac{\omega_n}{P_n} \left(\frac{H_n}{L_n} \right)^{\beta_n} - \frac{s_n}{P_n} \tag{A.5}$$

and noting that with $\hat{H}_n \equiv 1$ the relative change can be determined as

$$\hat{U} = \frac{1}{\varphi_n} \frac{\hat{\omega}_n}{\hat{P}_n} \left(\hat{L}_n \right)^{-\beta_n} - \frac{1 - \psi}{\psi} \frac{\hat{s}_n}{\hat{P}_n}. \tag{A.6}$$

We can use the labor condition that $L = \sum_{n=1}^{N} L_n \hat{L}_n$, which gives under the condition that labor $L \equiv 1$

$$\hat{L}_n = \frac{\hat{L}_n}{L} = \frac{\left(\frac{\hat{\omega}_n}{\varphi_n \hat{P}_n \hat{U} + (1-\psi) \hat{b}_n} \right)^{1/\beta_n}}{\sum_{i=1}^{N} L_i \left(\frac{\hat{\omega}_i}{\psi_i \hat{P}_i \hat{U} + (1-\psi) \hat{b}_i} \right)^{1/\beta_i}} L. \tag{A.7}$$

Under the condition $\hat{U} L = \sum_{n=1}^{N} \hat{U} L_n \hat{L}_n$, the change in the indirect utility becomes:

$$\hat{U} = \frac{1}{L} \sum_n L_n \hat{L}_n \left(\frac{1}{\varphi_n} \frac{\hat{\omega}_n}{\hat{P}_n} \left(\hat{L}_n \right)^{-\beta_n} - \frac{1 - \varphi_n}{\varphi_n} \frac{\hat{s}_n}{\hat{P}_n} \right). \tag{A.8}$$

Market clearing for final goods implies that:

$$X_n^{j\prime} = \alpha^j \left(\hat{\omega}_n \left(\hat{L}_n \right)^{1-\beta_n} \omega_n H_n^{\beta_n} \left(L_n \right)^{1-\beta_n} - S'_n \right) + \sum_{k=1}^{J} \gamma_n^{kj} \sum_{i=1}^{N} \pi_{in}^{k\prime} X_i^{k\prime}. \tag{A.9}$$

Using the condition that $\omega_n H_n^{\beta_n} L_n^{1-\beta_n} = I_n L_n + S_n$, we can rewrite the condition as:

$$X_n^{j'} = \alpha^j \left(\hat{\omega}_n \left(\hat{L}_n \right)^{1-\beta_n} [I_n L_n + S_n] - S_n' \right) + \sum_{k=1}^{J} \gamma_n^{kj} \sum_{i=1}^{N} \pi_{in}^{k\prime} X_i^{k\prime}. \tag{A.10}$$

Using the trade balance condition gives the relationship for the changes in factor prices:

$$\hat{\omega}_n \left(\hat{L}_n \right)^{1-\beta_n} \omega_n H_n^{\beta_n} (L_n)^{1-\beta_n} = \sum_{j=1}^{J} \gamma_n^j \sum_{i=1}^{N} \pi_{in}^{j\prime} X_i^{j\prime}. \tag{A.11}$$

Solution algorithm. Having determined the expressions for changes in labor and indirect utility, we consider next an exogenous change in fundamental productivity, $\hat{T}_n^j$. We apply the following iterative solution mechanism to solve for the counterfactual equilibrium. The derived set of unknowns is of size $2N+3JN+JN^2$, where specifically $\hat{\omega}_n(N)$, $\hat{L}_n(N)$, $X_i^{j'}(JN)$, $\hat{P}_n^j(JN)$, $\pi_{ni}^{j'}(JN^2)$ and $\hat{x}_n^j(JN)$. In step (1), we start by guessing a new vector of factor prices $\hat{\boldsymbol{\omega}}$.

Step 1: Obtain prices $\hat{P}_n^j$ and input costs $\hat{x}_n^j$ which are consistent with the changes in input costs (JN equations), $\hat{\boldsymbol{\omega}}$, which implies

$$\hat{x}_n^j = (\hat{\omega}_n)^{\gamma_n^j} \prod_{k=1}^{J} \left(\hat{P}_n^k \right)^{\gamma_n^{jk}} \tag{A.12}$$

and the changes in the aggregate price index (JN equations)

$$\hat{P}_n^j = \left(\sum_{j=1}^{J} \pi_{ni}^j \left[\hat{\kappa}_{ni}^j \hat{x}_i^j \right]^{-\theta^j} \hat{T}_n^{j^{\theta^j \gamma_n^j}} \right)^{-1/\theta^j} \tag{A.13}$$

Step 2: Solve for the trade shares, $\left(\pi_{ni}^{\prime j}\right)$ (JN^2 equations), which are consistent with the change in factor prices given $\hat{P}_n^j(\hat{\boldsymbol{\omega}})$ and $\hat{x}_n^j(\hat{\boldsymbol{\omega}})$ using the relationship

$$\pi_{ni}^{\prime j} = \pi_{ni}^j \left(\frac{\hat{x}_i^j}{\hat{P}_n^j} \hat{\kappa}_{ni}^j \right)^{-\theta^j} \hat{T}_n^{j^{\theta^j \gamma_i^j}} \tag{A.14}$$

Step 3: Solve for labor changes across regions, which are consistent with the change in factor prices given $\hat{P}_n^j(\hat{\boldsymbol{\omega}})$ and $\hat{x}_n^j(\hat{\boldsymbol{\omega}})$ using the labor mobility condition (N equations)

$$\hat{L}_n = \frac{\hat{H}_n \left(\frac{\hat{\omega}_n}{\varphi_n \hat{P}_n \hat{U} + (1-\psi)\hat{b}_n} \right)^{1/\beta_n}}{\sum_{i=1}^{N} L_i \hat{H}_i \left(\frac{\hat{\omega}_i}{\psi_i \hat{P}_i \hat{U} + (1-\psi)\hat{b}_i} \right)^{1/\beta_i}} L, \tag{A.15}$$

where the change in land and structures is set to $\hat{H}_n = 1$, $\forall n \in N$, and the change in indirect utility can be expressed by $\hat{U} = \frac{1}{L} \sum_n L_n \left(\frac{1}{\varphi_n} \frac{\hat{\omega}_n}{\hat{P}_n} \left(\hat{L}_n \right)^{1-\beta_n} - \frac{1-\varphi_n}{\varphi_n} \frac{\hat{L}_n \hat{b}_n}{\hat{P}_n} \right)$. Further, we have $\hat{b}_n = \frac{u_n' + s_n'}{u_n + s_n}$, $\psi = \frac{1}{1 + \frac{\Gamma_n + S_n}{L_n I_n}}$ and calculate the change in the aggregate price index as a weighted product of the sector-specific changes, where

$$\hat{P}_n = \prod_{j=1}^{J} \left(\hat{P}_n^j \right)^{\alpha^j}. \tag{A.16}$$

Step 4: Solve for the respective expenditure, which is consistent with the changes in factor prices using the regional market clearing condition in final goods (JN equations)

$$X_n^{j\prime} = \sum_{k=1}^{J} \gamma_n^{k,j} \left(\sum_{i=1}^{N} \pi_{in}^{k\prime} X_i^{k\prime} \right) + \alpha^j \left(\hat{\omega}_n \left(\hat{L}_n \right)^{1-\beta_n} (I_n L_n + \Gamma_n + S_n) - S_n^\prime - \Gamma^\prime_n \right) \tag{A.17}$$

which as a result yields a set of $N \times J$ equations in an equal number of unknowns, given by $\left\{ X_n^{j^\prime}(\hat{\boldsymbol{\omega}}) \right\}_{N \times J}$. To solve for this expression, we use matrix inversion.

Step 5: Update the guess for the change in factor prices, $\hat{\omega}_n^*$ using the relationship

$$\hat{\omega}_n = \frac{\gamma_n^j \sum_i (\pi_{in})^\prime (\hat{\boldsymbol{\omega}}) X_i^{j^\prime}(\hat{\boldsymbol{\omega}})}{\hat{L}_n(\hat{\boldsymbol{\omega}})^{1-\beta_n}(L_n I_n + \Gamma_n + S_n)} \tag{A.18}$$

Iterate over Step 1 to Step 5 until achieving convergence in the sense $\|\boldsymbol{\omega}^* - \hat{\boldsymbol{\omega}}\| < \epsilon$, where ϵ denotes the tolerance level.

Appendix B Channels for TFP, real GDP and welfare

The logarithm of TFP, $\ln A_n^j$, is defined as the difference of real gross output and the input bundles, that is

$$\ln A_n^j = \ln \left(\frac{w_n L_n^j + r_n H_n^j + \sum_{k=1}^{J} P_n^k M_n^{jk}}{P_n^j} \right) - (1-\beta_n)\gamma_n^j \ln L_n^j - \beta_n \gamma_n^j \ln H_n^j - \sum_{k=1}^{J} \gamma_n^{jk} \ln M_n^{jk}. \tag{B.1}$$

We can write

$$Y_n^j = w_n L_n^j + r_n H_n^j + \sum_{k=1}^{J} P_n^j M_n^{jk} = \frac{w_n L_n^j}{\gamma_n^j (1-\beta_n)} \tag{B.2}$$

We know that real GDP is the difference between real gross output and expenditures on materials. Changes in real GDP are calculated as $\widehat{\text{GDP}}_n^j = \ln(\hat{w}_n) + \ln(\hat{L}_n^j) - \ln(\hat{P}_n^j)$, using the relationship $\hat{P}_n^j = [\hat{\pi}_{nn}^j]^{1/\theta} \hat{x}_n^j [\hat{T}_n^j]^{-\gamma_i^j}$.

Appendix C Data

Table C1 in this appendix displays the different data sources. Bilateral trade flows on the region-sector level comes from the Forecast of Nationwide Transport Relations in Germany 2030 (VVP). The VVP data were collected in a project undertaken by Intraplan Consulting, Munich, in collaboration with BVU Consulting, Freiburg, for the Federal Ministry of Transport and Digital Infrastructure and is only available for 2010. The data are made available through the Institute for Transport Research of the German Aerospace Center under the link `http://daten.clearingstelle-verkehr.de/276/`.

The data contain bilateral trade volumes in metric tons at the product level by transport mode (road, rail, water) that went through German territory in 2010. We aggregate trade flows to the $N = 402$ German administrative districts (Kreise and kreisfreie Städte) and across transport modes at the 1-digit level of the ISIC Revision 4 classification. We convert the original

Table C1: Overview of the Data Sources and Variables

Bilateral trade flows (region-region-sector level)	Forecast of Nationwide Transport Relations in Germany 2030 (VVP)
Industry output (sector level)	World Input-Output Database (WIOD)
Input-Output linkages (sector level)	World Input-Output Database (WIOD)
Value-added (region-sector level)	Eurostat
Employment (region-sector level)	Eurostat
Wage (region level)	INKAR Database

Notes: This table reports the different data sources used in the model.

NST2007 product scheme provided by the VVP to the ISIC Revision 4 classification at the 1-digit level.[29] Moreover, we convert trade volumes to trade values by using appropriate unit values. We match aggregate trade flows in metric tons to output per region and sector in millions of euro and calculate the corresponding unit values. Using the unit values per region-sector pair together with information on region-sector specific trade volumes from the VVP we can match region-sector-specific gross output.

We also use data on nominal wages, region-sector specific employment, and output. Data for employment and wage income for each region come from Eurostat (Eurostat, 2016) and the INKAR Database (NUTS-3 level, see INKAR, 2016). We normalize employment, to sum up to one. We use the information on sector-specific output and input-output linkages from the World Input-Output Tables (WIOD, see Timmer et al., 2015). We allocate sector-specific output across regions according to region-specific employment shares. Information on sector-region specific value-added comes from Eurostat.

To classify all data according to a unique classification scheme, we use the ISIC Rev. 1 scheme. We transfer the trade data to this classification scheme relying on official correspondence tables provided by EU Ramon accessible under `http://ec.europa.eu/eurostat/ramon/relations/index.cfm?TargetUrl=LST_REL`.
Throughout the analysis, we rely on estimates for sector-specific trade elasticities from Caliendo and Parro (2015). Table C3 displays the respective values.

Panel (a) of Figure C1 shows the relationship between predicted and observed trade imbalances. We find trade surpluses of up to 11.01 billion euro for Munich (Landeshauptstadt), Berlin, Düsseldorf (kreisfreie Stadt) and Frankfurt am Main (kreisfreie Stadt), while Freising, Duisburg (kreisfreie Stadt) and Bielefeld (kreisfreie Stadt) are among the districts with the largest trade deficits between 2.73 and 4.45 billion euro. The observed imbalances, which are significant in size, justify our modeling of the national portfolio.

Panel (b) reveals that regions with a trade surplus are net contributors to the national portfolio, while regions with trade deficits are net recipients. To see this, we calculate the transfer rate, which is defined as the region n's income after redistribution relative to the income before redistribution. A transfer rate larger than one identifies regions as net recipients, values less than one as net donors.[30] The contribution share ι_n determines whether a region is a net donor or recipient. Given the observed trade imbalances and labor shares, some regions contribute all their rents to the national portfolio, while others make no contributions at all. For example, Ludwigshafen (kreisfreie Stadt) and Leverkusen (kreisfreie Stadt) have a contribution

[29] NST is the abbreviation for 'Nomenclature uniforme des marchandises pour les statistiques de transport'. This system represents a standard classification for transport statistics for goods transported by road, rail, inland waterways, and sea (maritime) at the European level since 2008 and is based on the classifications of products by activity (CPA). See Henkel and Seidel (2019) and Henkel et al. (2019) for more details about the dataset.

[30] Formally, the transfer rate is calculated as $\eta_n = [w_n L_n + \chi L_n + (1-\iota_n) r_n H_n] / (w_n L_n + r_n H_n)$, where $\chi = \sum_i \iota_i r_i H_i / L$ denotes the per capita receipts from the national portfolio, $w_n L_n$ reflects region n's wage income and $\iota_n r_n H_n$ defines the income from land and structures that is not distributed to the national portfolio.

Table C2: ISIC Revision 4 Sector Classification

Classification ISIC Rev. 4	**Sector**	**Description**
A	A	Agriculture, Forestry and Fishing
B, D and E	B,D,E	Mining and Quarrying Electricity, Gas, Steam and Air Conditioning Supply Water Supply; Sewerage, Waste Management and Remediation Activities
C	C	Manufacturing (e.g., Wood and of Products of Wood and Cork, except Furniture, Chemicals and Chemical products, Basic Pharmaceutical Products and Pharmaceutical Preparations, Rubber and Plastics Products, Electrical Equipment)
F	F	Construction (Construction of Buildings, Civil Engineering, Specialized Construction Activities
G, H and I	G−J	Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles Transportation and Storage Accommodation and food service activities
J		Information and Communication (e.g., Publishing activities)
K	K−N	Financial and Insurance activities
L		Real Estate Activities (Real Estate Activities with own or leased Property)
M and N		Professional, Scientific and Technical Activities (e.g., Legal and Accounting Activities), Administrative and Support Service Activities
O, P and Q	O−U	Public Administration and Defense; Compulsory Social Security Education, Human Health and Social Work Activities
R, S, T and U		Arts, Entertainment and Recreation Other service activities

Notes: This table displays the seven sectors: *Agriculture* (A), *Mining* (B/D/E), *Manufacturing* (C) and *Wholesale/Retail Trade* (G−J), *Construction* (F), *Financial and Insurance* (K−N) and *Public Administration/Defense/Education* (O−U). Sectors 1−4 are tradable sectors, sectors 5−7 non-tradable sectors.

Table C3: Trade Elasticity θ^j, by sector

Tradable Sector	ISIC Rev.4 Classification	Trade Elasticity θ^j
Agriculture, Forestry, Fishing	A	8.59
Mining/Quarrying, Electricity, Gas, Steam	B,D,E	14.83
Manufacturing	C	9.23
Wholesale/Retail Trade	G,H,I,J	8.04

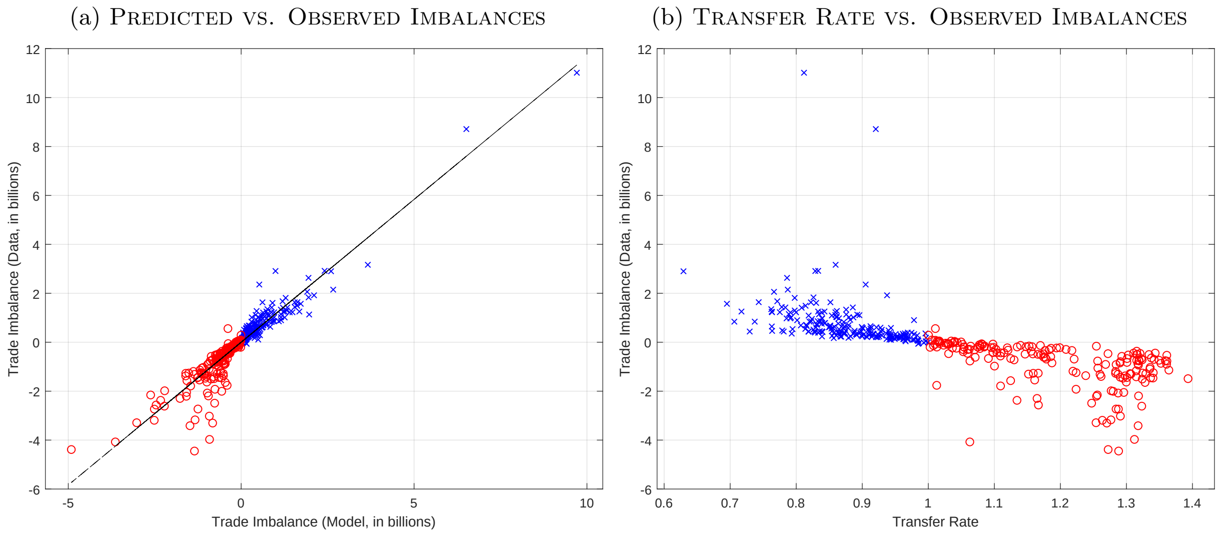
Notes: This table displays the sectoral dispersion of productivity, θ^j for tradable sectors. The values are based on Caliendo and Parro (2015). For the non-tradable sectors we assume a trade elasticity of $\theta^j = 4.55$.

share of $\iota_n = 1$, while Mecklenburgische Seenplatte and Vulkaneifel (Daun, Landkreis) make no contributions at all. Outliers are the big cities Hamburg and Munich (Landkreis), which have both substantial trade surpluses and large local rents. For them, only small contribution shares ι_n are sufficient to match the trade imbalances in the model to the data.

Appendix D Aggregation of TFP and real GDP

Regional, sectoral, and aggregate TFP. This section entails the aggregation steps of TFP and real GDP to sectoral, regional and national aggregates. The TFP aggregates are weighted by the region specific or sector-specific gross output shares. Specifically, the weighting factors include $w_n L_n^j$ and $\gamma_n^j(1-\beta_n)$. On the other hand, for the real GDP aggregates, we use the

Figure C1: Trade Imbalances and Contributions to the National Portfolio



Notes: Panel (a) plots predicted against observed trade imbalances between German NUTS-3 regions in 2010. Panel (b) shows how the observed imbalances relate to transfer rates. Note that net donors (with trade surpluses) have a transfer rate below one and are marked by crosses (in blue). Similarly, net recipients (with trade deficits) are identified by transfer rates above one and are marked by circles (in red).

respective value-added shares. For the regional TFP changes, we obtain:

$$\hat{A}_n = \sum_{j=1}^{J} \left(\frac{Y_n^j}{\sum_{j=1}^{J} Y_n^j} \right) \hat{A}_n^j = \sum_{j=1}^{J} \left(\frac{\frac{w_n L_n^j}{\gamma_n^j (1-\beta_n)}}{\sum_{j=1}^{J} \frac{w_n L_n^j}{\gamma_n^j (1-\beta_n)}} \right) \hat{A}_n^j. \tag{D.1}$$

The corresponding sector-specific TFP aggregate reads:

$$\hat{A}^j = \sum_{n=1}^{N} \left(\frac{Y_n^j}{\sum_{n=1}^{N} Y_n^j} \right) \hat{A}_n^j = \sum_{n=1}^{N} \left(\frac{\frac{w_n L_n^j}{\gamma_n^j (1-\beta_n)}}{\sum_{n=1}^{N} \frac{w_n L_n^j}{\gamma_n^j (1-\beta_n)}} \right) \hat{A}_n^j. \tag{D.2}$$

To derive the national aggregate, we sum over both dimensions and arrive at:

$$\hat{A} = \sum_{n=1}^{N} \sum_{j=1}^{J} \left(\frac{Y_n^j}{\sum_{j=1}^{J} Y_n^j} \right) \hat{A}_n^j = \sum_{n=1}^{N} \sum_{j=1}^{J} \left(\frac{\frac{w_n L_n^j}{\gamma_n^j (1-\beta_n)}}{\sum_{j=1}^{J} \frac{w_n L_n^j}{\gamma_n^j (1-\beta_n)}} \right) \hat{A}_n^j. \tag{D.3}$$

Regional, sectoral, and aggregate real GDP. The aggregation procedure for real GDP is similar except for the weighting, which relies on value-added measures. Respective value-added measures are given for sectors and regions, respectively by

$$\lambda_n^j = \frac{w_n L_n^j + r_n H_n^j}{\sum_j (w_n L_n^j + r_n H_n^j)} \qquad \text{and} \qquad \epsilon_n^j = \frac{w_n L_n^j + r_n H_n^j}{\sum_n (w_n L_n^j + r_n H_n^j)} \tag{D.4}$$

The regional change in real GDP can be determined by:

$$\widehat{\text{GDP}}_n = \sum_j \lambda_n^j \widehat{\text{GDP}}_n^j. \tag{D.5}$$

Similarly, the sectoral aggregate reads:

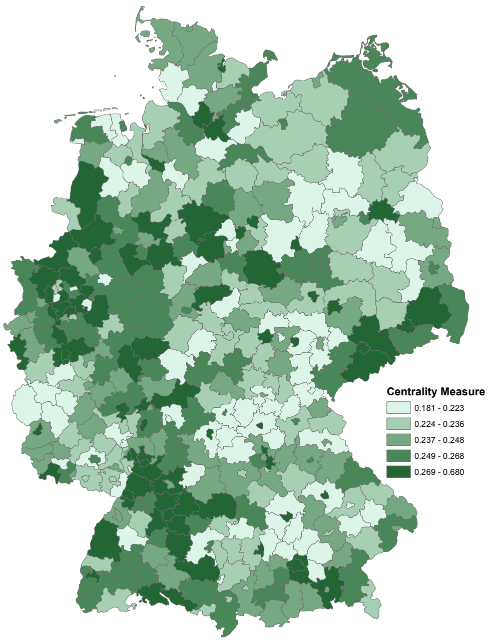
$$\widehat{\mathrm{GDP}}_j = \sum_n \epsilon_n^j \widehat{\mathrm{GDP}}_n^j. \tag{D.6}$$

The national aggregate can be written as:

$$\widehat{\mathrm{GDP}} = \sum_j \sum_n \frac{w_n L_n^j + r_n H_n^j}{\sum_j \sum_n (w_n L_n^j + r_n H_n^j)} \widehat{\mathrm{GDP}}_n^j. \tag{D.7}$$

Appendix E Counterfactual results: The key regions

Figure E1: Centrality Measure (in hundreds)



Notes: This figure depicts the 'centrality' measure (in hundreds) per region. A darker shading indicates higher values.

The model framework allows us to determine local rents per capita. They reflect the value-added by land and structures relative to local labor L_n. Panel (a) of Figure E2 displays the values. Panel (b) of Figure E2 shows the estimated contribution share ι_n. The contribution share determined to minimize the sum of squared residuals $\sum_{i=1}^{N}(\Gamma_n^M - \Gamma_n^D)^2$, where Γ_n^M reflects the model induced imbalances, Γ_n^D represents the data induced balances and the estimated shares are subject to the constraint $\iota_n \in [0, 1]$.

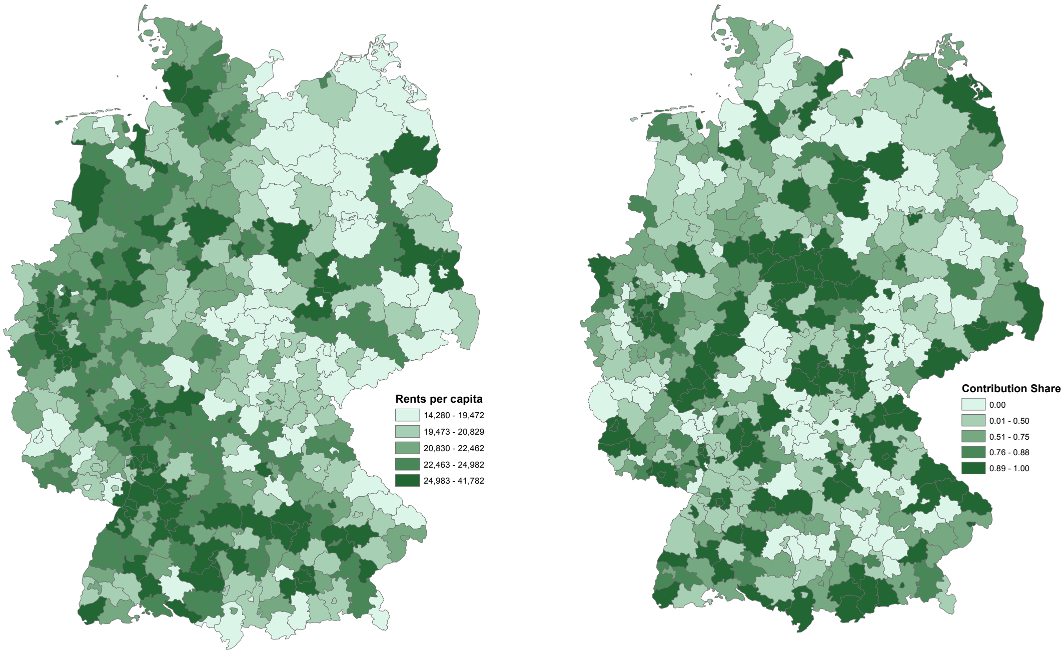
Table E1: Key and Bottom Regions

	Distribution and Key Regions		
	(a) $\text{TFP}^{elast.}$	(b) Real $\text{GDP}^{elast.}$	(c) $\text{Welfare}^{elast.}$
Rank 1	Ludwigshafen a.R.	Salzgitter	Ludwigshafen a.R.
Rank 2	Wiesbaden (Lhauptstadt)	Nürnberg	Bodenseekreis
Rank 3	Hochtaunuskreis	Dingolfing-Landau	Ingolstadt
Rank 4	Leverkusen	Mannheim	Leverkusen
Rank 5	Düsseldorf	Speyer	Schweinfurt
Rank 6	Münster	Rastatt	Erlangen
Rank 7	Munich (Lhaupstadt)	Krefeld	Tuttlingen
Rank 8	Starnberg	Bielefeld	Ostalbkreis
Rank 9	Darmstadt	Herne	Altoetting
Rank 10	Bodenseekreis	Kassel	Rottweil
Rank 11	Ingolstadt	Freising	Hochtaunuskreis
Rank 12	Wuppertal	Hagen	Biberach
Rank 13	Bonn	Heidenheim	Wiesbaden (Lhauptstadt)
Rank 14	Erlangen	Ulm	Munich (Lhauptstadt)
Rank 15	Wesermarsch	Schweinfurt	Wuppertal
...	...	...	...
Rank 388	Kyffhaeuserkreis	Landkreis Rostock	Neuburg-Schrobenhausen
Rank 389	Vogelsbergkreis	Spree-Neise Kreis	Saale-Orla-Kreis
Rank 390	Hassberge	Würzburg	Cuxhaven
Rank 391	Greiz	Cochem-Zell	Neumarkt i.d.Opf.
Rank 392	Bottrop	Rendsburg-Eckernfoerde	Pfaffenhofen a.d.Ilm
Rank 393	Zwickau	Altenburger Land	Harburg
Rank 394	Bad Kissingen	Harburg	Saalekreis
Rank 395	Ostprignitz-Ruppin	Cuxhaven	Rendsburg-Eckernfoerde
Rank 396	Eichsfeld	Wittmund	Mainz-Bingen
Rank 397	Saale-Holzland	Leer	Würzburg
Rank 398	Altenburger Land	Ludwigslust-Parchim	Cloppenburg
Rank 399	Saale-Orla Kreis	Steinburg	Günzburg
Rank 400	Ludwigslust-Parchim	Havelland	Schweinfurt
Rank 401	Eisenach	Schweinfurt	Steinburg
Rank 402	Havelland	Dahme-Spreefeld	Dahme-Spreefeld

Notes: This table displays the respective 15 key regions and bottom regions of in terms (a) TFP elasticity, (b) real GDP elasticity and (c) welfare elasticity.

Figure E2: LOCAL RENTS AND NATIONAL PORTFOLIO

(a) Rents per capita (b) Contribution Share



Notes: This figure plots the rents per capita (in euro) and the contribution share ι_n. A darker shading indicates higher values.

Appendix F Decomposing the aggregate effects

In the main text, we have emphasized the aggregate effects of local productivity changes. However, in general equilibrium, there is a direct effect of local productivity changes, and spillover effects via spatial linkages to other markets. Both effects then add up to the aggregate effect of a local productivity change in the economy. To highlight the relative importance of local and spillover effects for the aggregate effects on TFP and real GDP we follow Acemoglu et al. (2015), Adao et al. (2019), and Hsieh and Moretti (2019) and decompose the aggregate effects into local and corresponding spillover effects. The latter is a compound of all spillover effects in all other region-sectors pairs that were not hit by a direct local productivity shock. Changes in aggregate TFP can be written as follows:

$$\widehat{A} = \underbrace{\frac{Y_n}{Y}\hat{A}_n}_{\text{local effect}} + \underbrace{\sum_{i \neq n} \frac{Y_i}{Y}\hat{A}_i}_{\text{spillover effects}} , \tag{F.1}$$

where Y_n/Y represents the region-specific gross output share of region n, and $\hat{A}_n$ is the change in productivity (TFP) in the region. For real GDP, we obtain:

$$\widehat{GDP} = \underbrace{\frac{VA_n}{VA}\widehat{GDP}_n}_{\text{local effect}} + \underbrace{\sum_{i \neq n} \frac{VA_i}{VA}\widehat{GDP}_i}_{\text{spillover effects}}, \tag{F.2}$$

where region-specific value-added shares VA_n/VA weight the specific local changes in real GDP.[31]

[31] Note, $VA_n/VA = \sum_j \left(w_n L_n^j + r_n H_n\right) / \sum_n \sum_j \left(w_n L_n^j + r_n H_n\right)$.

We proceed in three steps. First, we determine the importance of spillover effects for the aggregate effects. We calculate the spillover effects as the difference between the aggregate and local effects for the affected region n. Second, we determine the relative importance of the local and spillover effects (in percentage point changes) by calculating their respective ratios. Having found that spillover effects play a major role, in a third step, we focus on the role of spatial linkages and labor mobility on aggregate changes.

Spillover effects. We find that the spillover effects make up for the largest part of the aggregate effect. Between 95.26 percent and 99.56 percent of the aggregate change in real GDP comes from output changes in regions not hit by the local productivity shock. A local productivity shock in one region only has a small effect in each other region, but the total of all spillover effects is a weighted average of a large set of regions $N-1$ that also constitute a larger fraction of total value-added or gross output. Hence, neglecting the impact of spillover effects would lead us to tremendously understate the aggregate effects of local productivity changes in our analysis.

Local versus spillover effects. Panel (a) and Panel (b) in Figure F1 display the relative importance of local and spillover effects for TFP and real GDP. We find large geographical heterogeneity in the relative importance of the local and spillover effects. The different panels show that local TFP effects are most important in cities like Berlin (4.21) percent and Hamburg (3.03) percent (in hundreds). The relative importance of the local real GDP effect is also pronounced for Berlin and Hamburg with 4.97 percent and 3.47 percent (in hundreds). On average, high gross output (Y_n/Y) and value-added shares VA_n/VA are a sufficient statistic for strong local effects relative to spillovers. Moreover, key regions with high aggregate elasticities (see Figure 1) also have high local relative to spillover effects. Large cities that constitute the economic centers, like Munich, Berlin, and Hamburg, also exert strong spillover effects to other less-congested regions, which still can attract a larger share of labor. This explains their high aggregate elasticities.[32] Thus, the impact of local productivity growth is positive everywhere, but the strength of the aggregate effects depend strongly on where productivity changes occur.

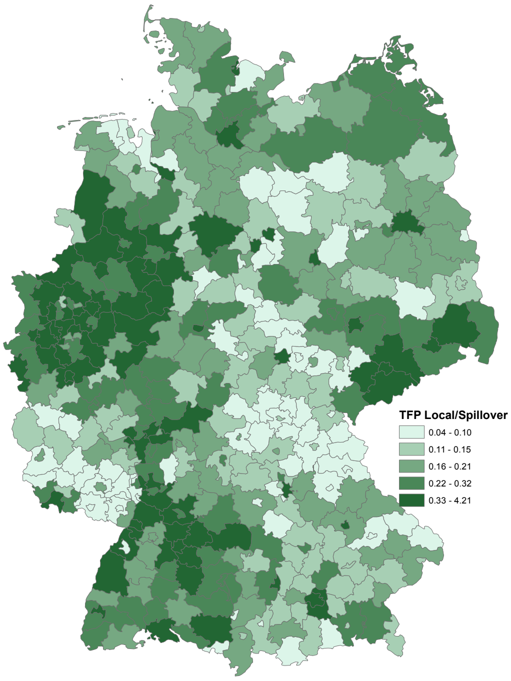
Spatial linkages and labor mobility. To quantify the importance of spatial linkages and labor mobility for the aggregate effects, we repeat the same exercise from above but abstract from sectoral linkages and/or labor mobility across regions. We find that both the sectoral linkages and the mobility of labor are crucial for the relative size of local and spillover effects. To determine the importance of sectoral linkages, we set up a baseline economy without sectors, but all regions are still allowed to trade their intermediate goods with each other. To abstract from sectoral linkages we set the share of inputs used in different sectors to zero $\gamma_n^{jk} = 0$ and the share of value-added to one $\gamma_n^j = 1$. In this sense, all production comes from local value-added. We find similar aggregate elasticities compared to the baseline case with sectoral linkages.[33] In the absence of sectoral linkages, however, there are no spillovers to other sectors, which leads to more pronounced local effects relative to the spillovers. For the economic centers, we find a relative local TFP effect of 4.79 percent (in hundreds, compared to 4.21 percent in the baseline), while the respective relative local effect of GDP increases to 5.01 percent (in hundreds,

[32]Figure F2 in this Appendix displays the unweighted changes in local TFP and local real GDP (measured in percent) arising from the local 10 percent productivity shock. Key regions concerning aggregate TFP have the highest unweighted local TFP effects, whereas for the respective key regions concerning real GDP the unweighted local effects are rather small. Relatively remote regions with a low degree of initial congestion have larger unweighted local GDP effects. For the key regions concerning real GDP the unweighted local effects, however, are scaled up by comparatively large local value-added shares VA_n/VA. This explains their relative large weighted local real GDP effects. For example, in Munich (Landeshauptstadt) the unweighted local GDP effect of 11.54 percent is scaled by a value-added share of 2.64 percent to a high local relative to the spillover effect of 3.08 percent.

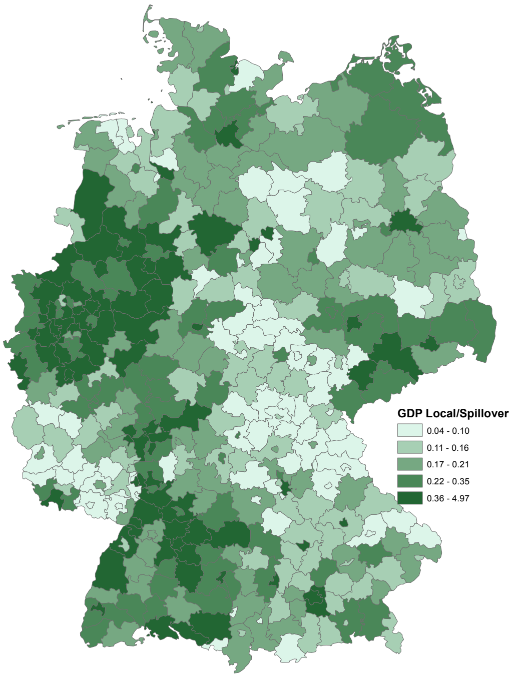
[33]The full set of elasticities is available on request.

Figure F1: RELATIVE IMPORTANCE OF THE LOCAL EFFECT, BY REGION

(a) TFP (in Hundreds)



(b) GDP (in Hundreds)



Notes: Panel (a) plots the relative importance of the local effect to the aggregate for TFP and Panel (b) plots the relative importance of the local effect to the aggregate for GDP following a 10 percent productivity shock. The effects are measured in hundred percent. A darker shading indicates higher values.

compared to 4.97 percent in the baseline). The local productivity changes also have important effects on the economy through the mobility of labor. A positive productivity shock in one region attracts workers from other regions contributing to the positive local effect. To quantify the importance of labor mobility for the aggregate elasticities, we determine the relative size of local and spillover effects in a scenario without labor mobility. In technical terms, we get rid of the utility equalization condition and abstract from labor mobility across regions. We find that abstracting from the mobility of labor does not affect the pattern of aggregate TFP, but for aggregate GDP. The reason is that the importance of the local effect relative to the spillover effects decreases.

Appendix G Data counterpart of measured TFP

To derive fundamental productivity changes $\hat{T}_n^j$, we first determine a data counterpart of the total factor productivity based on the model equation:

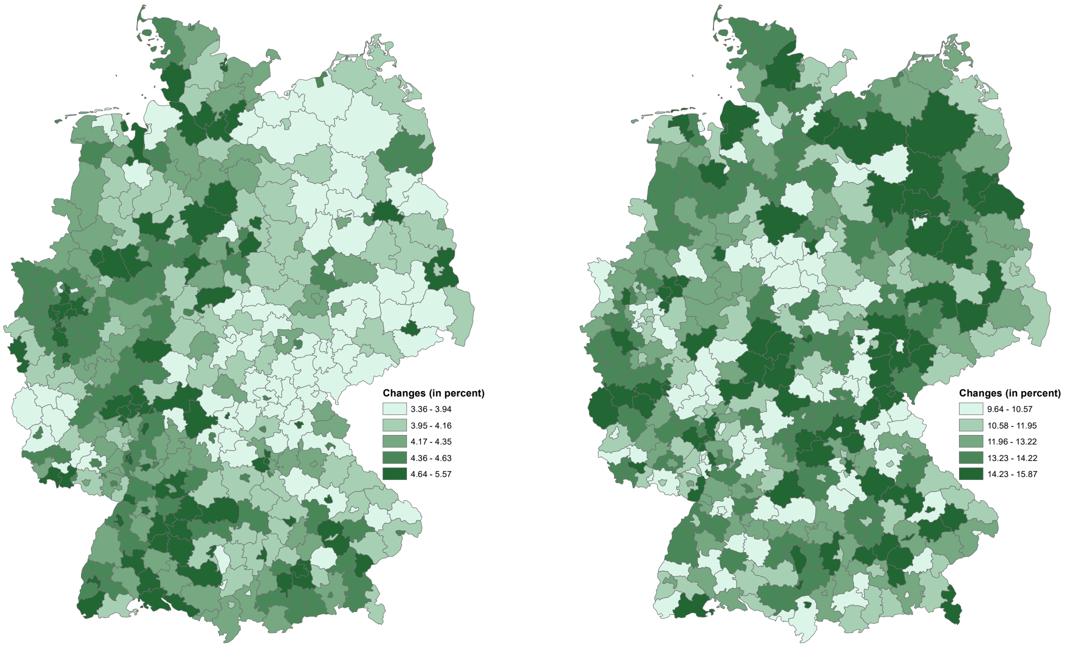
$$\ln\left(\hat{A}_n^j\right) = \ln\left(\widehat{\mathrm{GDP}}_n^j\right) - \ln\left(\hat{L}_n^j\right) - \ln\left(\frac{\hat{w}_n}{\hat{x}_n^j}\right). \tag{G.1}$$

The estimation requires data on region-sector specific real GDP changes, employment changes, worker compensation changes and inflation data, all for 2010 and 2015.

Real GDP changes, $\widehat{\mathrm{GDP}}_n^j$, are calculated by deflating nominal GDP data from Eurostat Re-

Figure F2: Unweighted Local Effects

(a) TFP Changes (in percent) (b) GDP Changes (in percent)



Notes: This figure displays the unweighted own-region changes following a 10 percent productivity shock. Panel (a) displays the percentage changes in TFP, Panel (b) displays the percentage changes in real GDP.

gional Database by the respective price index.[34] Information about changes in employment, $\hat{L}_n^j$, comes from the Eurostat Regional Database (Eurostat, 2016), too. The change in nominal wages $\hat{w}_n^j$ is based on the average wage sum per region normalized by the national average of wages per sector w^j. The region-specific wage data comes from INKAR Database, the sector-specific data from Destatis (German Statistical Office, 2017). Finally, we need to determine the change in input costs, x_n^j. We exploit equation (4) and note first, that $\omega_n = \left(\frac{r_n}{\beta_n}\right)^{\beta_n}\left(\frac{w_n}{1-\beta_n}\right)^{1-\beta_n}$. We exploit this relationship noting that

$$r_n H_n = \frac{\beta_n}{1-\beta_n} w_n L_n \Longleftrightarrow \hat{r}_n \hat{H}_n = \hat{w}_n \hat{L}_n. \tag{G.2}$$

Together with a fixed supply of the local factor land and structures, $\hat{H}_n \equiv 1$ and a proportional relationship between local rents and total wages $\hat{r}_n = \hat{w}_n \hat{L}_n$, we obtain

$$\omega_n^{\gamma_n^j} = \left[\left(\frac{r_n}{\beta_n}\right)^{\beta_n}\left(\frac{w_n}{1-\beta_n}\right)^{1-\beta_n}\right]^{\gamma_n^j} \Longleftrightarrow \hat{\omega}_n^{\gamma_n^j} = \left[\hat{w}_n \hat{L}_n^{\beta_n}\right]^{\gamma_n^j}. \tag{G.3}$$

This relationship can be used to finally express the changes in input costs.

$$\hat{x}_n^j = \frac{(x_n^j)'}{x_n^j} = (\hat{\omega}_n)^{\gamma_n^j(1-\beta_n)} \prod_{k=1}^{J}\left(\hat{P}_n^j\right)^{\gamma_n^{jk}} = \left[\hat{w}_n \hat{L}_n^{\beta_n}\right]^{\gamma_n^j} \prod_{k=1}^{J}\left(\hat{P}_n^j\right)^{\gamma_n^{jk}} \tag{G.4}$$

Taking the log of this equation, we obtain:

$$\ln(\hat{x}_n^j) = \gamma_n^j\left[\ln(\hat{w}_n) + \beta_n \ln(\hat{L}_n)\right] + \ln\left[\prod_{k=1}^{J}(\hat{P}_n^j)^{\gamma_n^{jk}}\right]. \tag{G.5}$$

[34]The data can be downloaded from `https://www.destatis.de/DE/ZahlenFakten/GesamtwirtschaftUmwelt/VGR/Inlandsprodukt/Tabellen/BruttoinlandVierteljahresdaten_xls.html`.

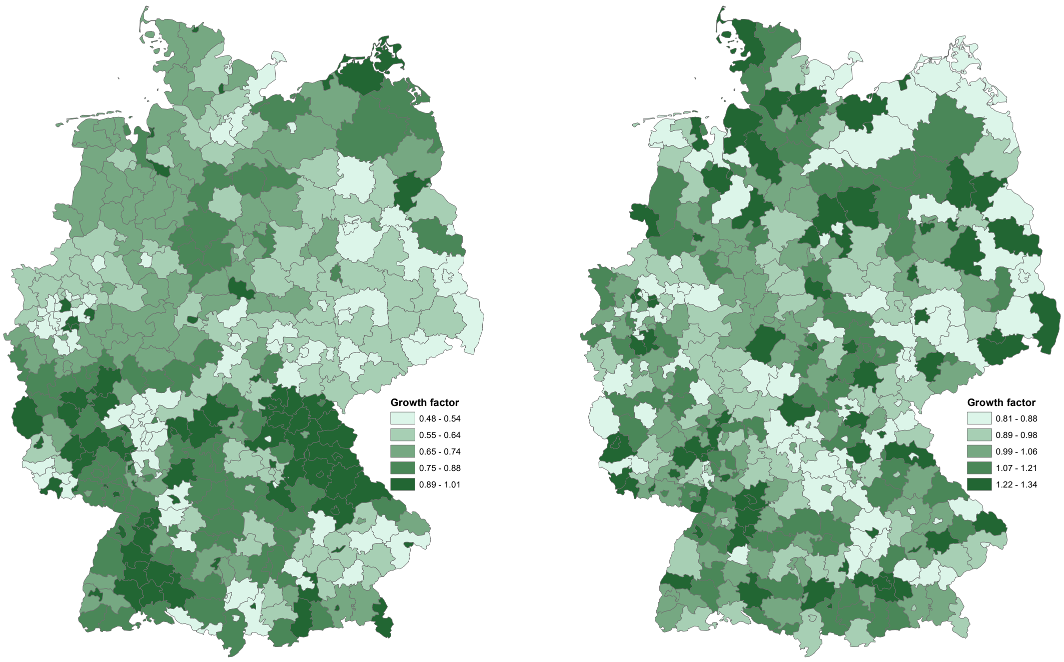
With this we can finally calculate $\ln(\hat{w}_n/\hat{x}_n^j)$. We lack changes in region-sector input price data, $\hat{P}_n^j$. To circumvent this issue, we approximate respective input price changes. We simulate a scaling factor such that the composite of the consumer price changes and this scaling factor matches the change of aggregate multifactor productivity $\hat{A} = 1.0226$ as given by KLEMS data (Ark and Jäger, 2017) and sector-specific total factor productivity from Destatis (see German Statistical Office, 2017 and OECD, 2019). The respective minimization routine reads:

$$\arg\min_{\hat{P}_n^j} \left(1.0226 - \sum_j \sum_n \frac{Y_n^j}{Y} \hat{A}_n^j\right)^2 + \left(A^j - \sum_n \frac{Y_n^j}{Y_j} \hat{A}_n^j\right)^2, \tag{G.6}$$

with the sector-specific total factor productivity changes from Destatis given by $A^j = [0.78, 0.96, 1.07, 1.06, 0.96, 1.01, 1.00]$ and Y_n^j/Y as the region-sector-specific gross output shares. The optimal $\hat{P}_n^j$ yield a perfect match for both constraints and are bounded between 0.9062 and 1.2812. Due to the structure of the data, the routine produces extreme values of $\hat{A}_n^j$. Hence, we winsorize the respective distribution and limit the extreme values to the 90th percentile and 10th percentile, respectively.

Figure G1: Predicted Changes in Productivity, $\hat{T}_n^j$

(a) Agriculture (b) Manufacturing



Notes: This figure plots the growth factors (< 1 reflects losses) in region-specific fundamental productivity $\hat{T}_n$ for (a) Agriculture and (b) Manufacturing. A darker shading indicates higher values. The plots for the remaining sectors are available upon request.