

Cheap Coal, Market Access, and Industry Location in Germany 1846 to 1882

Preliminary Draft

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Abstract

This paper compares the roles of access to coal and access to consumer markets in the regional development of manufacturing during the second half of the 19th century. The new economic geography emphasizes the role of market access in explaining the location of industry but, historically, natural resources were at least as important as consumer markets for industrial development. The empirical analysis extends the methodology developed by Berry (1994) to estimate a location choice model that accounts for unobserved spatial spillovers. The endogeneity of access is addressed by using instrumental variables. The results show that access to coal was more important than access to consumer markets for the location of metal production and textiles. Machine tool making was tied to mining during the industrial take-off, but consumer markets became more important as the industry branched out to serve other manufacturers. The findings indicate that coal mining played a large role in Germany's industrialization.

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1 Introduction

The new economic geography emphasizes the trade-off between proximity to consumers and proximity to inputs like labor and natural resources in a spatial general equilibrium model (Krugman 1991). A large number of empirical studies find an important role for access to consumers in explaining the tendency of manufacturing to concentrate geographically (Head and Mayer 2004, Hanson 2001, Davis and Weinstein 1999). Historically, natural resources were at least as important as consumer markets for the location of manufacturing. During the 19th century coal played an large role in the growth of metal production and manufacturing in general.¹ The transition from charcoal to coke smelting dramatically reduced the price of iron in Europe (Fremdling 1979) and coal fired steam engines helped to introduce the mass production of metal goods, machine tools, and textiles. Coal deposits were geographically concentrated and transportation on roads was prohibitively expensive, therefore access through railroads and waterways was an important factor for the development of manufacturing.

This paper compares the roles of access to coal and access to consumer markets in the regional development of manufacturing in Germany during the second half of the 19th century.² The first goal is to examine the importance of coal relative to consumer markets for the location and growth of manufacturing during industrialization. The second goal is to assess the contribution of railroad construction to the development of manufacturing. The railroad boom cut shipping costs by as much as 90 percent for overland transportation (Fremdling 1995). This was particularly important for Germany, because all of the country's navigable rivers run from south to north and therefore fail to connect eastern with western regions. The paper follows the growth of key manufacturing sectors in 80 German regions as they gained better access to coal mines and consumer markets.³ By studying the effects of improvements in access to coal and access to consumers the paper identifies some of the mechanisms through which railroads contributed to economic development during the 19th century.⁴

¹Coal includes bituminous and anthracite coal, which are both referred to as Steinkohle in German. Germany's deposits are mostly bituminous coal with the exception of the northern Ruhr Area which has anthracite as well.

²By Germany I mean the area of the German Empire which was founded in 1871.

³The regions are the districts or "Regierungsbezirke" of the German states and the later German Empire. They were the second smallest administrative units above the "Kreisaemter" and below the "Provinzen" and had an average population of approximately 500,000 people during the study period.

⁴In contrast to other recent work about railroads and economic growth (Donaldson and Hornbeck 2012) the analysis does not distinguish between regional growth that reflects national economic development and regional growth that is the result of industry displacement. This paper can therefore not offer an assessment of the total contribution of railroads to industrial development. Instead, it is more closely related to work by Atack et al. (2010, 2008), who study the impact of railroads on the rise of large factories and urbanization in the United States.

For the empirical analysis, I create a new data set of district-level employment in different manufacturing industries from the censuses of the German Zollverein in 1846 and 1861 and the censuses of the German Empire in 1875 and 1882. These data are combined with GIS information about the locations of these districts, navigable waterways, and railroads, which allows me to calculate the cost of shipping coal and lignite to each district as well as the cost of shipping manufactured goods to consumers.⁵ In the empirical analysis, I estimate the impact of these shipping costs on regional employment in key manufacturing sectors using the paired combinatorial logit model developed by Chu (1989). The benefit of this model is that it allows for spatial spillovers, which are very likely among neighboring districts. The model can be estimated with maximum likelihood if data about individual location choices are available. However, the information that remains from the German manufacturing censuses of the 19th century is aggregated at the district level, which makes maximum likelihood estimation impossible. Berry (1994) suggests an alternative approach that uses aggregate data together with generalized method of moments estimation. I extend Berry's methodology for the paired combinatorial logit model and use the fixed point algorithm proposed by Berry, Levinsohn, and Pakes (1995) in the estimation. The endogeneity of railway construction and population is addressed by using instrumental variables.

The results show that access to coal was more important than access to consumer markets for the location of employment in metal production and textiles. It is not surprising that coal mattered more than consumers in the production of metals where fuel was the most important input beside ore and output was not sold to consumers but to other manufacturing industries and construction. It is surprising, however, that textile manufacturers were concentrated in regions with cheap access to coal because fuel is generally not considered a major input for this sector. One explanation is that the weight of coal was high enough that even the relatively small amount needed to power spinning and weaving frames was sufficient for textile makers to move close to coal mining areas. In machine tool making, access to coal and lignite mattered much more than access to consumers during the industrial take-off between 1846 and 1861 but consumer markets became more important toward the end of the first wave of industrialization between 1875 and 1882. This finding matches the historical narrative about the German machine tool industry, which was tightly connected to mining and heavy industry during its early development but branched out to serve other industries later on (Redlich 1944). In contrast to machine tool makers, producers of metal goods stayed away from coal mining regions during the early industrial take-off but moved closer to coal fields toward the

⁵Lignite is also called soft or brown coal and has a lower energy content than bituminous and anthracite coal.

end of the first wave of industrialization. This is consistent with the sector's late transition from charcoal to coke fuel (Fremdling 1981).

The results shed light on two different debates in economic history. Economic historians have long been interested in the role of natural resources in economic development. A number of economic historians credit Britain's coal deposits with much of the success of the Industrial Revolution (Allen 2009, Pomeranz 2001, Wrigley 1988). This view has been challenged by Clark and Jacks (2007) who argue that British manufacturers could have been similarly successful by importing coal from other countries. My findings suggest that the growth of German manufacturing would have been smaller between 1846 and 1882 if manufacturers had relied on coal imports. Germany bought coal from Britain throughout the 19th century, but these imports never resulted in the development of industry on the German coast. Instead, the large growth of German metal production and machine tool making took place at the same time and in the same regions as the expansion of German coal mining. Even textile manufacturers located close to the German coal belt despite imports of raw cotton from Britain. My findings therefore suggest that domestic coal deposits were an important factor for industrial development.

The analysis also contributes to the debate about the regional differences in industrialization within Germany, which has largely focused on the political and institutional differences between the German regions prior to unification in 1871 (Tipton 2003, Ogilvie 1996, Kellenbenz 1991). There is no doubt that the many German kingdoms, duchies, and independent cities followed very different economic and social policies and that these policies influenced the development of industry throughout the 19th century. However, in contrast to these political structures the location of manufacturing changed significantly during the second half of 19th century. The coal fields in the Ruhr Area and Upper Silesia transformed from relatively empty places into centers of heavy industry, machine tool making, and even textile production while regions outside of the coal belt lost employment in these sectors. This suggests that the geographic concentration of the German coal fields can account for a substantial part of the regional variation in industrial development.

2 The Historical Background of Industrialization

Germany transformed from a mostly agricultural economy into an industrial leader during the second half of the 19th century. Steam powered machinery helped to introduce mass produc-

tion in metals and textiles, the railroad boom reduced transportation costs, and employment in manufacturing doubled between 1846 and 1882. However, the growth of manufacturing was concentrated at the regional level and some areas experienced large declines in industrial employment. This section provides a narrative of the development of important manufacturing sectors during this period and argues that their geographic concentration was, to a large extent, the result of their dependence on coal.

2.1 The Location of Markets and Coal

At the beginning of the 19th century Germany's largest manufacturing centers were located along the Rhine between the cities of Krefeld and Aachen and on the Elbe around Leipzig and Dresden. One of the most important manufacturing sectors was the production of textiles. The land around Aachen was a thriving center of wool spinning, weaving, and finishing mills (Kisch 1959). Similarly, in Leipzig and Dresden a large fraction of the population was employed in cotton textiles and machine production that specialized in spinning jennies and weaving frames (Wolff 1979). Why was employment concentrated in these two regions? Textile production was relatively footloose, because the main input of labor could be moved fairly easily. Hochstadt (1981) documents high mobility of workers between agricultural areas and German manufacturing towns as early as 1821, which indicates that the local supply of labor was not a constraint for manufacturers. Flax and wool were produced in many areas of Germany, which was still an agricultural economy at the time. Cotton was mainly imported from Britain (Brown 1992), but most of the relatively young cotton mills were located in older centers of flax and linen production (Wolff 1979). The need for water power represented a location constraint, because water powered textile mills had to locate on streams with large enough elevation drops and away from other water powered plants to avoid disruption from backwater (Gutberlet 2012). However, this constraint limited rather than encouraged the geographic concentration of textile making, because suitable streams could be found in most regions in Germany.

The greatest advantage that the Rhineland and Saxony had to offer to manufacturers at the beginning of the 19th century might have been access to large consumer markets. Both areas were densely populated and connected to markets outside of Germany through navigable rivers and the North Sea. The Rhine served as the main artery for trade between Switzerland, Germany, the Netherlands, and England across the Channel. Figure 1 shows that two of the largest population centers around Mainz, Frankfurt on the Main, and Aachen were located

near the Rhine. Similarly, the Elbe connected Germany with the Austrian Empire and the North Sea. Regions along the Elbe were not as densely populated as the Rhineland, but the areas around Dresden and the Elbe port of Hamburg had large populations. By locating near the Rhine or the Elbe manufacturers gained easy access to large local populations and in addition they could use relatively cheap river transportation to send their goods to the big markets in the Netherlands, Austria, Switzerland, Poland, and England.

During the second half of the 19th century Germany transformed from a largely agricultural economy into an industrial leader. Textile production and cottons in particular remained an important part of manufacturing, but the largest employment growth took place in metal production, metal goods, and machine tool making. Coal played an important part in the success stories of these sectors. Much of the early development of the German machine tool industry took place in machine shops that belonged to coal mines (Redlich 1944). The main task of these shops was to build and maintain steam engines to power water pumps and coal hammers. When this demand was satisfied they started to develop and sell steam engines for textile mills and other factories. Coal played an even more important role for German metal production. A large fraction of the demand for metal came from railroad construction, but German rails were too expensive compared to British imports as long as German ironworks used charcoal furnaces (Fremdling 1979). Domestic iron production soared only after iron makers succeeded in switching from charcoal to coke blast furnaces. This transition started in 1796 when the first coke blast furnace was built in Breslau but was not completed until 1830 because switching from charcoal to coke required the construction of new furnaces and a good understanding of the chemical processes that took place inside them (Pierenkemper 1979). Manufacturers of metal goods did not switch to coal until the second half of the 19th century, but then producers of wire, pipes, and nails abandoned charcoal as well (Fremdling 1981).

The introduction of steam engines in factories turned coal into an important input for almost all manufacturing industries. Coal was the standard fuel to heat steam engine boilers, although lignite could be used as a substitute. The first steam engine in German textile production was installed by the cotton spinning factory Lenssen & Beckenbach in Rheydt near Gladbach in 1827, although Adelman (1966) doubts that the engine was used for more than cotton preparation and keeping the factory rooms humid. Nonetheless, more cotton mills followed the example, so that by 1834 the neighboring district of Duesseldorf had nine cotton spinning factories with steam engines. The earliest steam engines were installed alongside old water wheels to increase the total available power and to ensure year round operation (Boehme

1969). Later steam engines made it possible for plants to form industry clusters without the elaborate water management needed for water wheels and without any access to running water at all. Table 1 shows that these advantages led to the widespread adoption of steam power in key manufacturing sectors like metal production, metal goods, machinery, and textiles. By 1875 the fraction of plants that used steam power was higher than the fraction of plants that used water power in all of the mentioned sectors. The average plant power from steam engines surpassed the average plant power from water wheels by a wide margin.

German coal output more than tripled between 1850 and 1882 to satisfy the growing demand from industry and transportation companies, but coal mining always remained geographically concentrated. Figure 2 show that all coal producing regions were located on a narrow belt across the middle of the country. The districts with the highest coal output were Duesseldorf, Arnsberg, and Trier in the west and in Oppeln in the east. The location of mining was largely determined by the location of accessible coal deposits, which were rare outside of this narrow belt (Pierenkemper 2002). Before mining and heavy industry took off around the middle of the 19th century, neither Arnsberg nor Oppeln were densely populated regions as Figure 1 shows. Only after Germany's industrialization began in earnest did these areas fill with miners, iron makers, and factory workers. Koellmann (1969) points out that the immense success of coal mining in Duesseldorf and Arnsberg led to an explosion of mining towns between 1850 and 1870. Figure 4 shows the substantial population growth in all coal mining areas during this time period, which shifted the geographic concentration of population away from the southwest into the west and east of Germany. Lignite, which was a substitute for coal in the production of metal goods and in heating steam engine boilers, was mined in a larger area in central Germany that can be seen in Figure 3. In contrast to coal mining, lignite production never attracted large population flows into this area.

The importance of coal for the development of manufacturing can be seen in the changes of the spatial distribution of employment during the second half of the 19th century. The largest growth in manufacturing employment took place around the coal belt. It is not surprising that metal production was already concentrated in this area in 1846 as Figure 5 shows, because most blast furnaces had switched from charcoal to coke at this point. During the following years employment in metal production increased from around 2,000 to over 6,000 people in some regions in the coal belt while it stayed below 500 people in most other regions. The development of machine tool making is maybe the most impressive example of manufacturing growth during this period. Figure 7 shows that very few regions had more than 1,000 employees in machine tool making in 1846 but by 1882 some regions in the Rhineland, in Saxony, and

in Silesia had over 7,000 employees. Figure 6 shows the distribution of employment in the production of metal goods, which includes pipes, wire, and products from sheet metal. In 1846 this industry was concentrated in Bavaria in southeast Germany, but by 1882 many of these regions had experienced a decline from more than 6,000 to less than 2,000 employees. In 1882 metal goods production was instead concentrated along the coal belt and around Berlin in central Germany. This movement is consistent with the late transition from charcoal to coal based production in this sector. Employment in textiles went through a similar spatial shift as metal goods production. Figure 8 shows that in 1846 the largest center of textile production was in southern Bavaria, but this cluster had almost disappeared by 1882. Instead, most employment in textiles was now concentrated in Silesia and around Berlin in central Germany.

2.2 Transporting Coal and Manufactured Goods

The locations of coal and consumers mattered for the regional development of manufacturing, because transportation was costly during the 19th century. Navigable rivers provided relatively cheap shipping and some of Germany's river systems could be navigated for long distances that spanned several countries. However, many regions had only poor access to waterways as Figure 1 shows. In particular, the only river that connected eastern and western Germany was the Main, which has its origin in Bavaria and flows into the Rhine after it reaches Frankfurt on the Main. One result of this geographic shortcoming was that heavy cargo between the commercial centers Aachen and Magdeburg either had to be transported south along the Rhine to Mainz, cut across to Bayreuth on the Main, and from there go back north along the Saale or go north along the Rhine through the Netherlands, along the coast on the North Sea, and back south on the Elbe to Magdeburg. The first option meant 880 kilometers of river shipping and the second option 577 kilometers of river and 390 kilometers of sea transportation to overcome a distance of 421 kilometers of relatively flat land. Of course, cargo could be hauled on roads, but the high freight rates charged by horse carriages almost certainly prohibited long distance transportation for goods with a high weight that did not have exceptional value. For example, in 1840 the average pit price of coal was 5.38 Marks per ton and the average freight rate on horse carriages was 0.40 Mark per ton kilometer (Fremdling 1979). This implies that the delivery price of coal would have doubled after a short 13.5 kilometers of transportation on road.

The costs of shipping coal and manufactured goods across Germany fell dramatically during the second half of the 19th century as the railroad boom cut freight rates by as much as 90

percent for overland transportation (Fremdling 1995). The first German steam railway opened between the Bavarian cities of Nuernberg and Fuerth in 1835. The track was relatively short (5.7 kilometers) and the main purpose of the private company that owned and managed the railroad was to transport business travelers and shoppers between the two cities. Heinze and Kill (1988) point out that the first railroads attracted mainly passenger traffic in the 1830s and 1840s because the short lines required repeated transshipment between different railroads and other modes of transportation which proved too expensive for cargo. Railroad companies completed the first long lines during the late 1840s. One of the most important railroads from this period connected Duesseldorf in the western Rhineland with Magdeburg in central Germany in 1847 and thereby solved the problem of the missing east-west connection. The map in Figure 10 shows that additional connections between western and central cities followed in the 1850s. After 1861 railroad projects shifted away from the construction of new trunk lines and focused on building local branches that reached smaller towns in rural areas, which can be seen in Figures 11 and 12.

In addition to long lines competitive freight rates were essential for shifting cargo traffic from waterways onto rails (Lotz 1900). Table 2 provides estimates of average national freight rates for different modes of transportation between 1846 and 1882.⁶ The estimates indicate a sharp decline in the rates charged by railroad companies, so that over time the railroad tariffs became more similar to the charges levied by river barges. This was not always the doing of the private companies that owned and managed most of the German railroads. The private railroad that served the area between Upper Silesia and Berlin introduced the first 1-Pfennig tariff for coal transports in 1849 under the pressure of the Prussian Secretary of Commerce (Heinze and Kill 1988). Other railroad companies followed, so that by 1862 the special coal tariff applied to all important northern German lines (Fremdling 1995). This might have been the main reason for the immense rise in the volume of coal shipments from less than 1 percent to more than 35 percent of all cargo on Prussian railways between 1850 and 1875.

Railroad construction and falling freight rates made it cheaper for manufacturers to import coal if their own location did not have mining operations and to export their products to larger markets if local demand was low. This expansion of factor and output markets made it possible to concentrate production in those areas with the best combination of access to natural resources and other inputs as well as access to large output markets. The railroads enabled producers to take advantage of economies of scale, which lowered production costs and helped

⁶The estimates are taken from different sources and some are calculated from small samples of routes, which means that the numbers have to be interpreted with care.

industries to grow nationally. To take advantage of the new opportunities manufacturers relocated from one region to another, which means that one region's growth might have been another region's loss. For example, Albert Poensgen moved his ironwork and wire drawing factory from the Eifel to Duesseldorf in 1860, taking over 200 employees, several rolling mills, and power hammers with him (Hatzfeld 1961). It is very likely that the subsequent growth of the Albert Poensgen Company in Duesseldorf was larger than it would have ever been in the Eifel, but it would nonetheless be wrong to fully count the success of Duesseldorf as national industrial growth. The following empirical analysis will focus on the regional development of manufacturing and should therefore not be misunderstood as a national growth accounting exercise. Its contribution is rather to identify and to compare the different mechanisms through which railroad construction affected industrialization.

3 Modeling Location Choice

Estimating the impact of changes in the costs of accessing coal and accessing consumer markets on the location and growth of manufacturing poses a number of challenges which are discussed in this section. I base the estimation on a discrete choice model in which manufacturing firms maximize profits by deciding where to locate each of their employees. Within this estimation framework three separate problems arise: the potential for spatial spillovers, the fact that the data about employment choices are aggregated at the district level, and the endogeneity of railroad construction and population. I use the paired combinatorial logit model by Chu (1989) to address the first problem. To combine this model with aggregate employment data, I extend the approach of Berry (1994) and use the fixed point algorithm by Berry, Levinsohn, and Pakes (1995). Finally, I construct a set of instruments to minimize estimation error from endogenous variables. The following sections explain each of these steps in detail.

3.1 A Combinatorial Logit Model of Location

The discrete choice literature pioneered by McFadden (1977) provides a framework for modeling the impact of regional characteristics like market access and access to coal on location decisions by manufacturers. The framework has been applied in industrial organization and economic geography to study location decisions by firms and plants across regions and neighborhoods inside cities (Hansen 1987, Carlton 1983). In contrast to these studies, I focus on the location of employment. During the second half of the 19th century the average plant size

increased dramatically in most manufacturing industries, which makes it difficult to measure industrial growth by the number of plants in a region. The starting point of the location model is the latent profit function π_{lit} , which captures the profit from locating an employee l in region i at time t

$$\begin{aligned}\pi_{lit} &= \beta_1 A_{it}^{\text{coal}} + \beta_2 A_{it}^{\text{lignite}} + \beta_3 A_{it}^{\text{German market}} + \beta_4 A_{it}^{\text{European market}} \\ &\quad + \Gamma_g + \tau_t + \xi_{it} + \epsilon_{lit} \\ &= \delta_{it} + \epsilon_{lit}\end{aligned}\tag{1}$$

On the right hand side of the profit function local access to coal is defined as

$$A_{it}^{\text{coal}} = \frac{1}{C_{it}^{\text{coal}}},\tag{2}$$

where C_{it}^{coal} is the minimum cost of shipping one ton of coal from a mining area to region i in year t . Access is defined as the inverse of the minimum shipping cost, which implies that the marginal effect of a reduction in transportation costs is higher for lower values of C_{it}^{coal} . I choose this functional form, because the geographic concentration of manufacturing suggests that regions with very high shipping costs for coal would not have benefited as much from a reduction in transportation costs as regions with average or low shipping costs. Local access to lignite A_{it}^{lignite} is defined in the same way as the minimum cost of transporting one ton of lignite from a mining area to region i in year t . I consider only the cheapest sources of coal and lignite for each region, because the large output of most mining areas should have allowed them to serve all surrounding manufacturers.

In contrast to access to coal and lignite, the variables that measure access to consumer markets take into account multiple markets because many manufacturers sent their output to more than one regional market. The size of each regional market is measured by its population so that the complete variable for access to German markets is defined as

$$A_{it}^{\text{German market}} = \sum_{j=1}^J \frac{1}{C_{ijt}} \times P_{jt},\tag{3}$$

where C_{ijt} measures the minimum cost for shipping one ton of goods between region i and market j and P_{jt} is the local population of market j at time t . The complete measure captures the total size of the national market that manufacturers in region i could access while taking into account the costs of reaching each regional market. Access to European markets is defined in the same way but includes only markets outside of Germany that were the main trading

partners for German manufacturers. Figure 13 shows the 11 countries that are included as European markets for German products.

The profit function includes two vectors of fixed effects as control variables. The first Γ_g is a vector of provincial fixed effects, which are meant to capture the impact of economic policy on industrialization in the ten provinces shown in Figure 14. The boundaries of the provinces are those of the German states in 1846 with the exception of Prussia, which is divided into three provinces. The division accounts for the fact that the Rhineland and Westfalia joined Prussia relatively late in 1815 and that Prussia especially protected agricultural interests in its northeastern districts (Kisch 1959). The small states of Braunschweig, Lippe, Mecklenburg and Schleswig are included in Prussia or Hannover depending on their trade policy and cooperation with these larger states in railroad construction (Fremdling 1975). It might be surprising that the provincial fixed effects are assumed to be constant over the entire study period between 1846 and 1882 despite the fact that the foundation of the German Empire in 1871 falls into the middle of this period. Unification established Prussian law in all provinces of the Empire and made it easier for German citizens to move between the different areas of the large country. However, most taxes, railroad regulation and finance, and economic policy remained strictly at the state level, which suggests that the institutional environment for manufacturers did not change significantly in 1871 (Wehler 1985). The year fixed effects τ_t are meant to capture changes in the business cycle that affected all regions equally.

The variable ξ_{it} includes all other unobserved factors that had an impact on the profitability of a region. Probably the most important factor which is not included explicitly is human capital, which differed greatly across regions as a result of differences in schooling, the location of universities and engineering colleges, as well as localized knowledge spillovers in established manufacturing centers. Other unobserved factors include the availability of financing, which must have differed across regions as a result of the uneven distribution of banks and investors. The estimation of the coefficients of interest requires that ξ_{it} is uncorrelated with a set of instrumental variables; a point that will be argued in the following section. Beyond this requirement the model makes no distributional assumptions about ξ_{it} .

I assume that the error term ϵ_{lit} follows an extreme value distribution and is independent across employees and time periods, but can be correlated across regions. This is an important relaxation of the standard assumptions about the logit error term in the discrete choice literature. Allowing for spatial autocorrelation in the logit error addresses two concerns. The fact that regions neighbored each other makes it likely that unobserved shocks to profits in one region spilled over to neighboring regions. If these spillovers are not accounted for the anal-

ysis can yield inconsistent standard errors (Anslin and Griffith 1988). Furthermore, allowing for spatial autocorrelation in the logit error relaxes the strict substitution patterns that are imposed by the standard multinomial logit model (MNL) (McFadden 1984). In the MNL the additive separability of the mean profit δ_{it} and the i.i.d errors ϵ_{lit} implies that all responses have the same cross-elasticities with respect to characteristics of another alternative. Imposing this restriction, which is often referred to as independence of irrelevant alternatives (IIA), in a context where it does not hold can lead to biased coefficient estimates (Koppelman and Wen 2000). In the context of location choice IIA is unlikely to hold, because firms that relocate employees almost certainly prefer neighboring regions to areas that are farther away. All else equal regions which are closer together should be better substitutes for each other.

To model this particular substitution pattern I follow Chu (1989) in assuming that ϵ_{lit} has an extreme value distribution with the bivariate CDF of ϵ_i and ϵ_j given by

$$F(\epsilon_i, \epsilon_j) = \exp \left(- \left[\exp \left(\frac{-\epsilon_i}{1 - \sigma_{ij}} \right) + \exp \left(\frac{-\epsilon_j}{1 - \sigma_{ij}} \right) \right]^{1 - \sigma_{ij}} \right) \times \exp [-(J - 2)\exp(-\epsilon_i)] \exp [-(J - 2)\exp(-\epsilon_j)] \quad (4)$$

The parameter σ_{ij} in the CDF captures the correlation between the error terms of region i and district j , on which I place the following restriction

$$\sigma_{ij} = \begin{cases} \sigma^* \frac{1}{D_{ij}^2} & \in [0, 1) \quad \text{for} \quad j = 1, 2, \dots, J \quad \neq \quad i = 1, 2, \dots, I \\ 0 & \text{for} \quad i = 0 \quad \text{or} \quad j = 0 \end{cases} \quad (5)$$

where D_{ij} is the straight line distance between i and j so that ϵ_i and ϵ_j are more highly correlated if regions i and j are geographically closer to each other.

I assume that a firm locates each employee in the region that maximizes the profit from his or her employment. This assumption together with the logit distribution of the error term ϵ_{ljt} yields a closed form solution for the probability of finding a randomly selected employee in region i at time t . Adding the assumption of spatial autocorrelation of the error term leads

to the following expression for this probability

$$\begin{aligned}
s_{it} &= \Pr. (l \in L_{it}) \\
&= \Pr. (\pi_{lit} > \pi_{ljt}) && \forall j \neq i \\
&= \Pr. (\delta_{it} - \delta_{jt} > \epsilon_{ljt} - \epsilon_{lit}) && \forall j \neq i \quad (6) \\
&= \frac{\sum_{i \neq j} \exp(\frac{\delta_{it}}{1-\sigma_{ij}}) \left[\exp(\frac{\delta_{it}}{1-\sigma_{ij}}) + \exp(\frac{\delta_{jt}}{1-\sigma_{ij}}) \right]^{-\sigma_{ij}}}{\sum_j \exp(\delta_{jt}) + \sum_{k=1}^{n-1} \sum_{m=k+1}^n \left[\exp(\frac{\delta_{kt}}{1-\sigma_{km}}) + \exp(\frac{\delta_{mt}}{1-\sigma_{km}}) \right]^{1-\sigma_{km}}}
\end{aligned}$$

It is important to point out that the alternative location choices $j = 0, 1, 2, \dots, J$ include the possibility of not locating an employee in any region if his or her employment would not be profitable anywhere. Including this outside option allows firms to increase employment in all regions over time if manufacturing becomes more profitable overall. This paper studies a period that witnessed the mechanization of manufacturing, incredible improvements in transportation, and substantial growth in manufacturing employment, all of which point to growing profitability over time. The outside option is therefore a crucial part of the location model.

3.2 Estimation

Previous applications of the paired combinatorial logit model have used individual level choice data and maximum likelihood to estimate the parameters of underlying utility functions (Chu 1989, Koppelman and Wen 2000). The published manufacturing censuses that are available for 19th century Germany aggregate these individual choices at the district level, which means that one cannot construct the empirical likelihood function needed for this approach. Berry (1994) demonstrates that it is possible to instead invert the probability function s_{it} to recover the mean profit levels δ_{it} and the unobserved ξ_{it} as functions of the model parameters. In the appendix I show that sufficient conditions for Berry's inversion hold for the probability function s_{it} in Equation 6. I use the fixed point algorithm proposed by Berry, Levinsohn and Pakes (1995) for the inversion, which cannot be done analytically.⁷ The inversion is nested inside the generalized method of moments estimation which solves for the parameters $\hat{\beta}$ and $\hat{\sigma}$.

The estimation can be summarized as follows. The identification of the parameters in the

⁷Nevo (2000) provides a practical guide to the model and estimation procedure developed by Berry (1994) and Berry, Levinsohn and Pakes (1995).

profit function is based on the moment condition

$$E(Z'\xi) = 0 \quad (7)$$

where ξ is the vector of unobserved economic conditions and Z is the set of exogenous regressors. The generalized method of moments estimator is given by

$$(\hat{\beta}, \hat{\sigma}) = \min_{\beta, \sigma} \left(Z'\hat{\xi}(Z'Z)^{-1}\hat{\xi}'Z \right) \quad (8)$$

Inside this minimization I use Berry, Levinsohn and Pakes' (1995) fixed point algorithm to solve for $\hat{\xi}$ by iterating over

$$\xi = \xi_0 + \log(s) - \log(s(\sigma, \beta, A^{\text{coal}}, A^{\text{lignite}}, A^{\text{German market}}, A^{\text{European market}}, \Gamma, \tau)) \quad (9)$$

I estimate standard errors for $\hat{\sigma}$ and $\hat{\beta}$ by using a numerical approximation to the Jacobian $\hat{G} = \nabla Z'\hat{\xi}$ to estimate the asymptotic variance

$$\hat{V} = (\hat{G}'W\hat{G})^{-1}\hat{G}'W\hat{\Omega}W\hat{G}(\hat{G}'W\hat{G})^{-1} \quad (10)$$

where $\hat{\Omega} = Z'\hat{\xi}\hat{\xi}'Z$ and $W = (Z'Z)^{-1}$.

3.3 Data and Variables

The information about employment in different industries comes from the manufacturing censuses of the German Zollverein in 1846 and 1861 and the censuses of the German Empire in 1875 and 1882. The results from these censuses were published at the district level for 76 districts in 1846, 87 districts in 1861, and 83 districts in 1875 and 1882. The districts are the "Regierungsbezirke" of the German states and the later German Empire, which were the second lowest administrative units above the smaller "Kreisaemter" and below the larger "Provinzen". The population statistics in Table 4 show that these districts were relatively large areas with an average population of approximately 500,000 people. Even the smallest district had more than 30,000 inhabitants. Most districts appear in all three censuses with no or only minor changes in their boundaries. However, I aggregate a number of districts in 1846 and 1861, which were merged with the foundation of the German Empire in 1871. These include Kassel, Waldeck, Anhalt, Reuss junge Linie, Wiesbaden, and Sachsen-Coburg-Gotha.

The Hanseatic cities Hamburg, Bremen and Luebeck, the Kingdom of Hannover, and the area of Alsace-Lorraine were not part of the Zollverein in 1846 or 1861, but joined the German Empire in 1871. I include the Hanseatic cities and Hannover in the empirical analysis, because I observe their transportation infrastructure, population, and mining output for the entire study period. Therefore they can be included consistently as consumer markets and potential sources of coal for the whole period. I exclude Alsace-Lorraine because I do not observe these variables for this area between 1846 and 1861. Alsace-Lorraine was a thriving center of mining and heavy industry, but the coal mines and population centers around Aachen and Trier were closer and better connected to the German regions in the sample. Thus, including Alsace-Lorraine would not change the measures of access to coal and consumer markets by very much.

The shipping costs are calculated using data from shapefiles provided by HGIS-Germany (Kunz 2008), which include the locations of all districts and their capitals as well as the locations of all railroads, navigable rivers, and canals in the area of the German Empire. The shapefiles also include information about the population and mining output of each district for most years between 1820 and 1914. To calculate the transportation costs between each pair of districts, I constructed four national transportation networks that include all of the contemporary railroads, navigable rivers, and canals for the four census years in my study period (Falzarano et al. 2007). I assigned the average freight rates from Table 2 to each mode of transportation and included the fixed transshipment costs for each node that allowed switching between railroads and waterways. To calculate access to German markets, I searched for the cheapest connection between each pair of district capitals using this transportation network.⁸ In cases where a district capital was not connected to any railroad or river, I created a straight line "road" to fill in the missing distance and assigned the estimated freight rate for transportation on horse carriage.

Access to European markets outside of Germany is not measured as precisely, because I did not have the same detailed transportation and population data available that I could access for Germany. I chose to include 11 national export markets based on the statistics about German railroad shipments from 1885 (Wolf 2009), which in the cases of Austria, Switzerland, Liechtenstein, the Netherlands, England, Denmark, and Sweden have obvious river or ocean connections to German cities along the shared borders or the coast. Since transportation on water was much cheaper than railroads for the entire study period, I assumed that German

⁸I use the district capital to measure the location of a district instead of the centroid, because in most cases the capital was located on the banks of a river or became the destination for the first railroad in the district, but the centroid was very often not located on the transportation network.

manufacturers chose these waterways and ocean crossings to export their goods. For Belgium, France, and Italy I used historical information about the construction dates and the length of the first railroads that connected these countries to Germany (Lotz 1900, Nietmann et al. 1892). For lack of more detailed information about regional infrastructure in these countries I chose the national capitals as the locations of these European markets and the closest German border cities as gateways that exports had to pass through. Figure 13 shows the locations of these European markets and the German cities which I defined as gateways. In some cases German districts had more than one gateway available for a particular export market; Warsaw in Poland for example could be reached by river from Bromberg and from Oppeln. In these cases I allowed each district in Germany to choose the route that minimized the total transportation costs for the entire journey. I used the national population estimates provided by HGIS (Kunz 2008) and Maddison (2010) as the market size for each export destination.

To find the lowest shipping costs for coal and lignite, I searched for the cheapest path between each district capital and each of the capitals of those districts that produced more than 10,000 tons of coal or lignite per year. Figures 2 and 3 show that there were a few coal mining regions with positive output that was less than 10,000 tons. I do not include these regions as sources of coal or lignite, because they would not have been able to supply a large manufacturing population with fuel. For those districts that produced more than 10,000 tons of coal or lignite I set C_{it}^{coal} or C_{it}^{lignite} equal to 1, which was less than the lowest price for shipping one ton for one kilometer. I also include Hamburg as a source of coal to account for the imports from Britain that came through this port and added the average freight charged by ships on the Channel (Fremdling 1995). Coal could have been imported from France and Belgium as well, but the rich coal deposits in the western German districts were closer and better connected to all German districts than the coal mines in these countries. I do not include any sources for lignite outside of Germany, because there is little evidence for international trade in this fuel.

Table 3 shows the sharp decline in the minimum cost of shipping one ton of coal or lignite to a district in Germany. The number of mining districts with output above 10,000 tons barely increased between 1846 and 1882, so that almost all of the change in access to fossil fuel can be attributed to the construction of railroads and the drop in freight rates. The summary statistics in Tables 4 and 5 describe changes in the size of consumer markets in Germany and Europe and the costs of reaching these markets. Recall that both variables enter the calculation of market access. The German and the European population increased between 1846 and 1882, which contributed to the growth of market access. However, this growth was

relatively small when it is compared to the incredible decline in the costs of reaching these markets. The average cost of shipping one ton of output to a regional market in Germany or a national market outside of Germany dropped by almost 90 percent between 1846 and 1882. This change in transportation costs is the main driver of the growth in market access during this period. Given the relatively similar construction of all four access variables and the similarly dramatic decline in shipping costs it is important to verify that the variables are not collinear. Table 7 shows that the correlation between each pair of variables is below 0.4 and therefore no cause for concern.

I aggregate individual industries into four broad sectors, which played important roles during early industrialization in Germany. The sectors are metal production, metal goods, machinery, and textiles, which together represent approximately 30 percent of total employment in manufacturing in 1846 and more than 40 percent in the later census years between 1861 and 1882 as shown in Table 6.⁹ The shares of district employment in each sector are based on total national potential employment, which includes all observed employees as well as all persons that would have been employed had the conditions been more profitable for a sector. To calculate this national potential employment, I multiplied the fraction of the German population that was employed in each sector in 1907 with the current population in each census year in my sample. Employment in manufacturing increased steadily during the 19th century, because industries became more profitable as industrialization progressed. Therefore the manufacturing census in 1907 provides a measure for the fraction of the population that could have been employed in a particular manufacturing sector earlier, if the conditions had been better already.¹⁰

3.4 Endogenous Railroads and Population

There are two different reasons for concern about endogeneity in the empirical model. Most German railways were built by private corporations, which considered local economic conditions and prospects for future growth when they decided on their routes. For example, Beyer (1978) writes about intense efforts by the merchants of Leipzig to secure a railroad connection to the rivers Saale and Elbe for easier access to the port of Hamburg. This suggests that

⁹Metals include iron and steel furnaces and mills, as well as silver, copper, nickel, lead, brass works. Metal goods include foundries and the production of metal pots, knives, and pins. Machines include guns, wagons, railway cars, ships, lamps, and scientific and musical instruments. Textiles include preparation of fibers, spinning, weaving, and finishing of cloth made from linen, silk, cotton, and wool. The exact number of industries varies across census years, because the number of manufacturing categories increased over time.

¹⁰The next manufacturing census after 1907 was collected in 1925. The occupational structure of this later census likely reflects changes in the economy that were due to World War I and not industrial progress.

industrial centers or places that had the potential to attract manufacturing received higher investment in railroad construction than places without this potential. I cannot measure many aspects of this economic potential directly, which means that they are included in the unobservable ξ . Since access to mines and markets is based on railroads, it is likely that all four access variables are correlated with ξ , which would cause a positive bias in the coefficient estimates for these variables. I use instrumental variables to address this concern.

To instrument for the cost of shipping one ton of coal to a district i at time t , I use the straight line distance between the capital of district i and the capital of the nearest coal mining district. I multiply this distance by $\frac{1}{\text{Network}_t}$, where Network_t is the length of the national transportation network at time t . The complete instrumental variable is defined as

$$C_{it}^{\text{coal,IV}} = D_i^{\text{coal}} \times \frac{1}{\text{Network}_t} \quad (11)$$

There are two ideas behind this instrument. The straight line distance between a district i and the nearest coal mining district should be correlated with the minimum cost of shipping coal to i , if this district had a direct connection to its nearest source of coal. The probability that this direct connection existed in a certain year should be correlated with the current size of the national transportation network, because the number of direct connections increased as more lines were added to the network. The complete instrument should be uncorrelated with unmeasured economic conditions in any particular district, because the straight line distance between districts is determined by nature and the total length of the transportation network was determined jointly by all districts with each individual district representing only a small share of the total network. The instrument for access to lignite is defined in the same way, but uses the straight line distance to the nearest lignite mining district.

The instruments for shipping costs in the market access variables are constructed similarly. To instrument for access to German markets, I use the straight line distances between each pair of districts in Germany multiplied by the inverse of the total length of the national transportation network. The argument for this instrument is again that the straight line distance between two places should be correlated with the transportation costs between them if they share a direct connection. The length of the national transportation network should have positively affected the probability that this direct connection actually existed. Access to German markets also includes district population, which raises a separate concern about endogeneity. Figure 4 shows the shift of the German population from the southwest to the coal mining areas in the west and the east. As a result of this shift, coal mining regions became large markets

for manufactured goods as well. Therefore, the empirical analysis could attribute some of the impact of access to coal to access to consumer markets, which would imply an upward bias in the coefficient estimates for market access and a downward bias in the coefficients on access to coal. To address this concern, I instrument for the current district population with the population lagged by 26 years, which puts the first observation in 1820 before the beginning of German industrialization. The full instrument is given by

$$\sum_j \frac{1}{C_{ijt}^{\text{German market,IV}}} P_{jt}^{IV} = \sum_j \frac{1}{D_{ij}^{\text{line}}} \times \frac{1}{\text{Network}_t} \times P_{j,t-26} \quad (12)$$

To instrument for the transportation costs in access to European markets I use the straight line approach together with the length of the German national transportation network. I do not lag the European population estimates, because it seems unlikely that regional economic conditions in Germany had a large influence on national populations in the neighboring countries.

4 Results and Discussion

Before turning to the estimation of the paired combinatorial logit model, I present the results from a simpler multinomial logit model. The two models differ only in their specification of the logit error term ϵ_{lit} , for which the simpler model assumes independence across individuals, time, and space. Comparing the results from this simpler estimation with the findings from the paired combinatorial logit model provides some indication for the endogeneity of access to fuel, and markets as well as unobserved spatial spillovers. Furthermore, the residuals from the multinomial logit regression can be used to test for spatial spillovers directly. The discussion of the results from the full combinatorial logit model is presented in the second part of this section.

4.1 Assessment of Endogeneity and Spatial Spillovers

The multinomial logit model has the advantage that its share function can be linearized using a simple log transformation, so that the coefficients in the profit function can be estimated with aggregate data and ordinary least squares (OLS) or two stage least squares (2SLS). Comparing the OLS to the 2SLS results provides some indication for the endogeneity of the access variables and whether the instruments address this problem. Before turning to this

comparison I want to present evidence for the strength of the instrumental variables that are used in the 2SLS regression and later in the estimation of the paired combinatorial logit model. Table 8 shows the coefficient estimates and standard errors from the first stage of the 2SLS regression, which reveal the expected positive and statistically significant relationships between each access variable and its instrument. The small standard errors on the diagonal from the top-left to the bottom-right corner of the table show that the instruments for access to coal and lignite as well as German consumer markets are very strong. All of the standard errors translate into t-statistics above 25.00, which implies that the coefficients are statistically significant at the 0.0001 percent confidence level. Only the standard error on the instrument for access to European markets in the bottom-right corner of the table is relatively large and translates into a t-statistic of only 5.63, which indicates some potential for weak instrument bias for this last access variable.

Comparing the estimates in Columns 1 and 2 as well as Columns 4 and 5 in Tables 9 and 10 shows that the instrumental variables increase the size of the coefficients for coal and lignite and decrease the coefficients for German consumer markets. This is consistent with the predicted bias due to the shift of population from the southwest to the mining areas in the west and the east of Germany. The OLS estimation wrongly attributes the growth of employment in the mining regions to the growing number of consumers in the areas. The instrument for access to German markets reduces this bias by lagging the population count by 26 years. The second concern about endogeneity was related to the construction of railroads in regions with a high potential for growth in manufacturing, which was expected to cause an upward bias in the coefficients on all four access variables. The regression results indicate that this second bias is smaller than the first, because instrumenting for both sources of endogeneity results in an increase of the coefficients on access to coal instead of a decrease.

The findings from the 2SLS multinomial logit regression are themselves potentially biased due to the restrictive substitution pattern of the multinomial logit model. Furthermore, the standard errors are possibly inconsistent as a result of unobserved spatial spillovers. The level of spatial autocorrelation in the residuals from the 2SLS regression can provide an indication of the severity of both issues. Table 11 offers an assessment of this autocorrelation using Moran's I, which measures the global spatial autocorrelation or average similarity between each residual and its neighboring values (Bailey and Gatrell 1995). The index Moran's I can range between -1 for perfect negative correlation and $+1$ for perfect positive correlation. The table shows that most sets of residuals exhibit positive autocorrelation, which is statistically significant in seven of the sixteen cases. This indicates that not accounting for spatial spillovers

could indeed lead to inconsistent estimation results.

The coefficient estimates from the paired combinatorial logit model (PCL), which addresses the concerns about endogeneity and spatial spillovers, are presented in Columns 3 and 6 of Tables 9 and 10. Comparing the estimates from the PCL in these columns to the results from the two stage least squares estimation of the multinomial logit model (2SLS) in Columns 2 and 5 shows changes in both the coefficient estimates and the standard errors. All of the coefficients for access to coal are larger in magnitude in the PCL compared to the 2SLS and all of them are statistically significant compared to only two out eight coefficients from the 2SLS. The high geographic concentration of manufacturing around the coal belt suggests that the larger PCL estimates better capture the relationship between coal mining and industry. The estimates for access to German markets are almost identical in the two different models and statistically significant in all cases. However, the magnitudes of the coefficients for access to European markets are smaller in the PCL compared to the 2SLS and none of the PCL estimates are statistically significant. I pointed out earlier that access to European markets is relatively poorly measured, therefore, it is not surprising that the impact of this variable is statistically insignificant. In addition to the coefficient estimates for access to coal and access to markets, Columns 3 and 6 of Tables 9 and 10 also show the estimated values of σ which captures the spatial autocorrelation of the logit error term. All four estimates of σ are positive, which is consistent with the argument that, all else equal, regions which are closer to each other are better substitutes. The finding lends support to the choice of the combinatorial logit model for this analysis.

4.2 Effects of Changing Access

The nonlinearity of the estimation makes it difficult to interpret the coefficients in Tables 9 and 10 directly. Therefore, Table 12 presents the average impact of a 1 Mark increase in the minimum costs of shipping one ton of coal or lignite to a district or shipping one ton of manufactured output from this district to a consumer market.¹¹ I calculated the effects of a fixed rise in shipping costs because it allows me to compare the disadvantage of expensive access to fuel to the disadvantage of expensive access to consumer markets. The thought experiment behind this comparison is that of a bureaucrat deciding which railroad or canal project to support to help manufacturers in his region. If the impact of a 1 Mark change in the

¹¹Since I assume that every district sells output to all other districts and foreign trade partners, the average marginal effect of increasing the costs of market access are also averaged across all individual markets. This means that estimated effect is the average impact of worsening access to just one market.

costs of shipping coal is higher than the impact of a 1 Mark change in the costs of shipping manufactured goods, then he should invest in infrastructure that would link his region to the coal belt. If, on the other hand, the impact of changing the shipping costs to consumer markets is larger, then he should invest in railroads and canals that would link his region to densely populated areas.¹²

The impact of these shipping costs is expressed as the number of employees that a region would lose if its costs of access increased. Column 1 in Table 12 shows the average change in employees for each sector and each access variable using all observations from 1846, 1861, 1875, and 1882. Columns 2 and 3 show the results from repeating the entire analysis for two shorter periods that cover the early industrial take-off from 1846 to 1861 and the end of the first wave of industrialization.¹³ Ignoring the effects of access to European markets, which statistically significant in very few cases, the average impact of higher shipping costs ranges from $-4,043$ to $+1,153$ employees. These are large effects considering that average district employment was between 1,033 in metal production in 1846 and 13,386 in textiles in 1882 as shown in Table 13. However, looking back at Figures 11 to 14 suggests that the effects are not unrealistic. The maps show that in each of the four manufacturing sectors employment increased by over 2,000 people in many districts. In addition, the maps for metal goods and textiles show that districts in Bavaria lost more than 3,000 employees in these sectors as other areas made gains.

The relative size of employment losses shows that proximity to coal was more important than proximity to consumers for the location of metals. On average, a district would have lost 1,747 employees as a result of higher costs for shipping coal compared 531 employees due to higher costs for shipping output to German markets. Columns 2 and 3 confirm that coal mattered much more to metal producers than consumers throughout the first wave of industrialization. Metal production was energy intensive and raw metal was used for investment goods like rails, bridges, and factories, therefore it makes sense that access to fuel was more important than

¹²Concerning the magnitude of this change, 1 Mark was slightly less than the average daily wage of 1.14 Mark for a blacksmith in Wuerttemberg between 1840 and 1849 or the 1.23 Mark for a coal miner in the Rhineland in 1846 (Kuczynski 1937). One Mark is also less than the standard deviations of the shipping costs for coal and lignite, which were approximately 9 Marks, and the standard deviations of the shipping costs to German and European consumer markets, which were approximately 30 Marks. However, the high geographic concentration of manufacturing indicates that these costs had their highest impact on short distances.

¹³The estimation is based on total potential employment in each sector, which changes every year in accordance with population growth, so I had to choose a particular year to calculate these effect. I chose 1861 for Column 1, 1846 for Column 2, and 1875 for Column 3. Choosing other years would change the absolute impact on employment, but the relative effects across different types of access and different sectors of manufacturing would be identical.

access to consumers. Comparing the impact of access to coal and access to lignite indicates that lignite was a poor substitute for coal, which is also not surprising since lignite could not be used in coke blast furnaces.

The findings for metal goods look very different from the results for raw metal production. As expected, the negative effects of higher shipping costs to German markets show that access to consumers mattered for this sector. In contrast, higher costs for access to coal and lignite had a positive impact on employment, which means that manufacturers of metal goods stayed away from mining regions. This is surprising because making wire and pots requires reheating, pressing, and pulling metal into shape, which means that metal goods manufacturers had a high demand for fuel. Columns 2 and 3 show that this positive relationship between employment and the shipping costs for fuel is relatively large in the early sample that includes 1846 and 1861, but becomes negative and insignificant in the later sample that includes 1875 and 1882. This indicates that metal goods manufacturers moved closer to coal and lignite regions toward the end of the first wave of industrialization. Figure 6 shows substantial growth of employment in metal goods production in Silesia and around Berlin after 1846 and the disappearance of a large cluster of employment in Bavaria, which supports this interpretation. The historical narrative about metal goods production in Germany offers an explanation for the late timing of this relocation. Fremdling (1981) points out that in contrast to ironworks, manufacturers of iron goods remained in traditional centers of metal production during the first half of the 19th century and used imported iron together with local charcoal to make knives, wire, and other iron and steel products.

The results for machine tool making show a change in the relative importance of fuel and consumer markets between the early industrial take-off and the end of the first wave of industrialization. During the early take-off between 1846 and 1861 higher shipping costs for coal would have led to a loss of 2,538 employees compared to a much smaller loss of 1,299 employees from higher costs for shipping output to market. For lignite the average effect was an even higher loss of 3,172 employees on average. Fuel was not a major input in machine tool making, but mining was the first sector that used steam engines and it was the only sector that used steam power widely in the early 19th century. This means that demand for large power tools was concentrated in mining regions during the early industrial take-off. Indeed, Redlich (1944) points out that all of Germany's leaders in steam engine construction worked in the machine shops of mining operations. My results for the later period that includes 1875 and 1882 indicate that access to consumer markets became more important than mining toward the end of the first wave of industrialization. Between 1875 and 1882 an increase in the

shipping costs to German markets would have led to a loss of 2,417 employees compared to only 164 and 123 due to more expensive access to coal and lignite. Figure 7 shows that during this period new centers of machine tool making appeared on the German coast and in Bavaria, areas which were far away from the coal belt and the lignite fields in central Germany. While employment on the coast was related to ship building, the cluster in Bavaria could have served manufacturers that remained in this traditional manufacturing center. Figures 6 and 8 show that the southern state was able to keep substantial employment in metal goods and textile production despite its distance from coal and lignite mines.

The most surprising findings of my analysis are for textile production. Column 1 in Table 12 shows that higher shipping costs for coal would have caused an average loss of 4,043 employees compared to only 2,123 due to higher shipping costs to German markets. Textile makers needed fuel to run steam powered spinning and weaving frames, but energy is generally considered a minor input in this sector relative to labor and raw materials. Anecdotal evidence suggests that textile mills chose locations close to coal mines. The 1853 brochure of the initial public offering of the Gladbach Spinning and Weaving Company (Gladbacher Spinnerei und Weberei) emphasizes the firm's proximity to the coal fields of the Ruhr in an attempt to convince potential investors of its great locational advantage (Adelmann 1966). It is possible that the high weight of coal relative to raw fibers and finished cloth was sufficient to draw textile mills with steam powered tools to the mining areas.

A second explanation for the location of textiles comes from the industry's dependence on machine tool makers. Powered textile frames had to be installed and maintained by trained engineers who knew about steam engines and power transmission. In Germany almost all of these technicians worked for mining operations in the early 19th century, a point which I made earlier in this section. The Aachen Wire Company (Draht-Fabrik-Compagnie in Aachen) provides an example for the connections between all three sectors. The company was founded in 1822 by leading woolen producers from Aachen to supply textile mills with card wire (Hatzfeld 1961). The machines for the wire factory were produced and installed by the firm Englerth, Reuleaux & Dobbs which had been founded in 1818 as a maker of mining equipment in Eschweiler only 20 kilometers to the west of Aachen. Mining gave rise to machine tool making, which in turn supported the modernization of textile production, so that all three sectors formed agglomerations in the same regions along the coal belt.

5 Conclusion

Coal became an important input for manufacturing during the first wave of industrialization as plants adopted steam powered machinery and switched from charcoal to coke fuel. Coal deposits were geographically concentrated and transportation on roads was prohibitively expensive, therefore access through railroads and waterways was an important factor for the growth of manufacturing. This paper shows that access to coal was more important than access to consumer markets for regional employment in the production of metals and textiles. In metal goods and machine tool making the relative importance of coal and consumer markets changed during the first wave of industrialization. In machine tool making coal became less important than consumer markets as the industry branched out to serve other manufacturers. In metal goods coal became more important than consumer markets as the sector went through its late transition from charcoal to coal based technologies. Together the results indicate that the large growth of metal production, metal goods, and machine tool making would not have happened without cheap access to coal. Even employment in textile production, which decreased in many areas with poor access to coal, might have been much lower had Germany not possessed large coal fields.

The findings contribute to two different discussions in economic history. Economic historians have long been interested in the role of natural resources in economic development. The view that coal deposits were important for the British Industrial Revolution (Allen 2009, Pomeranz 2001, Wrigley 1988) has recently been challenged by Clark and Jacks (2007) who argue that manufacturers could have relied on coal imports from other European countries instead of domestic production. Coal does not have to be domestic to be cheap; today Europe and the United States import coal from China because their high labor costs make imports cheaper than domestic production. However, it is interesting to note that Germany did not develop industrial centers near its northern coast during the 19th century despite coal imports from Britain. The costs of shipping one ton of coal across the Channel fell from over 11 to 7 Marks between 1846 and 1882, but the lack of manufacturing growth in the north suggests that this was still too expensive for industrial development. Instead, the large growth of heavy industry and machine tool making took place at the same time and in the same places as the expansion of German coal mining. My findings therefore support the view that domestic coal deposits were a large advantage for industrial development.

The important role of the railroad boom was to connect the coal mining regions with distant consumer markets. Railroad construction dramatically lowered the costs for overland

transportation and thereby made it possible for manufacturers to concentrate production in regions with cheap access to coal without losing access to large consumer markets elsewhere. In Germany metal goods producers and textile makers located near the coal belt even though large population centers like Hamburg, Berlin, and Munich were quite far from this area. The manufacturers in the coal belt were able to reach customers in these important markets, because railroads had created direct connections between all larger cities in Germany. The high transportation costs of coal and other connections with mining made it important to be close to the coal belt, but the proximity to coal was only useful as long as it did not make the costs of reaching final consumers prohibitively high.

My findings also suggest that the geographic concentration of coal fields in Germany can account for a substantial part of the variation in regional industrial development. Previous discussions of the inequality between German regions have often stressed the stark political differences between the many German states, which persisted even after the foundation of the German Empire in 1871 (Tipton 2003, Ogilvie 1996, Kellenbenz 1991). There is no doubt that the splintered German states and cities pursued very different political and economic agendas which influenced regional industrialization. However, in contrast to these political structures the location of manufacturing changed significantly during the second half of the 19th century. The coal fields in the Ruhr Area and Upper Silesia were agricultural areas with very little manufacturing employment before they transformed into centers of heavy industry, machine tool making, and even textile production. At the same time old manufacturing centers in Bavaria lost much of their employment in these sectors. This suggests that the geographic concentration of coal played a large role in shaping regional inequality during the first wave of industrialization in Germany.

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B Tables

Table 1: Water and Steam Power Use 1875

		Powered Plants	Mean Hp	Plants
Textile	Steam	0.51	24.37	
	Water	0.28	8.31	4,495
Metal	Steam	0.53	110.74	
	Water	0.085	10.22	1,647
Metal goods	Steam	0.16	2.49	
	Water	0.08	1.45	5,258
Machines	Steam	0.36	7.14	
	Water	0.06	0.78	4,747

Sources: Statistik des Deutschen Reich AF Vol.34 and Vol.35 (1879), HGIS-Germany (Kunz 2008)

Table 2: Average Freight Rates (Pfennig per tonkilometer)

Year	Waterways	Railroads	Roads	Ocean	Transshipment
1846	4.50 ¹	11.20 ⁵	40 ⁷	1.61 ⁸	50 ⁹
1861	1.60 ²	4.65 ⁵	40 ⁷	1.53 ⁸	50 ⁹
1875	1.55 ³	3.42 ⁵	40 ⁷	1.21 ⁸	50 ⁹
1882	0.97 ⁴	3.02 ⁶	40 ⁷	1.05 ⁸	50 ⁹

Sources:

¹ Average freight rate of shipments on the Elbe between Magdeburg, Dresden, and Hamburg in the year 1850 (Teubert 1918)

² Average freight rate of shipments on the Rhine between Strassburg, Saarbruecken, and Muehlhausen in the year 1869 (Teubert 1918)

³ Average freight rate of shipments on rivers (1.68) and canals (1.42) in the German Empire in the year 1872 (Teubert 1918)

⁴ Average freight rate of shipments on the Elbe between Aussig and Magdeburg in the year 1882 (Heubach 1898)

⁵ Average freight rate for coal in the years 1848, 1860, and 1870 (Fremdling 1979)

⁶ Freight rate for coal between Korbitz and Berlin in the year 1882 (Heubach 1898)

⁷ Average freight rate on horse carriage in the year 1840 (Fremdling 1979)

⁸ Average freight rate for coal in shipments from England to Hamburg in the years 1850/54, 1860/64, 187/75, and 1880/84 (Fremdling 1979)

⁹ Estimated average transshipment rate for 1913 (Regul 1933)

Table 3: Summary Statistics Transportation Costs of Coal and Lignite

	Year	N	Mean	Std.Dev.	Min	Max
Coal	1846	62	1,498.55	1,651.49	1	6,957.11
	1861	73	536.54	499.48	1	1,850.04
	1875	80	448.13	423.57	1	1,926.98
	1882	80	323.11	312.14	1	1,480.40
Lignite	1846	62	1,155.91	1,270.57	1	5,635.28
	1861	73	538.13	579.62	1	2,653.03
	1875	80	380.98	355.89	1	1,735.84
	1882	80	292.70	284.39	1	1,586.93

Sources: HGIS-Germany (Kunz 2008), Fremdling (1979), Regul (1933), Teubert (1918), and Heubach (1898)

Table 4: Summary Statistics Access to German Markets

	Year	N	Mean	Std.Dev.	Min	Max
Population	1846	80	455,921.00	262,165.90	30,068.00	1,165,994.00
	1861	80	479,140.20	287,108.00	34,391.00	1,295,959.00
	1875	80	514,334.80	350,327.50	33,133.00	1,472,254.00
	1882	80	552,429.60	381,510.10	35,000.00	1,654,511.00
Transport Costs	1846	62	9,683.69	1,859.27	7,094.25	15,137.02
	1861	73	2,192.18	585.06	1,532.26	4,240.07
	1875	80	1,530.45	354.18	1,080.20	2,831.98
	1882	80	1,110.56	278.24	794.48	2,138.24
Market Access	1846	62	466.29	261.05	36.03	1,175.42
	1861	73	507.66	288.56	55.90	1,324.96
	1875	80	555.98	351.75	65.44	1,513.28
	1882	80	644.68	428.40	85.95	2,437.33

Sources: HGIS-Germany (Kunz 2008), Fremdling (1979), Regul (1933), Teubert (1918), and Heubach (1898)

Table 5: Summary Statistics Access to European Markets

	Year	N	Mean	Std.Dev.	Min	Max
Population	1846	11	9,953,476	124,053	6,572	35,829,000
	1861	11	10,706,490	13,008,680	7,994	37,390,000
	1875	11	11,639,570	13,859,570	8,664	38,221,000
	1882	11	12,658,970	14,734,870	9,593	39,337,000
Transport Costs	1846	62	8,853.80	1,860.83	5,700.65	13,727.10
	1861	73	2,797.14	1,030.76	1,999.67	11,072.76
	1875	80	1,982.04	324.69	1,530.10	3,140.89
	1882	80	1,479.57	279.05	1,098.21	2,483.88
Market Access	1846	62	23.17	14.45	10.84	71.51
	1861	73	62.32	22.34	32.63	166.45
	1875	80	84.21	27.17	50.20	235.89
	1882	80	121.28	34.81	68.51	289.38

Sources: HGIS-Germany (Kunz 2008), Madison (2010), Fremdling (1979), Regul (1933), Teubert (1918), and Heubach (1898)

Table 6: Employment in Manufacturing Sectors

	1846	%	1861	%	1875	%	1882	%
Metal	64,046	6.17	89,060	2.9	219,600	5.03	206,240	4.36
Metal goods	130,262	12.56	267,764	8.86	305,280	7.00	433,280	9.15
Machines	45,198	4.45	156,074	5.16	308,720	7.07	349,520	7.38
Textiles	621,860	5.99	769,113	25.46	807,200	18.50	1,070,880	22.62
Manufacturing	1,036,826	100.00	3,020,521	100.00	4,363,440	100.00	4,734,320	100.00
N	62		73		80		80	

Sources: Tabellen der Handwerker und Fabriken des Zollvereins 1846 and 1861, Statistik des Deutschen Reich AF Vol.34 and Vol.35 (1879) and NF Vol.6 and Vol.7 (1885)

Table 7: Correlations between Types of Access

	A^{coal}	A^{lignite}	$A^{\text{German market}}$	$A^{\text{European markets}}$
A^{coal}	1.0000	0.0225	0.3805	0.1010
A^{lignite}	0.0225	1.0000	0.2544	-0.0622
$A^{\text{German market}}$	0.3805	0.2544	1.0000	0.1498
$A^{\text{European markets}}$	0.1010	-0.0622	0.1498	1.0000

Table 8: Instrumental Variables

	A^{coal}	A^{lignite}	$A^{\text{German market}}$	$A^{\text{Europe market}}$
$A^{\text{coal,IV}}$	7.2086 (0.1601)	-0.1601 (0.1420)	0.3435 (0.1714)	1.4399 (2.7698)
$A^{\text{lignite,IV}}$	-0.2129 (0.1096)	7.2554 (0.1463)	-0.1703 (0.1564)	0.0575 (2.1385)
$A^{\text{German market,IV}}$	0.4921 (0.2549)	0.0372 (0.2552)	8.4677 (0.3209)	1.9523 (4.0630)
$A^{\text{Europe market,IV}}$	0.0391 (0.0514)	0.0297 (0.0393)	-0.0304 (0.0416)	0.397 (0.0720)
Year Effects	Yes	Yes	Yes	Yes
Provincial Effects	Yes	Yes	Yes	Yes
N	295	295	295	295
F (excl. instruments)	617.07	682.76	203.83	9.34
Partial R^2 (excl. instruments)	0.7728	0.7902	0.7240	0.2544

Heteroskedasticity standard errors in parenthesis

Table 9: Coefficient Estimates for Metals and Metal goods

	Metals			Metal goods		
	MNL		PCL	MNL		PCL
	OLS	2SLS		OLS	2SLS	
	(1)	(2)	(3)	(4)	(5)	(6)
A^{coal}	0.6958 (0.1848)	0.8794 (0.2421)	1.5052 (0.1886)	0.0818 (0.2491)	0.0692 (0.3340)	-0.4775 (0.0058)
A^{alignite}	0.1769 (0.1500)	0.2472 (0.1714)	0.2629 (0.0713)	0.0409 (0.1726)	-0.0076 (0.2290)	-0.3499 (0.0118)
$A^{\text{German market}}$	2.2287 (0.4462)	1.7424 (0.5118)	1.2148 (0.0158)	1.5842 (0.3626)	1.0379 (0.4137)	1.1373 (0.0123)
$A^{\text{Europe market}}$	0.1451 (0.0028)	0.0131 (0.0066)	0.0186 (0.0308)	0.0414 (0.0026)	0.1177 (0.0064)	0.0024 (0.0443)
σ			0.2384 (0.1907)			0.2463 (0.0533)
Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Provincial Effects	Yes	Yes	Yes	Yes	Yes	Yes
N	290	290	290	283	283	283
F	31.66	25.98		81.29	65.47	
Centered R^2	0.6438	0.6379		0.7433	0.7349	

MNL regressions: heteroskedasticity robust standard errors in parenthesis

PCL: standard errors based on numerical approximation of the Jacobian matrix
(for details see the estimation section in the paper)

Table 10: Coefficient Estimates for Machines and Textiles

	Machines			Textiles		
	MNL		PCL	MNL		PCL
	OLS	2SLS		OLS	2SLS	
	(1)	(2)	(3)	(4)	(5)	(6)
A^{coal}	0.0132 (0.2093)	0.1097 (0.2645)	1.2227 (0.1299)	0.4250 (0.1801)	0.3912 (0.2666)	0.8772 (0.1360)
A^{lignite}	0.2538 (0.1548)	0.3372 (0.1880)	1.3840 (0.0787)	0.2854 (0.1469)	0.2824 (0.1813)	0.3897 (0.0444)
$A^{\text{German market}}$	1.7091 (0.4458)	1.2224 (0.5300)	1.2016 (0.0520)	1.7919 (0.4229)	1.7650 (0.6039)	1.1668 (0.0250)
$A^{\text{Europe market}}$	0.0758 (0.0022)	0.0887 (0.0062)	-0.0002 (0.2699)	0.0709 (0.0021)	0.0691 (0.0053)	0.0136 (0.0111)
σ			0.0005 (0.1620)			0.2356 (0.1738)
Year Effects	Yes	Yes	Yes	Yes	Yes	Yes
Provincial Effects	Yes	Yes	Yes	Yes	Yes	Yes
N	287	287	287	295	295	295
F	25.72	23.11		27.08	23.26	
Centered R^2	0.6572	0.6519		0.5974	0.5972	

MNL regressions: heteroskedasticity robust standard errors in parenthesis

PCL: standard errors based on numerical approximation of the Jacobian matrix
(for details see the estimation section in the paper)

Table 11: Spatial Autocorrelation of 2SLS Multinomial Logit Residuals

	Metals	Metal goods	Machines	Textiles
1846	0.0265 (0.2674)	0.2385 (0.0006)	0.1655 (0.0084)	0.0830 (0.0800)
1861	0.1429 (0.0142)	0.2943 (0.0012)	0.2608 (0.0006)	-0.0608 (0.2526)
1875	0.0003 (0.4218)	-0.0086 (0.5318)	-0.0866 (0.1300)	0.0519 (0.1772)
1882	-0.0582 (0.2502)	0.1010 (0.0546)	-0.0088 (0.5506)	0.0966 (0.0574)

P-values in parenthesis based on 4999 permutations

The spatial autocorrelation is measured by Morans' I based on 4 nearest neighbor spatial weighting matrix. The statistic ranges from -1 (perfect negative correlation) to 1 (perfect positive correlation).

Table 12: Average Marginal Effects of a 1 Mark Increase in Transportation Costs

	1846-82	1846-61	1875-82
	(1)	(2)	(3)
1. Metal			
Coal	-1747***	-393***	-910***
Lignite	-155***	-125***	-26***
German market	-531***	125***	-338***
European market	-2123	-411***	-486
2. Metal goods			
Coal	348***	1153***	-41
Lignite	522***	1013***	-246
German markets	-975***	-1379***	-369***
European markets	-104	-1857	-369
3. Machines			
Coal	-2014***	-2538***	-164
Lignite	-2280***	-3172***	-123
German markets	-935***	-1299***	-2417***
European markets	37	-30	-164
4. Textile			
Coal	-4043***	-5835***	-2605**
Lignite	-1155***	-1945***	-453
German markets	-2214***	-3934***	-1246***
European markets	-1155	-1245	-793

*** significant at $p < 0.01$, ** significant at $p < 0.05$, * significant at $p < 0.1$

The change in employees is based on the calculation of employment shares, which uses each industry's employment in 1907 and adjusts it for the population growth between 1846 and 1907. The average marginal effects in Column 1 are based on employment shares in 1861, Column 2 uses 1846 as the base year, and Column 3 uses 1875 as the base year.

Table 13: Summary Statistics Regional Employment

	Year	N	Mean	Std.Dev.	Min	Max
Metal	1846	62	1,033	1,438	0	8,492
	1861	73	1,221	2,152	0	15,752
	1875	80	2,745	5,841	29	39,189
	1882	80	2,588	6,483	7	45,096
Metal goods	1846	62	2,101	2,798	0	10,520
	1861	73	3,668	3,205	0	18,642
	1875	80	3,816	4,052	171	27,457
	1882	80	5,416	5,733	265	39,304
Machines	1846	62	729	848	0	3,580
	1861	73	2,139	1,806	0	9,348
	1875	80	3,860	3,822	84	25,675
	1882	80	4,369	4,398	96	23,905
Textiles	1846	62	10,030	15,042	2	93,287
	1861	73	10,536	16,392	2	97,557
	1875	80	10,091	14,375	362	95,792
	1882	80	13,386	21,702	293	134,388

Sources: Source: Tabellen der Handwerker und Fabriken des Zollvereins 1846 and 1861, Statistik des Deutschen Reich AF Vol.34 and Vol.35 (1879) and NF Vol.6 and Vol.7 (1885)

A Berry's Inversion

Since the combinatorial logit model differs considerably from the random coefficient model that Berry (1994) and Berry, Levinsohn and Pakes (1995) consider, I prove in this section that sufficient conditions are satisfied for the inversion of the probability function of the combinatorial logit model. Berry (1994) shows that sufficient conditions for the inversion of the probability function s_{it} are

1. $\frac{\partial s_{it}}{\partial \delta_{it}} > 0$
2. $\frac{\partial s_{it}}{\partial \delta_{jt}} < 0$

The probability function

$$s_i = \frac{\sum_{i \neq j} \exp\left(\frac{\delta_i}{1 - \sigma_{ij}}\right) \left[\exp\left(\frac{\delta_i}{1 - \sigma_{ij}}\right) + \exp\left(\frac{\delta_j}{1 - \sigma_{ij}}\right) \right]^{-\sigma_{ij}}}{\sum_j \exp(\delta_j) + \sum_{k=1}^{n-1} \sum_{m=k+1}^n \left[\exp\left(\frac{\delta_k}{1 - \sigma_{km}}\right) + \exp\left(\frac{\delta_m}{1 - \sigma_{km}}\right) \right]^{1 - \sigma_{km}}} \quad (13)$$

can be rewritten as

$$s_i = \frac{\sum_{i \neq j} \exp\left(\frac{\delta_i}{1 - \sigma_{ij}}\right) \left[\exp\left(\frac{\delta_i}{1 - \sigma_{ij}}\right) + \exp\left(\frac{\delta_j}{1 - \sigma_{ij}}\right) \right]^{-\sigma_{ij}}}{\sum_{k=0}^{n-1} \sum_{m=k+1}^n \left[\exp\left(\frac{\delta_k}{1 - \sigma_{km}}\right) + \exp\left(\frac{\delta_m}{1 - \sigma_{km}}\right) \right]^{1 - \sigma_{km}}} \quad (14)$$

For simplification define

$$\begin{aligned} A_i &= \sum_{i \neq j} \exp\left(\frac{\delta_i}{1 - \sigma_{ij}}\right) \\ H_i &= \sum_{i \neq j} \exp\left(\frac{\delta_i}{1 - \sigma_{ij}}\right) \left[\exp\left(\frac{\delta_i}{1 - \sigma_{ij}}\right) + \exp\left(\frac{\delta_j}{1 - \sigma_{ij}}\right) \right]^{-\sigma_{ij}} \\ G &= \sum_{k=0}^{n-1} \sum_{m=k+1}^n \left[\exp\left(\frac{\delta_k}{1 - \sigma_{km}}\right) + \exp\left(\frac{\delta_m}{1 - \sigma_{km}}\right) \right]^{1 - \sigma_{km}} \end{aligned} \quad (15)$$

Note that

$$\begin{aligned}
\frac{\partial s_i}{\partial \delta_i} &= \frac{\partial H_i}{\partial \delta_i} \frac{1}{G} + H_i \frac{1}{G^2} \frac{\partial G}{\partial \delta_i} \\
&= \frac{1}{G} \left[\frac{\partial H_i}{\partial \delta_i} - \frac{H_i}{G} \frac{\partial G}{\partial \delta_i} \right] \\
&= \frac{1}{G} \left[\frac{\partial H_i}{\partial \delta_i} - s_i \frac{\partial G}{\partial \delta_i} \right]
\end{aligned} \tag{16}$$

where

$$\begin{aligned}
\frac{\partial H_i}{\partial \delta_i} &= \sum_j \frac{1}{1 - \sigma_{ij}} A_i [A_i + A_j]^{-\sigma_{ij}} + A_i (-\sigma_{ij}) [A_i + A_j]^{-1 - \sigma_{ij}} \frac{1}{1 - \sigma_{ij}} A_i \\
&= \sum_j \frac{1}{1 - \sigma_{ij}} A_i [A_i + A_j]^{-\sigma_{ij}} \left[1 - \frac{\sigma_{ij} A_i}{A_i + A_j} \right] \\
&= \sum_j \frac{1 - \frac{\sigma_{ij} A_i}{A_i + A_j}}{1 - \sigma_{ij}} A_i [A_i + A_j]^{-\sigma_{ij}} \\
&> \sum_j A_i [A_i + A_j]^{-\sigma_{ij}} \\
&= H_i
\end{aligned} \tag{17}$$

and

$$\begin{aligned}
\frac{\partial G_i}{\partial \delta_i} &= \sum_j (1 - \sigma_{ij}) A_i [A_i + A_j]^{-\sigma_{ij}} \frac{1}{1 - \sigma_{ij}} A_i \\
&= H_i
\end{aligned} \tag{18}$$

Therefore

$$\begin{aligned}
\frac{\partial s_i}{\partial \delta_i} &= \frac{1}{G} \left[\frac{\partial H_i}{\partial \delta_i} - s_i \frac{\partial G}{\partial \delta_i} \right] \\
&> \frac{1}{G} [H_i - s_i H_i] \\
&= \frac{H_i}{G} [1 - s_i] \\
&= s_i [1 - s_i] \\
&> 0
\end{aligned} \tag{19}$$

Also note that since $\sigma \in [0, 1)$

$$\begin{aligned}
\frac{\partial s_i}{\partial \delta_j} &= \frac{1}{G} \left[\frac{\partial H_i}{\partial \delta_j} - H_i \frac{-1}{G_i^2} \frac{\partial G_i}{\partial \delta_i} \right] \\
&= A_i (-\sigma_{ij}) [A_i + A_j] \frac{1}{1 - \sigma_{ij}} A_j \frac{1}{G} \\
&\quad + H_i \frac{-1}{G^2} \sum_j (1 - \sigma_{ij}) A_i [A_i + A_j]^{-\sigma_{ij}} \frac{1}{1 - \sigma_{ij}} A_j \\
&< 0
\end{aligned} \tag{20}$$

QED