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Coal and Sugar: The Black and White Gold of Czech Industrialization (1841-1863)

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The black and white gold of Czech Industrialization (1841-1863)

Hana Nielsen

Abstract

This article studies the fast fossil fuel transition in the context of steam adoption in the Czech lands. I show how geographical proximity to coal brought forward the early industrialization of the Czech lands. The region's fast transition to modern fuels fundamentally transformed the industrial landscape and laid foundations for the development of new industries. Coal, steam and sugar became the central elements, moving the Czech lands closer to the European core. Overall, this article challenges the traditional view of the economic backwardness and shows on what grounds the Czech lands became the economic powerhouse of the Habsburg Empire.

Keywords: industrialization, distance to coal, steam engines, Poisson regression, spatial regression

JEL codes: O14, N73, C21, R12

1. Introduction

There are many standpoints from which to view Europe's industrial revolution but from that of energy, coal and steam are clearly its main attributes. While some consensus has been reached on the role of domestic coal in Britain's industrialization, for other regions the evidence is mixed and the shortage of modern sources of energy such as coal has been seen as a barrier to industrialization or even the causes of regional backwardness (Bardini, 1997; Berend and Berend, 2013).

Within the larger European context the case of the Czech lands is particularly interesting. Traditionally portrayed as an example of backwardness, the Czech lands were plagued with multiple institutional impediments in pre-industrial times (Gerschenkron, 1962; Good, 1984). This view has been contested by recent writers on economic history, who argue that the industrialization of the Czech lands during the 19th century was in fact rather spectacular, from a low-performing country in pre-industrial Europe to the 'economic powerhouse' of the Habsburg Empire (Klein and Ogilvie, 2015). It was in the age of steam that the Czech lands became one of the fastest growing and most successful regions in Europe despite their late industrialization (Klein, 2011). In their chapter, Klein et al. (in O'Rourke and Williamson, 2017) suggest that the imaginary line between the European 'core' and the periphery ran through the Habsburg economy and not through its western border as previously suggested. This would place the economic development in the Czech lands on a par with that of the Austrian and German lands and at the forefront of the European core. This paper supports the re-assessment of the Czech lands as an economic powerhouse for the eastern parts of Europe and puts forward the root causes of this pattern of development.

The part played by coal in the industrial revolution has been debated for decades and remains uncertain. It has been argued that, together with a finite land, the inability of a society to harness power for mechanization limits its economic growth. This is believed to have delayed the further expansion and the onset of modern economic growth by economies which were at the time based on organic production. According to Malthus, fuel was one of the four necessities of life and its abundance was crucial for any further development. While the ecology of pre-industrial Europe was already significantly stressed by the growing population and the need for large agrarian areas, fuel – firewood in particular – was growing scarce. Kenneth Pomeranz (Pomeranz, 2000) discusses the shortage of fuel wood and consequently the importance of proximity to coal as foremost among the factors that composed the industrial revolution. Similarly, David Landes (Landes, 1969), Tony Wrigley (Wrigley, 2010), Astrid Kander, Paul Warde and Paolo Malanima (Kander et al., 2013), Robert Allen (Allen, 2009) and most recently Alan Fernihough & Kevin O'Rourke (Fernihough and O'Rourke, 2014) argue that it was the growth in the deployment of coal that was an essential factor of industrialization. In coal-poor Italy, for example, Bardini concludes that the high costs of coal 'created a sectoral selection against steam-dependent technologies' (Bardini, 1997).

This is contrary to Clark and Jacks (Clark and Jacks, 2007), who argue that coal, in fact, contributed only negligibly to the industrial revolution though it may have been important for the location of the iron-working. Henriques and Sharp illustrate how Denmark, lacking virtually any domestic coal reserves, managed to industrialize and importantly to a large degree use coal-driven technology (Henriques and Sharp, 2016). They conclude, nevertheless, that it was the specific Danish geography ("nowhere is more than a few miles away from the coast") which allowed for the fast expansion of fossil-fueled production through relatively cheap coal imports (Henriques and Sharp, 2016:846). Deirdre McCloskey and Joel Mokyr both argue that it was in fact the technological advances which led to an industrial revolution, rather than any single factor of production such as coal (McCloskey, 2010; Mokyr, 2012). Theoretically, coal or firewood could have always been imported and with the improvements in the transport sector, these costs would have declined in the course of time. The complete lack of any quantitative evidence of the importance of coal beyond the North-West European paradigm limits our full understanding of the topic.

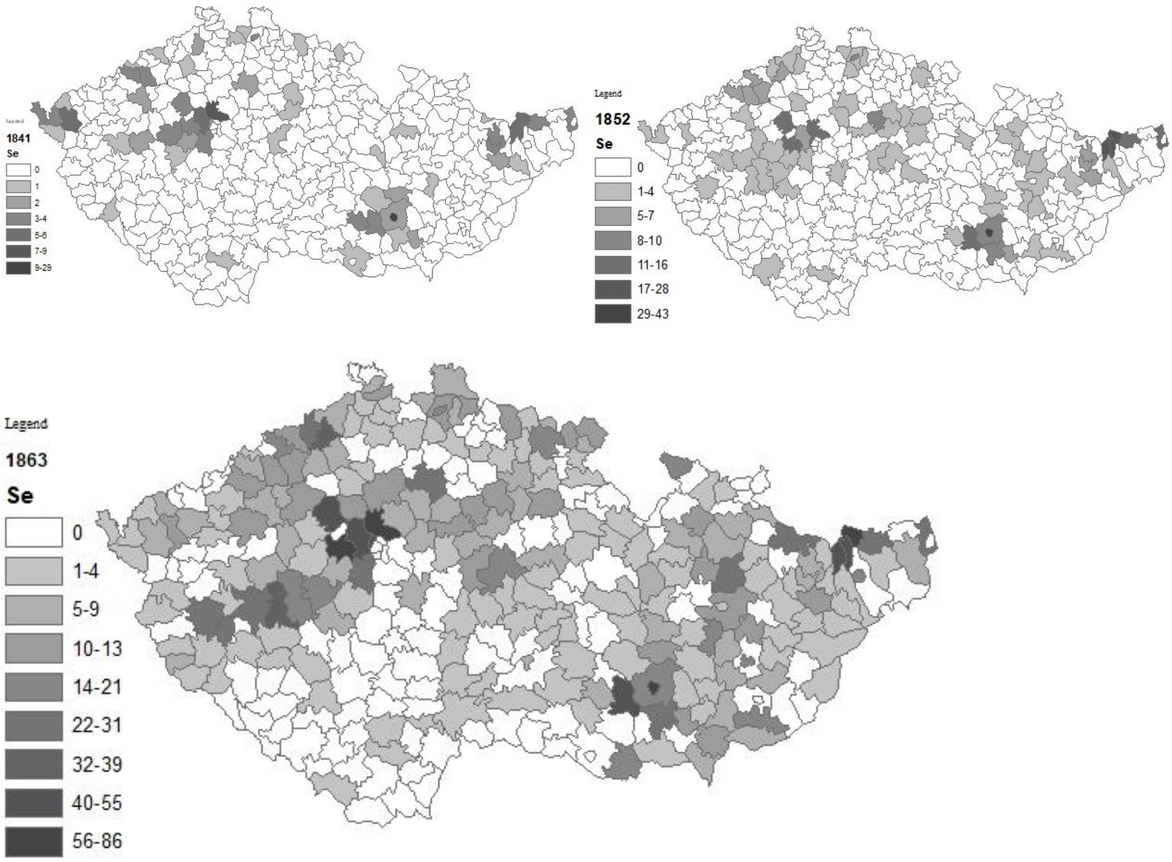
The aim of this paper is to analyze the economic development of the Czech lands from the energy perspective, its transition from an organic to a fossil-fuel dominated economy. This will take into account the determinants of industrial location and the geography of development. In a pre-railway age, the proximity to coal was especially considered a prerequisite for the development of major industrial complexes (Mathias, 1983), a notion which is explored in the present paper. Importantly, proximity to coal-mines is analyzed as a mechanism for the increased adoption and use of modern steam technology, taking the steam engine as a proxy of mechanization and technical change. The field of economic geography traditionally discusses two major theoretical mechanisms: the H-O (Heckscher–Ohlin) and more recently the NEG (New Economic Geography) (Roses and Wolf, 2018). According to the H-O model (Kim, 1999; Klein and Crafts, 2011), the location of a particular industry is determined by its particular resource endowments (in this case, coal) and the maximization of its comparative advantage compared to other regions. NEG, in contrast, while balancing out the resource-based location hypothesis, studies the location decision from the demand side, focusing primarily on the importance of agglomeration effects, transport modes and economies of scale. According to NEG, it is these forces which increasingly attract industries to specific locations where they can take advantage of the existing positive feedback loops. This is often termed the “second nature” and usually follows the “first nature” of location choice (Krugman, 1991). More steam and energy dependent industries (such as the food industry) will thus locate in areas with good access to coal but also in areas with a history of food processing at the time, since the agglomeration effects start to dominate the initial natural advantages, whether it be fertile agricultural land, access to coal or access to cities. As a result, some industries will tend to cluster in particular areas.

Various methods have arisen of capturing and measuring spatial processes with only a few attempts to quantify the root causes of the spatial pattern of economic development in Europe dating back to the early industrialization period. Nicholas Crafts and Nikolaus Wolf (2014) offer a detailed study on the location choices of textile mills in Britain in 1838. The authors find that cheap sources of energy were a key determinant, but they note that these were not the only drivers of industrial location. According to them, the specific combination of natural endowments together with market access characteristics determined the location choices of these firms. Surprisingly, lower coal prices were not found to have a significant impact on the number of cotton mills, though they had a clear impact on the actual size of mills and employment. In other words, coal prices were found to be significant for larger cotton mills. Similar results on the complementing role of endowments and the growing importance of agglomeration effects were also found for Poland (Wolf, 2007), Spain (Roses, 2003), Germany (Gutberlet, 2014), Italy (Missiaia, 2016) and the USA (Cermeño, 2018). For steam engines specifically, Rosenberg and Trajtenberg (Rosenberg and Trajtenberg, 2004) find that the diffusion of the Corliss steam engine in the United States led to industry’s massive reallocation from rural to large urban areas, further reinforcing agglomeration economies and population growth. In other words, the steam engine removed the locational constraints of the pre-industrial age and made increased urbanization possible. Kim, however, disagrees that the advent of steam engines drove the relocation of manufacturers to urban centers (Kim, 2005).

This paper studies cross-sectionally and in a panel setting the relationship between coal-using steam technology and geographical distance to a coal mining district between 1841 and 1863, by observing the county-specific mechanisms and the unique impact of resource endowments. Departing from the coal debate literature, this paper hypothesizes that the actual geographical proximity to coal was the major initiator of technological change and the onset of modern industrialization which would not otherwise have ensued. I use a combination of newly collected and digitalized data on industrial steam engines at a high level of disaggregation to capture the natural resource endowments and a variety of other district-specific variables to illustrate the strong and persistent relationship between steam technology adoption and coal availability. The steam engine data cover all steam engines and their respective horsepower (HP) deployed in the industrial sectors, such as machinery, textiles and food production. Steam engines used for coal mining were excluded from the empirical analysis, as were steam engines used in the agricultural sector. The data cover three benchmark years – 1841, 1852 and 1863 – which correspond with the onset of modern economic growth in the region and the first transition to a fossil fuel. In fact, the particular period of research stretching through the fundamentals of Czech industrialization captures one of the most spectacular periods, when there was a rapid transition to modern sources of energy. The paper shows that coal mattered for the industrial revolution in the Czech lands; the technological advances in the use of steam which are commonly associated with the first industrial revolution were not only related to coal in substance but also geographically related to the proximity to coal. I use Poisson regression to capture the effect of distance to a coal mine on the number and horsepower of the steam engines that were installed. I first employ simple cross-sectional analysis on the major drivers of steam technology diffusion across the Czech counties, followed by a fixed-effects model. The findings from the Poisson regression point to a strong and persistent relationship between the spread of steam technology and the local availability of coal, but it also shows some aspects of industrial scaling in proximity to coal. I also employ an instrumental variable (IV) strategy to account for the potential endogeneity of the distance to a coal mine, using several instruments, such as distance measures (distance to carboniferous strata, as in de Pleijt et al., 2019; Fernihough and O'Rourke, (2014) or global centrality as in Head and Mayer (2006)). The findings from both the OLS and IV estimates support the hypothesis about the importance and persistence of the distance to coal for the exploitation of steam technology. I find that industries with a significant dependence on steam in their production, such as food processing, will tend to locate close to coal-mines to secure a consistent supply of this energy source, especially in the absence of a railroad. The magnitude and persistence of the resource endowment effect are studied in more detail. Furthermore, spatial analysis of the data shows the appearance of new steam clusters and other areas with high concentrations of industrial steam, most of which were consistently located around coal-mines. The fact that the Czech lands had significant coal reserves not only fueled the new industrial activities but also shaped significantly the

Czech industrial landscape. Although coal was already used to a significant extent in the textile sector, newly established sectors such as sugar refineries and other food producing branches not only increased the demand for domestic coal, but, with their close ties to the agricultural sector, created new industrial centers and work opportunities in previously backward rural areas of the country. I show that in the absence of favorable geographical position, actual proximity to coal was the initiator of technological change which would not have otherwise materialized during the early stages of development. The local availability of coal was the primary driver of the disembarkation line running through the Habsburg Empire between the European 'core' and the periphery. Figure 1 plots the location of steam engines during the first industrial revolution, which is the major outcome to be explored and the point of departure for this paper.

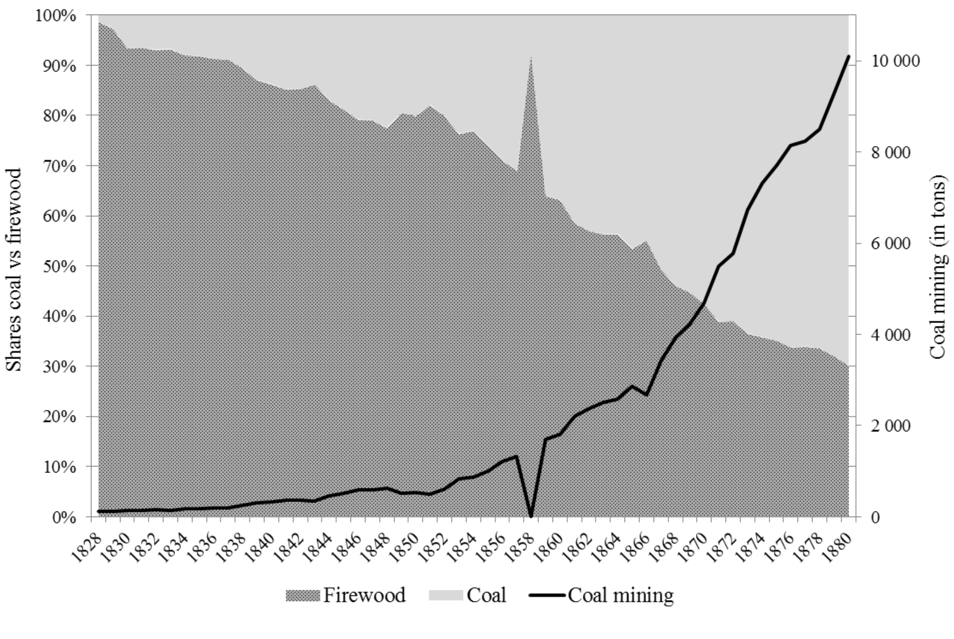
Figure 1. The number of steam engines installed by 1841, 1852 and 1863



2. Historical background

Despite their limited access to foreign markets, the Czech lands had in one aspect a relatively favorable position in the European semi-periphery – natural resources. The region was rich in firewood and, most importantly, in coal reserves. Although largely unexploited until the beginning of the 19th century, the presence of coal had been known since the 15th century (Karnikova, 1958). In 1830, barely 5 % of all the consumed energy derived from coal but it took only some 35 years for coal to reach a 50 % share of the domestic energy use (Nielsen et al., 2018) (Figure 2). This shift from wood to coal is often termed the first fossil-fuel transition and the time that it took differed substantially across developed countries. In France and the USA, for example, it has been estimated that the tipping point (a benchmark when coal surpassed the use of wood) occurred in 1875 and 1885 respectively. However, in Japan the tipping point is set to roughly 1901, in the USSR to 1930, in China to1965 and in India to some time in the 1970s (Smil, 2014). The Czech lands' fast transition to coal, indeed one of the fastest in the European continent, is not surprising. According to Smil (Smil, 2014) it is primarily small economies endowed with resources that are able to make relatively fast energy transitions. Similarly, latecomers can take advantage of successful technological developments and import foreign technologies, thereby accelerating their domestic fossil-fuel transitions (Panayotou, 1993).

Figure 2. Czech transition to coal 1828-1880



Source: (Kuskova et al., 2008; Nielsen, 2017)

Some qualitative studies discuss the slow adoption of coal in the production processes in the early years. Karnikova (1958) discusses the general aversion to coal at the very beginning of the 19th century mainly because of the need to adjust production systems previously based on firewood, which was often a costly process. Among consumers, there was skepticism about the use of goods such as food and glass that had been produced with coal. Contemporary writers were puzzled about coal aversion in the Czech lands and particularly the comparatively low levels of coal use in major urban areas in the early 19th century (Ackerbau-Ministerium, 1870). As a result, coal was at first used only as a complementary source of energy on the large estates of the gentry who also owned most of the mines. The use of coal in production therefore developed very sporadically and slowly until the late 1820s. Prague and its suburbs were exceptions; coal started to become an important energy source there, mainly in the expanding industrial sectors. But the final stimulus to the rapid transition to coal came with the introduction of steam engines, in production after 1820 (Karnikova, 1958). Steam engines created a new complementarity and shaped the demand for the extensive and so far unused coal reserves. Although steam engines could in theory run on wood, they rarely did so either in the Czech lands, as the available official statistics indicate (Karnikova, 1958), or in England (Nuvolari et al., 2011). Of the first ten steam engines installed, only two operated on firewood and by 1850 wood-burning steam engines more or less vanished from the country (Karnikova, 1958). After the mining sector itself, it was the textiles sector that to begin with was the largest consumer of the coal used in steam engines, as was also the case in England, for example (Crafts and Wolf, 2014). But uniquely, the most rapid increase in the demand for coal in the Czech lands came from the expanding sugar industry (Karnikova, 1958). Most of the sugar refineries, highly innovative at the time, were the earliest adopters of steam. In fact, the widespread use of firewood never occurred in this sector; some contemporary estimates put the consumption of industrial firewood by sugar refineries as low as 2% of the total. Coal was not only vital for the steam engines, but was also widely used in the boilers and the cooking processes during the production of sugar (Riha, 1976). According to industrial statistics, the production of 1 kg of refined sugar required a staggering 13 kg of coal in 1841, reduced to 8 kg in 1852 and less than 3,9 kg by 1866 (Noback, 1871; Schnabel, 1848; Walkhoff, 1866). As a result, the sugar industry was not only the first branch of industry to fully adopt coal, but became the largest single consumer of it, accounting in 1841 for 26% of all mined coal. Between 1841 and 1866, the fuel efficiency of sugar production improved substantially, driven in particular by two major technological discoveries. But despite this massive decline of relative energy intensity, the sector remained the largest industrial consumer of coal until the end of the 19th century owing to the expansion of sugar production, only overtaken by the iron and steel sector (Table 1 shows estimates of the sectoral energy consumption in 1863 based on the my own calculations).

Table 1. Estimates of final energy consumption by industrial sector in 1863

		Final sectoral energy consumption	**Of which fossil fuels % (coal)**	**Of which traditional energy sources % (firewood and draft animals)**	**Total industrial energy consumption (%)**
Mining	Anthracite production	7,830,190	46%	54%	11%
Metallurgy (excl. Iron)	Zinc production	41,847	100%	0%	0%
	Copper production	15,344	100%	0%	0%
Iron	Pig iron production	3,845,299	41%	59%	6%
	Steel goods production	8,115,311	58%	42%	12%
	Machinery	707,807	46%	54%	1%
Foodstuffs	Beer production	340,157	35%	65%	0%
	Spirits production	445,245	45%	55%	1%
	Malt	1,550	0%	100%	0%
	Flour	838,118	93%	7%	1%
	Sugar production	6,978,463	100%	0%	10%
Textiles	Cotton yarn	1,244,207	99%	1%	2%
	Cotton fabrics	767,876	99%	1%	1%
	Wool yarn	824,461	100%	0%	1%
	Wool fabrics	1,555,039	100%	0%	2%
	Jute & linen yarn	1,336,642	100%	0%	2%
	Jute & linen fabrics	41,101	93%	7%	0%
Glass and ceramics	Glass	7,314,185	35%	65%	11%
	Porcelain	1,607,449	100%	0%	2%
	Bricks, cement	2,778,477	0%	100%	4%
Chemicals		312,905	62%	38%	0%
Wood		1,980,742	46%	54%	3%
Pulp and paper		558,575	46%	54%	1%
Other industry		19,051,978	38%	62%	28%
TOTAL INDUSTRY (GJ)		68,532,968	36,899,341	31,633,627	100%

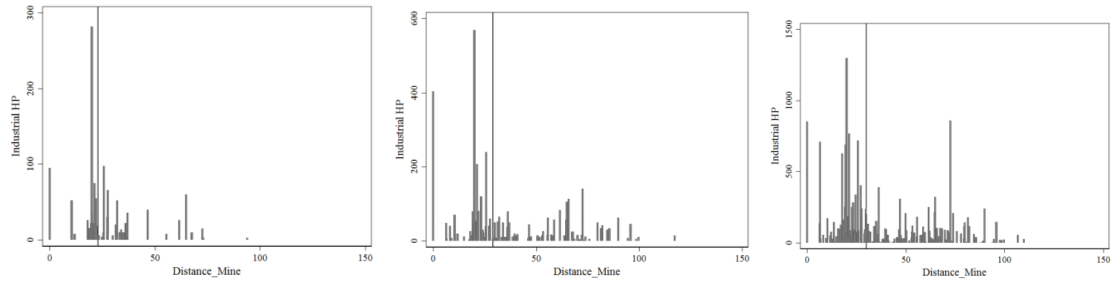
Source: Author's estimates based on Kander et al. (2017), Nielsen et al. (2018) and contemporary industrial reports (Brousek, 1987; Karnikova, 1958; Schnabel, 1848; Sommer, 1856).
Note: Total energy consumption data include totals of food and feed (draft animals), fuelwood and coal. For more information on the methodology, see Kander et al., 2013 and Nielsen, 2017) or to download aggregate level data (https://histecon.fas.harvard.edu/energyhistory/energydata.html).

In the absence of coal, one could argue, firewood was a possible substitute. However, a simple counterfactual calculation reveals that only the sugar refining sector would increase the Czech consumption of firewood by 20% by the mid-19th century and at a rate which could hardly be met by the declining forest areas between 1850-1875 (Karnikova, 1958). Furthermore, the replacement of coal by firewood would inevitably lead to higher energy costs in the period 1841-1852. Particularly in early 1850s, based on Cvrcek's estimates of relative prices for 1 mil BTU of firewood and coal (Cvrcek, 2013), the energy costs to the sugar refineries could be as much as 40% higher, a substantial increase for an industry where fuel accounted for up to 18-25% of production costs (Credner, 1857; Walkhoff, 1866)[1]. Moreover, fuel substitution would only be possible if the sugar refineries had access to forests, whereas the opposite conditions prevailed. In 1838, 70 % of all sugar refineries were located outside of forest areas, a share which had increased to 85% by 1851 (Karnikova, 1958). Similar estimates were found for the newly established breweries and distilleries. Coal was thus a vital source of energy to the food sector, which increasingly located near to a coal mine. The limited access to railroads, particularly in the early stages of industrialization, made the long-distance transport of coal and widespread application of coal in the production processes unfeasible.

Historically, the first steam engines were deployed in the mining sector, from which the use of steam slowly spread across other manufacturing sectors. The increase in the number of steam engines was significant in the period of study; it occurred chiefly in districts within a radius of 50 km from a coal-mine which had the largest concentration of steam power (Figure 3).

[1] By 1863, the cost advantage of coal to firewood largely disappeared. The cost share of fuel in the production costs also declined after 1850. The issue of the expanding sugar production and the future fuel demands has been widely discussed already in early 1850s with Credner's first projections of the coal consumption (Credner, 1857). Especially in the early years, the sector was so dependent on coal supplies that any price fluctuations of coal could pose a serious threat to the sector's future expansion (Credner, 1857; Sommer, 1856). Already the 1866 edition of the practical guide for sugar refining in the Monarchy discusses to a large extent the opportunities for improved fuel utilization (Walkhoff, 1866). The Czech sugar producers were also active in the political arena and lobbying and formed a Union for the Advancement of Sugar Production already in 1836, and later a Union for the Sugar Beet Industry in the Austrian Monarchy in 1854 (Rudolph, 1976), mainly with the aim to lobby for government support, protective tariffs or export premia.

Figure 3. Horsepower of industrial steam engines and distance to coal



(a) 1841 (b) 1852 (c) 1863

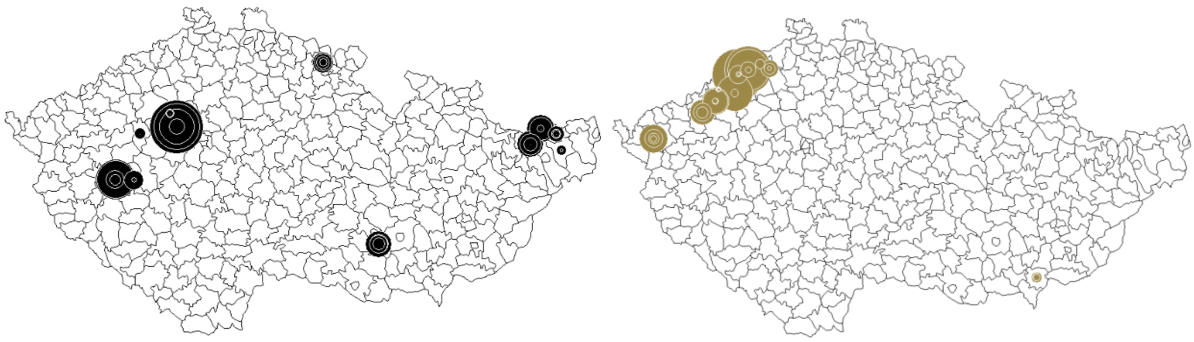
Note. Excluding mining steam engines and steam engines used in agriculture and public utilities. Vertical lines indicate the average distance to a coal mine, which was respectively 23, 29 and 30 km in the years chosen.

Nevertheless, the expansion of the country's railroad network, which was in fact substantial within this period of study, enabled other districts without immediate access to coal to adopt modern steam technology within their production processes as well. In our data, the average distance between districts with steam engines and a coal mine increased from 23 to 30 km. In the absence of coal pithead prices, this distance measure was adopted as the major determinant of access to coal. Scattered data for a limited number of individual mines were found for the period 1861 and 1865, but I decided not to use coal prices within the analysis, due to the great number of missing observations for earlier benchmark years. The omission of coal prices is also justified by the relatively low differences in pithead prices across the Czech lands, especially when compared to Britain. There the disparity between the lowest and highest coal prices amounted to a factor of almost 6, while the available Czech data show a price variation of 2,2 at most between any two coal-mines. Furthermore, although previous studies have found a negative relationship between coal prices and the probability of steam power, this relationship was found to be largely insignificant for the number of steam engines (Crafts and Wolf, 2014).

Two major types of coal were mined in the Czech lands – black (anthracite) and brown (lignite). The location of major brown coal-mines was very much concentrated in the western part of the Bohemian crownlands, while black coal-mines were spread across the whole territory, with Ostrava in the east becoming the largest center (Figure 4). Until 1850, virtually all mined coal was black and it was mined solely for domestic consumption. After 1850, the mining of brown coal took off and by early 1870s it accounted for 50% of total mining output, though most of this was destined for export. In terms of energy quality, brown coal is considered the lowest rank of coal because of its low heat content. Energy quality is defined as the ratio of energy volume to the sum of heat units and the value is far lower for brown coal than for black (Stern and Kander, 2012). Obviously, the higher the energy quality and density of an energy source, the lower the transportation and storage costs (Smil, 2015:12). Throughout the history of industrialization, economic growth has not only been shown to expand energy, but is equally accompanied by a constant substitution of fuels with higher energy quality. The geographical location of the Czech coal-mines has not altered substantially, though several mines were closed down during the period of study while others opened for the first time. In the decade 1830-1840 there was a total of 14 active mining areas (both black and brown coal); in 1852 this increased to 15 and in 1863 there was a total of 18 districts with operational mines.

Overall, throughout the period of study, the Czech lands and Austria were considered self-sufficient in fuel supplies (Karnikova, 1958:60), though some minor exports from mines located very close to the river Elbe were recorded as early as 1805. These exports were exclusively destined for the markets in neighboring Saxony and picked up especially after 1852 with exports of brown coal. Interestingly, the lower quality brown coal accounted for all coal exports until WWI.

Figure 4. Major mines in the Czech lands and its relative output in 1863



(a) Black coal b) Brown coal

Source: Author's own visualizations based on Ackerbau-Ministerium (1870); Karnikova, (1958)

3. Empirical model

This paper makes use of a micro-level spatial dataset and models the relationship between the number of installed steam engines with their respective horsepower (the dependent variable) and a vector of specific locational factors (for predictor variables, see Table 2).

Main hypothesis: proximity to a coal mine determines the likelihood of a steam engine's being installed

Using the count data regression model, I assessed the potential behavior of steam engine owners in support of the theory of location choice. According to this, an entrepreneur/firm will strive to maximize profit while keeping costs as low as possible when deciding where to install the next steam engine, by weighing the individual characteristics of the location against the input needs of each production process. The Poisson regression model is an appropriate method for analyzing count data, under the assumption that the number of steam engines in a specific area follows a Poisson distribution (Cameron and Trivedi, 2013)[2]. The Poisson regression model is advantageous when dealing with large sets of spatial data since each spatial choice becomes an observation (Cameron and Trivedi, 2013; Guimarães et al., 2004). However, the relatively large number of districts with zero steam engines (mainly in the early years) and the risk of geographical clustering may be problematic. In this paper, I divided the geographical entity of the Czech lands into 337 unique historical districts.

Table 2 provides an overview of a selection of independent variables. Furthermore, additional dummy variables were included to capture foreign borders (specific for Prussia, Saxony and Bavaria), rivers (large navigable rivers and other rivers), having a 'city' status or bordering on a 'city' district ('suburb').

Table 2. Descriptive statistics of selected variables of Czech districts

Independent variable	**Observations**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Distance to coal mine in km (1841)	337	49	29	-	143
Distance to coal mine in km (1852)	337	49	30	-	143
Distance to coal mine in km (1863)	337	47	29	-	136
Distance to railroad in km (1841)	337	55	33	-	128
Distance to railroad in km (1852)	337	33	28	-	122
Distance to railroad in km (1863)	337	20	20	-	94
Least distance to town (km)	337	64	36	-	161
Distance to Vienna (km)	337	226	71	62	378
Domestic market potential (1841)	337	187,978	447,224	7,213	5,915,343
Domestic market potential (1852)	337	407,831	804,025	8,162	8,813,234
Domestic market potential (1863)	337	695,653	1,131,303	9,089	11,500,000
Draft energy in GJ (1857)	337	58,833	28,890	4,029	184,881
Share of Jews % (1857)	337	1.87	3.28	-	37.74
Categorical variables					
Soil suitability (categorical variable: 1-4)	337	2.47	0.75	1.00	4.00
Dummy variables (Yes=1, No=0)					
Bordering with Saxony	337	0.07	0.26	-	1.00
Bordering with Prussia	337	0.10	0.30	-	1.00

[2] In a Poisson distribution, its mean is equal to its variance (Liviano and Arauzo-Carod, 2014)

Bordering with Bavaria	337	0.04	0.21	-	1.00
City	337	0.04	0.20	-	1.00
Suburb	337	0.04	0.19	-	1.00
Presence of large navigable rivers	337	0.08	0.27	-	1.00
Other rivers	337	0.45	0.50	-	1.00
Dependent variable	**Total**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Steam engines total (1841)	161	0	2	-	29
Steam engines HP (1841)	1,911	6	22	-	282
Industrial steam engines total (1841)	134	0	2	-	29
Industrial steam engines HP (1841)	1,552	5	20	-	282
Steam engines total (1852)	495	1	4	-	43
Steam engines HP (1852)	7,202	21	69	-	579
Industrial steam engines total (1852)	381	1	3	-	41
Industrial steam engines HP (1852)	5,380	16	51	-	569
Steam engines total (1863)	2,069	6	12	-	86
Steam engines HP (1863)	33,954	101	263	-	2,161
Industrial steam engines total (1863)	1,630	5	9	-	80
Industrial steam engines HP (1863)	24,049	71	153	-	1,298

3.1 Count models: Poisson regression

The paper estimated the expected total of installed horsepower for each district against the variety of locational characteristics discussed in the section on data (Table 2). For each benchmark year the model controlled for the size of the area (the surface area of the district). This was mainly because larger districts are more likely than small districts to feature a higher installed of steam engines and the potential impact of this can be ruled out by controlling for the size of the district.

To start with, the paper used three cross-sections which enabled me to observe a possible pattern of change in probability against a number of locational characteristics. Next to cross-sectional testing of the relationship, the paper also used panel settings, with both random and fixed effects. The method used was based on a similar concept adopted by Crafts and Wolf (2014) and assumed profit maximization behavior on the part of an entrepreneur. The basic assumption was that an entrepreneur or firm owner would strive to maximize profits by minimizing production costs (both fixed and variable) or maximizing the benefits from market access. This could be done by locating steam engines in specific places with access to cheap material/energy input or labor. Since the focus of this paper was on the geographical distance to coal mines as an important determinant of steam engine location, the model measured the relationship between this distance (and thus the variable cost of production) and the probability of an entrepreneur installing a steam engine *i* in the production processes in location *j* as follows:

$$\textbf{(1)}\ P_{ij} = P(\pi_{ij}{}^{*} > \pi_{ij}{}^{*} \forall k = 1, ...J{:}k \neq j)) = P(\varepsilon_{ik} - \varepsilon_{ij} \leq V_{ij} - V_{ik} \forall k = 1, ...J{:}k \neq j)$$

Thus, the probability of observing location choice *j* for steam engines *i* depends on the distribution of the stochastic part ε, given the deterministic part *V*. The Poisson regression assumes that the expected number of steam engines *I* in district *j*, *E(nj)* is independently Poisson distributed with district-specific mean as follows:

$$\textbf{(2)}\ E(n_j) = e^{xj\beta}$$

The vector of coefficients β as shown in the equation above was estimated using the maximum likelihood model and was interpreted as the elasticity of the expected total of horsepower installed in district *j* as a result of the change in the locational characteristics of district *j*. I included only steam engines which were used in industrial production and excluded steam engines used in mining, the agricultural sector and utilities (see Table 3 for an aggregated overview of industrial steam engines).

In order to evaluate the importance of various locational characteristics, particularly the changes in variance during the first industrial revolution, it is important to fully understand what drives location choice as analyzed in the most recent economic history papers. Generally, studies tend to distinguish between ‘first’ and ‘second’ nature characteristics. ‘First nature’ characteristics, sometimes referred to as ‘original’ characteristics, are often treated as fixed because they denote pre-existing conditions which cannot be affected, such as the existence of coal mines and other natural phenomena. ‘Second’ nature characteristics, or ‘acquired’ conditions, relate to factors which arise as a consequence of an interaction between possible locations, such as market access or access to a railroad network. Following the pioneering work by Krugman (1991), much research has been devoted to the role of second nature in the spatial distribution of industrial activity, particularly to the importance of increasing returns in location choice (Krugman, 1991).

In this paper, I included a set of geographical and institutional variables to account for cross-district variations in the total of horsepower of installed (industrial) steam engines. These controls were: (1) distance measures (in km) to the nearest railroad, to a city (the nearest district that was granted city status) and to Vienna; (2) dummy variable that took a value of 1 if the district had an official 'city' status, or 'suburb' status if it bordered on a 'city'; (3) dummy variable for the presence of large navigable rivers and other rivers; (4) a categorical variable to assess the soil suitability of the district; (5) the natural logarithm of the domestic market potential; and (6) a dummy variable which took the value of 1 for the presence of a foreign border with Bavaria, Prussia or Silesia as a proxy for proto-industrial activity before the industrialization as well as potential access to foreign markets. All models also controlled for the actual size of the district (km^2). Unless stated otherwise, standard errors were clustered at the district level.

In the baseline strategy, however, I also estimated the following equation in order to capture the impact of time-varying dependent variables, where the original model was modified into a panel model with fixed effects. Within this model, all time-invariant dependent variables (such as soil suitability or foreign borders) were compressed into the α_i term, taking the following form:

(3) $Y_{it} = \beta_1 + \beta_2 X_{2it} + \beta_3 X_{3it} + \beta_4 X_{4it}.+.. + \alpha_i + \delta_t + \mu_{it}$

where Y_{it} refers to the total of steam horsepower (or steam engines), X_2, X_3 *and* X_4 refer to the only time-varying variables of distance to coal mine, distance to a railroad and domestic market potential; α_i is the intercept of all time-invariant variables; and δ_t refers to the time-specific intercept.

3.2 Endogeneity and identification issues

3.2.1 Poisson regression with instrumental variables

To further address the potential endogeneity bias, I used an instrumental variable (IV) strategy for measuring the distance to a coal mine. In total, I used four different IV specifications to deal with this problem followed by the Poisson model with continuous endogenous covariates (as shown in Equation 3).

First (IV1), the distance measure was instrumented with the use of a new distance variable which measured the distance from the district to a carboniferous strata (de Pleijt et al., 2019; Fernihough and O'Rourke, 2014). This measure was calculated using the geomorphological maps from the Czech geological office and capture the distance to the nearest geologically defined carboniferous location. To some extent also, as shown in Figure 5 in the data section, the relationship between these two distance measures – distance to a coal mine and distance to a carboniferous location – does show significant correlation.

The second instrument (IV2) as an alternative measure of access to coal took the form of all the steam engines used in mining. Mining steam engines were otherwise entirely excluded from the analysis. The argument behind IV2 was that industrial steam engines were more likely to be installed in districts where coal was being mined. This would mean that new industrial steam engines (and industries in general) would not be established merely in geographic proximity to a coal mine, but literally on top of it.

Third, total energy consumption (IV3) was used to instrument the distance measure and captures the energy intensity of the respective district. The argument here is that districts close to coal mines would increasingly make use of the growing and accessible supply of coal which would in turn speed up the transition to modern fuels (fossil fuels) and increase the energy consumption of the district. The actual measure included the consumption of food (population-count based), feed (draft energy of horses, cows and oxen), firewood (population and industry based) and coal (industrial consumption only). The estimate controls for the regional industrial shares, but indirectly included also the energy consumed in steam engines which might lead to an upward bias in the estimate of the causal β parameter.

The centrality IV (IV4), as in Head and Mayer, (2006), was the most exogenous instrument of all the four. It is the sum of inverse distances of all the Czech districts in this analysis. Although this measure depends largely on numerous exogenous geographic features (rivers, mountains, etc.), its restriction to the Czech lands indirectly defines some form of center. Despite these shortcomings, I used the global centrality measure alongside the other three instruments to support the robustness of my model.

3.2.2 Poisson regression with spatial interaction

The use of a simple model to analyze a complex and multidimensional phenomenon such as the adoption of coal-using technology may be questioned. However, the major purpose of this paper is to observe whether the changes in the calculated response values confirm or reject our hypothesis – regarding the location choice and the importance of distance to a coal mine. In other words, the expectation is that the β coefficient (the variable of distance to a coal mine) will have negative values. In this paper, it was reasonable to assume that when making the decision about where to install an additional steam engine, an entrepreneur or firm took into account not only the characteristics of the local area, but also the characteristics of other nearby areas (Liviano and Arauzo-Carod, 2014). Therefore, in order to control for the risk of omitted variable bias, a spatial Poisson regression model was also used in order to capture potential spillover/clustering effects in the data, which is one of the disadvantages of the Poisson model (Guimarães et al., 2004). Clustering in the concentration of steam engines can be demonstrated with the use of global and local spatial autocorrelation indices. The basic intuition here is that districts with high concentrations of steam engines will most likely border districts with similar concentrations, as deduced from Tobler's first law of geography. Spatial autocorrelation can be detected using Moran's I statistic, Getis and Ord's G, and Geary's c, used to identify the existence of potential clusters by providing the degree of similarity between regions. Global spatial autocorrelation, thus, assigns a single value to the whole area of the Czech lands and was therefore very useful for identifying such spatial correlation in the data. More on the spatial analysis and reasoning behind the choice of spatial parameter is summarized in the Appendix.

The spatial variable in the model accounted for the change in the number of steam engines used in the bordering districts and captured the effect of increased spatial concentration (Guimarães et al., 2004). The final choice of the baseline strategy for the spatial Poisson model took the form of the following equation:

(4) $Y_{it} = \rho W_j Y_{it} + X_{it}\beta + \mu_{it} + \varepsilon_{it}$

where ρ referred to the spatial lag for location *i* in year *t* and γ was the spatial lag for location *i* in the previous period (year *t-1)*.

3.3 Data

In order to analyze the role that coal availability has played in driving the process of industrialization in the Czech lands, the paper examined the district-level data available for the period 1841-1863. Aggregate data on the total domestic coal consumption are a good indicator of the first fossil fuel transition in the Czech lands; however, district-level data enabled me to analyze the actual drivers of this rapid transition, since important local variations may be hidden in the aggregate indicators, while detailed city-level data may not capture the complexities outside of the city's borders.

Table 3 summarizes the adoption of steam engines in the Czech lands between 1841 and 1863. The number of steam engines increased from around 150 in 1841 to well over 2,000 by 1863. In the early stages of the industrial revolution, much of the industry (or proto-industry) was concentrated in the border areas with Saxony, Prussia and Bavaria, and in the two largest urban areas surrounding the current territories of Prague and Brno. Historically, the location of industries in border areas was common. Indeed, the often mountainous border areas which were unsuitable for agriculture were the first ones to develop proto-industries, particularly in the manufacture of textiles and glass (Komlos, 1983). The most striking development was seen in the food industry, where steam engines rapidly multiplied. In 1863, moreover, of all the steam engines installed in the food industry, nearly 80% were in sugar refineries and further 11% were in breweries and liquor factories (Table 3).

Table 3. Steam engines in industry 1841-1863, totals by number of steam engines (SE) and installed horsepower (HP)

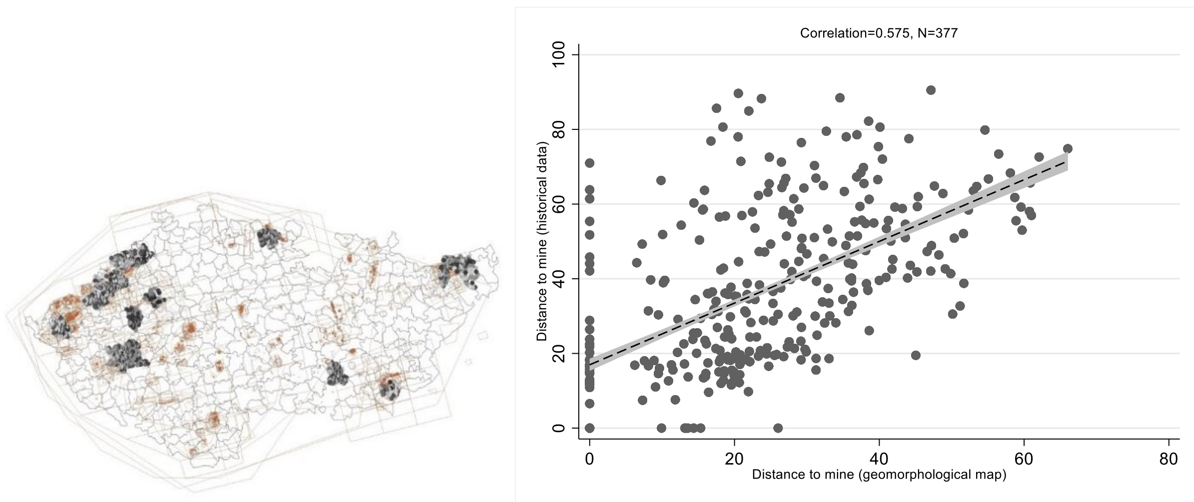
	1841		1852		1863	
	Steam engines (SE)	Installed horsepower (HP)	Steam engines (SE)	Installed horsepower (HP)	Steam engines (SE)	Installed horsepower (HP)
All steam	161	1,911	495	7,202	2,069	33,954
Agriculture	0	0	0	0	10	73
Mining	26	351	114	2129	420	10,361
All industries	134	1,552	381	5,380	1,630	24,049
Machinery	3	21	19	114	57	468
Metallurgy	20	266	55	1236	237	6,810
Non-metallic	3	6	3	34	27	273
Chemicals	4	28	10	77	63	618
Food processing	15	110	134	1,252	752	6,139
Textiles	85	1,057	146	2,517	386	8,244
Utilities	0	0	12	43	41	247

Source. Collected by Cvrcek (based on (K.K. Ministerium fur Handel – Direction der administrativen Statistik, 1842; Statistik, 1864, 1852)

In order to map the location of steam engines and to link the proximity to coal-mines with the number of steam engines in individual districts, I used the GIS data of the historical administrative boundaries of Austria-Hungary, as provided by the Mosaic Project (Rumpler and Seger, 2010). To explore the spatial drivers of steam adoption, the available shapefiles were merged with the data on steam engines collected by Tomas Cvrcek (based on (K.K. Ministerium fur Handel – Direction der administrativen Statistik, 1842; Statistik, 1864, 1852)) and the mining output of major coal-mines (Ackerbau-Ministerium, 1870; Geinitz, 1865; Karnikova, 1958:50-51) and further complemented by other district-level variables collected from contemporary statistical yearbooks of the Austro-Hungarian Empire. All distances within the paper were calculated using the Vincenty equation on a reference ellipsoid (Vincenty, 1975) as the distance between the centroids of their respective districts. In practice, the distance might thus be greater (or less) than using the straight line distance, but for the purposes of econometric testing this proxy is the most efficient one (given the absence of a detailed road map for each individual district). Furthermore, for accuracy and as a robustness check, the historical coal-mining data from contemporary sources used in this paper were overlapped with the current geomorphological map of explored mines used as an instrument (Figure 5).

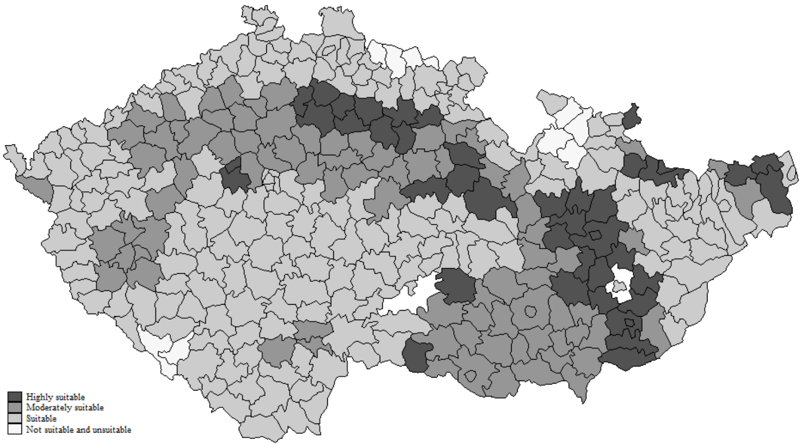
An additional number of control variables was constructed, analyzed and geographically linked to the historical locations of steam engines. The variables, which are further summarized below, included geographical, institutional and spatial variables.

Figure 5 Geomorphological map of the Czech lands and historical coal mining data



Historically, the role of agricultural produce and improved nutrition in driving population growth has been put forward as one of the mechanisms of urbanization and industrialization (Berger, 2016; Nunn and Qian, 2011). For the purposes of the econometric model, data on the suitability of the soil for growing sugar beet in particular were adopted from the GAEZ/IIASA database on soil suitability and potential yield (IIASA and FAO, n.d.). The database gives a crop suitability index with a relatively high degree of detail, which was georeferenced to the historical map of the Czech lands. The data provided divide the Czech territory into 5 separate categories ranked according to their potential for rain-fed intermediate input of sugar beet crops (Figure 6), which is likely to reflect the historical conditions of the Czech agricultural lands fairly accurately. The soil suitability variable was included due to its potential impact on the location of steam engines in food processing. This impact is likely to have worked positively as well as negatively. The positive effect is due to the complementarity of the food processing industry and the local production and concentration of agricultural goods, which further reduce the costs of transportation. Moreover, the transportation of agricultural goods is often of a different nature than the transportation of other goods, given the relatively fast perishability of agricultural produce. At the same time, soil suitability may also work in the other direction and negatively affect the likelihood of steam engine location. This negative effect can be understood as a substitution effect, 'via an increase in opportunity costs of allocating inputs to non-agricultural activities' (Klein and Ogilvie, 2015:504). Thus, the potential owners of steam engines in the agriculturally most productive parts of the country would probably weigh the opportunity costs of allocating resources into new technology against further intensification of the agricultural output (ibid).

Figure 6 ***Soil suitability*** (specifically for sugar beet crops)



Source. (IIASA and FAO, n.d.)

Besides the spatial distribution of natural advantages such as coal or suitable agricultural land, district market potential is often referred to as one of the key determinants of industrial location with new activities more likely in locations that had a higher market potential (Harris, 1954). In the early stages of industrial development, regions are self-sufficient in production and small independent local centers are distributed evenly across the country. With the rise of industrialization, a single strong center (often a political center) begins to dominate the economy and attracts increasingly productive factors which in turn generate a surplus of production. With the technological changes of transportation and particularly the falling costs of various transport modes during the first period of industrialization, production concentration spreads also to other new centers which now can realize their comparative advantage and produce not only for their domestic needs but importantly also for exports to other regions (Potter et al., 1999:97-100). The growing concentration of production in certain regions thus results in significant agglomeration effects, which tend to attract other firms through the mechanism of increasing home-market demand. As a result, certain regions experience a process of industrial concentration (or clustering), while other regions 'de-industrialize' and suffer a substantial outflow of productive resources. This paper controls for agglomeration effects by taking into account the juridical statute of the district within the Austro-Hungarian Empire and by calculating the domestic market potential. In the days of the Austro-Hungarian Empire, certain urban areas were granted special 'city' status. It has been assumed that the importance of the 'city' status had a predominantly political rather than economic impact. Contrary to other urban areas, 'cities' featured greater political autonomy, though they remained subordinate to the Austrian emperor (Zitko, 2015:5). In the Czech lands, 13 districts had the status of 'city' and 14 further districts bordered on these cities. The remaining 310 districts were neither city nor suburb but differed in their distance to the nearest city. I used both the status of the districts and the geographical distance to the nearest city as control variables. Domestic market potential was calculated following the standard Harris methodology as a sum of purchasing power in other locations weighed by transportation costs (Cermeño, 2018; Crafts and Mulatu, 2005; Martinez-Galarraga et al., 2015), but with two major adjustments. First, given the lack of data on the GDP or purchasing power of the individual districts, their population in the year 1857 was used. Second, to capture the changes related to the expansion of the railroad system, the market potential took into account the ongoing rollout of the railways as new districts progressively gained access to the network. This allowed me to control for the ongoing reduction of transportation costs as districts gained access to the new infrastructure. The domestic market potential thus took into account the present population, geographic distance to other districts, transportation costs and access to a railroad. While the population was based on the 1857 benchmark, the adjustment for the changing transport costs and access to railroad resulted in a time-varying component in the calculation of the domestic market potential.

$$Domestic\ MP_i = \sum_{(j-i)}^{(l,n)} \frac{Population_j}{d_{i,j}^{\theta}} + local\ MP_i$$

where the first half of equation followed Donaldson and Hornbeck's methodology (Donaldson and Hornbeck, 2016), assuming that the coefficient 0 was not equal to 1, as in Harris' basic specification, but captured the variation created by having or lacking access to the railway network during the period of study with four different values for theta, corresponding to the following possible scenarios:

- District_origin (Railroad=1) & District_destination (Railroad=0), =0.5
- District_origin (Railroad=0) & District_destination (Railroad=1), =0.8
- District_origin (Railroad=1), & District_destination (Railroad=1), =0.1
- District_origin (Railroad=0) & District_destination (Railroad=0), =1

Local market potential, or local population potential, was then calculated as a proxy of the inverse distance-weighted sum of the population at the time within a 30km radius from the centroid of each district:

$$Local\ MP_i = \sum_{j=1}^{n} Population_j d_{i,j}^{-1};$$

for all *i, j,* where $Population_i$ was the population of district *i*. The threshold of a 30km radius was based on existing empirical evidence. Table 4 summarizes the development of domestic market potential at an aggregated level.

Table 4. Evolution of the domestic market potential at an aggregated level by Czech crown lands and regions in 1841, 1852 and 1863

Crown land	Region	Share of Czech territory	Share of population in 1857	Domestic Market Potential (% of Czech total)		
				1841	1852	1863
Bohemia	Budweis	5.1%	3.6%	5.8%	3.8%	2.9%
	Bunzlau	4.4%	5.2%	2.6%	1.3%	6.1%
	Caslau	4.8%	4.8%	2.4%	5.9%	4.4%
	Chrudim	4.1%	4.8%	2.3%	10.4%	7.9%
	Eger	5.7%	4.9%	2.2%	1.1%	0.7%
	Jicin	3.6%	4.6%	2.3%	1.2%	3.4%
	Koniggratz	3.7%	4.9%	2.3%	1.2%	6.7%
	Leitmeritz	4.1%	5.8%	2.7%	6.4%	6.1%
	Pilsen	6.3%	5.1%	2.3%	1.2%	5.4%
	Pisek	5.9%	4.4%	2.0%	1.0%	0.6%
	Prag Umg	8.4%	8.9%	18.2%	17.8%	17.5%
	Prag Stadt	0.0%	1.9%	9.3%	6.4%	4.9%
	Saaz	4.2%	3.4%	1.6%	0.8%	0.5%
	Tabor	5.6%	4.5%	2.3%	1.2%	0.7%
	SUM	65.8%	66.9%	58.3%	59.7%	67.6%
Moravia	Brunn	5.8%	6.4%	13.3%	12.7%	10.2%
	Hradisch	5.2%	4.0%	11.8%	8.1%	5.3%
	Iglau	3.8%	3.0%	1.4%	0.7%	0.5%

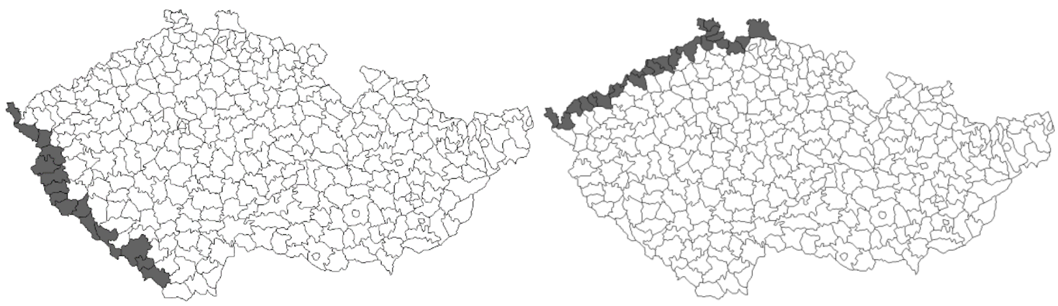
	Neutitschein	3.9%	3.2%	1.5%	4.1%	3.0%
	Olmutz	5.3%	5.8%	7.4%	7.6%	5.7%
	Znaim	3.7%	3.7%	3.3%	2.1%	1.5%
	SUM	27.7%	26.1%	38.8%	35.3%	26.3%
Silesia	Schlesien	6.4%	6.9%	2.9%	4.9%	5.6%
	Troppau	0.0%	0.2%	0.1%	0.1%	0.5%
	SUM	6.4%	7.0%	3.0%	5.0%	6.1%
TOTAL		100%	100%	100%	100%	100%

As shown in research on pre-industrial Sweden (Bergenfeldt, 2014), in the absence of railroads 80 % of all transport of grain to the markets was within a radius of 30 km. Bergenfeldt argues that for suppliers of heavy products there was a threshold of 50-60 km which they were willing to undertake to sell their produce, since it allowed a two-way journey to the buyer in one day. During the period 1841-1863, some 30% of all districts were located within the 30km distance to a coal mine while most (70%) of the districts were located further away.

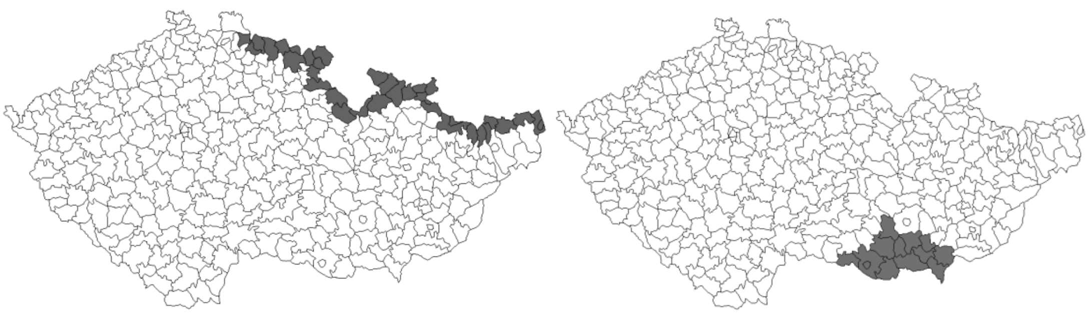
This study did not calculate the foreign market potential because of its time scope (before 1870), which has been characterized by low levels of involvement in foreign trade, particularly before 1880, though low shares of traded goods in the European markets lasted throughout the existence of the Empire (Good, 1984:249; Rudolph, 1976). Contrary to other export-oriented countries such as the UK, overall in the Austrian-Hungarian empire 'foreign trade played a much less important role and production was to a large extent aimed at the domestic market' (Gingrich, 2011). This was very much supported by the trade policy following the Napoleonic wars and before the Cobden-Chevalier Treaty of 1860, where most European countries had high levels of protection or even, as was the case of Austria-Hungary, had straightforward trade prohibition policies on most manufactured goods (Tena-Junguito et al., 2012). Two major trading partners nevertheless became important for the Czech lands, particularly after 1880 – the current territories of Germany in the north (with the port of Hamburg) and Vienna in the South (Rudolph, 1976:45). Vienna became directly connected by railroad to Brno in 1839, while many of the exports through Germany were shipped along the Elbe. This river also became a major transportation mode for the imports of American raw cotton to the rapidly expanding textile sector in the Czech lands. To control for the effect of these non-Czech territories, the study took into account the districts bordering on the German-speaking regions, geographic proximity to Vienna (Figure 7) and access to large navigable rivers, such as the Elbe. Smaller rivers were not used for long-haul freight transport, but often provided an additional source of power or production input.

There were other reasons than trade to control for foreign borders. The mountainous landscape and the lack of suitable agricultural land gave these border areas a lasting tradition of proto-industrial manufacturing. Previous research has found that the availability of arable land was negatively related to non-agricultural activity (Klein and Ogilvie, 2015). This was particularly obvious in the border areas of the Czech lands where the two largest proto-industrial clusters formed and later accounted for the largest shares of the country's pre-industrial exports – glass and textiles (Muller and Wanner, 2011:7,24). Consequently, the high involvement in non-agricultural activities in pre-industrial Czech lands may have stimulated the deployment of steam engines, particularly in the textile sector. Another feature associated with the border effect is the larger shares of foreign population (often German-speaking) and Jews (in the western and northern parts of the country). In Czech history, for example, the Jewish and other non-Czech population was 'central to the growth of non-agricultural activities', mainly because they were not allowed to engage in many occupations, including agricultural work (Klein and Ogilvie, 2015:506).

Figure 7. Foreign borders and proximity to Vienna



(a) Bavaria (b) Saxony



(c) Prussia (d) Districts within a radius of 100 km from Vienna

Last, access to railroads and the expansion of the railroad network (Figure 8) is without doubt an important potential driver of steam adoption. Being located in close proximity to a railroad is likely to have substantially expanded the markets for industrial production, but importantly also helped to secure the reliable transport of production inputs, such as coal. Gaining access to a railroad, as others have shown, led primarily to a change in the location of economic activity (Atack et al., 2010; Berger and Enflo, 2015; Hornung, 2015). This paper controlled for access to railroads directly by calculating the geographical distance to the nearest railroad (in km), and indirectly through the domestic market potential. In 1841, only 28 districts were connected to a railroad; by 1852, a further 36 districts had gained access to the railroad network and by 1863 a total of 101 districts were connected.

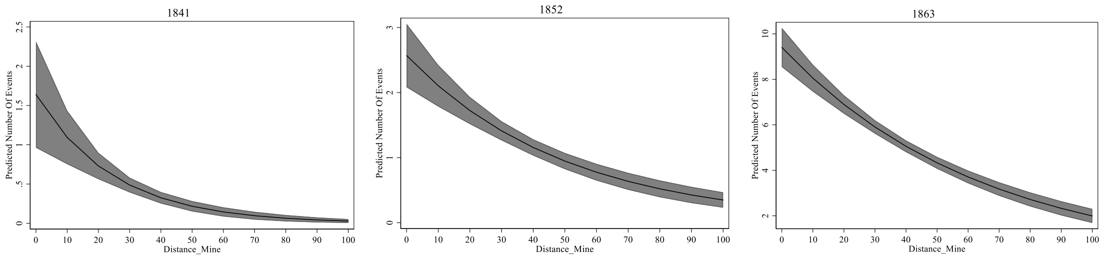
Figure 8. The expansion of the railroad network (1841-1863)

(a) 1841 (b) 1852 (c) 1863

4. Empirical results

To start with, a Poisson cross-section regression model was fitted for the location of the steam engines (and their respective horsepower) for the three benchmark years of the study – 1841, 1852 and 1863. Obviously, the number of steam engines and total of horsepower installed differed considerably between 1841 and 1863. In 1841, the number of observations was limited to 54 districts with at least one steam engine with the remaining 283 districts recording 0. The last benchmark year, 1863, is of particular interest not only as the result of a great many observations; it is also a year approaching the peak of Czech industrialization and the transition to coal, around 1870. Indeed, the economic crisis of 1873 which hit the central European countries in particular is often seen as the completion point of the first industrial revolution in the Czech lands (Horska-Vrbova, 1965). Furthermore, the Austrian manufacturing output peaked in 1871 according to Klein et al. (in O'Rourke and Williamson, 2017), which is why early 1870s has commonly been perceived by economic historians as an end of a rapid development in the region. In 1863, thus, the level of centralized factory production was already very high and the steam engine had become a universal source of power in all the manufacturing branches of the Czech lands (Horska-Vrbova, 1965).

Figure 9. Predicted margins of the number of industrial steam engines according to their distance to a coal mine in the period 1841-1863



(a) 1841 (b) 1852 (c) 1863

The results of the first Poisson regression with cross-sections are summarized in Table 5 while the graphical illustration, focusing only on the actual number of steam engines, is presented in Figure 9 to aid the interpretation of the regression results. Figure 9 shows the predictive margins calculated with the regression outputs of the number of steam engines and highlights the relationship between the number of steam engines and the distance to a coal mine.

The coefficients in Table 5 contrast the Poisson regression model applied on a cross-section as well as combined in a panel data model and focus primarily on the total horsepower installed. In order to analyze only the impact of the variables that changed over time, the data were also fitted within a panel setup with fixed effect. Within this setup, I studied only the impact of the time-varying dependent variables, in this case the distance to the nearest coal mine, distance to a railroad and the domestic market potential, i.e., the ‘first’ and ‘second’ nature causes. By using the district fixed effects, I could thus control for all the unobservable characteristics among the districts. The overall results of the fixed effect model are presented in specifications I-IV of Table 5. It should be stressed that ‘all steam engines’ refers to the total of all steam engines installed in industrial production, mining, agriculture and public utilities. ‘Industrial steam engines’ then refers to the steam engines used in the production of manufactured goods. For specific results on the food processing and textiles sectors only, the reader is referred to section 2 of the Appendix.

The results in Table 5 show that in 1841, for example, moving one unit (1 km) away from a coal mine led to an estimated decline in the total of installed horsepower by almost 5% while by 1863 the coefficient indicates a decline of 2%. Especially in the early industrialization period, access to cheap coal mattered much more than access to the markets (domestic market potential) or other geographical variables. To ease the interpretation and magnitude of the results for the distance to a coal mine variable and the market potential, I normalize the coefficients by the standard deviation of the respective variable to make the interpretation of marginal effects easier (fixed-effect models with specifications 6 and 8). For the distance to a coal mine variable, the table reports the impact of one standard deviation increase in the distance to be associated with a decline of -2.4 in the standard deviation of the installed industrial steam engines. For the other two variables, distance to a railroad and local market potential, the impact is far smaller (Table 5, specifications 6 and 8). Overall, these results confirm the expectations about the negative relationship between the distance to coal and steam concentrations.

Table 5. Results of the Poisson model on total of industrial steam engines (SE) and horsepower (HP) in individual districts

	Cross-sectional data			Panel data					
	1841 All industrial HP	1852 All industrial horsepower (HP)	1863 All industrial horsepower HP	(I) All steam engines (SE)	(II) All industrial steam engines (SE)		(III) All industrial horsepower (HP)		(III) All industrial horsepower (HP)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Geographical variables									
Distance to mine	-0.05 ***	- 0.02 ***	- 0.02 ***	-0.07 ***	- 0.09 ***	-2.362	-0.09 ***	-2.352	-0.09 ***
(km)	(.002)	(.001)	(.)	(.013)	(.016)		(.004)		(.004)
Distance to railroad	- 0.00	- 0.00 **	- 0.01 ***	-0.03 ***	-0.03 ***	-0.835	-0.03 ***	-0.954	-0.03 ***
(km)	(.002)	(.001)	(.001)	(.002)	(.002)		(.001)		(.001)
Distance to town	- 0.02 ***	- 0.01 ***	- 0.01 ***						
(km)	(.002)	(.001)	(.)						
Distance to Vienna	- 0.00 **	0.00	0.00 ***						
(km)	(.001)	(.)	(.)						
Soil suitability	- 0.21 ***	- 0.24 ***	- 0.00						
	(.053)	(.022)	(.009)						
Large rivers	- 0.06	- 0.38 ***	- 0.39 ***						
	(.101)	(.052)	(.023)						
Rivers	0.52 ***	0.23 ***	0.04 **						
	(.059)	(.03)	(.014)						
Institutional and political entity variables									
Market potential	- 0.13 ***	0.20 ***	0.15 ***	0.53 ***	0.53 ***	0.677	0.51 ***	0.64	0.51 ***
(log)	(.033)	(.014)	(.007)	(.042)	(.049)		(.014)		(.014)
Jew share	- 0.02	- 0.03 ***	- 0.05 ***						
(%)	(.014)	(.007)	(.003)						
Foreign borders									
Saxony	1.10 ***	0.44 ***	- 0.14 ***						
	(.106)	(.063)	(.032)						

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Prussia	-1.26 ***	0.25 ***	0.35 ***				
	(.142)	(.044)	(.02)				
Bavaria	2.86 ***	1.26 ***	-0.08				
	(.171)	(.111)	(.059)				
Spatial lag							0.07 ***
(Industrial steam engines in neighboring districts)							(.002)
City and suburb controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Area control	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District fixed effects	na	na	na	Yes	Yes	Yes	Yes
Observations	337	337	337	933	903	903	903
R-squared	0.56	0.49	0.45				

Note. Poisson regression in two specifications: cross-section and panel setting. ‘All industrial steam engines’ refers to steam engines installed in the following industrial sectors: machinery, metallurgy, non-metallic production, chemicals, food processing and textiles. Steam engines installed in mining, agriculture and utilities were excluded from the analysis. The analysis is primarily of the total of installed horsepower; results for installed steam engines are available upon request. A negative relationship between the dependent variable (installed horsepower) and the relative distance measures indicates the negative impact of increasing distances on the measured outcome. Model specifications in columns (6) and (8) refer to the coefficients calculated in (5) and (6) normalized by the standard deviation of the respective variable to make the interpretation of marginal effects easier - one standard deviation increase in the respective variable and its associated change. Standard errors in parentheses. Significance: *p<0,1; **p<0,05 and ***p<0,01.

The soil suitability variable was included in the regression due to its potential impact on the location of steam engines. The food processing industry increased its share of the total of steam engines in the country during the first industrial revolution and by 1863 the sector accounted for the largest share of steam engines. Interestingly, districts with the most suitable land show a negative effect on the total of installed horsepower in all the benchmark years, highlighting the substitution effect ‘via an increase in opportunity costs of allocating inputs to non-agricultural activities’ (Klein and Ogilvie, 2015:504). Potential entrepreneurs in agriculturally productive regions opted for a further intensification of the agricultural output rather than investing in new steam technology (ibid).

Other natural determinants were rivers and large navigable rivers. Interestingly, in the early stages of the industrial development the existence of smaller rivers was found to have a significant impact on the installed horsepower. Districts with access to rivers were 52% more likely in 1841 to increase the installed horsepower capacity. Given the fact that many of the steam engines installed by 1841 served the textiles industry, which was historically dependent on access to water, this result is very much in line with that from the English textile mills in 1838 (Crafts and Wolf, 2014) where direct access to water was a source of energy. With the ongoing substitutions of water through steam also in the textiles sector between 1841 and 1863, the effect of access to rivers was already declining significantly in 1852 and had become only marginal by 1863. The role of large rivers shows a substantial and negative effect on the probability of steam engine location throughout the period of study. This is a rather surprising finding, because large navigable rivers would be seen in the absence of railroads as essential for freight transport. In the Czech lands, however, the nature and magnitude of foreign trade in the period of the present study was still largely underdeveloped. Between 1841 and 1870, some 50-80% of total exports from the Czech lands consisted of brown coal exports but exports of manufactured goods were still at a very low level, especially by 1863 (Kander et al., 2017; Schnabel, 1848). On the import side alone, large rivers were important for the steady supply of raw materials for the expanding textiles sector (mainly raw cotton, because flax and hemp were imported from the Hungarian part of the Empire and not through the traditional large rivers in northern Bohemia). The relatively small scale of the Czech textiles industry (compared to the West) and the traditional location of this often home-based sector in agriculturally inferior areas, however, limited the relocation of the sector nearer to large rivers to secure larger supplies of raw materials.[3]

The presence of foreign borders was assessed as a potential driver of steam adoption. With the exception of Prussia in 1841, districts sharing borders with a foreign country exhibit a greater total of steam horsepower installed. By looking at the more disaggregated foreign borders, districts bordering on Bavaria and Saxony showed the most significant and positive effect on the number of steam engines in 1841, though diminishing by 1852. The historical roots of cross-border trade with Bavaria and Saxony, the most advanced neighbors of the Austro-Hungarian Empire, and the flourishing of the economy in these regions within this particular period, are likely to be the explanation of this effect. The increase in trade barriers between Saxony and Bohemia after Saxony joined the German customs union in 1834 inevitably led to a significant decline in trade between the two states (Ploeckl, 2008). Although the evidence for 1841 still points to a significant and positive impact, this was probably a result of some smuggling activities along the border areas which eventually disappeared by 1863 (ibid). Similar developments were the cause of the declining impact of the Bavarian border with German unification forces and common market creation which led to losses in terms of market access for traditional Czech produce. Still, the increasingly positive and significant impact of Prussia on the bordering Czech districts can be seen as late as 1863, which is likely to have been due to the industrialization of the eastern part of Prussia, mainly fueled by the expansion of mining in Silesia. Although the Prussian economy had been growing quickly since the early 19th century, the eastern part of the territory remained more sparsely populated and had no railroad connection until 1848 when the construction of the 'Ostbahn' was initiated (Hornung, 2015, 2014). This is also why the impact of neighboring Prussia is first visible in the 1852 regression results. Overall, the declining impact of foreign borders between 1841 and 1863, as well as the insignificant effect of large navigable rivers on the installing of industrial horsepower point not to foreign demand but to the importance of internal forces which were the major drivers of Czech industrial progress.

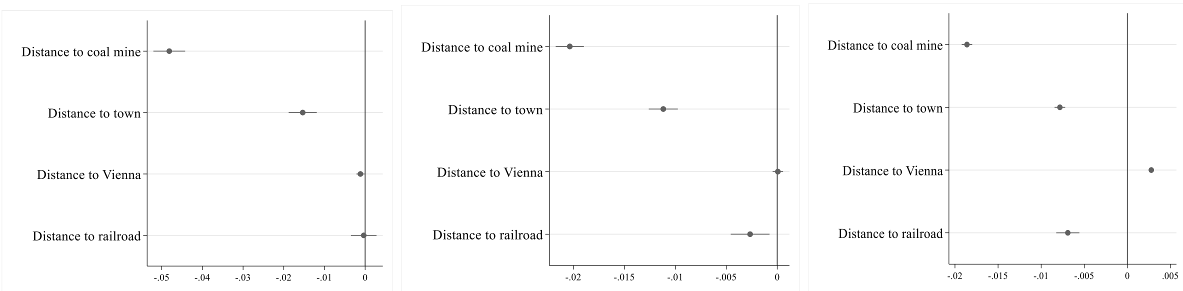
The relative size of the agglomeration effect, the 'second' nature variable, was assessed with a measure of the domestic market potential. Furthermore a control variable for city and suburban districts was used as well as the distance to the nearest city and

[3] Another argument linked to the presence of a river could be its potential correlation with suitable agricultural land. Some weak correlation was found for Bohemia, though the overall correlation coefficient was close to zero (0,15).

specifically also to Vienna. In the past, areas with a high population density, such as towns or suburbs, increased the demand for rural goods and crafts. As Table 5 shows, domestic market potential at first had a small but negative effect on the installed horsepower which, nevertheless, turned into a positive and relatively substantial effect after 1852 and also in the panel setting. In the fixed effects model, a 10% increase in the domestic market potential was associated with a 66% increase in the industrial horsepower. The effect of distance to cities was, as expected, significant and negative, though with a lower explanatory power than distance to a coal mine. The low effect of distance to districts which had a 'city' status supports the existing literature, pointing out merely symbolic value of this status (Cermeño and Enflo, 2019). Moreover, the decline in the importance of cities and suburbs on the total of installed horsepower in particular, is probably an indication of the development of the Czech rural economy and the flow of resources to previously underdeveloped parts of the country. Historically, the concurrence between agricultural and non-agricultural activities in rural Czech lands was affected through material input costs (Klein and Ogilvie, 2015), but it is likely that access to the broader railroad network and thus greater market potential wiped out some of those cost differences. In relation to the upcoming food industry and sugar, the opportunity costs of allocating agricultural labor to those sectors were not significant, given the fact that most of the sugar processing activities were confined to the autumn/winter months of the year, thus in fact providing additional jobs for agricultural laborers in the idle season (Horská, 1970). Indeed, the availability of cheap labor for the newly established food processing industries in these locations was a key determinant of industrial location.

The role of railroads in determining the number of steam engines in a district was further assessed. In 1841, 28 districts (7 % of the total) were connected to a railroad; as the results show, railroad access had no significant impact on the total of installed horsepower. By 1852, an additional 36 districts had gained access to the railroad network and in 1863 a total of 101 districts (nearly a third of all districts) were connected. It has been generally believed that railroad expansion during the first industrialization was crucial, especially for districts without natural resource endowments (particularly coal resources) to industrialize and adopt steam technology in their manufacturing processes. In fact, the access to a railroad which could supply the manufacturer with the required coal without imposing large increases on the costs of production was the strongest incentive to adopt steam technology. Moreover, this positive and significant impact of the railroad network was not only driven by the easier access to coal and other materials of production, but also enabled the manufacturers to enter new markets instead of being limited by the size of their local market. The results of this paper show that the distance to a railroad network had a positive effect on the predicted number of steam engines and the total horsepower of the district, though with a comparatively low explanatory power. I further study the short-run impact of gaining direct access to railroad on installed horsepower and the differential impact on the individual Czech crownlands. While not being presented in the main body of this paper (see Appendix, section 3 for further detail), the results of the diff-in-diff estimates of the Poisson regression show that gaining direct access to a railroad has further intensified the industrialization of the Bohemian industrial clusters as coal-near districts experienced twice as large impact of railroad expansion on the installed horsepower compared to more distant districts. In Moravia, on the other hand, access to a railroad network helped to industrialize rural areas with coal-distant districts gaining the most from railroad expansion. It is difficult to further assess the magnitude of the railroad coefficient, since some of the effect is also indirectly channeled through the domestic market as a potential variable. A graphic comparison of the coefficients of the four distance measures in the model shows the most significant and persistent effect across time for the 'distance to coal mine' measure (Figure 10). Furthermore, while the size of the coal coefficient diminished between 1841 and 1863, a calculation of the average marginal effect shows that the impact of the distance to a railroad further intensified in 1852 and substantially so in 1863.

Figure 10. Poisson regression model and the effect of the various measures of distance in (a) 1841, (b) 1852 and (c) 1863 (specification 1-3 in Table 5)



4.1 Robustness checks

To address possible measurement errors and endogeneity of our main variable of distance to a coal mine, I instrumented this geographical proximity with other variables. In total I used four instrumental variables (Table 6): carboniferous geological strata based on data from the Czech Geological Institute (a similar approach as used by de Pleijt et al., (2019); Fernihough and O'Rourke (2014)), the total of installed horsepower in mining only, the total energy consumption of the district (reconstructed from historical data) and a measure of geographical centrality (Head and Mayer, 2006).

Table 6. Robustness of the distance to coal mine effect to alternative specifications

Measure or instrument for distance to coal mine in district *i*	1% Significance	Coefficient
(1) Poisson random effects	Yes	-0,065
(2) Poisson fixed effects $Y_{it} = \beta_1 + \beta_2 X_{2it} + \beta_3 X_{3it} + \beta_4 X_{4it} .+.. + \alpha_i + \delta_t + \mu_{it}$	Yes	-0,087
(3) Poisson spatial lag effects $Y_{it} = \rho W_j Y_{it} + \gamma W_j Y_{it-1} + X_{it}\beta + \mu_{it} + \varepsilon_{it}$	Yes	-0,089
(4) IV1: Distance to carboniferous strata (Geomorphological map)	Yes	-0,032
(5) IV2: Steam engines used in coal mining only	Yes	-0,079
(6) IV3: Total energy consumption (1863 only), fossil and traditional energy sources (fuelwood, food and fodder)	Yes	-0,143
(7) IV4: Czech centrality	No (5% significance)	-0,025

Note. Poisson regressions as indicated in Table 5, specification 7. With the exception of the first Poisson with random effects, all regressions include the districts controls and fixed effects.

Instrumenting with the use of distance to carboniferous strata (IV1) lowers in some respects the magnitude of the coefficient of distance to coal, though it remains highly significant. Using only the data on steam engines installed for coal mining purposes (IV2) gives the results which are almost the same as the original Poisson regression results with fixed effects. IV3 refers to the total energy consumption of the district in question and is based on my own calculations by taking into account the population/household data (firewood, food & feed) and the industrial structure (coal and firewood). This measure to some extent overlaps with the steam engine, which possibly inflates the magnitude of the distance to coal variable. The measure of centrality (IV4) refers to the sum of all districts in the Czech lands. This measure reduces most the size of the distance to coal coefficient and comes with a 5%

significance level (as compared to the 1% significance level present for the remaining robustness checks), though the direction of the effect does not change. While this instrumentation (IV4) is also the most exogenous one, it does not eradicate the persistent impact of distance to coal on the total of installed horsepower.

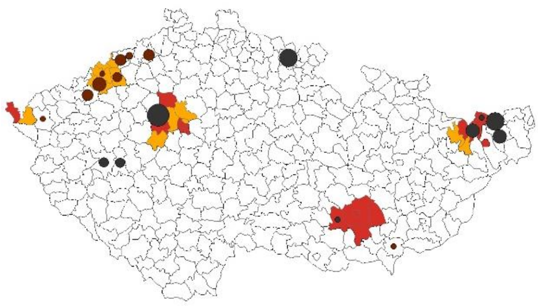
4.2 Spatial analysis

Industrial clustering and the adoption of steam may have had an effect on the number of steam engines across neighboring districts. For example, if one district adopts steam engines on a large scale in its industries, neighboring districts may be quicker to adopt this new technology than districts further away, through either technological spillovers or the expansion of other related industries. Here the question arises to what degree neighboring districts affected each other. In other words, what was the probability that districts bordering on steam-endowed districts would also adopt steam engines in their production processes.

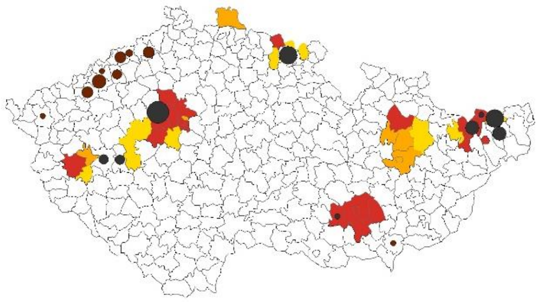
In the results of the base model in Table 5, the significant and positive coefficient of the spatial lag indicates that an additional one steam engine in a neighboring district increased the installed horsepower by nearly 7.3%. I went on to run the same Poisson model on a spatially lagged variable of steam engines for the individual sectors. The most striking is the effect that neighboring steam engines had on the magnitude of horsepower installed in the food processing sector, where only one additional steam engine in a neighboring district led to a nearly 25% increased likelihood of installed horsepower., while for the textile sector, for example, the impact was not significant and near zero. The impact of the spatial lag was most significant in the food processing sector where the cross-district diffusion forces were strongest.

The calculations of measures of spatial autocorrelation point to the strong presence of spatial clusters in our data.Therefore, the paper further investigates in exactly which geographic locations these clusters or hotspots were formed and whether these were located in coal-mining areas. An analysis of local indices of spatial autocorrelation was the most suitable method in this respect because it let me point out exactly those districts with the strongest positive (or alternatively negative) clustering in steam engines. The calculation was based on the Getis–Ord G^*_i (d) statistic (Kondo, 2016a, 2016b) which allowed a cluster map to be plotted, identifying possible clusters with high steam concentrations, often termed the 'hot spots'. Figure 11 shows the results of doing so. Furthermore, I take into account the implications of counterfactuals in which observed distance to a coal mine is replaced by the sample average observation for the variable (45.9 km). The results of this counterfactual calculation and its impact on the location of industrial steam hot spots is visualized in Figure 11 (c). In this counterfactual scenario, as the map indicates, a number of hot spots would not have materialized - such as the area of current Pilsen region in the western part of the country.

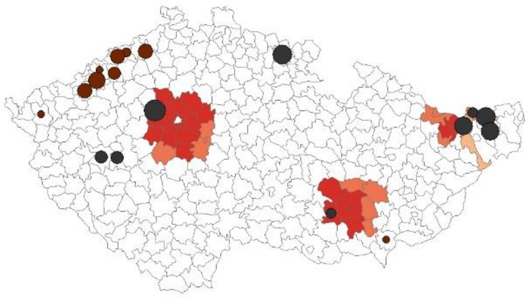
Figure 11. Hot spots of industrial steam horsepower (mining steam engines excluded)



(a) 1841



(b) 1863



(c) 1863 counterfactual

Note. Red indicates hotspots at a 99% significance level, orange at 95% and yellow at 90%. Black and brown circles refer to the coal mining output for each coal type. No data refers to all of the remaining districts, which were found non-significant for the spatial cluster map. No cold spots were identified throughout the period of study. 1863 counterfactual refers to predicted number of industrial horsepower in a counterfactual model where distance to a coal mine was replaced with the year mean (45.9 km).

The cluster map forming Figure 11 highlights the existence of steam engine clusters which were identified given the 10, 5 and 1 % significance levels. Districts in red here represent districts which had a particularly high concentration of steam horsepower and were surrounded by districts with equally high steam concentrations. These spatial clusters with high steam concentration are commonly referred to as the ‘hot spots’. Analogous to the ‘hot spots’ are ‘cold spots’, areas with low values which are usually shaded blue in a cluster map. ‘Cold spots’ were not identified in any of the periods of study, at the 10, 5 or 1 % significance level. As the map illustrates, there is a clear pattern in the data showing hot spots with high steam concentration being located around coal mining districts. The number of districts which would be described as hot spots increased between 1841 and 1863 from 29 to 42. While in 1841, seven of the identified steam hotspots were situated in close proximity to an area mining brown coal, in 1863 no hotspot was any longer close to a brown coal-mining district. Instead, of the total of 42 hotspots of industrial steam use, 35 were found closely located to a black coal mine. This is very much in line with the expansive nature of the first industrialization, taking place not only because of the increasing quantity of energy sources but also their quality. The access to domestic high quality black coal sealed the success of continued economic progress.

A particularly interesting example of an entirely new steam hotspot created next to a coal mine is the region surrounding the city of Pilsen in the most western part of the country where coal had been mined for decades. It was actually the railway connection between Pilsen and Prague (1861-1863) that spurred the inception of its food and machine-building industries (Karnikova, 1958) and consequently the creation of an industrial cluster[4].

Two conclusions can thus be drawn simply by looking at Figure 11. First, the map of Czech steam clusters is more or less a map of major black coal fields which is largely in line with the findings for the English industrial revolution (Pollard, 1981). Interestingly, no steam clusters or hot spots were identified surrounding the brown coal mines along the North-Western borders with Saxony which can be explained by the relatively high share of brown coal being exported to neighboring Saxony. In contrast, domestic black coal, which was of far higher quality was not exported until WWII and therefore exclusively used to fuel domestic industries. Second, in the words of Pollard (1973, pp.636-637) himself: “The industrialization of Europe did not proceed country by country. On the contrary, industrialization would appear as red dots, surrounded by areas of lighter red diminishing to white, and with the spread of industrialization these dots would scatter across the map with little reference to political boundaries”. This was indeed also the case in the Czech lands with a number of red dots signaling a high level of steam adoption and, as this paper implies, industrial progress which was largely concentrated to areas in close proximity to black coal-mining. While other research finds that much of the industrial progress in the whole Austro-

[4] Pilsen is the hometown of the Pilsner Urquell brewery and the industrial concern Skoda Works. At the same time, little is known about its industrial origins so closely tied into the expanding food processing sectors of the Czech lands. The first Pilsner-type lager was brewed in 1842 and has since revolutionized the world beer market with ‘pilsner’ accounting for two-thirds of the world’s beer production. The Skoda Works, known for its transportation and weaponry production, started off in 1859 as an engineering company supplying equipment for sugar refineries and breweries.

Hungarian empire was largely uneven (Cvrcek, 2013), similar developments were also found at the level of individual crown lands.

5. Discussion: the wider implications

The importance of coal for the developments in the Czech lands had some wider implications which would relate to events outside of the period of study. In the Czech context, the importance of access to coal was not only in the adoption of steam; it was its peculiar significance for the food processing industry, which grew exponentially after the 1830s, as this paper has shown, and which became the cornerstone of the Czech industrial heritage. It was also in the period 1841-1863 that the food industry experienced immense technological development and the rapid adoption of steam technology. It has been estimated that by 1850 some 85% of all sugar refineries were located in rural areas without forests and the industry was entirely dependent on coal supplies (Karnikova, 1958).Similar estimates were found for the newly established breweries and distilleries. Although not discussed as extensively in this paper, the origin of the major Czech breweries and distilleries dates back to the same period as that of the sugar refineries (1841-1863). Indeed, both food processing branches, sugar and beer, developed in parallel with each other, largely benefiting from technological expertise and knowledge sharing. Moreover, sugar was widely used in brewing and distilling[5].

Furthermore, 1841-1863, the period of study, is particularly interesting for the food processing sector which went through a series of institutional changes. In 1848, the abolition of robot had some far-reaching consequences for Czech economic development. According to the act of abolition, the serfs were freed and the right to possess land was transferred directly to them. The landlords consequently received compensation for their loss of earnings, so even though they lost their access to cheap labor the landowners suddenly had far more available capital. As a result, the period following the revolutionary year of 1848 was characterized by the changing location of existing sugar factories, especially the closing down and relocation of smaller scale units (Malek, 2010). Besides this immense impact on the scale of sugar production in the Czech lands, the institutional changes of 1848 had some profound consequences for the development of new ethnic groups of entrepreneurs and laid the foundations for the formation of the future Czech working class (Karnikova, 1958). In particular, increasingly more refineries were founded after the late 1850s by the upcoming

[5] For example, Pilsner Urquell was established in 1842.

Czech rural bourgeoisie, in contrast to the many refineries previously established by large feudal landowners. At the same time, the rise of rural ‘entrepreneurs’ led to the creation of rural shareholder businesses to secure stable access to capital.

It was in the same period, that the Czech breweries went through similar developments in the changes to the ownership structures and high degree of modernization and mechanization. Consequently, the high mechanization and use of steam created a demand for coal but importantly also for Czech machinery and iron and steel goods (Good, 1984). This production was traditionally located in the Alpine regions of the Habsburg Empire, but the demand for increased mechanization of the food production sector shifted the production center. The metallurgy and machinery sector thus developed as a consequence of the growing needs of the food processing industry for steam engines and other machinery (Riha, 1976). In fact, at the end of the first wave of industrialization in the early 1870s (Rudolph, 1976:58), 52 % of all machine building companies were producing machinery for the food processing industry alone. By 1880, the Czech engineering sector gained a comparative advantage in the technology of refineries and Czech firms began to build refineries in over 40 countries around the world (Smrcek, 2010). In the same decade, 1880s, the production of iron and steel in the Czech lands exceeded that of other parts of the Empire, gradually turning the region into the machine shop of the Empire. In fact, by the eve of WWI the Czech lands were producing 75% of the combined industrial output of the Empire, had become the world’s third largest sugar producer and the world’s fifth largest machinery exporter (Rudolph, 1976:39-65).

Although the food processing sector mainly offered complementary seasonal work to agricultural laborers and did not result in a vast migration flow to the agricultural areas (and although the level of mechanization and productivity was very high), it had a profound impact on minimizing the regional disparity between urban and rural centers during the first industrial revolution.

Moreover, the growing importance of the food processing industries had a significant impact on the location of the major railroads (Vyskocil, 2010). In the initial stages of railroad construction the gentry actively lobbied (e.g. by offering available land) for rail tracks that would run close to their estates. Later, particularly after 1880, the impact of sugar producers on the design of railroads became even more pronounced with refineries themselves financing and building their own tracks, usually termed the ‘sugar beet tracks’. Sugar and sugar beet in fact became the most commonly transported produce in the period (ibid). Coupled with the railroad expansion, the Czech development block around coal and sugar laid the foundations for the future developments of the Czech lands. The legacy of Czech sugar production dominated the process of industrialization not only due to its complementarity with beer brewing and distilling (refineries and breweries were often very closely related). It also brought many innovations in terms of production processes and product development. Importantly, it brought about the rise of the machinery and iron and steel sectors of the Czech economy, a development which is often used to explain the regional disparities in the Empire. What however needs to be remembered is that this development was merely a culmination of events which went on in the early stages of industrialization before its peak in 1870, all of which were largely related to the increased deployment of coal.

6. Conclusion

Recent literature has re-interpreted the economic backwardness of the Czech lands, often with a focus on the rise of the machine building industries and their importance for the industrial take-off. Nevertheless, the importance of coal for the development and the spatial pattern of industrial activity have remained largely outside the discussion. I argue that it was coal in geographical proximity (and substance) that was the primary driver and the root cause of industrialization in the Czech lands, a development which progressed through a series of small steps before its culmination in the early 1870s. Using Poisson regression, I show a strong and persistent relationship between the spread of steam technology and local coal availability. Instrumental variable estimates further support the robustness of these results. The findings from both the OLS and IV estimates support the hypothesized importance and persistence of the distance to a coal-mine for the exploitation of steam technology. I find that industries with a significant dependence on steam in their production, which are sensitive to changes in the variable costs, will tend to locate in close proximity to coal-mines to secure a consistent supply of this source of energy, especially in the absence of railroads. The overall results of the analysis point to the persistent importance of coal and the increasing role of domestic drivers and industrial clustering in determining the location and adoption of steam technology during the first industrial revolution in the Czech lands, the upcoming center of the industrial production of Austria-Hungary. I show that sugar refining and food processing overall have been the largest single consumers of coal and the presence of domestic coal reserves was fundamental in the expansion of the sector within the period 1841-1863 and the fast transition of the Czech lands to a fossil-fuel-dominated economy. The expansion of the food sector was even more far-reaching than this paper can capture. This newly established sector not only became the largest consumer of coal but had some long-lasting implications for the upcoming engineering branch. Indeed, it was this unique combination of agriculture-based industries in conjunction with domestic coal reserves that brought about the fast energy transition and the absolute dominance of Czech industrial developments, bringing it near the European core.

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Appendix

A. Spatial lag and error models

In order to account for the possibility that certain districts might affect each other because of spatial spillovers or due to market potential and agglomeration affects, the paper also used spatial regressions. This is an important check because it enabled me to identify possible relationship between my variables (steam engines and distance to coal) and the existence of clusters by taking into account the spatial dependence among my observations. Spatial regression is based primarily on the theory of Tobler (1970), according to which 'all places are related but nearby places are more related than distant places' (Tobler, 1970). Within this paper where the focus is on the diffusion of steam engines, spatial regression seems as a very good alternative to traditional regression models because of the existence of other processes which may drive or prevent the technology diffusion and which may have an impact across a group of districts. As in Ward & Gleditsch this spatial dependence can either be captured in the error term (spatial error model) or in the outcome variable (spatial lag model) (Ward and Gleditsch, 2018). In the spatial lag model it is assumed that the value taken by Y is affected by the values Y taken in the neighboring regions:

(6) $$Y_{it} = \beta_1 + \beta_2 X_{it}{}^{DistanceMine} + \rho W_j Y_{it} + \varepsilon_j$$

Where Y denotes an N x 1 vector of observations on the number of steam engines, X denotes an N x j matrix of observations on the least distance to coal; ρ denotes the spatial autoregressive parameter, W denotes the N x N spatial weight matrix; ξ denotes an N x 1 vector of spatial errors; ε denotes an N x 1 vector of normally distributed, homoscedastic and uncorrelated errors. The basic intuition here is that districts are expected to have more steam engines if, on average, their neighbors have high share of steam within its processes as well. The presence of spatial lag would then suggest, in case of steam engines, that a certain diffusion process may have taken place across the districts.

The spatial error model, on the other hand, is presented as:

(7) $$Y_{it} = \beta_2 + \beta_2 X_{it}{}^{DistanceMine} + \lambda W_j \xi_j + \varepsilon_j$$

Where the spatial autoregressive parameter is denoted by λ and all the other terms are defined as above. Unlike the spatial lag model, spatial error model tests for autocorrelation among residuals. A model having a positive spatial error often indicates an existence of an omitted variable that is spatially clustered and is therefore a good measure of the goodness of fit of our original model. Figure A1 explains the differences between both spatial models.

Figure A1. The logic behind spatial models

(a) Spatial lag model (b) Spatial error model

Table A1 displays three various sets of estimates for the relationship between the number of steam engines in one district, its distance to a coal mine and a number of other explanatory factors, when using simple OLS as well as model with spatially lagged dependent variable (SLDV) and spatial error model (SEM). In all cases the estimates of the impact of coal distance on the total of steam engines are highly significant and negative and conform the initial assumption, that the shorter the distance to coal the larger the concentration of steam engines in the district. Comparing the β-coefficients of distance to coal across all three models, it can be seen that the magnitude and significance levels remain at similar levels in the 1841 data. The major implications of this is that location of steam and consequently the industrial centers was primarily destined by the districts location in respect to natural endowments (coal in our case) and market potential. The spatial effect, if any, was of little significance in the early stages of industrialization. In 1863, using the spatially lagged variable model (SLDV), the coefficient for the effect of distance is smaller (-0,945) than when using the spatially error model (SEM) or OLS (-1,16). This is a possible indication that the non-spatial OLS model overestimates the impact distance to coal mine as it does not account for spatial clustering among neighboring districts.

Table A1. Industrial steam engines and least distance to mine using OLS and spatial regression models (SLDV and SEM) in 1841 and 1863

	Industrial steam engines in 1841						**Industrial steam engines in 1863**					
	OLS		SLDV		SEM		OLS		SLDV		SEM	
Distance to a coal mine	-0.134	***	-0.130	***	-0.127		-1.165	***	-0.945	***	-1.164	***
	(0.037)		(0.037)		(0.037)		(0.275)		(0.289)		(0.317)	
Railroad distance	-0.026		-0.027		-0.027		-0.322		-0.090		-0.236	
	(0.037)		(0.037)		(0.037)		(0.500)		(0.504)		(0.558)	
Market potential	3.558	***	3.480	***	3.523		27.147	***	26.160	***	26.140	***
	(1.338)		(1.323)		(1.329)		(6.700)		(6.616)		(6.826)	
Rho			0.172	*					0.194	**		
			(0.100)						(0.090)			
Lambda					0.159						0.170	*
					(0.103)						(0.095)	
Number of observations	337		337		337		337		337		337	

In this respect, the spatially lagged variable model (SLDV) corrects for this by including the spatial lag as an omitted variable. Therefore, in the SLDV model some of the impact on the number of steam engines in county i will be realized not only through the distance to coal and but also through the feedback effect from neighboring county j. To be more precise, 1863 results identify the presence of spatial impact (using both SLDV as well as SEM models) as indicated by the statistically significant spatial parameters ρ and λ. In a traditional OLS framework the presence of spatial element remains unidentified which in turn leads to overestimation of the impact of other factors. The outcome variable (in this case steam engines) in district *i* is affected by the outcome variable in the neighboring districts which can be seen in the SLDV model. The SEM model and its spatial parameter λ at a 10% significance level is then less efficient one than the parameter ρ of SLDV model. Consequently, the SLDV is the preferred model for the later benchmark year of the analysis while in 1841 OLS model is an efficient one to use. Based on this evidence, the paper has therefore used a spatial parameter which accounts for the installed steam engines in neighboring districts, or to be more precise the installments within a 30 km radius from the respective district in the respective benchmark year. In other words, I took account of currently installed steam engines and did not include past installations and time lags. Including both spatial as well as spatial time lag would reduce the number of observations and was therefore not used for the calculations presented in the main body of this paper. The results of the spatial Poisson model with both spatial and time lags can be seen in Table A2.

Table A2. Poisson regression with both spatial and time lags. Note. Standard errors in parentheses. Significance: *p<0,1; **p<0,05 and ***p<0,01.

	Poisson model		**Spatial Poisson model**					
	All industrial HP		All industrial HP		HP in textiles		HP in food processing	
	(I)		(II)		(III)		(IV)	
Distance to coal mine	-0.125	***	-0.089	***	-0.077	***	-0.094	***
	(0.004)		(0.004)		(0.006)		(0.012)	
Spatial and time lags								
Installed HP in neighboring counties			0.017	***	0.016	***	0.020	***
			(0.000)		(0.000)		(0.001)	
Installed HP in neighboring counties (t-1) (1852 installments)			0.020	***	0.012	***	0.037	***
			(0.002)		(0.002)		(0.004)	
Installed HP in neighboring counties (t-2) (1841 installments)			-0.054	***	-0.057	***	-0.101	***
			(0.003)		(0.004)		(0.005)	
Land fixed effects	Yes		Yes		Yes		Yes	
County fixed effects	Yes		Yes		Yes		Yes	
Observations	612		612		300		117	
City and suburb controls	Yes		Yes		Yes		Yes	

B. Poisson regression: the food processing sector versus textiles

Even though, the results of the Poisson model showed significance of distance to a coal mine, the results may differ for various industrial branches. In order to assess the role of coal for the most important and dynamic productive sectors of the Czech industrial revolution, Poisson model was run at a more disaggregated level of the food processing and textile sector. Historically, steam technology was first deployed in mines while the textiles industries experienced one of the most rapid and 'substantial change in terms of power technology'(Crafts and Wolf, 2014; Rose, 1996). In the UK in 1838, cheap source of energy was found to be a determinant of the location probability of cotton textile mill, be it access to water power or cheap coal for the actual size of the mill (Crafts and Wolf, 2014). Besides the proximity to energy sources, a combination of other 'acquired advantages' was found to be important, in particular proximity to ports, railroads as well as agglomeration effects (Crafts and Wolf, 2014). In the Czech lands, the textiles sector was one of the largest consumers of primary energy at the very beginning of the industrial revolution. By 1863, however, sugar refining, other food processing and metals accounted for the largest share of industrial energy consumption. The disaggregation of the horsepower data by productive sector, thus, allows distinguishing the industry-specific determinants of its location. Results in table A3 for the food and textile industry offer an interesting narrative on the developments of the industrial location. Clearly, for both sectors, proximity to a coal mine was a significant driver, but the importance differed across both sectors. In the panel setting (specification I-II), food processing was more dependent on distance to a coal mine but also domestic market potential, probably due to the perishability nature of its produce and the continuous need for production inputs. The higher impact of distance to coal in the food sector can then be explained by the sole reliance of the whole sector (not only steam engines, but also for boiling and preparation) on coal. Contrary to other productive sectors which still to a certain degree utilized firewood or water power, the production of sugar was entirely fueled by coal. In fact, of all productive sectors, the food processing sector shows by far the highest coefficient of the distance to coal (results for other industrial sectors available upon demand). As shown in the existing literature, it has been estimated that by 1850 some 85% of all sugar refineries were located in rural areas without forests and were entirely dependent on regular coal supplies (Karnikova, 1958) and similar estimates were found for the newly established breweries and distilleries.

The sudden rise of this new productive sector has, indeed, shaped the industrial landscape to a significant degree, with new factories founded not only in a proximity to its production input (districts with suitable land) but also in relation to the only sources of available energy.

***Table A3. Results of the Poisson model of steam engines and horsepower location in the food industry and textiles between 1841 and 1863*.**

Standard errors in parentheses. Significance: *p<0,1; **p<0,05 and ***p<0,01.

	Cross-sectional data				**Panel data**	
	1841	1841	1863	1863	(I)	(II)
	Textiles HP	Food HP	Textiles HP	Food HP	Textiles HP	Food HP
	(1)	(2)	(3)	(4)	(5)	(6)
Distance to coal mine	-0.043***	-0.021***	-0.015***	-0.018***	-0.100***	-0.154***
Railroad distance	0.006***	-0.011***	0.001***	-0.007***	-0.030***	0.159***
Least distance to city	-0.018***	-0.010	-0.017***	-0.008***		
Distance to Vienna	0.002***	-0.005**	0.001***	0.001***		
Soil suitability	-0.147**	0.687***	-0.631***	0.593***		
Bordering on: Saxony	1.336***	-15.185	0.399***	-0.622***		
Prussia	-2.381***	-1.513**	0.947***	-0.481***		
Bavaria	3.028***	-13.720	0.466***	0.716***		
Market potential	0.006***	-0.310**	0.264***	0.188***	0.091***	0.969***
Large rivers	-0.046	-16.272	-1.082***	0.050		
Other rivers	1.049***	1.255***	0.762***	0.220***		
County fixed effects	na	na	Na	Na	Yes	Yes
Observations	337	337	337	337	306	363
City and suburb controls	Yes	Yes	Yes	Yes	Yes	Yes

C. The railroad effect

As with other industrial steam engines, the role railroads had on the adoption of steam in especially coal-distant districts was important, though the magnitude of the effect differed between the two largest Czech crownlands - Moravia and Bohemia. I test this by running diff-in-diff estimates of the Poisson regression for districts gaining a direct access to the railroad network. The magnitude of the effect of the railroad expansion differed between respective crownlands of Czechia as Table A4 illustrates. Districts situated within a 30 km radius from a coal mine, which gained a railroad access between 1841 and 1852 (so relatively early on), benefited the most from this new infrastructure in terms of installed horsepower. The overall positive impact of railroad expansion had, however, different magnitude of impact across the crown lands of the Czech lands. While in Bohemia, districts already relatively closely located to a coal mine increased even more its installed horsepower by getting access to a railroad, in Moravia it was mainly the more distant districts which benefited the most. The effect of the railroad has thus further intensified the industrialization of the Bohemian industrial clusters as coal-near districts experienced twice as large impact of railroad expansion on the installed horsepower compared to more distant districts. In Moravia, on the other hand, access to a railroad network helped to industrialize rural areas with coal-distant districts gaining the most from railroad expansion.

Table A4. The short-run impact of gaining direct access to railroad on installed horsepower: Differences in differences estimates of the Poisson regression

		All districts		Districts within 30km from a coal mine		Districts more than 30km from a coal mine	
Dependent variable: Installed HP in all industrial steam engines (mining excluded)							
Railroad between 1841-1852	Czech lands	2,100	***	2,192	***	1,825	***
		(0,024)		(0,031)		(0,044)	
	Bohemia	2,188	***	2,457	***	1,661	***
		(0,032)		(0,045)		(0,052)	
	Moravia	1,911	***	1,830	***	2,419	***
		(0,048)		(0,051)		(0,145)	
	Silesia	2,059	***	2,057	***	2,064	***
		(0,062)		(0,075)		(0,113)	
Railroad between 1852-1863	Czech lands	1,793	***	1,754	***	1,828	***
		(0,017)		(0,020)		(0,037)	
	Bohemia	2,122	***	2,210	***	1,798	***
		(0,026)		(0,032)		(0,049)	
	Moravia	1,482	***	1,412	***	1,794	***
		(0,028)		(0,031)		(0,067)	
	Silesia	1,494	***	1,386	***	2,064	***
		(0,042)		(0,045)		(0,113)	

Note. Treatment effect estimations of a given outcome variable (installed HP) from a fixed-effects Poisson regression baseline. The coefficients refer to the effect of railroad expansion on the installed horsepower between treated districts (those gaining access to railroad) and control districts (those that did not gain railroad connection).

I also run corresponding diff-in-diff estimates of the Poisson regression for districts gaining a direct access to the railroad network with a focus on the installed horsepower in the textiles and the food processing sector (Table A5). While the magnitude of railroad impact on the number of installed horsepower is rather low, gaining access to the railroad had a substantial impact on the installments in the food processing. While districts already located close to a coal mine more than doubled the installed horsepower with the emergence of a railroad, more distant districts recorded an increase by a factor of four. Particularly in Moravia, the impact of the railroad was astonishingly high (450%), signaling the strong dependence of the sector on the new infrastructural developments. Sugar and sugar beet in fact became the most commonly transported produce in the period.

Table A5. The short-run impact of the railroad expansion wave on installed horsepower in the textiles and food processing sectors: Differences in differences estimates of the Poisson regression

		All districts		Districts within 30km from a coal mine		Districts more than 30km from a coal mine	
	Dependent variable: Installed HP in textiles						
Railroad	Czech lands	1,372	***	1,296	***	1,526	***
		(0,032)		(0,044)		(0,049)	
	Bohemia	1,385	***	1,529	***	1,359	***
		(0,041)		(0,064)		(0,057)	
	Moravia	1,225	***	1,168	***	1,606	***
		(0,063)		(0,067)		(0,188)	
	Silesia	1,589	***	0,376	**	2,069	***
		(0,091)		(0,148)		(0,115)	
	Dependent variable: Installed HP in food processing						
Railroad	Czech lands	2,674	***	2,530	***	3,910	***
		(0,062)		(0,066)		(0,261)	
	Bohemia	2,655	***	2,514	***	3,677	***
		(0,082)		(0,090)		(0,293)	
	Moravia	2,619	***	2,328	***	4,509	***
		(0,121)		(0,126)		(0,579)	
	Silesia	2,820	***	2,820	***	na	
		(0,154)		(0,154)		na	

Note. Treatment effect estimations of a given outcome variable (installed HP) from a fixed-effects Poisson regression baseline. The coefficients refer to the effect of railroad expansion on the installed horsepower between treated districts (those gaining access to railroad) and control districts (those that did not gain railroad connection).

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