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Is mechanisation labour displacing? We use two all-inclusive industrial censuses from 19th-century France to examine the effect on wages and employment of one of the greatest waves of mechanisation in history: the diffusion of steam power. Many and costly workers were positively associated with the later adoption of steam. This suggests that mechanisation intended to save on the labour bill. But after controlling for selection effects, our diff-in-diff analysis shows that steam-adopting industries ended up employing both more and better-paid workers on average than their non-steam-adopting counterparts. This disputes the widespread view that past mechanisations entailed technical unemployment and falling labour compensation.

JEL Classification: I15, J42, J31, L92, O14, O33

Keywords: employment, Health, Human Capital, Industrialisation, Innovation, Labour, Motive Power, Wages

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The impact of mechanisation on wages and employment: Evidence from the diffusion of steam power[1]

By Leonardo Ridolfi (Siena University), Carla Salvo (Sapienza University of Rome), and Jacob Weisdorf (Sapienza University of Rome)

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1 Introduction

Does automation save labour? This question is at the heart of a growing theoretical and empirical debate (e.g. Acemoglu and Restrepo 2018; Autor and Salomons 2018; Atack et al 2019; Frey 2019). Overlapping waves of contemporary mechanisations make it difficult to isolate their individual empirical effects. This study turns to a time when mechanisation was rarer and its influence on labour therefore easier to identify. We consider one of the most significant waves of mechanisation in history: the rise and spread of steam power (e.g. Crafts 2008). The empirical setting is 19th-century France, a time and place where steam-technology boomed (e.g. Franck and Galor 2021a), and where detailed historical statistics allow us to explore its effect on labour. We use difference-in-difference estimation together with nearest-neighbour score-matching on data from the two earliest national industrial censuses, recorded in the 1840s and the 1860s. These data enable a comparison of the wages and labour-use among industries that did and did not adopt steam power between the two census registrations.

The findings uncovered in our study speak to several debates concerning both the causes and consequences of mechanisation. First, when dealing with selection into innovation, we evaluate five leading hypotheses about the triggering forces of early mechanisations: the *high-wage* hypothesis that expensive labour and cheap steam-power energy (coal) prompted producers to innovate (Allen 2009, 2011); the *resource-abundance* hypothesis that plentiful traditional motive powers (water in France) stalled innovations (e.g. Crouzet 1996; Benoit 2020); the *health-and-knowledge* hypothesis that well-nourished and well-educated populations helped facilitate innovations (Mokyr 1990; Squicciarini and Voigtländer 2015; Kelly et al 2014, 2022); the *market-force* hypothesis that market size and closeness to technological knowledge incentivised innovation (e.g. Schmookler 1966; Acemoglu and Linn 2004; Franck and Galor 2021a); and the *finance-led-growth* hypothesis that funding stimulated innovations (e.g. Madsen and Ang 2016; Rousseau and Sylla 2005).

Our findings are consistent with the central mechanisms of all five hypotheses. Many and highly-paid workers alongside closeness to coalfields significantly raised the likelihood of steam adoption. Steam was also more likely to occur where water power was absent or inadequate. While basic literacy skills and university knowledge did not propel the diffusion of steam power, specialised technical and scientific knowledge significantly increased the probability of installing steam. This included technical knowledge about how to build the steam engine alongside information correlated with subscriptions to scientific encyclopaedias. Market size, transport infrastructure, finance, and healthy workers also raised the likelihood of steam adoption.

The study's key findings meanwhile relate to longstanding debates about the effects of innovation on labour. Earlier works on the topic are overwhelmed with 'technological anxiety' (Mokyr et al 2015, title). For example, Karl Marx and John Maynard Keynes both famously regarded technical unemployment as a serious consequence of innovation (Marx 1844, p. 25-30; Keynes 1931, p. 364). Equally, the shift from artisan to factory production that went hand in hand with the spread of steam power is usually perceived as having been skill- and therefore wage-saving (e.g. Goldin and Katz 1996; Berg 1994; Atack et al 2004, 2008, 2019). Chronicles about machine-breaking riots sparked by workers' fear that machines would render their skills redundant (e.g. Nuvolari 2002; Caprettini and Voth 2020; Jarrige 2021) have helped cement the impression that historical waves of mechanisations deteriorated labour conditions.

Our findings contrast these views. After adjusting for selection effects, we observe that steam-adopting industries ended up employing up to 97% more workers and paying them up to 14% higher wages on average than their non-steam-adopting counterparts. Because the adoption of steam power in our statistics could have emerged at any point during a 20-year window of observation, our numbers are a mixture of short- and medium-term effects. The positive effect of mechanisation on wages indicates that technical change has widened the wage structure also during the earlier stages of industrial development and not just more recently (Goldin and Katz 1996, 1998). Further, the idea that steam power – one of the greatest mechanisations in history – was labour biased (e.g. Rousseau 2008) confronts the Habakkuk thesis that labour shortage led to higher wages and ultimately drove labour-saving industrial innovations (Habakkuk 1962; Allen 2009).

One issue might be that Habakkuk (in the case of America) and Allen (in the case of England) repeatedly sourced their labour-saving examples from specific innovations in the field of textiles. Perhaps these examples have loomed too large in the context of historical mechanisation. Steam technology had much wider application than inventions in textiles, involving much broader sections of the workforce. Sporadic deviations in the literature on technical anxiety agree with our conclusion (e.g. Mokyr et al. 2015). For example, Mokyr (2002, p. 256) asserts that technical unemployment during early phases of industrialisation did not occur on the large scale that machine-breaking narratives have suggested. Similarly, MacLeod (1988, pp. 160-71) observed that as little as 20% of industrial inventions in Britain between 1660 and 1800 aimed to save on labour.

Our research also contemplates the complementarity of old and new technologies with respect to their effects on labour. Steam engines in France either replaced the traditional water mills completely, or they supplemented them to increase output capacity or secure continued production during periods of drought (Dubuc 1952; Benoit 2020). We observe that the effect of innovation on wages and employment depended on whether steam supplemented or substituted water. Where steam replaced water entirely (i.e. *creative destruction*), it increased both the use of labour and its compensation. Where steam complemented water (technical supplementation), it increased the number of workers employed but not their wages. Creative destruction therefore benefitted workers both in terms of payment and employment. The combined use of old and new technologies instead increased labour about twice as much on average compared to the creative destruction scenario.

Our analysis also shows how geography was instrumental in generating regional inequality. Districts naturally endowed with transport infrastructure or coal deposits were more likely to install steam, which ultimately helped improve local wages and employment. This points to geography-dependent innovations as a central intermediary in the observed correlation of earlier studies between geography and contemporary economic performance (e.g. Henderson et al 2018). Yet, our research also shows that geography is not always destiny. Districts deprived of natural sources of water were more likely to innovate and this way overcome environmental limitations. Our work thus indicates that regions of abundant water (an advantage during pre-industrial times when water mills were a main source of manufacturing power) turned disadvantageous (at least from the viewpoint of labour) after steam technology emerged. This suggests that the evil-flowers argument proposed in Franck and Galor (2021b) – that early industrialisation adversely affected long-run prosperity – might be a recurring outcome of shifting waves of technology. Other features offsetting poor geography in 19th-century France included access to finance and scientific knowledge, the historical origins of which thus deserve further investigation.

The article proceeds as follows. Section 2 outlines the historical spread of steam power in France. Section 3 describes the data used in our analysis. Section 4 discusses the theoretical contributions underpinning our analysis. It also presents the identification strategy and the regression results. Section 5 concludes.

2 Background

Steam power is a prototypical general-purpose technology aimed to mechanise production (e.g. Crafts 2008; Bresnahan 2010). England was the first country worldwide to create and adopt steam technology commercially. The first steam engine was put to use in 1702. Steam in England subsequently spread over the course of the next two centuries. The industrial statistics needed to conduct the analysis below for England however are only available after 1900 (Smith and Penneck 2009). By that time, the next large wave of general-purpose technology (electricity) had already started to take over. The industrial data for France used below are from the mid-19th century, i.e. several decades before electric power was used commercially.

France is often portrayed as a technological laggard compared to England. This was certainly true concerning its use of steam power (e.g. Nuvolari 2010). The first commercial steam engine in France dates back to 1732. It served to pump water out of mines in Fresnes-sur-Escaut in the north of France (Franck and Galor 2021a). The company archives of Boulton and Watt in Britain reveal numerous inquiries from France concerning the Watt steam engine in the late 18th- and early 19th-century (Tann and Breckin 1978). But very few of these inquiries translated into actual orders. For example, Boulton and Watt delivered 110 steam engines to overseas customers between 1776 and 1825. Only six of these engines were sent to France for a total of 314 horsepower. This was a far cry from the estimated 200,000 horsepower used in Britain at the time (Van Neck 1982).

Large-scale steam adoption in France occurred only after the 1820s. The Continental Blockade is considered part of the reason for the slow export of steam into France up until then (Payen 1969). However, the successful diffusion of steam power in France thereafter is primarily ascribed to improved steam technology. The high-pressure, low-fuel-consumption engine developed by Trevithick and Woolf allegedly made it profitable to install steam even in areas where the main source of energy used to run the engines (coal) was relatively costly (Nuvolari 2010). The Woolf steam engine gradually spread from the north of France in the late 1830s to most of the rest of the country during subsequent decades (Diebolt et al 2021).

Expensive coal is usually an obstruction to economic development (e.g. Fernihough and O'Rourke 2021). Allen (2009, 2011) has accordingly argued that low-priced coal was a key reason why England industrialised before France. Allen's hypothesis contrasts earlier work holding that cheap coal could always be imported into France if needed (Crouzet 1974, p. 173). Crouzet (1996) pointed to heavy investments in water power instead as a central reason for the country's slow adoption of steam technology. Our findings below agree with both Allen and Crouzet's ideas.

France was certainly better endowed with water than England, and so relied heavier on this for industrial power than the British (Benoit 2020). According to Benoit, the use of hydraulic energy in France rather than steam power was thus a matter of rational choice. Coal extraction was limited to specific regions, and high transport costs made its use expensive. Early steam engines in France were typically used where there were no other alternatives, or where the water supply was insufficient and stopped production during periods of drought (Dubuc 1952; Benoit 2020).

Ginette Latour, in a letter uncovered from the Departmental Archive of Besancon (Beuchot 2022), depicts a situation probably relevant for many factory owners at the time. It describes a production plant, *Usine de la Gouille*, located on the Doubs river near Besancon.: "The plant draws its energy from this river. The owner, Mr. Bouchot was refused, by the Chief Engineer of the Canal, a new water intake at the level of a double lock, because that would lead to lowering the level of the Doubs' river. Mr. Bouchot, despite the higher cost, was led to install two steam engines to be able to continue manufacturing all year round. This new equipment involves the hiring of 6 to 8 workers, a foreman and a supervising mechanic."

Abundant water is not the only reason put forth in the literature for France's tardy industrial modernisation. Probably starting with Clapham (1936), the motives listed below jointly comprise the *stagnation hypothesis*. Explanations include limited population growth and regional disintegration (Daudin 2010); labour scarcity (Franck 2022); absence of economies-of-scale (Nye 1987; Sicsic 1994: Doraszelski 2004); inferior health and human capital (Kelly et al 2014, 2022); exposure to foreign competition (Becuwe et al 2018; Juhász 2018; Salvo 2022); issues of firm reorganisation (Juhász et al 2021); a retarding role of the state (Khan 2020); and price instability (Sharp and Weisdorf 2012).

An emerging *revisionist* view contends that France was not as retarded as originally thought. The stagnation hypothesis largely builds on comparison of France with England rather than with economies more directly comparable to France. Output and wage estimates of the 18th- and 19th-centuries (e.g. Toutain 1987; Horn 2008; Ridolfi 2019; Ridolfi and Nuvolari 2021) show that economic development in France compared to countries other than Britain was both "respectable and quite creditable" (Crouzet 2003, p. 225). Recent work even indicates that France and England were fairly similar in terms of patent activities (Nuvolari et al 2020), and that France probably made better productive use of its advanced human capital than traditionally believed (e.g. Squicciarini and Voigtländer 2015; Diebolt et al 2021). Several of the factors discussed above are quantified and considered for their role in innovation in our analysis below.

3 Data

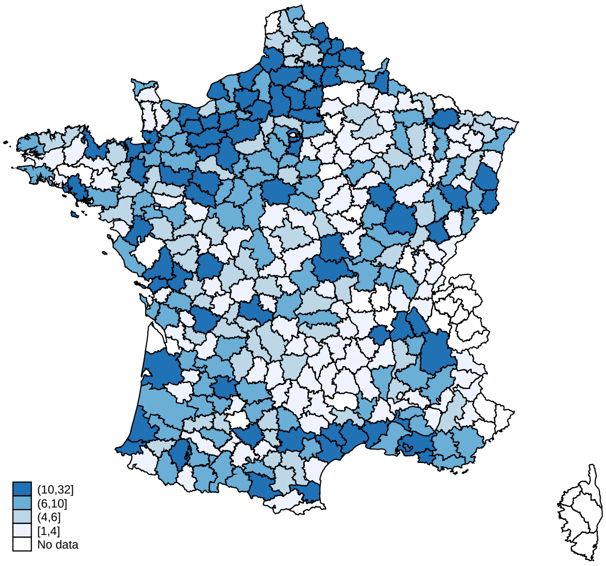
The statistics used in our analysis consist of two parts. One part concerns the information reported in the two earliest industrial surveys carried out by the French Bureau of Statistics during the mid-19th century (Chanut et al 2000). The two surveys are all-encompassing and include the three key variables used in our analysis: wages, employment, and use of motive power. The second group of data concerns district-specific information. These statistics – drawn from a variety of sources listed in Appendix A – serve to help identify local conditions that influenced the likelihood of innovation, such as access to water power and closeness to coalfields.

Industry-specific data

Local factors of production are believed to heavily influence the decision to innovate. For example, John Habakkuk has argued that labour scarcity was an incentive to mechanise production in America (e.g. Habakkuk 1962). Similarly, expensive labour (signalling labour scarcity) relative to the cost of energy (coal in the case of steam power) is said to have been an inducement for producers to mechanise production in England (e.g. Allen 2009). Equally, industries located in districts with rich water streams or windy conditions might have been reluctant to take up steam because of abundant traditional motive powers (e.g. Crouzet 1996). Such conditions need to be accounted for in order to deal with potential selection effects into steam adoption.

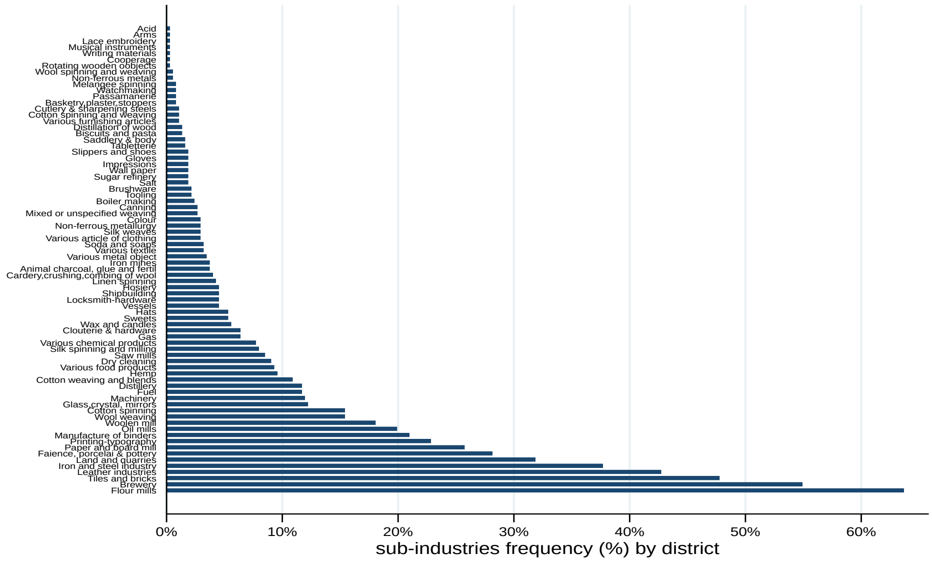
The two earliest industrial censuses in France are helpful in this regard. The first survey was carried out in the 1840s and the second in the 1860s (see Chanut et al 2000). Both surveys report the use of labour (by gender and children) and their average wages at the firm level. They also describe the firm's use of motive power in production. Firms were anonymised in the official statistics of the 1860s, meaning that individual firms cannot be traced across time. We resolve this issue by grouping firms together at the district (*arrondissement*) and subindustry levels. This grouping procedure conveniently solves another issue. Namely that small firms (with less than ten employees) were bundled together at the district level by the Bureau of Statistics (Doraszelski 2004, pp. 259-260; Chanut et al 2000, pp. 15-21).

Figure 1: Active subindustries in the 1840s, by district



The censuses mention a total of 82 industrial subsectors and 377 districts. Not all districts included all subsectors. Some had several, others had none or only a few (Figure 1). On the busy end, the district of Lille in Hauts-de-France had a total of 32 operating subsectors in the 1840s. On the less active end, the district of Poligny in the Jura had only three active ones. The three most widely represented subsectors across France (see Figure 2) were flour milling (active in 64% of all districts), breweries (55%), and brick production (48%). The three least common subsectors were engaged with the production of acid, arms, and musical instrument (each of these were active in less than one percent of all districts). The full dataset mentions a total of 3,793 operating local subindustries in the 1840s and 6,421 in the 1860s. Out of these, 2,554 local subindustries were active across both censuses. This number drops to 1,932 local subindustries (the size of our baseline sample) after we remove those with steam installed already in the 1840s. The descriptive statistics of the local subindustries included in the baseline sample are found in Table 1. The baseline sample concerns 72 of the full 82 subsectors mentioned in the two surveys.

Figure 2: The 72 subindustries in the 1840s, by district coverage



Our main interest concerns three industry-specific factors: wages, employment, and use of motive power. Four types of motive power were mentioned in the surveys: animal, water, wind, and steam. Some subindustries used one or multiple, others none. For example, steam power in the 1840s was used intensively in spinning, shipbuilding, and the production of rotating wooden objects (Figure 3). Steam was not in use at all in watchmaking, lace embroidery, and the production of musical instruments. Eight percent of the sampled subindustries used steam exclusively in the 1840s (Table 2). A further 10% used steam in combination with other motive powers, mainly water (Figure 3). These numbers roughly doubled over the next two decades (Table 2), capturing the speed of diffusion of steam between the two surveys.

Wages and employment also varied considerably across subindustries. For example, male workers in shoemaking were paid about half as much as workers employed in acid making (Figure 4). Inter-industrial differences were due in part to regional wage variation. Male wages in flour milling in the industrial regions of northern France were some three times higher than those paid in the less industrialised or less densely populated regions in the south of France (Figure 5). Employment varied in a fashion similar to wages. Steel production and certain textile industries engaged considerable shares of industrial workers (Figure 6). Brewing, saw-milling, and acid production employed much smaller portions of the industrial workforce. Employment within subindustries was subject to extensive variation, too, as the case of flour milling shows (Figure 7).

Table 1: Descriptive statistics of subindustry-specific variables

	Mean		*Std. Dev*		*Min*		*Max*		*N*	
Variables	*1840s*	*1860s*	*1840s*	*1860s*	*1840s*	*1860s*	*1840s*	*1860s*	*1840s*	*1860s*
Male wage	195	226	64	60	55	48	550	500	1,932	1,932
Female wage	92	110	30	30	5	40	275	250	898	1,197
Child wage	68	83	28	26	5	20	250	180	940	946
Total employment	206	258	1,020	1,185	2	2	32,500	39,835	1,932	1,932
Male employees	136	168	520	729	2	2	12,710	25,078	1,932	1,932
Female employees	48	72	475	443	0	0	18,000	10,255	1,932	1,932
Child employee	22	18	142	127	0	0	4,906	4,659	1,932	1,932
Steam yes/no	0	0.33	0	0.47	0	0	0	1	1,932	1,932
Water mills yes/no	0.36	0.38	0.48	0.49	0	0	1	1	1,932	1,932
Wind mills yes/no	0.07	0.08	0.26	0.27	0	0	1	1	1,932	1,932
Animal mills yes/no	0.13	0.19	0.34	0.39	0	0	1	1	1,932	1,932
Water mills	14.45	83.13	57.40	259.5	0	0	750	2712	1,932	1,932
Wind mills	3.15	11.43	24.60	77.84	0	0	420	1343	1,932	1,932
Animal mills	0.50	1.50	3.18	6.73	0	0	90	162	1,932	1,932

Notes: Wages are measured in *centimes*. Employment refers to the number of workers. Water, wind, and animal mills in the 1860s are measured in terms of their horsepower. *Sources*: see the text.

Table 2: The use of motive powers in the 1840s and 1860s

Type of power	*1840s*	*1860s*
No power	43.0%	31.1%
Only steam	7.7%	15.8%
Only water	20.8%	12.9%
Only animal	6.9%	7.0%
Only wind	0.7%	0.4%
Steam and water	7.6%	15.4%
Steam and animal	2.6%	4.9%
Steam and wind	0.2%	0.2%
Other combinations	10.5%	12.26%
Totals	100%	100%

Sources: see the text.

Figure 3: The shares of motive-power mills in 1840s, by subindustry and type

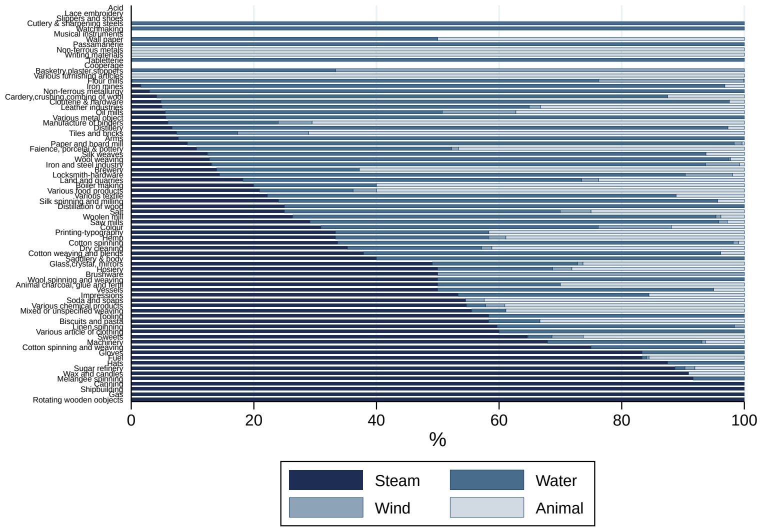


Figure 4: The average male wages in the 1840s, by subindustry

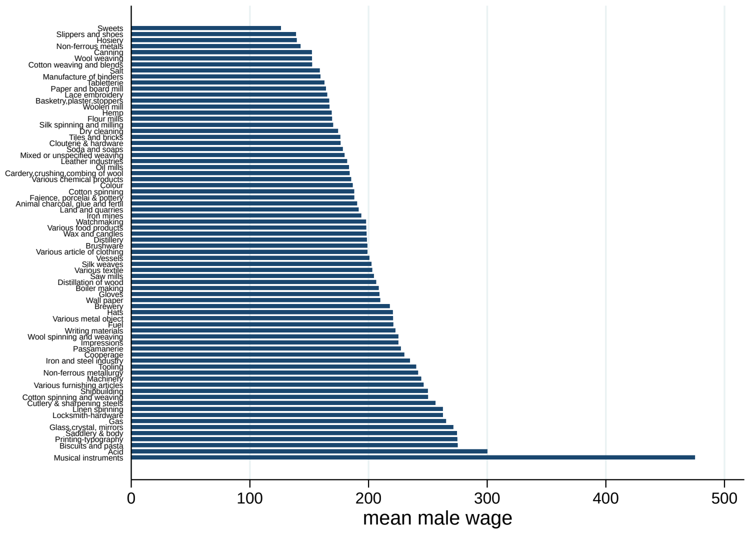


Figure 5: The average male wages in flour milling in the 1840s, by district

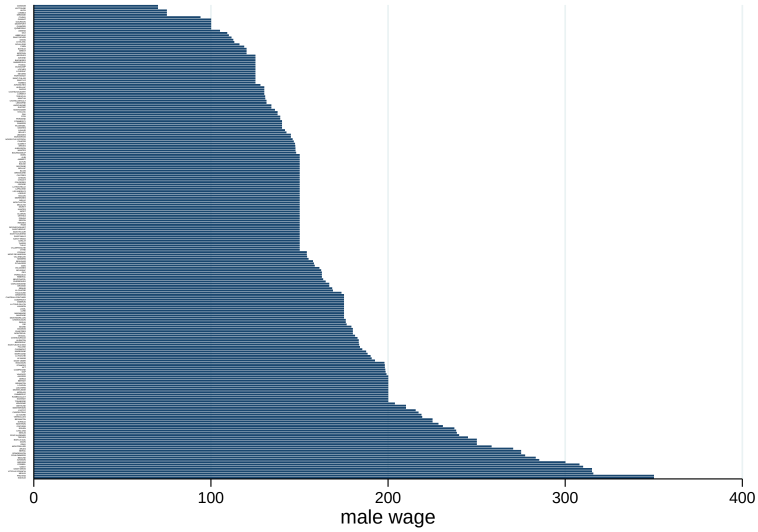


Figure 6: The employment in the 1840s, by subindustry

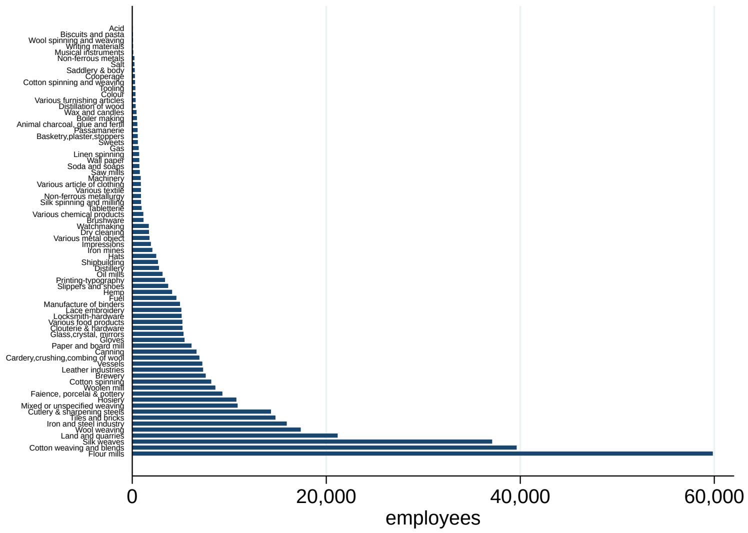


Figure 7: The total employment in flour milling in the 1840s, by district

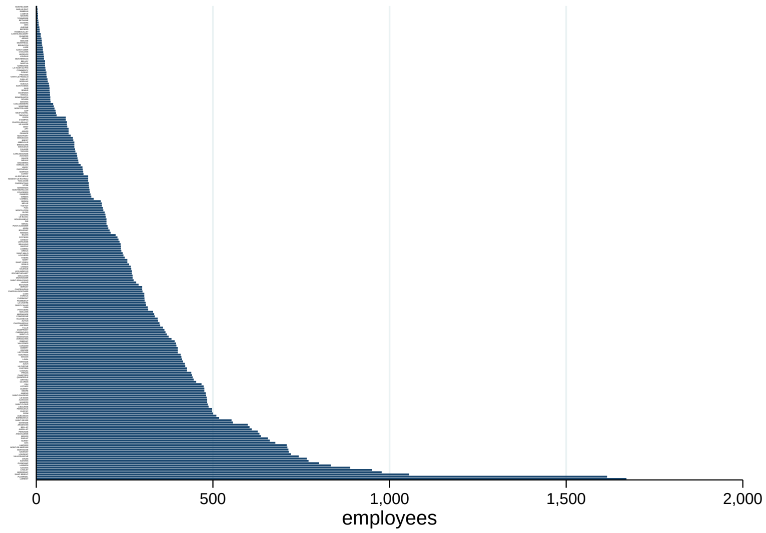


Figure 8: The shares of water- and wind-mills used in flour milling in the 1840s, by district

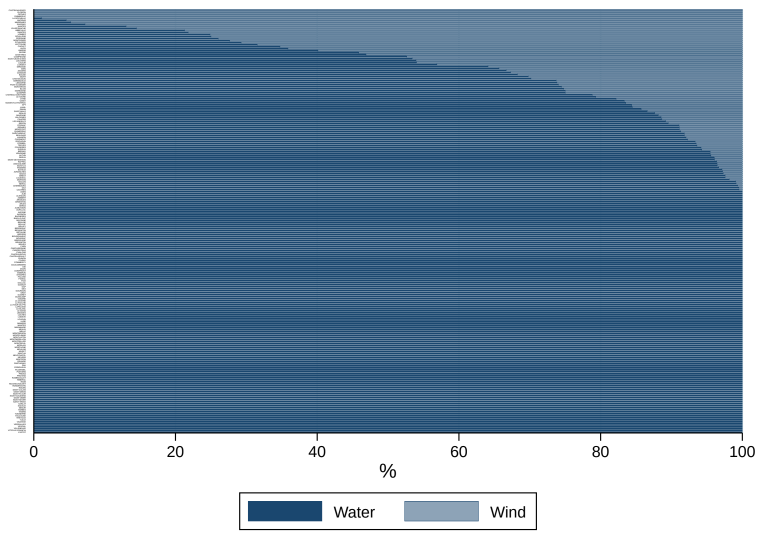


Table 3: Descriptive statistics of district-specific variables

District variables	*Mean*	*Std. Dev.*	*Min*	*Max*
Longitude	2.3	2.6	-4.5	8
Distance from Fresnes km^2	469.3	220.5	9.9	873.6
Distance from coal mines km^2	90	56.5	0	296.3
Rainfall mm	863.7	162	596.6	1425.1
Land suitability	3.7	1.1	1.3	7.9
Literacy rate in the 1830s	0.4	0.2	0.1	0.9
Coastline or navigable river	0.43	0.49	0	1
Temperature in °C	10.7	1.7	1.8	14.4
University in the 1840s	0	0.2	0	1
Encyclopaedia subscription in 1750	22.3	56.3	0	451
Population in 1836	90675.03	39330.57	18709	309349
Surface in ha	150535.7	64122.06	20215	512529
Heights in the 1830s	1668	12.5	1636	1696
Banks in the 1840s	2	2.7	0	18
Steam in district in the 1840s	0.63	0.48	0	1

Sources: see the text and Appendix A.

District-specific data

Local conditions other than wages, wind, and water streams might have influenced the decision to innovate. For example, industries located in populous districts or districts with access to coasts or navigable rivers could reach larger markets. These industries thus faced different incentives to innovate than industries in other districts. Equally, industries in districts with inferior land quality, and thus a poorer agricultural population, might have met lower demand for industrial goods and therefore decided to innovate less than industries in more agriculturally affluent districts. Local conditions like these need to be accounted for in order to avoid selection effects.

Geographical determinants of innovation

Differences in geography are accounted for in the usual way (e.g. Franck and Galor 2021a). That is, we control for variation in land suitability (Figure B-2 in Appendix B); temperature (Figure B-3); rainfall (Figure B-4); longitude (Figure B-5); and access to coastlines or navigable rivers (Figures

B-6). The local prevalence of traditional motive powers described above is dealt with by accounting for industry-specific use of wind-, water- and animal-power in the 1840s (Figure 8). The prevalence of water for innovation is especially relevant, as the water-abundance hypothesis (Crouzet 1996) mentioned above has suggested. Finally, because steam engines ran primarily on coal, we also control for closeness to coalfields (Figure B-7). District-specific descriptive statistics are found in Table 3. Non-sampled districts are shown in Figure B-1.

Other potential determinants of innovation

Geography is not the only factor to trigger innovation. Recent scholarship has pointed to a host of possible inducements. These are summarised below in the form of four hypotheses. The first is Robert Allen's *high-wage* hypothesis. Allen has argued in a series of books and papers that England was the first country worldwide to industrialise because British labour was costlier there than elsewhere and energy (coal) was cheaper (e.g. Allen 2009, 2011). We consider Allen's hypothesis by exploring whether subindustries that paid relatively high wages (see Figures 4 and 5 above) or were located near coalfields (see Figure B-7) were more likely to adopt steam than others.

The second hypothesis argues that healthy and knowledgeable labour was critical to early innovation. This idea is associated with a series of studies by Morgan Kelly, Joel Mokyr, and Cormac Ó Gráda (e.g. Mokyr 1990; Kelly et al 2014, 2022). Good health supposedly improved workers' ability to entertain advanced ideas, and knowledge helped them convert their ideas into useful technologies. Knowledge ranged from the intellectual capacities that come with skilled training to the practical knowledge needed to design, build, and maintain advanced machinery. Note that Mokyr *et al*'s hypothesis aligns with Allen's *high-wage* proposition in that high wages are able to afford both healthier and better educated workers (see Crafts 2011).

We account for local variations in health and knowledge as follows. Differences in health are proxied by the heights of local potential male conscripts in the late 1820s (Figure B-8). Differences in knowledge are captured in three ways: as academic, scientific, and practical knowledge. Academic knowledge is proxied by the literacy rates of local potential conscripts in the late 1820s (Figure B-9) and by the presence of a local university in the 1840s (Figure B-10). Scientific knowledge falls into two categories: general and specific. General scientific knowledge is caught by local rates of subscription to scientific encyclopaedias in 1750 (Figure B-11). Specific scientific knowledge is captured by whether or not steam power was installed in another local subindustry in the 1840s (Figure B-12). Finally, practical knowledge – measuring the local capacity to build, install, and maintain steam engines – is captured by whether a district had an active metal sector in the 1840s (Figure B-13). Note that missing district-level information were inferred from the departmental averages in the cases of heights (10% inferred), literacy (21%), and population size (0.8%). Our results below are robust to removing the districts of missing statistics instead.

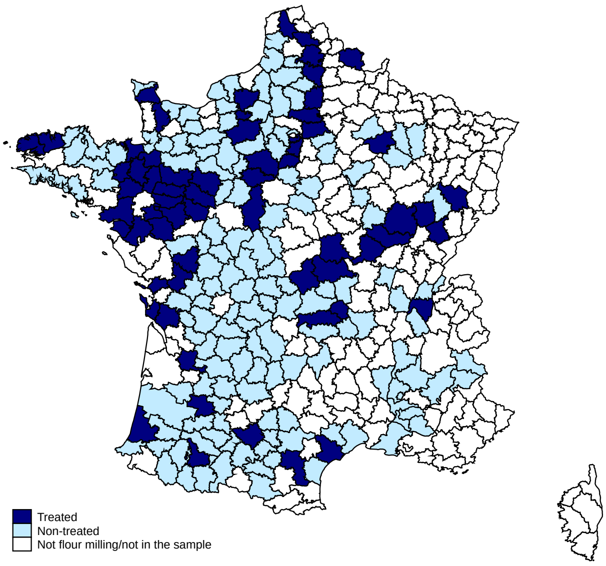
The third hypothesis about the underlying forces of innovation concerns the role of market potential. We consider two types of market forces. One regards the size of local markets, captured by variation in district-level population densities (Figure B-14) and by whether the district had access to coasts or navigable rivers (Figure B-6). The second type of market potential concerns access to technological (i.e. steam) knowledge. Here, Raphael Franck and Oded Galor have argued that British steam knowledge spread from the northern part of France near the English Channel to the rest of the country (Franck and Galor 2021a). They account for access to steam-power knowledge by measuring the distance to Fresnes-sur-Escaut in the north of France, where steam was employed in France for the first time. We adopt the same approach here (Figure B-15).

The fourth and final theory considered is the *finance-led-growth* hypothesis (e.g. Madsen and Ang 2016). Gerschenkron (1962) many years ago emphasised the role of banks in the historical development of Europe. Testing this idea, Peter Rousseau and Richard Sylla found that financial structures predated important technical developments in the early 19th-century United States (Rousseau and Sylla 2005). We account for the relevance of financial structures by controlling for the number of banks by district in the 1840s (Figure B-16). Adding the water-abundance hypothesis discussed earlier (Crouzet 1996), these hypotheses alongside the other variables considered in this section are used below to correct for selection effects.

4 Analysis

We use a difference-in-difference approach to explore the effect of innovation on wages and employment. The approach has two steps. The first step – sometimes referred to as *pre-processing* – serves to identify variables from the 1840s (or before) that are correlated with the later adoption of steam power. A commonly-used alternative to the pre-processing procedure is to check for parallel trends in the data before the 1840s. Here, since we employ the two earliest industrial surveys available, we are unable to examine parallel trends prior to the 1840s. Instead, we use the variables observed in the 1840s (or before) to match steam and non-steam adopting subindustries with regards to their statistical likelihood to innovate. This second step of our analysis thus accounts for selection effects for a more accurate diff-in-diff estimation.

Figure 9: Treated and non-treated local flour-milling industries



4.1 The pre-processing step

A local subindustry is said to be *treated* if steam power was installed between the 1840s and the 1860s. Local subindustries with steam installed prior to the 1840s were dropped from the sample. This left us with a baseline sample of 1,932 local subindustries active across both censuses, as explained in Section 3. Figure 9 shows the treated (dark blue) and non-treated (light blue) districts in the case of flour milling – the most common subindustry in the 1840s. White areas signify districts where flour milling was absent or steam installed already in the 1840s. Similar graphs (not reported here) can be made for each of the remaining 71 subsampled subindustries.

The pre-processing step uses a Probit model. The model controls for a variety of district-specific geographical variables described above including land suitability, temperature, rainfall, longitude, access to coasts or navigable rivers, and closeness to coal and to Fresnes-sur-Escaut (see Appendix B). The role of the geographical factors themselves for the probability of treatment is considered later on. The model also controls for industry and macro-region fixed effects. Macro regions are listed in Appendix C. All variables in the regressions below are log-linearized except dummies.

Table 4: The likelihood of treatment by wages and employment in the 1840s

Outcome variable: Steam adopted in the 1860s	Probit (1)	Probit (2)	Probit (3)	OLS (4)
Male wages in the 1840s	0.479***		0.533***	0.139***
	(0.134)		(0.137)	(0.0380)
Total employment in 1840s		0.171***	0.176***	0.0451***
		(0.0251)	(0.0252)	(0.00718)
Geographical controls	Yes	Yes	Yes	Yes
Subindustry and region FE	Yes	Yes	Yes	Yes
r2	.	.	.	0.269
N	1,932	1,932	1,932	1,932

Notes: Robust standard errors in parentheses: † p<0.15, * p<0.10, ** p<0.05, *** p<0.010. All variables except dummies are in logs. Geographical controls are district-specific and include closeness to coal and Fresnes, land suitability, temperature, rainfall, longitude, and access to rivers or coasts. *Sources*: see the text.

Table 5: The likelihood of treatment by the wages of men, women, and children

Outcome variable: Steam adopted in the 1860s	Probit (1)	Probit (2)	Probit (3)	Probit (4)	Probit (5)	Probit (6)
Male wages in the 1840s	0.479***			0.601**		
	(0.134)			(0.247)		
Female wages in the 1840s		0.325*			0.420**	
		(0.185)			(0.213)	
Child wages in the 1840s			0.238†			0.533***
			(0.159)			(0.190)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Subindustry and region FE	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.227	0.274	0.270	0.312	0.310	0.314
N	1,932	898	940	690	690	690

Notes: Robust standard errors in parentheses: † p<0.15, * p<0.10, ** p<0.05, *** p<0.010. Pseudo R2 for Probit. All variables except dummies are in logs. Geographical controls are district-specific include closeness to coal and Fresnes, land suitability, temperature, rainfall, longitude, and access to rivers or coasts. *Sources*: see the text.

Industry-specific variables

We first use the Probit model to explain the likelihood of treatment by male wages and total employment. Both are local subindustry averages observed in the 1840s. Table 4 shows that both variables are positively correlated with the adoption of steam. This finding confirms part of the *high-wage* hypothesis discussed above. Namely that expensive labour was a driving force in innovation. We also run an OLS model to check the consistency of the Probit model's results. The positive association between wages and innovation reported in Table 4 did not just apply to males. Expensive (high-waged) women and children were also positively and significantly associated with treatment (Table 5). If high wages signal that labour in these areas or subindustries were in scarce supply, then the results of Tables 4 and 5 align with the Habakkuk thesis discussed above.

We now add the use of traditional motive powers to the model (see Table 6). Usage of wind power in the 1840s was not significantly associated with treatment. Water meanwhile was crucial, as emphasised in Crouzet (1996). The influence of water-use on innovation was ambiguous. It depended on whether steam supplemented or substituted water power. In particular, steam was more likely to occur where water was absent (Column 1). Steam would also occur where water was present, but then it was often used in combination with water power (Column 3) though less so the more water mills were used in the 1840s (Column 4). Innovation therefore typically happened either where water was absent or insufficient. Subindustries using animal power in the 1840s were also significantly more likely to install steam (Column 1).

District-specific variables

Does geography explain treatment? Table 7 is confirmative. For example, closeness to coalfields was critical. This aligns with the second part of Allen's *high-wage* hypothesis, predicting that industries located in districts of cheap coal were more likely to shift to steam power. Similarly, closeness to Fresnes-sur-Escaut where steam knowledge supposedly spread from (Franck and Galor 2021a) alongside temperature, longitude, and access to coast or navigable rivers (i.e. transport infrastructure) also raised the likelihood of treatment.

Table 6: The likelihood of treatment in with and without water power in the 1860s

Outcome variable: Steam adopted in the 1860s	Probit (1)	Probit (2)	Probit (3)	Probit (4)
Power-use in the 1860s	*Steam without water*	*Steam without water*	*Steam with water*	*Steam with water*
Water mill in the 1840s (yes/no)	-0.436*** (0.132)		0.473*** (0.117)	
Water mills in the 1840s conditional on using water power		-0.253 (0.208)		-0.217** (0.0883)
Wind mill in the 1840s (yes/no)	0.241 (0.231)	-0.566 (0.714)	0.0553 (0.153)	0.231 (0.190)
Animal mill in the 1840s (yes/no)	0.425*** (0.115)	0.698 (0.532)	-0.0101 (0.131)	0.0725 (0.262)
Male wage in the 1840s	0.570*** (0.160)	0.954† (0.609)	0.198 (0.166)	0.417† (0.258)
Employment in the 1840s	0.121*** (0.0300)	0.117 (0.115)	0.126*** (0.0321)	0.259*** (0.0739)
Geographical controls	Yes	Yes	Yes	Yes
Subindustry and region FE	Yes	Yes	Yes	Yes
R2	0.257	0.604	0.326	0.291
N	1,932	360	1,932	546

Notes: Robust standard errors in parentheses: † p<0.15, * p<0.10, ** p<0.05, *** p<0.010. Pseudo R2 for Probit. All variables except dummies are in logs. Geographical controls are district-specific and include closeness to coal and Fresnes, land suitability, temperature, rainfall, longitude, and access to rivers or coasts. *Sources*: see the text.

Table 7: The likelihood of treatment by geographical characteristics

Outcome variable: Steam in the 1860s	Probit (1)	Probit (2)	Probit (3)	Probit (4)	Probit (5)	Probit (6)	Probit (7)	Probit (8)	OLS (9)
Closeness to coal	1.505***							1.170***	0.329***
	(0.251)							(0.266)	(0.0867)
Closeness to Fresnes		20.06***						16.14**	4.160***
		(5.337)						(6.501)	(1.387)
Land suitability			-0.0205					0.181	0.0402
			(0.141)					(0.156)	(0.0444)
River or coastline				0.428***				0.290***	0.0948***
				(0.0686)				(0.0753)	(0.0216)
Rainfall					-1.042***			-0.345	-0.119
					(0.291)			(0.335)	(0.0854)
Temperature						1.794***		1.626***	0.219***
						(0.326)		(0.417)	(0.0587)
Longitude							0.584	0.907**	0.202†
							(0.412)	(0.452)	(0.123)
Subindustry and region FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.195	0.189	0.180	0.196	0.185	0.192	0.181	0.222	0.249
N	1,932	1,932	1,932	1,932	1,932	1,932	1,932	1,932	1,932

Notes: Robust standard errors in parentheses: † p<0.15, * p<0.10, ** p<0.05, *** p<0.010. Pseudo R2 for Probit. All variables except dummies are in logs. *Sources*: see the text.

Table 8: The likelihood of treatment by human capital

Outcome variable: Steam in the 1860s	Probit (1)	Probit (2)	Probit (3)	Probit (4)	Probit (5)	Probit (6)	OLS (7)
Literacy in the 1820s	0.115 (0.106)					-0.00916 (0.110)	0.00281 (0.0275)
University in the 1840s		0.402*** (0.137)				0.106 (0.146)	0.0282 (0.0451)
Encyclopaedias in 1750			0.282*** (0.0478)			0.225*** (0.0513)	0.0723*** (0.0156)
Steam in the 1840s				0.405*** (0.0848)		0.331*** (0.0863)	0.0855*** (0.0222)
Metal sector in the 1840s					0.275*** (0.0734)	0.207*** (0.0756)	0.0537** (0.0213)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Subindustry and region FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.223	0.237	0.226	0.231	0.228	0.246	0.273
N	1,932	1,932	1,932	1,932	1,932	1,932	1,932

Notes: Robust standard errors in parentheses: † p<0.15, * p<0.10, ** p<0.05, *** p<0.010. Pseudo R2 for Probit. All variables except dummies are in logs. Geographical controls are district-specific and include closeness to coal and Fresnes, land suitability, temperature, rainfall, longitude, and access to rivers or coasts. *Sources*: see the text.

Next, we use several measures to assess whether human capital was important to innovation. Table 8 shows that literacy skills were not significantly associated with treatment while subscriptions to encyclopaedias were. These conclusions agree with the findings reported in Squicciarini and Voigtländer (2015). University knowledge was also positively linked to treatment, but not significantly so when evaluated against other measures of knowledge. Moreover, if another local subindustry used steam power in the 1840s, then this significantly raised the likelihood that other local subindustries adopted it, too. Finally, having a local metal sector in the 1840s improved the probability of treatment. These findings endorse the hypothesis that scientific and practical knowledge were important forces in early industrial innovations (see Kelly et al 2014, 2022).

Table 9: The likelihood of innovation in the 1860s by market-related factors

Outcome variable: Steam adopted in the 1860s	Probit (1)	Probit (2)	Probit (3)	Probit (4)	OLS (5)
Population density in 1836	0.676***			0.605***	0.176***
	(0.0974)			(0.0994)	(0.0279)
Heights in the 1820s		26.12***		12.80†	3.798†
		(8.375)		(8.670)	(2.363)
Banks in the 1840s			0.196***	0.150***	0.0420***
			(0.0460)	(0.0471)	(0.0136)
Geographical controls	Yes	Yes	Yes	Yes	Yes
Subindustry and region FE	Yes	Yes	Yes	Yes	Yes
R2	0.243	0.226	0.230	0.249	0.276
N	1,932	1,932	1,932	1,932	1,932

Notes: Robust standard errors in parentheses: † p<0.15, * p<0.10, ** p<0.05, *** p<0.010. Pseudo R2 for Probit. All variables except dummies are in logs. Geographical controls are district-specific and include closeness to coal and Fresnes, land suitability, temperature, rainfall, longitude, and access to rivers or coasts. *Sources*: see the text.

Three market-related factors still need scrutiny for their impact on innovation. Table 9 shows that market size (captured by local population densities) was positively and significantly associated with treatment. The Table also supports Kelly et al (2014, 2022)'s hypothesis that the prevalence of healthy labour (measured by the average height of local conscripts) encouraged innovation. Lastly, access to finance (proxied by the number of local banks) significantly raised the prospect of treatment.

4.2 The diff-in-diff-with-matching step

The pre-processing step above revealed that numerous pre-treatment factors were statistically significantly associated with treatment. These selection effects will be accounted for when we proceed to isolate the impact of steam adoption on wages and employment below using a matching procedure. But first some considerations regarding the *a priori*.

Earlier studies on the consequences of innovation

Previous studies have pointed towards negative effects of past innovations on wages and employment. These works fall into two categories. The first category concerns the so-called *deskilling* hypothesis often associated with Goldin and Katz (1996, 1998). The hypothesis holds that early industrialisation reduced the need for skilled labour in production. More specifically, the pre-industrial artisanal workshop relied on highly-specialised handicraft proficiencies. But the emerging (mechanised) factory system tended to rely on low- or unskilled labour instead (e.g. Berg 1994; De Pleijt and Weisdorf 2017). Recent empirical assessments of the deskilling hypothesis have however pointed in the opposite direction. De Pleijt et al (2020) has linked intensive use of steam power in 18th-century England to skill-formation rather than skill-reduction. Franck and Galor (2021a) has observed a similar pattern in 19th-century France. These studies thus suggest that average wages might have risen in response to early innovations rather than declining, at least when it came to the spread of steam technology.

The second category of studies on the effect of innovation considers the so-called *labour-saving* hypothesis. This literature contends that mechanisation served to save on the wage bill. The view aligns with Allen's *high-wage* hypothesis discussed above. It also accords with our pre-processing analysis showing that expensive labour prompted 19th-century French producers to innovate. Labour-saving reasons for innovations are cited both in studies of more recent times (e.g. Autor et al 2003; Acemoglu and Autor 2011) and in historical contexts (e.g. Habakkuk 1962; Allen 2009, 2011; Atack et al 2019). These studies also connect to the literature on technical unemployment discussed in Section 2 above. The theoretical studies mostly point to innovation as being labour displacing. Empirical evidence (though scant) advocates the opposite. For example, Von Tunzelmann (1994, pp. 289-91) found limited support for the idea that technological change was labour saving during Britain's Industrial revolution. Equally, MacLeod (1988, pp. 160-71) noted that only one in five British industrial inventions between 1660 and 1800 aimed to save labour.

The effect of innovation on wages

We are now ready to explore the effects of steam adoption on wages and employment in 19th-century France. To this end, we use a diff-in-diff approach to compare male, female, and children's wage developments between the 1840s and the 1860s among steam and non-steam adopting industries. Table 10 reminds us what our pre-processing step above showed. Namely that steam-adopting industries paid significantly higher wages prior to installing steam, something that applied to men

(Column 1), women (Column 3), and children (Column 5) alike. However, before we can properly determine the impact of steam-power adoption on wages, we first need to account for these selection effects.

Pre-treatment biases are removed using a nearest-neighbour propensity-score matching model (e.g. Ho et al 2007). The matching model creates a subsample of local subindustries that are statistically similar in terms of their pre-treatment variables. The matching is a two-step algorithm. The model first searches for non-treated local subindustries that are statistically similar to the treated ones. It then continues to search for the treated subindustries that best match the non-treated ones. The second step only takes effect in case the subindustries are not fully matched in the first step. The size of the matched subsamples is thus usually smaller than the unmatched samples, mainly in terms of the non-treated subindustries but sometimes also in terms of the treated ones. The size of the subsamples is reported in the regression tables below.

We use different matching models for different outcome variables. For example, when we consider the effect of steam on male wages and employment, we match the local subindustries on male wages and employment in the 1840s. The same in the cases of women and children *mutatis mutandis*. The pre-treatment variables used in each of the matching procedures described below are reported in Appendix D along with the matching statistics. The tables and figures in the appendix illustrate the biases alongside the bias corrections. Note that the rule-of-thumb of the matching procedure – reducing the biases to around five percent – is generally fulfilled (Table D-8).

Columns (2), (4), and (6) in Table 10 show that the matching successfully renders the subsampled treated and non-treated subindustries statistically similar in terms of their pre-treatment variables (see Appendix D). For example, the (log of) the average male wages paid in the 1840s in the subsampled non-treated subindustries after matching was 5.258 (Column 2). The comparable number in the subsampled treated subindustries was 5.262. The reported numbers are not statistically-significantly different in any of the three cases (Columns 2, 4, and 6). This effectively means that the subindustries in the matched subsamples are statistically equally likely to innovate prior to treatment, even if only some of them are eventually treated (i.e. adopt steam).

We can now turn to the post-matching, post-treatment wage estimates. Male, female, and children's wages in the matched subsamples (Columns 2, 4, and 6 of Table 10) are all statistically significantly higher post-treatment among steam-adopting subindustries (5.463 for males) compared to their non-steam adopting counterparts (5.407 for males). Onwards to the diff-in-diff estimates, these show that steam-adopting industries ended up paying significantly higher wage compensations to males (4.8% more) and females (6.9% more) compared to subindustries where steam was not adopted. Children's wages (though 6.2% higher in steam adopting subindustries) were not statistically-significantly different. Appendix E reports the results in Table 10 graphically. These show that wages went up in both steam and non-steam adopting subindustries, though more among the innovating ones.

The effect of innovation on employment

Turning to the impact of steam adoption on the use of labour, Table 11 reminds us that larger subindustries were more likely to select into treatment (Columns 1, 3, 5, and 7). After correcting for the selection effects (see Appendix D again), it is clear that steam-adopting subindustries employed more males, females, and child workers post-treatment on average compared to their non-steam adopting counterparts. The diff-in-diff estimates inform that labour-use in innovating subindustries was a staggering 97% higher in the case of male workers (Column 4); 46% higher in the case of female workers (Column 6); and 59% higher in the case of child workers (Column 8). Total employment was 73% higher on average in steam-adopting industries compared to their non-innovating peers (Column 2).

Appendix E reports the results of Table 11 graphically. While both total employment and total male employment increased among innovating subindustries, it dropped among non-innovating ones we start them off around the same size (matched panel). This finding suggests that innovating businesses gain terrain over non-innovating ones. The same pattern held true in the case of child employment, whereas female employment increased both in steam and non-steam adopting subindustries.

The role of water power in steam adoption

Section 4.1 indicated that subindustries with little or no water power were more prone to innovate than water-abundant ones were. But what happened to water-using subindustries post-innovation? Was steam power a substitute or supplement among those that exploited water prior to treatment? Do the wage and employment effects of innovation observed above depend on this?

To find out, we consider two scenarios. In both scenarios, the subsampled subindustries all used water in the 1840s, and the non-treated subindustries continued to use water also in the 1860s. The subsample of treated subindustries in the first scenario all replaced water with steam. We refer to this as *technical substitution* or *creative destruction*. Technical substitution significantly increased both the number of male workers employed (by 41%) and their average wages (by 14%) after matching (see Columns 2 and 4 of Table 12). The subsample of treated subindustries in the second scenario all continued to use water post-treatment. We refer to the mix of old and new technologies as *technical supplementation*. Technical supplementation significantly increased the number of male workers (by 91%) after matching but not their average wages (Columns 6 and 8 of Table 12). Creative destruction in this sense was better for workers' compensation, but technical supplementation was better for employment. Appendix E reports the results of Table 12 graphically.

5 Conclusion

Policymakers widely agree that innovations are vital for countries to thrive in an increasingly competitive global economy. This view is however accompanied by scepticism about whether innovation will harm workers through wage-cuts and job-losses. The early phases of industrialisation witnessed similar concerns, with past workers fearing that mechanisation would render their skills redundant. They dreaded they either had to buckle down and perform unskilled work for lower wages or encounter joblessness. These predictions might have applied in specific areas of past production (e.g. textiles). But they are not consistent with the experience drawn from a large episode of mechanisation observed in 19th-century France. Here, instead, the diffusion of steam engines was associated with more employment and higher labour compensations in innovating industries compared to non-innovating ones. This finding suggests that one of the greatest waves of mechanisation in history – steam power – was labour augmenting.

Future studies could take several routes for a deeper understanding of the impact on labour of large-scale mechanisations in history. One route could attempt to shed further light on the deskilling hypothesis. This would involve uncovering historical data that enable an investigation of the shift in skill-use at the subindustry (or even firm) level in response to innovation. Second, a study of even more immediate effects of innovation than those observed here would inform whether the idea of technical anxiety is more pertinent shortly after treatment. Third, a detailed analysis of the effect of changing output prices on innovation (rather than changing relative factor prices) could help explain why labour-augmenting technologies were profitably put to use where labour was supposedly scarce. Finally, the history of the local conditions that helped overcome poor geography (e.g. financial institutions, healthy workers, human capital, etc.) might be worth examining to better appreciate the root causes of long-term economic development.

Table 10: The effect of innovation on the wages of males, females, and children

Outcome	*Male wages*		*Female wages*		*Child wages*	
Matched	No	Yes	No	Yes	No	Yes
	(1)	(2)	(3)	(4)	(5)	(6)
Before						
Control	5.202	5.258	4.438	4.479	4.118	4.186
Treated	5.264	5.265	4.520	4.517	4.212	4.202
Diff (T-C)	0.062***	0.007	0.082***	0.038	0.094***	0.015
	(0.015)	(0.024)	(0.024)	(0.034)	(0.031)	(0.047)
After						
Control	5.348	5.407	4.607	4.633	4.302	4.333
Treated	5.463	5.463	4.744	4.740	4.420	4.411
Diff (T-C)	0.115***	0.055***	0.137***	0.106***	0.117***	0.078*
	(0.012)	(0.019)	(0.019)	(0.029)	(0.024)	(0.040)
Diff-in-Diff	0.053***	0.048**	0.054**	0.069**	0.023	0.062
	(0.013)	(0.022)	(0.023)	(0.033)	(0.029)	(0.043)
N control	2,596	782	886	290	698	252
N treated	1,268	1,256	594	574	538	508
N total	3,864	2,038	1,480	864	1,236	760

Notes: Diff-in-diff model with nearest-neighbour matching scores with common support. Standard errors in brackets are clustered by subindustry and district. Significance: † p<0.15, * p<0.10, ** p<0.05, *** p<0.010. All variables are in log except dummies. Matching procedure: see Appendix D. *Sources*: see the text.

Table 11: The effect of innovation on the number of workers employed

Outcome	*Total labour*		*Male labour*		*Female labour*		*Child labour*	
Matched	No	Yes	No	Yes	No	Yes	No	Yes
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Before								
Control	3.763	4.213	3.499	3.955	2.835	3.204	2.506	2.881
Treated	4.323	4.314	3.985	3.977	3.158	3.154	2.906	2.903
Diff (T-C)	0.559***	0.101	0.485***	0.022	0.324**	-0.050	0.400***	0.022
	(0.075)	(0.110)	(0.072)	(0.110)	(0.129)	(0.213)	(0.122)	(0.184)
After								
Control	3.723	3.970	3.460	3.666	2.902	3.432	2.220	2.321
Treated	5.016	5.008	4.668	4.659	3.842	3.837	2.945	2.934
Diff (T-C)	1.293***	1.038***	1.208***	0.993***	0.940***	0.405*	0.724***	0.613***
	(0.071)	(0.114)	(0.069)	(0.109)	(0.129)	(0.228)	(0.122)	(0.187)
Diff-in-Diff	0.734***	0.937***	0.723***	0.972***	0.616***	0.455***	0.324***	0.591***
	(0.064)	(0.104)	(0.063)	(0.104)	(0.115)	(0.166)	(0.122)	(0.191)
N control	2,596	798	2,596	798	886	290	698	252
N treated	1,268	1,258	1,268	1,258	594	574	538	508
N total	3,864	2,056	3,864	2,056	1,480	864	1,236	760

Notes: Diff-in-diff model with nearest-neighbour matching scores with common support. Standard errors in brackets are clustered by subindustry and district. Significance: † p<0.15, * p<0.10, ** p<0.05, *** p<0.010. All variables are in log except dummies. Matching procedure: see Appendix D. *Sources*: see the text.

Table 12: The effect of technical substitution and supplementation on male wages and labour

Outcome	*Male wages*		*Male labour*		*Male wages*		*Male labour*	
Power-use in the 1860s	Steam without water (technical *substitution*)				Steam with water (technical *supplementation*)			
Matched	No	Yes	No	Yes	No	Yes	No	Yes
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Before								
Control	5.133	5.316	4.289	3.606	5.133	5.196	4.289	4.192
Treated	5.317	5.297	3.788	3.775	5.222	5.215	4.351	4.291
Diff (T-C)	0.183***	-0.019	-0.501**	0.169	0.089***	0.019	0.062	0.099
	(0.037)	(0.064)	(0.216)	(0.311)	(0.025)	(0.047)	(0.129)	(0.198)
After								
Control	5.290	5.372	4.119	3.581	5.290	5.366	4.119	3.900
Treated	5.503	5.492	4.180	4.164	5.410	5.398	4.978	4.912
Diff (T-C)	0.213***	0.120**	0.062	0.583*	0.120***	0.032	0.860***	1.012***
	(0.030)	(0.050)	(0.197)	(0.304)	(0.120)	(0.028)	(0.114)	(0.185)
Diff-in-Diff	0.029	0.139**	0.563***	0.414†	0.032	0.013	0.798***	0.913***
	(0.033)	(0.067)	(0.181)	(0.254)	(0.023)	(0.041)	(0.114)	(0.152)
N control	620	72	620	72	620	230	620	230
N treated	100	90	100	90	472	428	472	428
N total	720	162	720	162	1092	658	1092	658

Notes: Diff-in-diff model with nearest-neighbour matching scores with common support. Standard errors in brackets are clustered by subindustry and district. Significance: † p<0.15, * p<0.10, ** p<0.05, *** p<0.010. All variables are in log except dummies. Matching procedure: see Appendix D. *Sources*: see the text.

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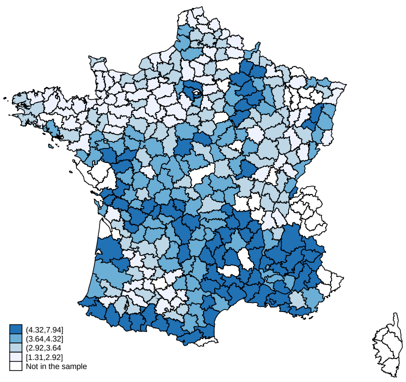
Appendix A: Variable sources and macro regions

Variables	Sources
Industry specific:	*Statistique de la France: Industrie* (Chanut et al 2000)
District specific:	
Longitude	https://www.mapsofworld.com/lat_long/france-lat-long.html
Distance to Fresnes-sur-Escaut km^2	Franck and Galor (2021a)
Distance from coal mines km^2	https://commons.wikimedia.org/wiki/Category:Coal_mines_in_France
Rainfall mm	https://www.fao.org/
Land suitability	https://www.fao.org/
Literacy rate in the 1830s	https://didomena.ehess.fr/concern/data_sets/cv43nx276
Coastline or navigable river	https://www.french-waterways.com/waterways/canals-rivers-france/
Temperature in °C	https://www.fao.org/
University in the 1840s	https://en.wikipedia.org/wiki/List_of_modern_universities_in_Europe_(1801–1945)
Encyclopaedia subscription in 1750	Squicciarini and Voigtländer (2015)
Population in 1836	https://www.insee.fr/
Heights in the 1830s	https://didomena.ehess.fr/concern/data_sets/cv43nx276
Banks in the 1840s	https://didomena.ehess.fr/concern/file_sets/4f16c332r
Steam in district in the 1840s	*Statistique de la France: Industrie* (Chanut et al 2000)
Metal-sector in district in the 1840s	*Statistique de la France: Industrie* (Chanut et al 2000)

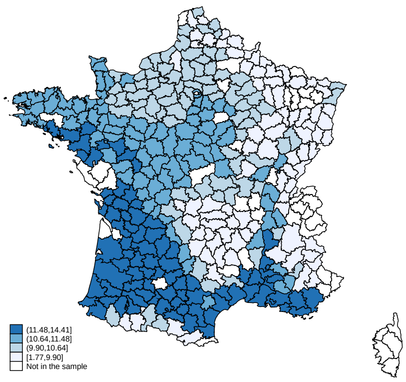
Appendix B

B-1 District not in the sample

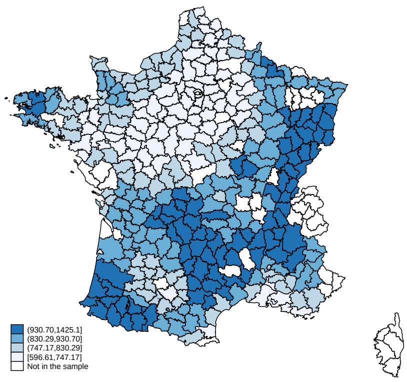
B-2 Land suitability



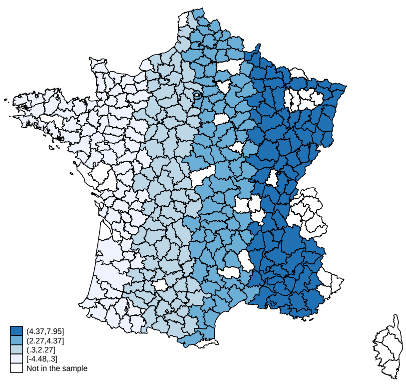
B-3 Temperature



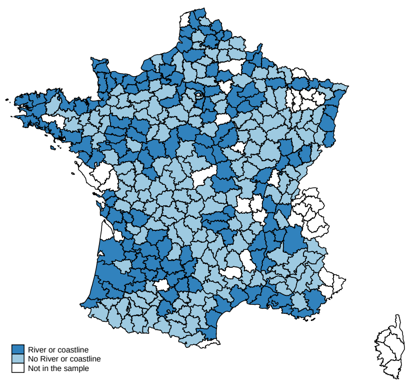
B-4 Rainfall



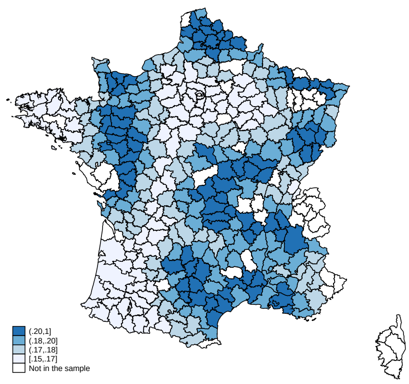
B-5 Longitude



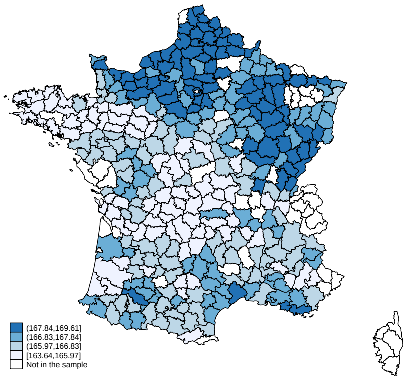
B-6 River or coastline



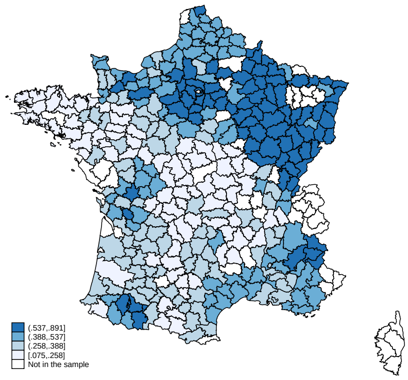
B-7 Closeness to coalfields



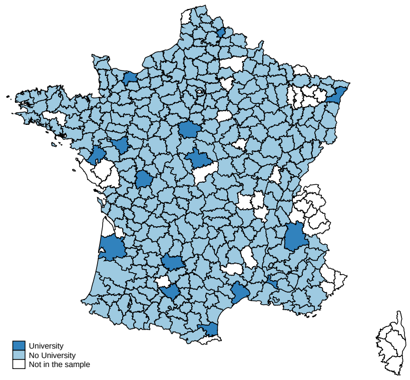
B-8 Heights



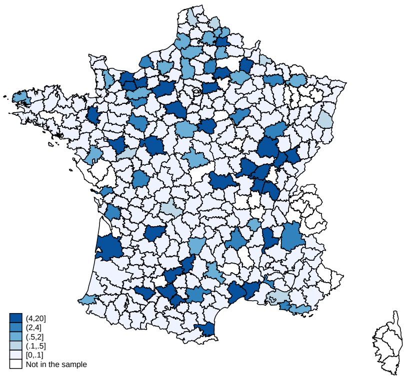
B-9 Literacy



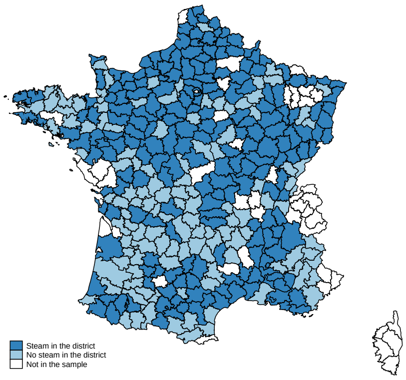
B-10 University



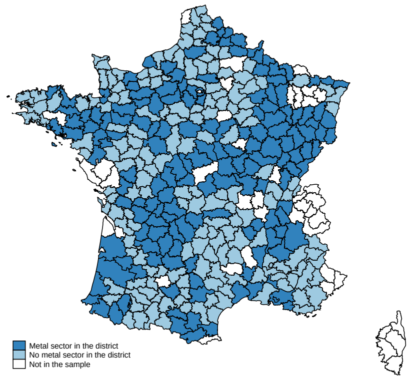
B-11 Encyclopaedia



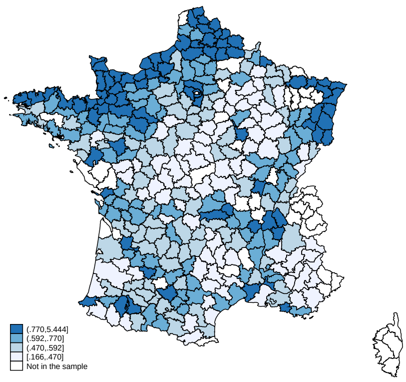
B-12 Steam in district



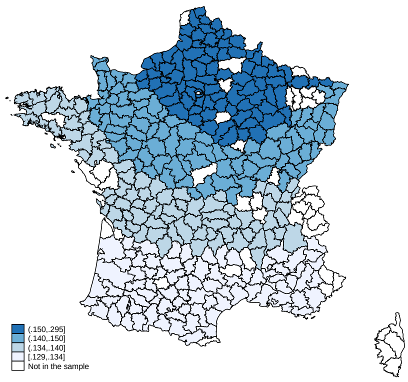
B-13 Metal sector in district



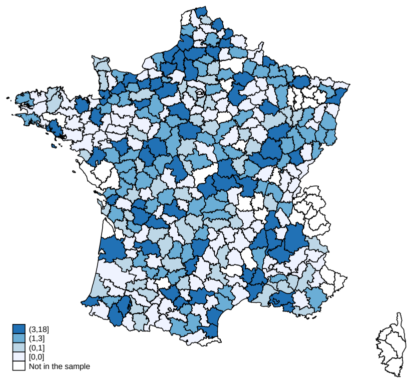
B-14 Population density



B-15 Closeness to Fresnes



B-16 Banks in district



Appendix C: The twelve macro regions in France

1) Auvergne-Rhône-Alpes
2) Bourgogne-Franche-Comté
3) Bretagne
4) Centre-Val de Loire
5) Grand Est
6) Hauts-de-France
7) Normandie
8) Nouvelle-Aquitaine
9) Occitanic
10) Pays de la Loire
11) Provence-Alpes-Côte d'Azur
12) Île-de-France

Appendix D: Matching graphs and tables

Figure D-1: Matching for male wages

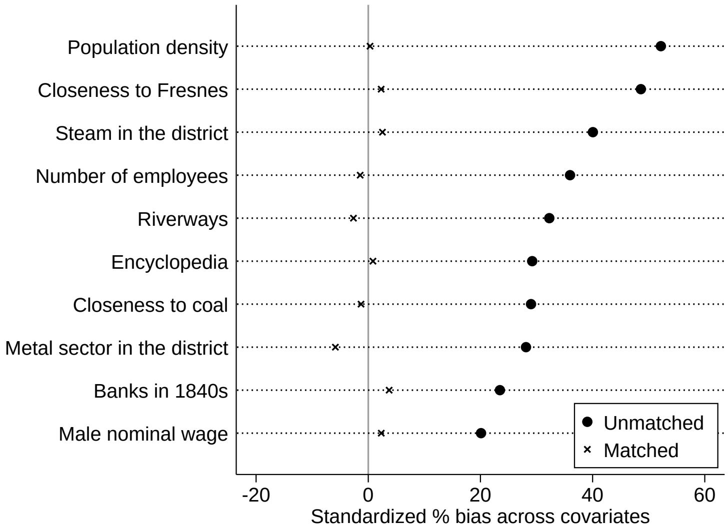


Table D-1: Matching for male wages by variable

		Mean			*t-test*	
Variable	*Matched*	*Treated*	*Control*	*%bias*	*t*	*p>|t|*
Number of employees	No	4.3229	3.7635	36.0	7.37	0.000
	Yes	4.3153	4.3376	-1.4	-0.26	0.796
Male nominal wage	No	5.2644	5.2022	20.1	4.12	0.000
	Yes	5.2653	5.2582	2.3	0.41	0.685
River or coastline	No	.47003	.31433	32.3	6.75	0.000
	Yes	.46497	.47771	-2.6	-0.45	0.651
Encyclopaedia	No	.57228	.35208	29.2	6.18	0.000
	Yes	.57232	.56598	0.8	0.14	0.889
Steam in district	No	.81073	.63482	40.1	7.99	0.000
	Yes	.80892	.79777	2.5	0.50	0.620
Metal sector in the district	No	.64984	.51233	28.1	5.76	0.000
	Yes	.6465	.67516	-5.9	-1.07	0.284
Population density	No	-.22641	-.47713	52.2	11.27	0.000
	Yes	-.23551	-.23704	0.3	0.05	0.958
Bank in the 1840s	No	1.1039	.9124	23.5	4.97	0.000
	Yes	1.0958	1.0654	3.7	0.62	0.534
Closeness to Fresnes	No	.14113	.13278	48.6	11.01	0.000
	Yes	.14001	.13961	2.3	0.39	0.695
Closeness to coal	No	.23411	.19308	29.0	6.44	0.000
	Yes	.22972	.23154	-1.3	-0.20	0.844

Source: see the text.

Figure D-2: Matching for male employees

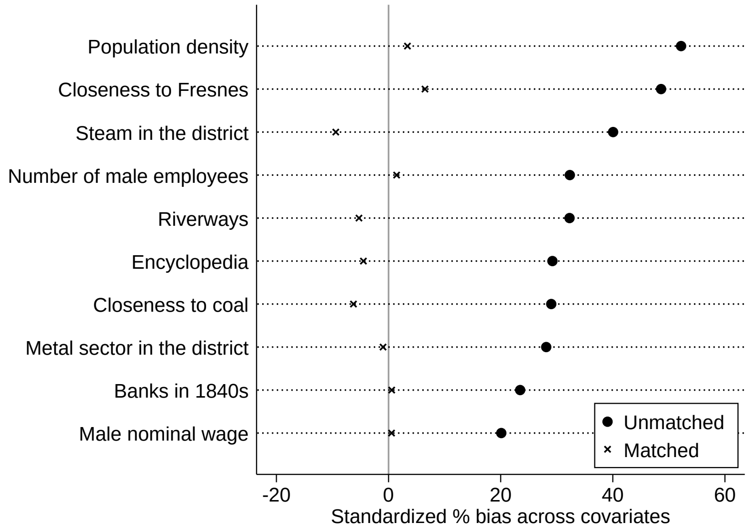


Table D-2: Matching for male employees by variable

		Mean			*t-test*	
Variable	*Matched*	*Treated*	*Control*	*%bias*	*t*	*p>|t|*
Number of male employees	No	3.9848	3.4993	32.3	6.64	0.000
	Yes	3.9768	3.9551	1.4	0.26	0.793
Male nominal wage	No	5.2644	5.2022	20.1	4.12	0.000
	Yes	5.2649	5.2633	0.5	0.09	0.924
River	No	.47003	.31433	32.3	6.75	0.000
	Yes	.46582	.49126	-5.3	-0.90	0.367
Encyclopaedia	No	.57228	.35208	29.2	6.18	0.000
	Yes	.57232	.60611	-4.5	-0.73	0.465
Steam in district	No	.81073	.63482	40.1	7.99	0.000
	Yes	.80922	.85056	-9.4	-1.95	0.051
Metal sector in the district	No	.64984	.51233	28.1	5.76	0.000
	Yes	.64706	.65183	-1.0	-0.18	0.859
Population density	No	-.22641	-.47713	52.2	11.27	0.000
	Yes	-.23398	-.2502	3.4	0.55	0.585
Bank in the 1840s	No	1.1039	.9124	23.5	4.97	0.000
	Yes	1.0972	1.0926	0.6	0.09	0.925
Closeness to Fresnes	No	.14113	.13278	48.6	11.01	0.000
	Yes	.1402	.13908	6.5	1.08	0.280
Closeness to coal	No	.23411	.19308	29.0	6.44	0.000
	Yes	.23046	.23931	-6.3	-0.93	0.353

Source: see the text.

Figure D-3: Matching for female wages and employment

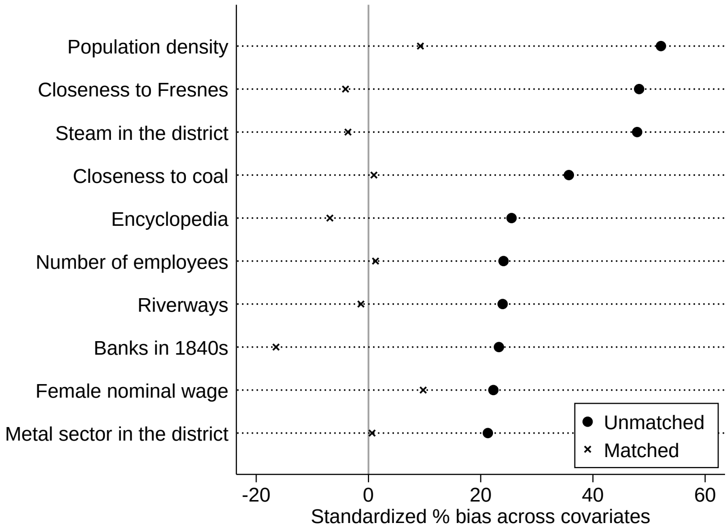


Table D-3: Matching for female wages and employment by variable

		Mean			*t-test*	
Variable	*Matched*	*Treated*	*Control*	*%bias*	*t*	*p>|t|*
Number of employees	No	4.8009	4.4669	24.1	3.48	0.001
	Yes	4.789	4.7715	1.3	0.16	0.873
Female nominal wage	No	4.5212	4.4496	22.3	3.17	0.002
	Yes	4.5187	4.4873	9.8	1.30	0.193
River	No	.41486	.30087	23.9	3.48	0.001
	Yes	.39936	.40575	-1.3	-0.16	0.871
Encyclopaedia	No	.54151	.35348	25.5	3.75	0.000
	Yes	.54259	.59328	-6.9	-0.80	0.422
Steam in district	No	.82353	.61391	47.9	6.67	0.000
	Yes	.81789	.83387	-3.6	-0.53	0.599
Metal sector in the district	No	.613	.50783	21.3	3.05	0.002
	Yes	.60064	.59744	0.6	0.08	0.935
Population density	No	-.26778	-.50548	52.1	7.69	0.000
	Yes	-.30194	-.34418	9.3	1.18	0.240
Bank in the 1840s	No	1.1215	.935	23.3	3.40	0.001
	Yes	1.1099	1.242	-16.5	-2.05	0.041
Closeness to Fresnes	No	.14071	.13261	48.2	7.56	0.000
	Yes	.1382	.13889	-4.1	-0.60	0.548
Closeness to coal	No	.23288	.18444	35.7	5.59	0.000
	Yes	.2213	.21998	1.0	0.11	0.915

Source: see the text.

Figure D-4: Matching for child wages and employment

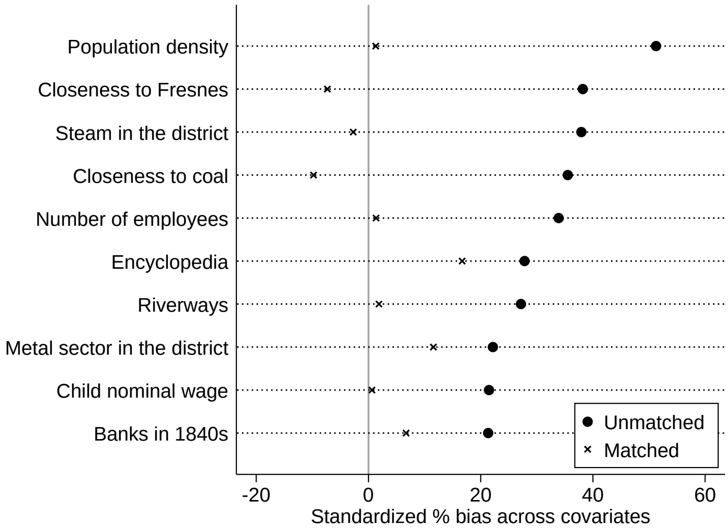


Table D-4: Matching for child wages and employment by variable

		Mean			*t-test*	
Variable	*Matched*	*Treated*	*Control*	*%bias*	*t*	*p>|t|*
Number of employees	No	4.8494	4.3817	33.9	5.03	0.000
	Yes	4.8215	4.8028	1.4	0.17	0.863
Child nominal wage	No	4.2021	4.119	21.5	3.19	0.001
	Yes	4.19	4.1875	0.6	0.08	0.935
River	No	.42776	.29813	27.2	4.08	0.000
	Yes	.40597	.39701	1.9	0.24	0.813
Encyclopaedia	No	.55781	.34987	27.8	4.21	0.000
	Yes	.56563	.44084	16.7	2.07	0.039
Steam in district	No	.80737	.64055	37.9	5.50	0.000
	Yes	.80597	.81791	-2.7	-0.39	0.693
Metal sector in the district	No	.64023	.53152	22.2	3.28	0.001
	Yes	.62985	.57313	11.6	1.50	0.134
Population density	No	-.24494	-.48867	51.3	7.86	0.000
	Yes	-.3034	-.30958	1.3	0.18	0.854
Bank in the 1840s	No	1.1014	.92877	. 21.3	3.22	0.001
	Yes	1.1059	1.0516	6.7	0.86	0.392
Closeness to Fresnes	No	.13972	.13365	38.2	6.03	0.000
	Yes	.13746	.13863	-7.3	-1.12	0.264
Closeness to coal	No	.23085	.1839	35.5	5.67	0.000
	Yes	.21817	.2311	-9.8	-1.06	0.287

Source: see the text.

Figure D-5: Matching for total employment

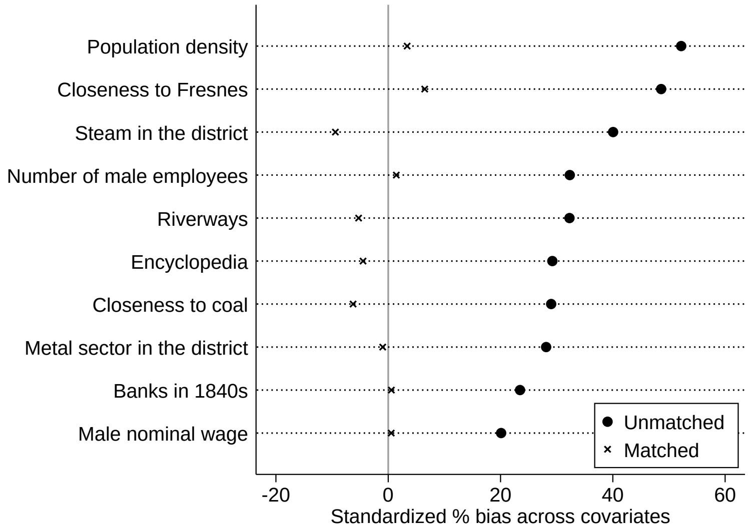


Table D-5: Matching for total employment by variable

		Mean			*t-test*	
Variable	*Matched*	*Treated*	*Control*	*%bias*	*t*	*p>|t|*
Number of male employees	No	3.9848	3.4993	32.3	6.64	0.000
	Yes	3.9768	3.9551	1.4	0.26	0.793
Male nominal wage	No	5.2644	5.2022	20.1	4.12	0.000
	Yes	5.2649	5.2633	0.5	0.09	0.924
River	No	.47003	.31433	32.3	6.75	0.000
	Yes	.46582	.49126	-5.3	-0.90	0.367
Encyclopaedia	No	.57228	.35208	29.2	6.18	0.000
	Yes	.57232	.60611	-4.5	-0.73	0.465
Steam in district	No	.81073	.63482	40.1	7.99	0.000
	Yes	.80922	.85056	-9.4	-1.95	0.051
Metal sector in the district	No	.64984	.51233	28.1	5.76	0.000
	Yes	.64706	.65183	-1.0	-0.18	0.859
Population density	No	-.22641	-.47713	52.2	11.27	0.000
	Yes	-.23398	-.2502	3.4	0.55	0.585
Bank in the 1840s	No	1.1039	.9124	23.5	4.97	0.000
	Yes	1.0972	1.0926	0.6	0.09	0.925
Closeness to Fresnes	No	.14113	.13278	48.6	11.01	0.000
	Yes	.1402	.13908	6.5	1.08	0.280
Closeness to coal	No	.23411	.19308	29.0	6.44	0.000
	Yes	.23046	.23931	-6.3	-0.93	0.353

Source: see the text.

Figure D-6: Matching for technical substitution (steam only)

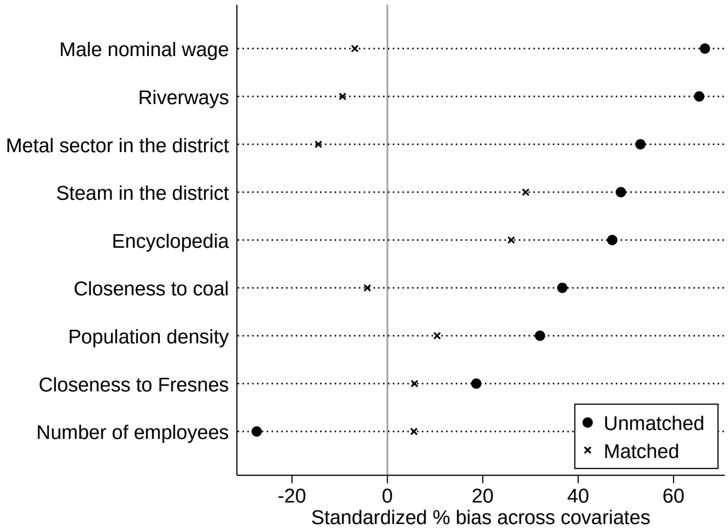


Table D-6: Matching for technical substitution (steam only in the 1860s)

		Mean			*t-test*	
Variable	*Matched*	*Treated*	*Control*	*%bias*	*t*	*p>|t|*
Number of male employees	No	4.2345	4.6204	-27.4	-1.76	0.079
	Yes	4.2042	4.1258	5.6	0.28	0.779
Male nominal wage	No	5.3167	5.1332	66.6	3.98	0.000
	Yes	5.2972	5.316	-6.8	-0.32	0.752
River	No	.58	.27097	65.4	4.48	0.000
	Yes	.53333	.57778	-9.4	-0.42	0.676
Encyclopaedia	No	.59275	.25635	47.1	3.42	0.001
	Yes	.52325	.33795	26.0	1.16	0.248
Steam in district	No	.78	.55484	49.0	3.03	0.003
	Yes	.75556	.62222	29.0	1.37	0.176
Metal sector in the district	No	.78	.53548	53.1	3.28	0.001
	Yes	.75556	.82222	-14.5	-0.77	0.444
Population density	No	-.3772	-.52453	32.0	2.29	0.023
	Yes	-.38029	-.42833	10.4	0.53	0.599
Closeness to Fresnes	No	.13371	.13174	18.6	1.36	0.174
	Yes	.13427	.13367	5.7	0.26	0.795
Closeness to coal	No	.22617	.18024	36.7	3.20	0.002
	Yes	.19679	.20205	-4.2	-0.20	0.839

Source: see the text.

Figure D-7: Matching for technical complementation (steam and water)

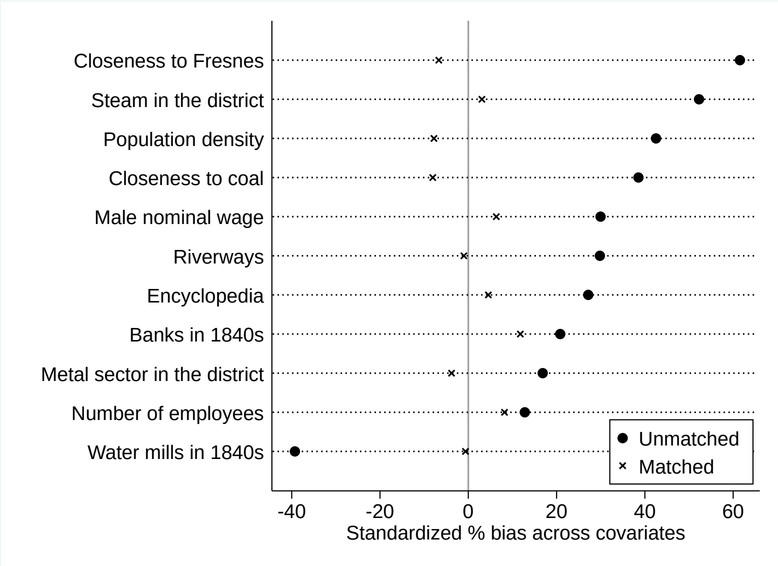


Table D-7: Matching for technical complementation (steam and water together in the 1860s)

		Mean			*t-test*	
Variable	*Matched*	*Treated*	*Control*	*%bias*	*t*	*p>|t|*
Number of male employees	No	4.8072	4.6204	12.8	1.48	0.138
	Yes	4.7396	4.6198	8.2	0.88	0.381
Male nominal wage	No	5.2219	5.1332	30.0	3.44	0.001
	Yes	5.2151	5.1963	6.3	0.62	0.538
River	No	.41102	.27097	29.8	3.48	0.001
	Yes	.3785	.38318	-1.0	-0.10	0.921
Encyclopaedia	No	.44541	.25635	27.2	3.19	0.001
	Yes	.4552	.4236	4.5	0.43	0.667
Steam in district	No	.79237	.55484	52.3	5.97	0.000
	Yes	.78972	.7757	3.1	0.35	0.726
Metal sector in the district	No	.61864	.53548	16.9	1.95	0.052
	Yes	.60748	.62617	-3.8	-0.40	0.692
Population density	No	-.34734	-.52453	42.5	4.94	0.000
	Yes	-.38058	-.34817	-7.8	-0.76	0.448
Bank in the 1840s	No	.98274	.82116	20.8	2.43	0.015
	Yes	.9822	.89073	11.8	1.21	0.226
Closeness to Fresnes	No	.1392	.13174	61.5	7.35	0.000
	Yes	.13714	.13795	-6.7	-0.81	0.418
Closeness to coal	No	.22998	.18024	38.5	4.66	0.000
	Yes	.20919	.21957	-8.0	-0.73	0.463
Water mills in 1840s	No	2.0917	2.726	-39.3	-4.48	0.000
	Yes	2.1633	2.1736	-0.6	-0.07	0.942

Source: see the text.

Table D-8: Matching by sample

Sample: male wages	*Ps R2*	*LR chi2*	*p>chi2*	*MeanBias*	*MeanBias*	*B*	*R*	*%Var*
Unmatched	0.126	307.62	0.000	33.9	30.8	86.0	1.52	71
Matched	0.001	2.55	0.990	2.3	2.3	9.0	0.96	0

Sample: male employment	*Ps R2*	*LR chi2*	*p>chi2*	*MeanBias*	*MeanBias*	*B*	*R*	*%Var*
Unmatched	0.120	293.82	0.000	33.5	30.8	83.6	1.60	71
Matched	0.005	8.34	0.595	3.9	3.9	16.3	0.95	14

Sample: female wages/emp.	*Ps R2*	*LR chi2*	*p>chi2*	*MeanBias*	*MeanBias*	*B*	*R*	*%Var*
Unmatched	0.118	138.89	0.000	32.4	24.8	80.0	1.90	57
Matched	0.012	10.13	0.429	5.4	3.9	25.5	1.10	0

Sample: child wages/emp.	*Ps R2*	*LR chi2*	*p>chi2*	*MeanBias*	*MeanBias*	*B*	*R*	*%Var*
Unmatched	0.120	149.05	0.000	31.7	30.9	82.3	1.75	71
Matched	0.009	8.55	0.575	6.0	4.7	22.6	1.01	29

Sample: total employment	*Ps R2*	*LR chi2*	*p>chi2*	*MeanBias*	*MedBias*	*B*	*R*	*%Var*
Unmatched	0.120	293.82	0.000	33.5	30.8	83.6	1.60	71
Matched	0.005	8.34	0.595	3.9	3.9	16.3	0.95	14

Sample: technical substitution	*Ps R2*	*LR chi2*	*p>chi2*	*MeanBias*	*MedBias*	*B*	*R*	*%Var*
Unmatched	0.177	51.33	0.000	44.0	47.1	115.6	1.01	33
Matched	0.034	4.22	0.896	12.4	9.4	43.4	1.17	17

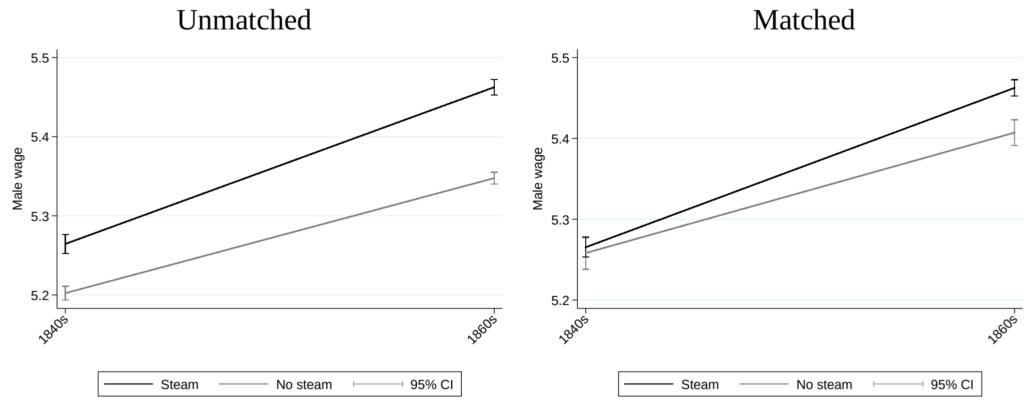
Sample: technical complementation	*Ps R2*	*LR chi2*	*p>chi2*	*MeanBias*	*MedBias*	*B*	*R*	*%Var*
Unmatched	0.191	142.77	0.000	33.8	30.0	106.6	1.67	50
Matched	0.010	5.91	0.879	5.6	6.3	23.6	1.11	38

Source: see the text.

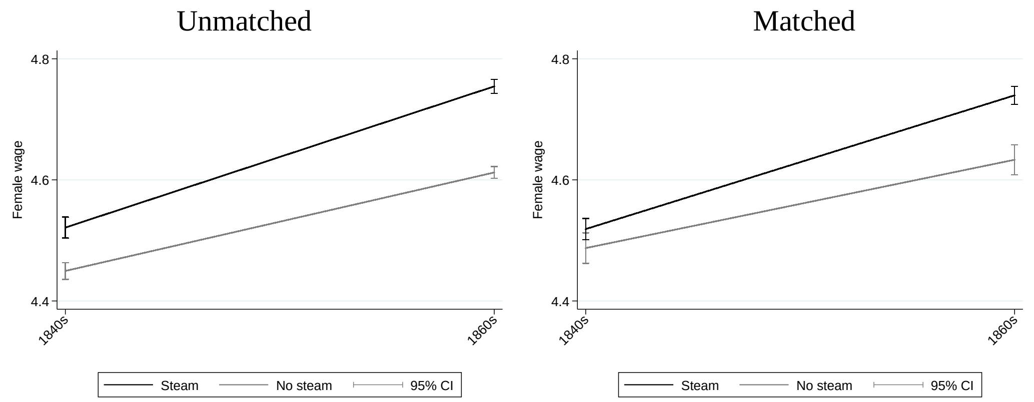
Appendix E: The graphical results of the difference-in-difference analysis

Figure E-1: Average wages of workers by group and treatment

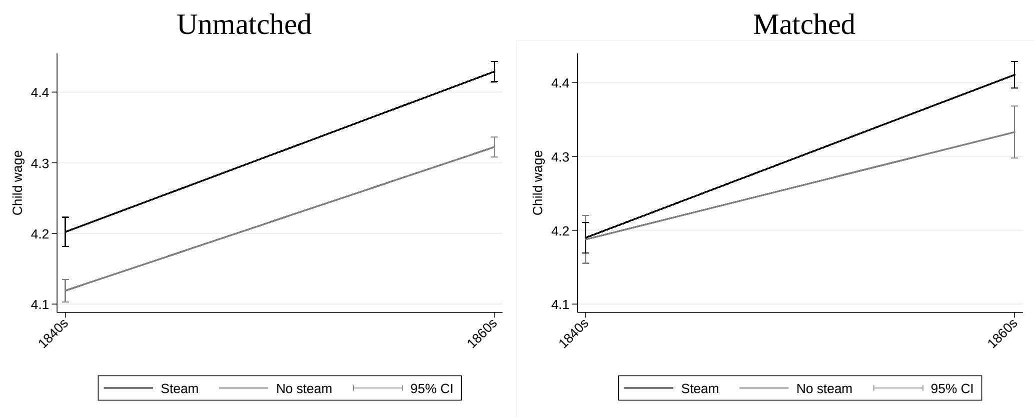
(a) Male wages



(b) Female wages



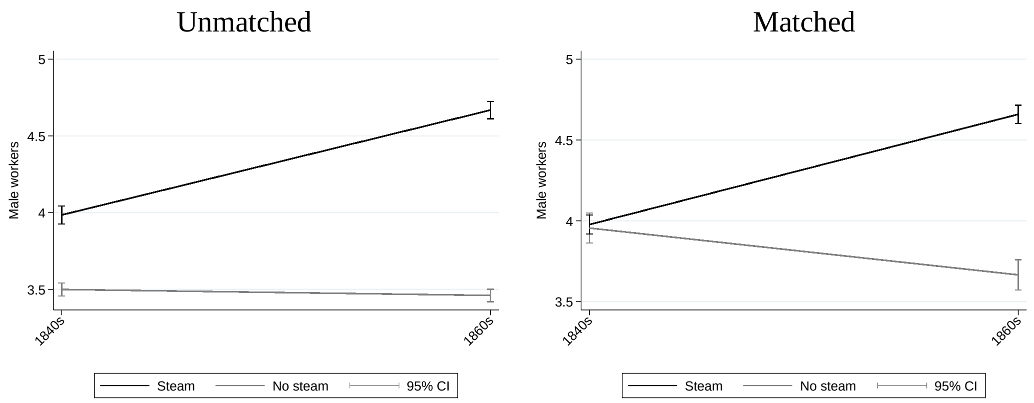
(c) Child wages



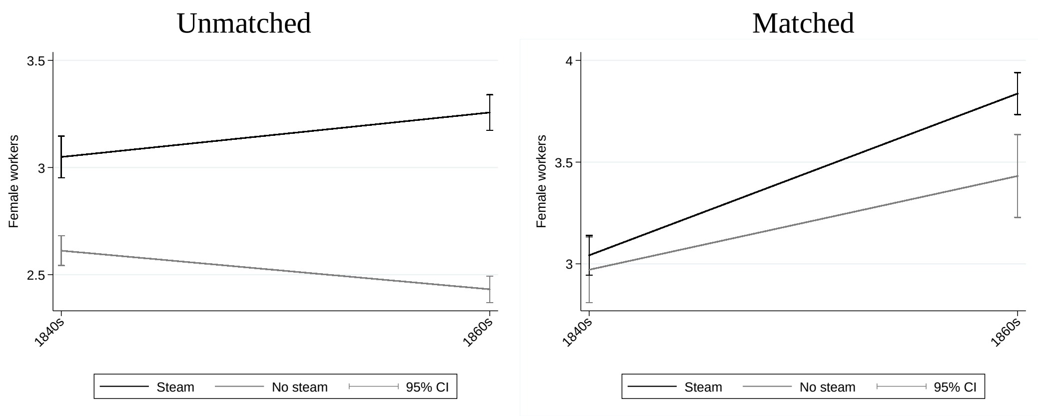
Note: See Table 10 for details. *Sources*: see the text.

Figure E-2: Number of workers by group and treatment: unmatched (left) and matched (right)

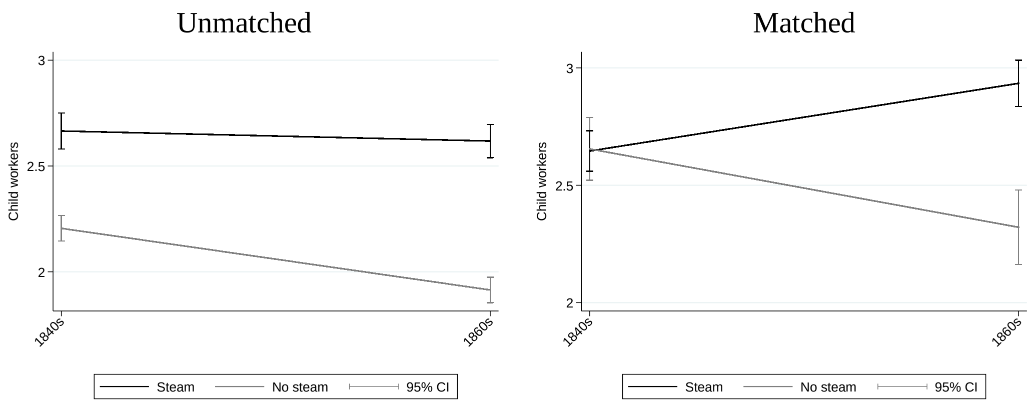
(a) Male employment



(b) Female employment



(c) Child employment

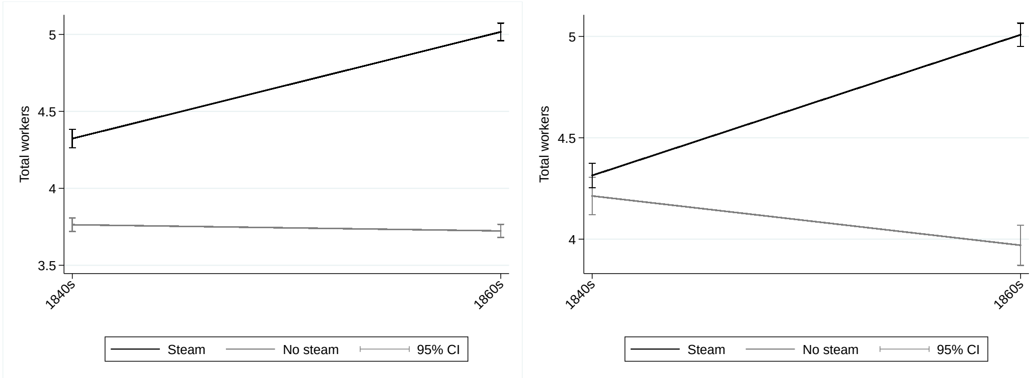


Note: See Table 11 for details. *Sources*: see the text.

Figure E-2 cont'd: Number of workers by treatment: unmatched (left) and matched (right)

(a) Male employment

Unmatched Matched

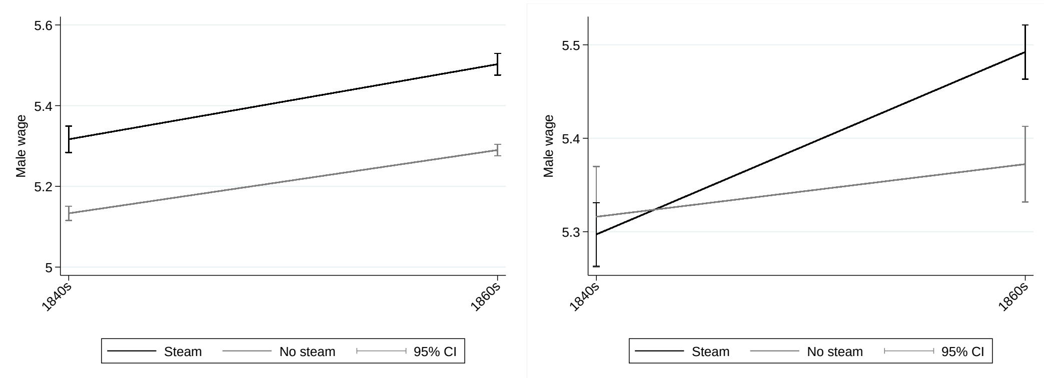


Note: see Table 11 for details. *Sources*: see the text.

Figure E-3: Technical substitution (steam without water): unmatched (left) and matched (right)

(a) Male wages

Unmatched Matched



(b) Male workers

Unmatched Matched

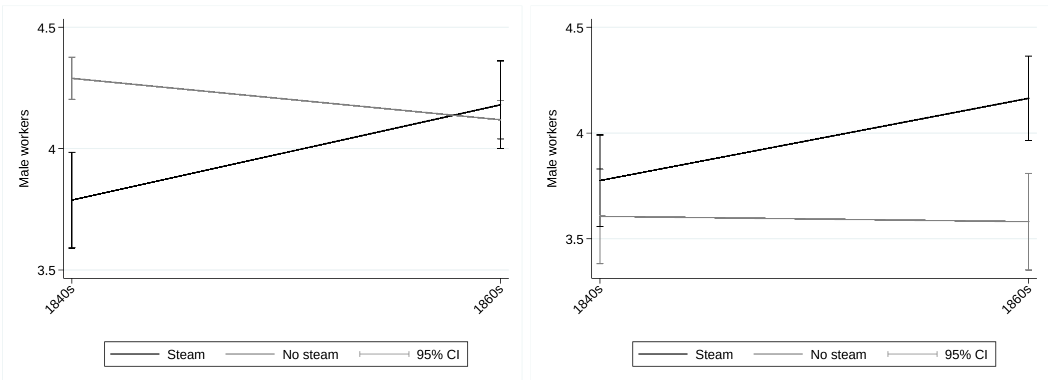
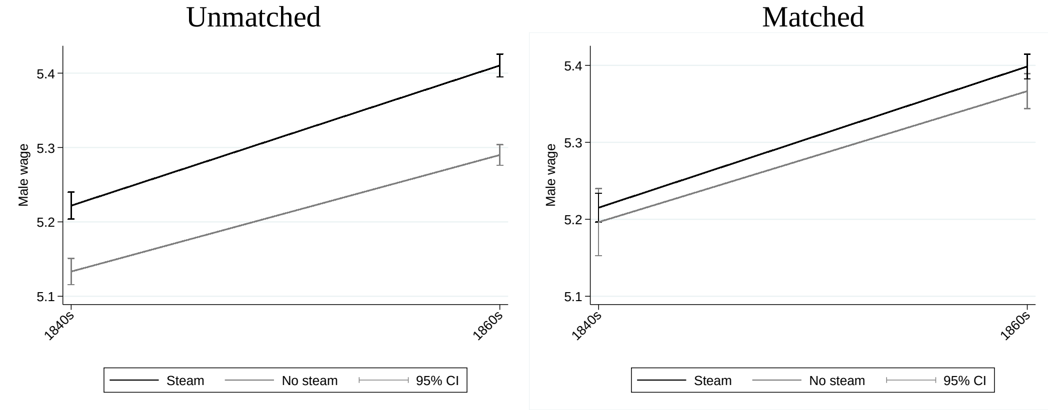
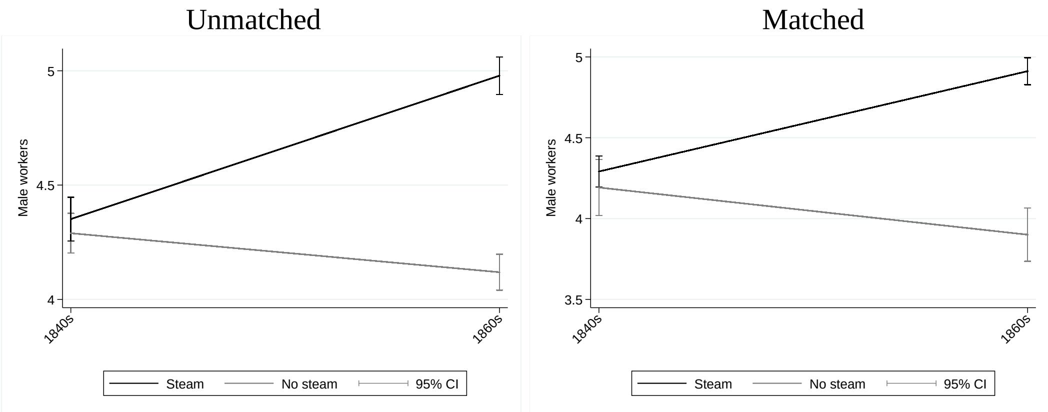


Figure E-3 cont'd: Technical supplementation (steam with water): unmatched (left) and matched (right)

(c) Male wages



(d) Male employment



Note: see Table 12 for details. *Sources*: see the text.