The Wheels of Change: Human Capital, Millwrights, and Industrialization in Eighteenth-Century England[1]

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Measures of human capital correlate strongly with technological change and economic growth across regions. However, the endogeneity of these measures complicated this interpretation. This paper aims to identify the causal effect of human capital in the context of Britain's industrialization in the eighteenth century, by uncovering the geographical origins of its highly skilled mechanical labor. We achieve this by exploiting the persistent effect of the spatial location of early medieval watermills across England (as registered in Domesday Book in 1086) on the spatial distribution of a specific group of mechanical workmen known as *wrights*, who specialized in building watermills, and using the exogenous source of cross-district variation in geographical suitability for the construction of watermills in the early medieval period, to instrument for the availability of *wrights* in the first half of the eighteenth century (1710-50). In the case of England, the mechanical skills that evolved in response to the extensive adoption of watermills for grinding in the early middle ages, were complementary to technological change and turned out to be an important power behind England's leadership in the second half of the eighteenth century.

1. Introduction

The key role of human capital in the process of innovation and economic success has been emphasized by economists since the 1960's. The seminal paper on the matter (Nelson and Phelps, 1966) was published almost half a century ago, and postulated that both technological advance and technological catch-up depended strongly on the level of human capital. Three decades later, human capital has become a central component in many growth models, in various formulations (Romer, 1990; Galor & Weil, 1999, 2000; Acemoglu, 2003, and others). In his classic Presidential address, Richard A. Easterlin (1981) posed the basic question: why isn't the whole world developed? His answer was quite unambiguous: modern economic growth depended on the diffusion and absorption of new techniques. But technology has to be learned, Easterlin argued, and the diffusion of modern technology thus utterly depends on formal schooling and human capital. Empirical support to this view was provided by

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Glaeser et al. (2004), who criticized the view of institutions as central to the explanation of differences in economic performance, and pointed instead to differences in schooling and school attendance.

There is still however some room for doubt. Some contemporary development economists have expressed the almost heretical view that despite huge investments in education, the response of economic growth to the "education explosion" has been little or none (Easterly, 2001, p. 73). Econometric work has found little support for a major role for education in the 1990s (Pritchett, 2001). Moreover, there are many other issues in the postulated role of human capital in growth suggesting that education or more generally human capital are not the magic formula for rapid economic development. In the context of the British Industrial Revolution, there is further room for skepticism (Mitch, 1992; Crafts, 1996; Clark, 2005). The seminal work of David Mitch (1999), has shown that on the eve of the Industrial Revolution Britain had at best mediocre levels of schooling and literacy. Literacy rates were about 60 percent for British males and 40 percent for females around 1800, more or less on a par with Belgium, slightly better than France, but worse than the Netherlands and Germany (Reis, 2005, p. 202). During the Industrial Revolution itself there was at best sluggish improvement in literacy in Britain (Mitch, 1999, p. 244; De Pleijt, 2018). Literacy rates, of course, reflect an upper bound of the proportion of children going to school, because many youngsters acquired literacy from their parents or private tutors. By 1830, 28 percent of the male population in the age bracket between five and fourteen were enrolled in schools in England and Wales. The figure rises to 50 percent in 1850, significantly less than in Prussia where the percentages were respectively 70 percent in 1830 and 73 percent in 1850, and even marginally behind France (39 percent and 51 percent) (Lindert, 2004, pp. 125–26). For the follower countries, the evidence is mixed. O'Rourke and Williamson (1995) and Taylor (1999) conclude from country-level cross-sectional and panel analyses that human capital was not a crucial driver of economic catch-up in the 19th century. In contrast, Becker, Hornung, and Woessmann (2011) document that elementary education predicts employment levels in metals and other industries, but not in textiles in nineteenth century Prussia,m and De Pleijt, Nuvolari and Weisdorf (2019) establish a positive correlation between the use of steam engines and the formation of human capital in the mid-eighteenth century.

Recent work on human capital suggests modifications to our thinking about the role of human capital. One is that the *content* of education mattered as much or more than just pure quantity of education (years of schooling). For example, Cantoni and Yuchtman (2014) show that medieval universities played a causal role in expanding economic activity by training students in the law and contributing to the development of legal institutions, encouraging greater economic activity in medieval Germany. On the other hand, having youngsters spend many years studying the Chinese *Four Books* and *Five Classics* or the Jewish Talmud may have been culturally valuable but added little to economic progress and innovation. The other is that the distribution of human capital matters, and that the decisive factor is the size and content of Upper Tail Human Capital (Mokyr, 2009; Meisenzahl and Mokyr, 2012; Squicciarini and Voigtländer, 2015; Feldman and van der Beek, 2016). The idea is that the quality and competence of workers in the top few percent of the distribution of technical and mechanical ability mattered more to technological advances than the capabilities of the *average* worker. In that context, what was crucial to innovation and technological leadership in the early stages of the British Industrial Revolution was the supply of top-quality artisanal skill. The evidence that British craftsmen were of superior quality during the Industrial Revolution and thus paved the road for British inventions to be scaled-up, debugged, installed, maintained, and operated by workers who had a high level of mechanical competence has been presented elsewhere (Kelly, Mokyr, and Ó Gráda 2014, 2019). These workers comprised somewhere between 1-2 percent of the labor force, far more than the few "great men" that hagiographic writers of the Victorian era crowed about, but still just a relatively small sliver of the overall labor force. Contemporaries on both sides of the channel were aware of this gap, but until recently its causes and ramifications have been little explored.

In this paper we test the importance of top-quality artisanal skill by focusing on the availability of a particular occupational group of workmen referred to as *wrights*, who were skilled carpenters specialized in watermills (i.e. structures that use a water wheel to drive a mechanical process) and exploiting the persistent correlation between their spatial distribution in the first half of the eighteenth century, and, the location of early medieval watermills across England (as registered in Domesday Book in 1086). ~~As is shown in the paper,~~ proximity to more watermills in 1086 is associated with more *wrights* per capita in the eighteenth century (1710-50). To avoid the possibility of a bias in the decision to construct watermills we eventually use locations' potential suitability for the construction of a watermill during the early middle ages as a geographical instrument for the availability of these highly skilled mechanical workers and find a significant effect on the location of the English industrializing sectors on the eve of the industrial revolution.

Our hypothesis is that the evolution of human capital in the form of highly skilled craftsmen was conditioned by the initial production technologies of basic goods which in turn were determined by geographical factors.[5] In the case of England, the initial demand for such workers with high mechanical skills originated from the adoption of watermills for grain grinding in the early middle ages. Once in place, their availability generated a relative advantage for the adoption of water power technology to other industrial uses (e.g. *fulling mill*s in textile, *blowing mills* in tin smelting, *water raising mills* in mines, and *forging mills* in iron-works). This relationship was most pronounced in the textile sector, in which fulling mills were widely adopted by the beginning of the fourteenth century (Carus-Wilson, 1941; Lucas, 2005). The industry in fact shifted its location from the urban centers of the Eastern plains to the hilly Northern and Western rural districts in the thirteenth and fourteenth centuries. It reveals concentrations of fulling mills in the West Riding of Yorkshire, in the Lake District, in Cornwall, Devon, Somerset and the Cotswolds, in Wiltshire and in the Kennet Valley, location, which remained important cloth centers until the early sixteenth century and later on in the first half of the eighteenth centuries. This spatial continuity implies the existence of strong path dependence in the location of the industry, and in the mechanical principles of innovations.

Due to wrights' technical competence to construct, maintain, and, improve the machinery, their numbers grew hand-in-hand with the technological changes that took place in the textile sector during the first half of the eighteenth century (Feldman & van der Beek, 2016). This process continued at least until the middle of the eighteenth century when changes in legislation stimulated investments in transportation infrastructure (e.g. turnpikes, waterways) and in agriculture (changes in land laws and enclosures), enhanced regional specialization. By the end of the eighteenth century when the steam engine began to replace the waterwheel as a source of energy, *engineer*s — a profession that in part grew out of the skilled millwrights of the pre-Industrial Revolution era — became the newly demanded skill (Musson & Robinson, 1960; MacLeod and Nuvolari, 2009). Our hypothesis is thus that the adoption of grinding mills was

[5] Other determinants of the early production technology, i.e. institutions, are taken as exogenous in this study.

important not only as a source of motive energy but also as a stimulus to skill accumulation and a focusing device for innovation.[6]

To test our hypothesis, we use district-level data on England's government area districts, containing information from various sources. We use the Apprentices Tax Registers to proxy for the numbers of wrights and for the expansion of production in every district, by employing the number of apprentices to masters in the relevant occupations before the onset of the Industrial Revolution (1710-50).[7] Since the number of wrights and of the other apprentices are correlated with the population size in the district, we normalize the number of apprentices by the population of the district as reported in HYDE project (Klein Goldewijk et al. (2010), Klein Goldewijk et al. (2011)). This is a common proxy for population in the literature. Furthermore, we control for the district's potential agricultural suitability. Reassuringly, our results are not affected by these controls.

Our exogenous source of identification for the availability of wrights in a district is based on the distribution of mills mentioned in *Domesday Book* in 1086. The common view is that these mills were water-powered and used for grain grinding.[8] Thus, they allow us to identify the districts in which wrights grew in response to the adoption of grinding mills, before the introduction of industrial mills, and thus, to overcome the simultaneous process in which the numbers of wrights and mills were mutually determined in the eighteenth century. Our results show that the spread of Domesday mills is indeed positively correlated with that of wright apprentices more than 600 years later (Adjusted R^2=0.59). Using all the geographical and economical controls mentioned above, we show that an additional mill per thousand people in a district in 1086 is associated with an average increase of 0.13 wright apprentices per thousand people in 1710-1750 in a district. Instrumenting mid eighteenth-century wrights using the Domesday mills, our IV estimates show that an additional wright apprentice in the district was associated with an average increase of 0.55 draper (wool manufacturers) apprentices on average. The effect on iron works was very similar: 0.46 smith

[6] In this regard the use of watermills resembles coal that similarly provided a major source of innovation and skilled engineers who played major roles in generating a host of inventions that spilled over to other sector, not least the steam engine itself (Kelly et al., 2019).

[7] Board of Stamps: *Apprenticeship Books*, Series IR 1.

[8] It is common to assume that all mills mentioned in Domesday were grinding mills (e.g. Langdon, 2004, p. 11), though there is no direct evidence for it. There probably were mills used for purposes other than grain milling but they were few. For a discussion on the topic see Bennett & Elton, 1899, pp. 107-8.

apprentices in response to an additional wright. These results suggest strongly that the existence of water mills in a district had a significant effect on industrialization.

To validate our IV and address the concern that the estimators we obtain may be biased due to some omitted unobservable characteristic of the locations where mills were chosen to be constructed in the early middle ages (e.g. water streams, fertile lands), we also estimate the regressions instrumenting wrights by an alternative IV. We take advantage of the fact that the construction of grinding mills, in contrast with industrial mills, depended on high potential for wheat growing on top of the availability of suitable water streams.[9] Our second instrument for wrights was therefore constructed to capture the suitability of a district for the construction of grinding watermills. It consists of the length of rivers in the district that have moderate levels of ruggedness, interacted with districts that are highly suitable for wheat cultivation.[10] This exercise results in a slightly higher coefficient of 0.73 (compared with 0.55 using the Domesday mills as IV). In addition, since the correlation between drapers and wrights may reflect a broader association between different industries, we perform two placebo tests to test whether our instrument is associated to draper apprentices via other occupations, and second, whether wright apprentices are associated with other occupations. The analysis reveals that this is not the case. These two tests lend credence that our instrument satisfies the exclusion restriction.

2. Related literature

As discussed in the introduction, this paper is related to strands of literature on the role of human capital in the transition to growth and in particular to Britain's industrialization. Our main contribution to the existing debate in this literature is that we concentrate on a particular occupational group of top-quality artisanal skill, following Mokyr's (2009) argument that what was crucial to innovation and technological leadership in the early stages of the British Industrial Revolution was the supply of top-quality artisanal skill.

Our paper also relates to a literature that examines the location of the industrial revolution, and the textile industry in particular. There is a long tradition in economic history that places coal at the center of the Industrial Revolution and the location of coalfields as the

[9] Given their high fixed costs it would be unprofitable to construct a grinding mill in areas without large yields of wheat (see Karine van der Beek, 2010)

[10] A detailed explanation as to the construction of our IV is provided in section 6.

main determinant of its location (e.g. Wrigley 1961; Crafts and Mulatu 2006; Fernihough and O'Rourke 2014). A recent study by Nicholas Crafts and Nikolaus Wolf (2014) finds that Britain's cotton textiles factories in 1838 "preferred those locations with good availability of water power, rugged terrain, a history of textile invention, close to ports, and with good market". The prices of coal did not have a significant effect on the probability that there was a cotton mill in a given location, but it did increase employment in the cotton industry. The finding that the history of textile invention mattered, stresses role played by the location of textile centers, mainly woollen centers, prior to the Industrial Revolution.[11] It is important to stress that despite its symbiotic relationship with water power, the woolen industry was quite heterogeneous across England (Jenkins and Ponting, 1987, pp. 1-11). The regional variation between the Yorkshire and the west counties (especially Gloucestershire and Wiltshire) was quite remarkable. The West Country had overall more fertile soils, and as regional specialization became more pronounced in the late eighteenth ad nineteenth centuries, the small-scale domestic industry — a classic instance of "proto-industry" of Yorkshire grew faster than their competitors further south. Regional specialization mercilessly led to a "great reversal" — the remarkable switch from a textile sector that was spread in disparate regions to a heavy concentration of the textile industry in the north-west. Yet at the start of the eighteenth century this would have been hard to foresee, as the woolen industries were still surviving in the English South (Jones, 2010). In the eighteenth century, however, output in the wool industries in the West Country and East Anglia was, as far as we can tell, more or less stagnant whereas that in Yorkshire grew rapidly.[12] In this paper we are focusing on its geographical distribution of the textile industry on *the eve of* the Industrial Revolution; we do not imply that there was any simple mapping from this locational pattern to subsequent industrial growth.

To the best of our knowledge, this paper is one of the first to empirically test of the hypothesis regarding the important role of mechanical skills in the process of industrialization in the context of eighteenth century Britain, especially in textiles and engineering (see also Kelly et al., 2019). Its main contribution to this literature is that it introduces human capital

[11] Cotton manufacturing was relatively marginal in the first half of the eighteenth century.

[12] Deane (1957, p. 220) has estimated that the proportion of total wool output of all kinds in Yorkshire rose from one-third in 1772 to three-fifths by the end of the eighteenth century. Pat Hudson has estimated that the share of the West Riding of Yorkshire in national wool production rose in the eighteenth century from 20 percent to 60 percent (Hudson, 1992, p.116). Other sources, while fragmentary, seem to be consistent with this trend for the earlier eighteenth century. For more details, see Ó Gráda, 2019.

as a central variable for industrial development, while systematically controlling for a variety of competing explanations. These include water streams, ruggedness, the presence of coal, land fertility, climate, distance from ports and more. Furthermore, we use a comprehensive and coherent data set that contains occupational information at the locality level for every year between 1710 and 1750. In addition, we use an instrument that traces the source of the evolution of skills, and allows us to infer a causal relationship between mechanical competence and industrial expansion by exploiting the specific characteristics of mills before the 12th century, which were only used for grinding. The paper shows that the availability of mechanically skilled workmen in the early eighteenth century was highly correlated with locations that were suitable for grinding mills during the early middle ages. Moreover, their availability had a positive and significant effect on the extent of production in textile, as well as in ironworks and other industries that employed water powered machinery.

Consistent with the conclusions in Crafts and Wolf (2014) we conclude that there is a strong spatial continuity of textile centers' location from the Middle Ages well into the mid-eighteenth century, as well as a strong persistence, not only in the location of the industry, but also in the choice of the technological principles that characterized innovations. The strong correlation that we find with suitability for grinding mills (rather than any type of mill) can be explained by the impact of the sunk costs of earlier investment in equipment such as waterwheels and by agglomeration economies of locating near specialized workmen and other producers and which eventually acted to "lock in" the industry to its heartlands.

Lastly, our study is also related to a broader strand in the literature, which highlights the persistent effect of geographical initial conditions on regional development and path dependent trajectories of growth. It is particularly related to Trew (2014), who employs a calibrated model to estimate the role that geographical heterogeneity among English parishes played in the takeoff from stagnation to growth in the First Industrial Revolution. He argues that since innovation in the First Industrial Revolution was energy-intensive, regions abundant in coal had a comparative advantage for manufacturing goods and shows that industrialization concentrated in geographical hot- spots, where the geographical characteristics generated a comparative advantage for manufacturing goods. Our paper concentrates on the location of manufacturing prior to its dependence on coal, showing both that such location was persistent and that coal did not matter much in this period (appendix E).

3. Mills and Skills

Mechanical engineering was one of the unsung heroes of the Industrial Revolution. Most scholars writing about the origins of the profession during the Industrial Revolution recognize that "millwrights can be considered the most direct ancestors of professional engineers" (Musson & Robinson, 1960; MacLeod and Nuvolari, 2009, p. 229). In a widely-cited passage, the great engineer William Fairbairn wrote in the 1850s that "the millwright of former days was to a great extent the sole representative of mechanical arts, and was looked upon as the authority of all the applications of wind and water … as a motive power. He was the engineer of the district in which he lived, a kind of jack-of-all-trades, who could with equal facility work the lathe, the anvil, or the carpenter's bench." He was an itinerant engineer and mechanic of high reputation who could "turn, bore and forge ... was a fair arithmetician who knew something of geometry and do much of the work now done by civil engineers" (Fairbairn, 1861, pp. v-vi). Anton Howe's sample of 400 innovators in the period before and during the Industrial Revolution shows that almost a quarter of them were millwrights or similarly trained craftsmen such as "mechanics" and "engineers" (Howe, 2016, pp. 22-23).

While Fairbairn was describing the millwrights of the early nineteenth century, matters were similar five centuries earlier when the abilities of millwrights and high-end carpenters (two overlapping categories) were much in demand by millers because of the much-needed technical expertise that they brought to mills (Langdon, 2004, p. 203). It goes without saying that these medieval "engineers" were craftsmen relying on dexterity and tacit knowledge, and possessed little or no formal understanding of mechanics. As Tann (1974) notes, in the early eighteenth century they were still working primarily with wood, but a few parts had to be made of iron (such as the iron hoop and plates that kept the vertical water wheel in place), thus requiring a breadth of expertise or an ability to cooperate with other artisans that went beyond simple carpentry (Holt, 1988, pp. 117-18, 123-25). A compendium of occupations published anonymously in London in 1747 maintained that even though millwrighting was a branch of carpentry, it was "very ingenious" and to understand and perform it well, a person must have "a good turn of mind for mechanics and at least some knowledge of arithmetic" (Anonymous, 1747, p. 151).

During the Industrial Revolution, the class of artisans trained as millwrights generated a large number of outstanding engineers and mechanics who contributed widely to technological advances in a variety of areas. The best-known engineer of the Industrial Revolution originally apprenticed as a millwright was James Brindley, the great builder of canals during the early canal era after 1750. A considerable number of important inventions during the Industrial Revolution were made by people originally trained as millwrights. The most famous of these inventors were Bryan Donkin, the co-inventor of food canning and a paper making machine, and Andrew Meikle, the Scottish inventor of the threshing machine. Meikle was also famous for having trained John Rennie, generally recognized as one of the great engineers of the Industrial Revolution and the co-inventor of the pathbreaking breast-wheel water mill (with John Smeaton). John Rennie's first apprentice was Peter Ewart (1767-1842), who helped Rennie build the first steam-driven grain mills in London and later worked for Matthew Boulton in his famous mint and after 1792 was fully engaged in the textile industry. John Penn of Greenwich (1770-1843) was the founder of a famous engineering works in Greenwich that specialized in agricultural machinery and later under his eponymous (and more famous) son produced marine steam engines. Thomas Hewes (1768-1832), too, was trained as a millwright but soon was working for the textile manufacturing entrepreneurs of Manchester, among others installing steam engines at McConnell and Kennedy, one of the best- known cotton mills of the early Industrial Revolution. Joseph Nickalls (1758-93) was a London millwright who worked closely with the great engineer John Smeaton and was one of the first and most respected civil engineers during the canal-building era. John Torr Foulds (1742-1815), who worked closely with Nickalls, helped renovate the London Bridge water works, which had been pumping drinking water to London for many decades and had a "bent for study and experiment" and won a gold medal from the Society of Arts for a machine for cutting off piles under water (Moher, 1986). Thomas Yeoman (1709/10-1781) was one of the few millwrights who straddled the worlds of mill machinery and finer tool- and instrument making (among his achievements were installing the newly-invented ventilation systems on British merchant ships).

Right below these well-known millwright-engineers was a cadre of millwrights with less name recognition, yet who played pivotal roles in the growth of the industries that made the Industrial Revolution and should be seen as "tweakers and implementers" (Meisenzahl and Mokyr, 2012). William Fairbairn reported in his autobiography that a certain Mr. Lowe from Nottingham (clearly a millwright), who had set up the watermill supporting a cotton mill in Ayr, Scotland, "was in demand in every part of the country where cotton mills were built" (Fairbairn, 1877, p. 121).[13] A few of those able but obscure mechanics are mentioned in Cookson's detailed work on the Yorkshire textile machinery, and illustrate the wide usefulness of well-trained artisans.[14]

Yet the role of millwrights as a highly-skilled source of mechanical competence has been disputed and Fairbairn's ebullient description has been contested. The early eighteenth century engineer and mathematician, John T. Desaguliers, one of the pivotal figures in the British Industrial Enlightenment, was highly dismissive of the role of millwrights and complained that Britain was over-run with poorly educated millwrights who claimed to be engineers but set up waterworks without rigorous calculations (Carpenter, 2011, p. 282).[15] In the first half of the eighteenth century most millwrights were still seen as glorified carpenters and not particularly skillful. Campbell (1747) in his famous book on the "trades" (occupations) of London notes that "the Mill-Wright is an ingenious and laborious business in which there is a great variety ...but the wages given to Journeymen is no more than a common Carpenter" (p. 323). The authoritative biography of Fairbairn disputes his characterization and insists that as late as the mid-eighteenth century "the majority of them were artisans and much more akin to carpenters and concentrated on simple work" (Byrom, 2017, p. 88).[16] Terry Reynolds in his classic account of the history of the water mill summarizes the consensus by doubting whether before 1750 the typical millwright could do any of the things that Fairbairn listed and cites approvingly a 1775 writer who noted that the construction of water mills was "for the most part left to people not well skilled in the principles of mechanics." He also notes that any systematic analysis of efficiency and construction based on hydraulics before the early eighteenth century would have been unthinkable as the earliest serious theoretical works on the subject date from that period, and would have unlikely to have been read by the bulk of

[13] Fairbairn himself consulted widely to cotton mills and made many suggestions that led to improvement in the machinery, such as his work with Adam and George Murray, a large cotton spinner in Manchester, where he proposed improvements in the transmission shafts of the machinery that led to considerable productivity gains (Fairbairn, 1877, pp. 112- 14).

[14] Among them are millwrights such as John Jubb, Joseph Tempest, and Joshua Wrigley (Cookson, 2018, pp. 40, 46, 52, 73), all of whom were engaged in the woolen textile machine industry in one way or another.

[15] In Vol. II of his celebrated *Course of Experimental Philosophy* Desaguliers berated the ignorance of "engineers and "projectors" who set up ruinous waterworks but who hardly know "how to measure the quantity of water required to turn an undershot or overshot mill" (1763, Vol. II, pp. 414-15).

[16] Tann (1974, p. 80) equally stresses that the work was "a branch of carpentry" yet cites approving the anonymous 1747 source that stressed the diversity of mills and the knowledge requirements that this diversity imposed on wrights.

practical millwrights (Reynolds, 1983, pp. 191-95).

That said, however, it is clear that even though the traditional millwright's work was mostly in wood, it required the skills of designing and installing shafting and gearing, and millwright competence was very much part of the culture of accuracy and low-tolerance engineering that evolved before and during the Industrial Revolution (Heilbron, 1990; Winchester, 2018).[17] Medieval and early-modern millwrights may not have been skilled engineers by the standards of the mid nineteenth century, but clearly they were relatively well-trained craftsmen with a good if intuitive understanding of mechanics and power-transmission, an understanding of the properties of timber and iron, and some informal notions about force and velocity (even if they used a different vocabulary). The millstones in grain mills had to revolve fast enough so that the kernels of wheat poured into the center and then expelled as flour at the edges, and the waterwheel was mounted vertically and thus had to be transferred through ninety degrees, requiring a cog- or trundle wheel to transmit the motion to a lantern-pinion wheel on the vertical mill.[18] Because all mills involved a constant-moving mechanism and due to the relatively low quality of the materials of which the mill was built, the gears and shafts were subject to wear-and-tear and required frequent repairs that required substantial expertise. The constraints of materials led to constraints on the workmanship: because of the limitations on the materials, "medieval man did not strive for more complicated machinery than he already possessed and wisely sought efficiency in simplicity" (Holt, 1988, pp. 123, 132). The high degree of expertise possessed by millwrights is consistent with the observation that many of the early medieval mills were built by Benedictine and Cistercian monks, who embodied much of the human capital and skills in the period (Bloch, 1966, p. 151; Lucas, 2006, pp. 154-66).

Moreover, the millwrights were flexible enough to adapt to new demands on their competence as technology changed. In the twelfth century the watermill was supplemented by windmills, and the adaptation of the mechanism to a new external source of power demonstrates a technical agility at a high level.[19] The same is true for the replacement of horizontal with vertical waterwheels between the tenth and the thirteenth centuries in England, although on the Continent horizontal wheels persisted. The vertical wheels were far

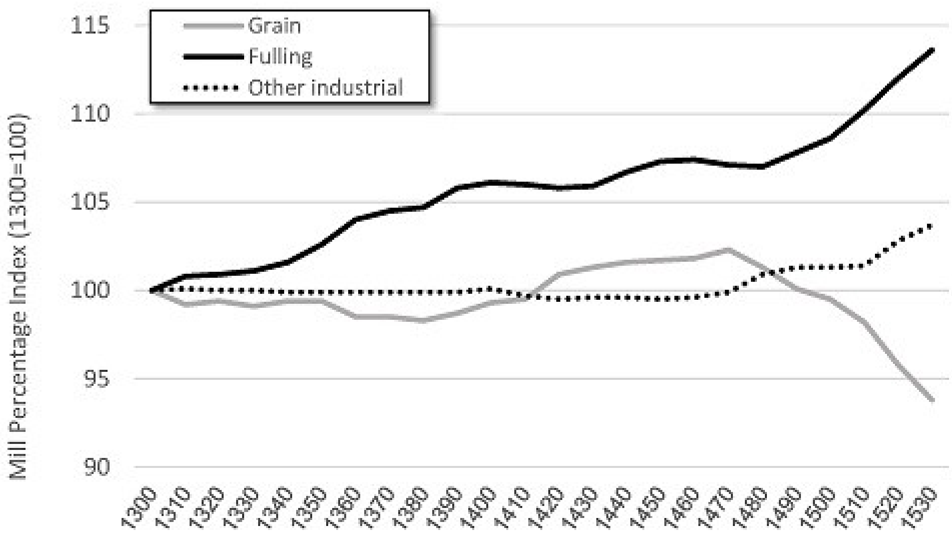
[17] Oddly enough, Winchester (2018) in his popular depiction of rise of precision engineering makes no mention of millwrights.
[18] For the technical details see Holt (1988, p. 117).
[19] Windmills needed to solve the problem of to keep the sails facing the wind; the fixed post that could be turned in a circle in its entirety became the dominant design

more expensive and complicated to construct, but more efficient and perhaps associated with tighter seigneurial control. Tidal mills were known throughout western Europe in the Middle Ages but their technology was not all that different from conventional watermills (Lucas, 2006, p. 86). Outside some regions in France, watermills were used primarily for grain and fulling; other industrial uses can be demonstrated but were probably not as common as the literature arguing for an Industrial Revolution in the middle ages suggests (Lucas, 2006, p. 262, 277). All the same, mills were commonplace in England, and Domesday book mentions c. 6,000 watermills used exclusively for flour (Holt, 1988, p. 119).

The traditional millwright, then, may not have been quite as learned and sophisticated as Fairbairn's description suggests, but neither was he as ignorant as Desaguliers may have thought. We should locate him in the upper tail of the distribution of artisanal skills, skills that like all artisanal skills before the Industrial Revolution were largely tacit and transmitted through personal contact (apprenticeship) (Humphries, 2003). By the late eighteenth century millwrights had clearly become a kind of labor aristocracy. Cookson (1994, p. 46) shows that there was a social as well as a technical distinction between millwrights on the one hand, and lower-level artisans such as smiths and carpenters on the other. Yorkshire millwrights in the late eighteenth century enjoyed relatively high status, as suggested by the form of address, the title 'Mr' used in many instances. She also cites none less than Maudslay himself to the effect that millwrights considered themselves superior to mere "engineers" and thought it was a disgrace to work with them (2018, p. 76). Clearly millwrights during the Industrial Revolution were a kind of labor aristocracy, comparable to mule operators.

Many of the millwrights became relevant to other industries besides grinding at the beginning of the fourteenth century, when the mechanical principles of watermills were adopted to other industrial uses. Such industrial mills were for example, the *fulling mills* in cloth manufacturing, *forging mills* in iron making, *tin mills* for crushing tin-ore, *blowing mills* for smelting, *tanning mills* in leather-working, *tool-grinding mills*, *saw mills, water raising mills* in mines, and others. According to Langdon's 2004 sample, the number of such industrial mills in England expanded by more than 130 percent between the years 1300-1540 (Langdon, 2004, p.41 figure 2.8). Their share of the total number of mills increased as well, as shown in Figure 1, and represented almost a quarter of the mills by the end of the fifteenth century (Langdon, 2004, pp.43-44).

Figure1. Percentage Index of industrial mills vs. grain mills: 1300 – 1540 (100=1300)



Source: Langdon, 2004, Table 2.2, p.35.

As suggested by *figure 1*, the connection of millwrights' skills to industrial mills ran primarily through fulling mills: the heaviest machinery used in textile manufacture at that time, the "stocks" (hammers used to beat the cloth), the water wheels, and the transmission gear in fulling mills, had traditionally been the preserve of the millwright (Cookson, 1994, p. 19). By the 1780s, however, in some cases artisans calling themselves millwrights sold other textile machinery to the rapidly evolving textile mills (Tann, 1974, p. 82).

The complementarity between the technologies of the grain grinding mill and the other industrial mills was obviously high as the latter evolved from the former. The setup of the water control system (depending on the type of mill: i.e. leat mills, wear-and-leat mills, millpond mills, etc.) and waterwheel were similar, and the inner-workings of the two machines were based on the same mechanical principles. "Most of them in the medieval period worked from cams or wooden projections set into the mill axle, which 'tripped' any number of devices, such as vertical stamps, horizontal hammers, bellows or saws" (Langdon, 2004, p. 98). Whether the mills were used for grinding, fulling, or for other industrial uses, their construction was led by the same artisans. These men were much like building contractors today. They negotiated with the client, designed the mill, organized the workmen and materials employed to build it and supervised the construction (Langdon, 2004, p. 252).

Millwrights were a major force behind machinery improvement centuries earlier.[20]

Cookson stresses that these cases were rather unusual and that other skilled artisans were equally likely to be able to supply the machinery. Moreover, she argues, millwrights were much in demand in the late eighteenth century and might have been too busy to diversify into textile machinery (Cookson, 1994, p. 49). At least as far as the Yorkshire textile machinery is concerned, she doubts any *direct* linkage between millwrights and textile machinery. Where millwrights may have been more important is as technical consultants to entrepreneurs (Tann, 1974, p. 85) or as masters who trained technically competent apprentices who then went off to work in the growing textile industry, calling themselves "engineers" or "machinists." Moreover, millwrights helped construct the early factories: Richard Arkwright relied on two well-known millwrights: Thomas Lowe of Nottingham and John Sutcliffe of Halifax, both of whom were involved in the set-up of a substantial number of early textile factories (Cookson, 2018, p. 37). Clearly, the abundance of millwrights in a region was not a sufficient condition for rapid industrialization. The west counties, where much of the woolen industries were still located by 1750, gradually lost their position to Yorkshire in the last third of the nineteenth century (Jones, 2010, pp. 47-70).

That said, the technical changes in textiles after 1750 involved radical technological breakthroughs in the textile industry: it marked the spectacular rise of the mechanized cotton industry, still quite marginal as late as 1780. The skills that had accumulated over the centuries in the woolen and especially the worsted industries were found to be useful in cotton. The technical challenges of mechanization of carding, spinning, weaving and finishing differed between the different branches of the textile industry, with cotton being most similar to worsted. It was quite different for linen because of its different physical characteristics (Cookson, 2018, p. 15). Yet over time the existing skill base in 1750, which had been largely engaged in making equipment for the wool, worsted and linen industries, was sufficiently adaptable and powerful to eventually mechanize every branch of the textile industry, even if the speed of progress differed, with cotton clearly in the lead. In that skill base, many

[20] Such was the case with the fulling mill, which, according to John Luccok, a woolstapler, who wrote about England's woollen industry in 1805 (Luccok, 1805, p.167): "In the last age, the operation of the fulling mill was very laborious and tedious. A piece of cloth was then submitted to it for thirty successive hours, whereas now it is often rendered sufficiently thick in seven or eight; an instance of (economy in the use of time and labor which augurs well for the interest of the manufacture."

millwrights were key players.

The Industrial Revolution decisively changed the roles of millwrights in the industrializing regions, and the profession morphed into something different that we would call today mechanical engineering (MacLeod and Nuvolari, 2009). The transition was characteristic of what the Industrial Revolution was all about: formal expertise and professionalization slowly evolved from highly-skilled craftsmanship.[21] Watermills were slowly being replaced by steam and traditional millwrighting skills were gradually becoming obsolete. But the transition to steam was slow and uneven and not complete until the second half of the nineteenth century. At least in the early stages of the Industrial Revolution, many traditional upper-tail skills were still needed. In the cotton industry, the transition to factories were achieved through reliance on traditional millwrights, who installed the new equipment (Tann, 1974, p. 83). Cookson (2018, p. 69) reminds us that the vast bulk of eighteenth-century machines still were made of wood and required the high-end specialized carpentry skills that millwrights possessed. Only after 1790, with the sharp decline in the price of iron did iron slowly replace wood and demanded new skills. Yet highly skilled artisans thinking of themselves as millwrights did not disappear, even as they had transform into or to make room for more specialized engineers. In his lectures written in the 1850s, Fairbairn (born in 1789) reminisced on the position of millwrights in his younger years in the early decades of the nineteenth century: “a good millwright was a man of large resources; he was generally well educated ... he had a knowledge of mill machinery, pumps, and cranes, and could turn his hand to the bench or the forge with equal adroitness and facility. This was the class of men with whom I associated in early life — proud of their calling, fertile in resources, and aware of their value in a country where the industrial arts were rapidly developing. It was then that the millwright in his character of ‘jack-of-all-trades’ was in his element ... It was no wonder, therefore, that at the commencement of the new movements in practical science, occasioned by the inventions of Watt and Arkwright, the millwright should assume a position of importance” (Fairbairn, 1860, pp. 212-13).

The concept of the millwright as an all-around technically competent craftsman remained

[21] In the 1820s handbooks in engineering started to appear, codifying what until then was mostly tacit and informal knowledge. The best-known is doubtless John Nicholson, *Millwright’s Guide* (1830), a rather detailed treatise, which tried to make best-practices in water power accessible. It was published as part of a series expressly designed to be adapted to the daily business of the “operative artist.”

paramount during the Industrial Revolution. Textile engineering installations categorized their equipment as either “millwright’s work” or “clockmakers work” and these concept “were soon enshrined in insurance policies” (Cookson, 2018, p. 68). Clearly the exact meaning of the term “millwright” was evolving, but Cookson (2018, p. 72) points out that their role as professional consultants, akin to coal viewers, remained of central importance to the textile industry. A prime example here is the career of Thomas Cheek Hewes, mentioned above. Hewes had employed Fairbairn in the 1810s, and while he specialized in waterwheels rather than steam engines, he was a significant inventor, introducing water works of the suspension type and governors (an idea borrowed from Watt). Despite his training as a traditional millwright, he was one of the pioneers of the use of iron in the construction of waterwheels. In part thanks to his work, water power survived far longer as a source of energy than the advent of steam might have suggested (Chrimes, 2002a).[22]

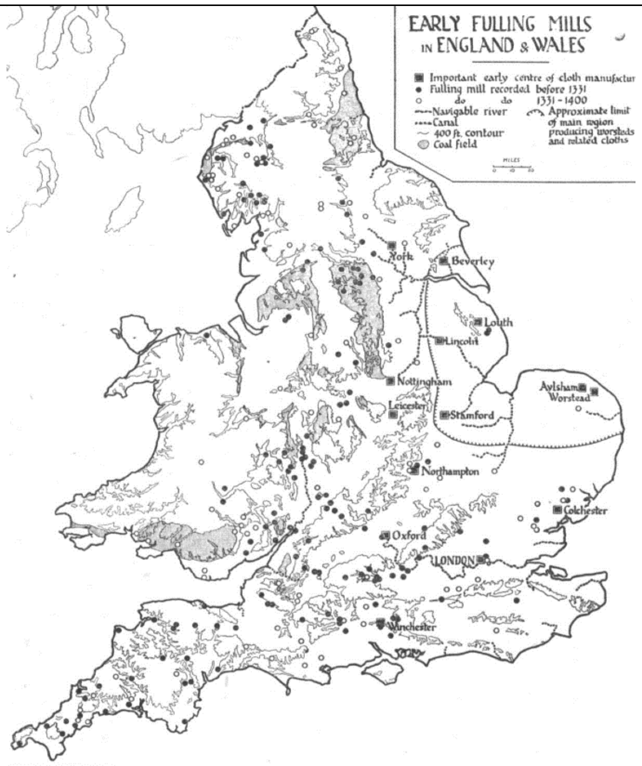
4. The location of the textile industry

It is important to bear in mind that the incentives for mechanization in textile manufacturing in the early eighteenth century, were driven by the textile industry as a whole, rather than cotton, which constituted a small share of the industry at the time. An illustrative example is the construction of the silk-throwing mill by the Lombe brothers in Derby, widely seen as one of the first modern large-scale factories. The elaborate water-powered machinery that drove the equipment was set up around 1720 by the Derbyshire millwright and engineer George Sorocold (1668-1739), who had earlier carried out pioneering work in the construction of water supply works (Chrimes, 2002b, p. 643). This feature can also be observed in the titles of patents from this time, which suggest that cotton played a rather marginal role in inventors’ considerations (Woodcroft, 1969). Kay’s flying shuttle patent (no. 542, 26th May 1733) is the classic example: “Machine for opening and dressing wool; shuttle for weaving broad-cloths, broad-baize, sail-cloths, or any other cloths, woollen or linen”. Cotton is not mentioned in the title. Richard Arkwright’s famous water frame patent (no.931, 3rd July 1769) says it is “for the making of weft or yarn from cotton, flax, and wool”; and his carding machine (no.1111, 16th Dec 1775) was for “preparing silk, cotton, flax, and wool for

[22] Despite the possibility that they had a falling out, Fairbairn (1860, p. 229) graciously credited Hewes with substantial improvements in watermills in the 1820s.

spinning". Edmund Cartwright's earlier patent titles just say a machine for weaving, without specifying the types of cloth, but his 1789 patent (no.1696) says it is for "wool, tow, hemp, flax, and cotton", his 1790 patents are for (no.1747) "hemp, flax, wool, hair, silk, and cotton", and his 1792 patent (no.1876) for "wool, hemp, flax, silk, hair, and cotton".

Figure2. The location of Early fulling mills



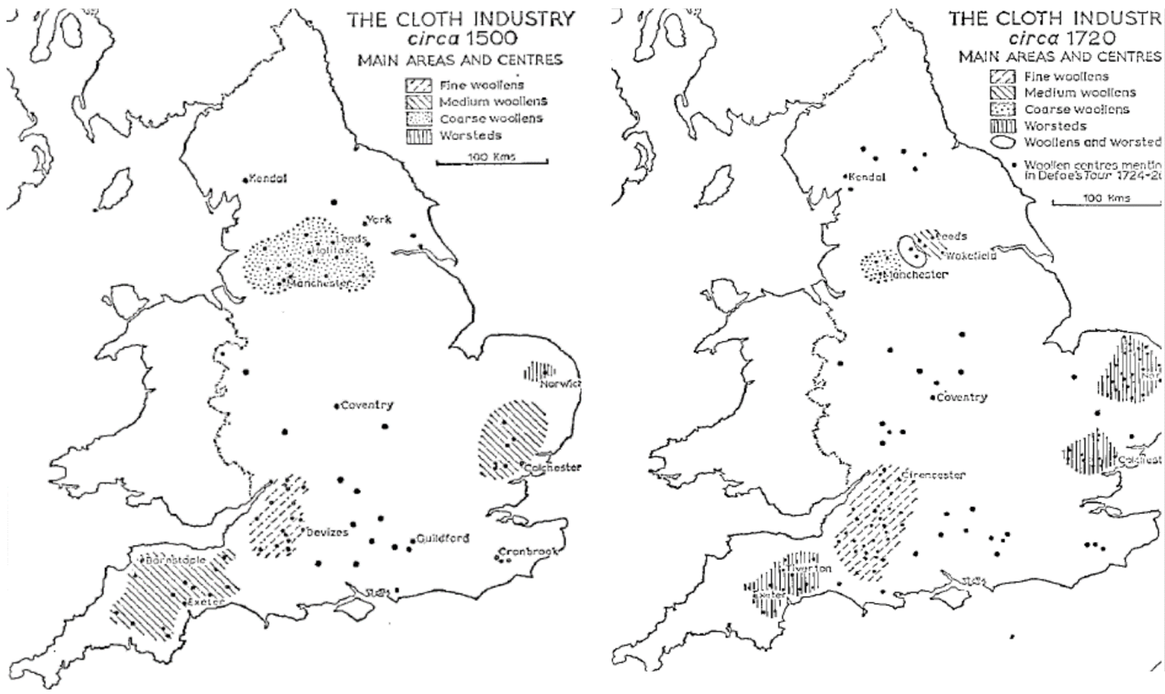
Source: Pelham (1944), p. 53.

Carus-Wilson (1941), Pelham (1944) and others have argued that the location of the industry shifted from the urban centers of the Eastern plains, to the hilly Northern and Western rural districts in late thirteenth century. As can be observed in the map in figure 2, Pelham found concentrations of fulling mills in the West Riding of Yorkshire, in the Lake District, in Cornwall, Devon, Somerset and the Cotswolds, in Wiltshire and in the Kennet Valley.[23] These are in fact the same locations in which the main cloth manufacturing centers can be found later on, less scattered, in the early sixteenth century and in the first half of the eighteenth centuries, and even in the beginning of the nineteenth century (figure 3)[24].

[23] The empty circles mark the fulling mill that were mentioned in 1331-1400.
[24] It is important to note that worsted was only scoured after being woven, but not fulled.

Figure 3. Location of main textile centers in the sixteenth and eighteenth centuries

Figure3a. circa 1500	*Figure3b. circa* 1720



Source: Darby (1973), Figure49, p. 224 | Source: Darby (1973), Figure77, p. 359

There remain, however, many open questions regarding the choice of locations the industry shifted to. Carus-Wilson (1941) famously argued that the shift was a response to the introduction of fulling mills to the process of cloth manufacturing and therefore the new locations were determined by the suitability for the construction of fulling mills (i.e. water streams). The worsted manufacturing, which is said to have developed in Flanders and brought to East Anglia (Norwich, in the Stour and Brett valleys of Suffolk and around Colchester and Braintree in Essex) during the sixteenth century by the large influx of Protestant refugees, had widely diffused to the West Riding Woolen District By 1700-20 (Darby, 1973 pp. 90-1). More recently, Sugden et al. (2018), provided new evidence that confirms this account. They show that the shift of the woollen manufacture to the West Riding began in the late seventeenth century and was essentially completed before the traditional starting point of the industrial revolution. They also argue that this shift concentrated mainly in areas close to coalfields, even though the usage of coal, and thus industrialization, occurred almost a century later. They attribute the vocational pattern to the lower cost of living due to cheaper coal for heating (also claimed in Crafts and Wolf 2014).

Our paper points to an additional key factor that played a role in determining the new location of the cloth industry: the availability of specialized and experienced mechanics and skilled artisans. Obviously, these were locations that specialized in mills prior to the introduction of fulling mills (i.e. grain grinding mills). The presence of workmen specialized in the construction of mills and in their inner workings constituted an important advantage for setting up a cloth manufacturing center based on mechanical fulling.

5. Description of the Data

We construct a cross section dataset of England's government area districts, which compose its 48 counties. [25] The dataset contains historical information about occupations, geographical features, and production factors in 36,147 locations and combines a number of historical sources.

5.1. Occupational variables

To approximate the size of various skilled occupational groups and industrial sectors in England during the eighteenth century (mainly those of wrights and of the textile sector), we use information on the number of apprentices to masters in the same trades from The *Apprenticeship Stamp Tax registers* (1710-1805).[26] The entries in the registers represent *indentures* (i.e. apprenticeship contracts whereby masters agreed to instruct their trade for a set term of years, usually seven, in exchange for a sum of money, the *premium*) and contain information on masters' trade , location and on the *premium* paid. The entries begin in 1710, following the introduction of a stamp duty payment on apprenticeship contracts, such that, indentures were void without the stamp. We limit the research period to 1750 to avoid reverse causality and other endogeneity problems which may arise from the effect of the beginning of industrialization on apprenticeship choices (Feldman and van der Beek, 2016).

[25] There are 326 districts, however, due to missing data in the HYDE project on population in Isles of Scilly, we are left with 325 districts.

[26] The registers are organized in 72 volumes, which are available on a microfilm format at the National Archives, Kew, in London.

Figure5. Apprentices to *drapers* 1710-50

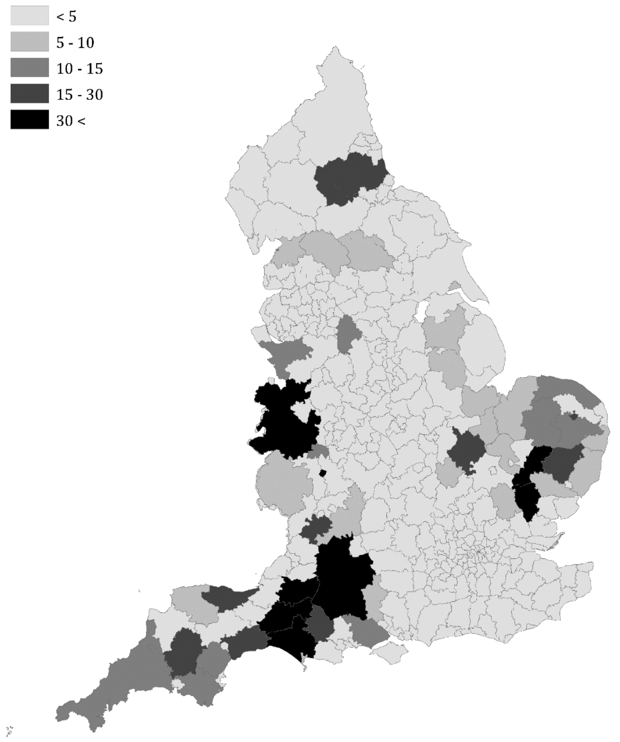
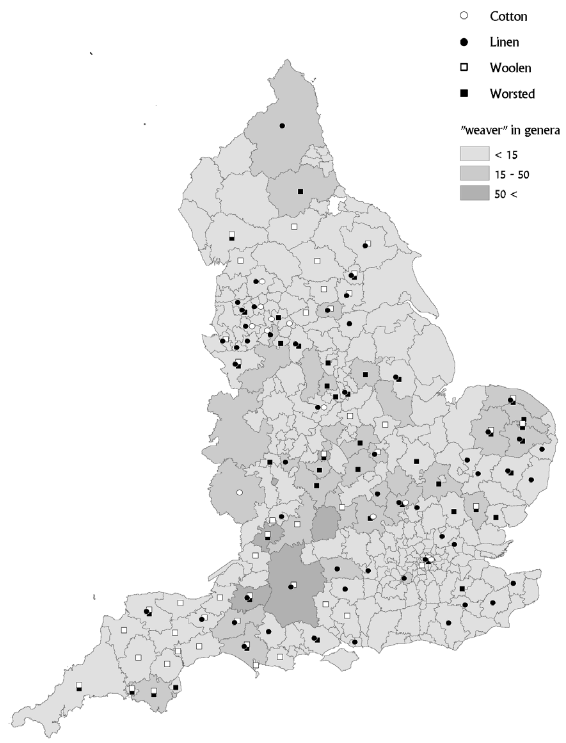


Figure6. Apprentices to *weavers* 1710-50



Source: see text. Apprentice numbers are in per capita terms (population is in thousands). By *drapers* we refer to masters described as drapers, clothiers, or, cloth merchants. As to *weavers*, most master weavers were simply registered as such, however in some cases the fiber, fabric, or, pattern was also mentioned (e.g. check weaver, or maker, cloth weaver, cotton checker, cotton weaver, fustian weaver, linen check maker, linen cloth weaver, linen weaver, serge weaver, wool weaver, worsted weaver, etc.).

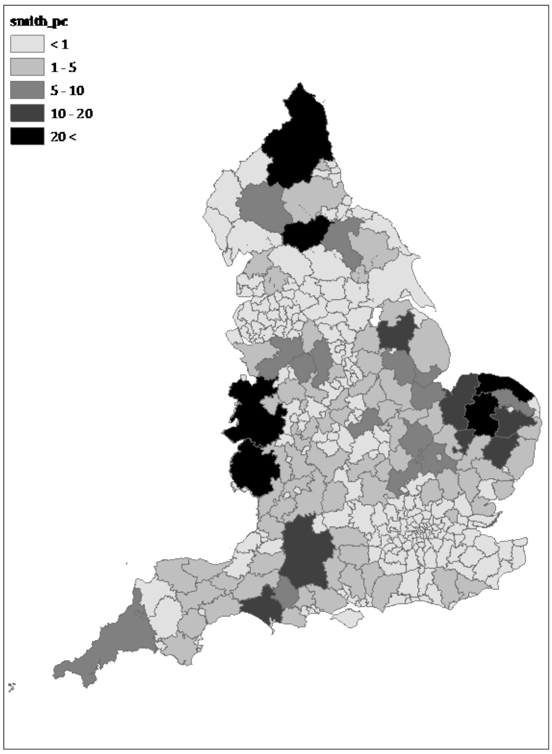
Using locations as they appear in *TownsList*, the most comprehensive database of locations of cities, towns and villages in the United Kingdom, we find apprentices in 10,201 of the 36,144 English locations (we exclude Scotland, Ireland and Wales) in the years 1710-1750.[27] In all the other locations, the number of apprentices is set to zero. Finally, we aggregate the number of apprentices in each occupation to the district level.[28] All of our occupational variables are measured in per capita terms. Estimates on population size are taken from the HYDE project (Klein Goldewijk et al., 2010; Klein Goldewijk et al., 2011) and specified in thousands throughout the paper. These data are given as a grid cell of $0.5' \times 0.5'$ degrees (i.e., approximately 1 km^2). We aggregate these for each district and divide all our profession data by these estimates.

[27] This dataset is available at www.townslist.co.uk

[28] The classification of occupations into broader categories was based on Feldman & Van der Beek, 2016.

Our main left-hand side variable, the extent of cloth production in every district in 1710-1750, is proxied using two alternative measures. The first is the number of apprentices to cloth merchants (referred to here as *drapers*), and the second is the number of apprentices to weavers.[29] As Figures 5 and 6 show, both measures capture the spatial distribution of cloth manufacturing as it appears in the map produced by Darby (1973), presented in figure 3b.[30] For other industrial occupations, we also use data on iron-work apprentices. In particular, we use data on smith apprentices per capita. Figure 7 shows the spatial distributions of smith apprentices per capita. Interestingly, their spatial distribution is similar to the one of the textile industry presented in Figures 5 and 6.

Figure7. Apprentices to *smiths* 1710-50



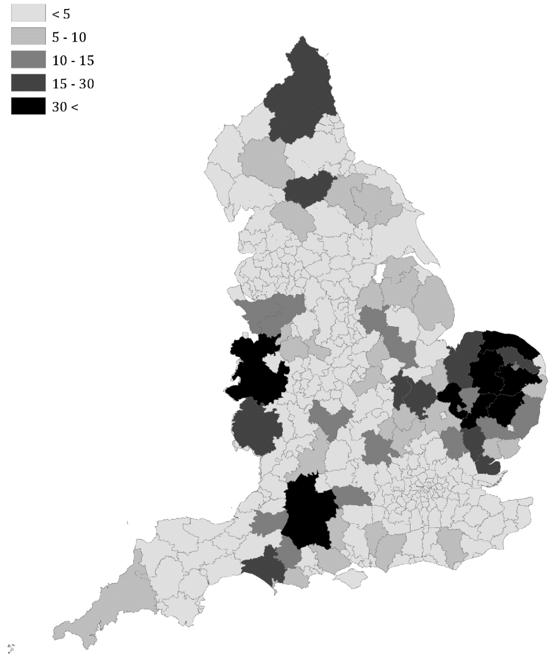
Source: see text. These are apprentices to masters referred to as smiths

[29] By drapers we refer to masters described as drapers, clothiers, or, cloth merchants. As to weavers, most master weavers were simply registered as such, however in some cases the fiber, fabric, or, pattern was also mentioned (e.g. check weaver, or maker, cloth weaver, cotton checker, cotton weaver, fustian weaver, linen check maker, linen cloth weaver, linen weaver, serge weaver, wool weaver, worsted weaver, etc.).

[30] Our measures also seem correlated with the distribution of textile workers in England during the 15th-16th centuries in Sugden et al. (2018) as it appears in Figure 3, p. 40.

Figure 8 presents the distribution of our main right-hand side variable, the number of apprentices to wrights. These are apprentices to masters referred to as mill carpenter, millwright, wheelwright, or simply, wright.

Figure 8. Apprentices to *wrights* 1710-50



Source: see text.

5.2. Additional Variables

We use different variables for providing evidence for the mediating channel through which mechanical skilled workers have affected the location of the textile industry, as well as controlling for other potential confounding effects. These data include data from The Domesday Book on the number of water mills and other variables documented in the Book, and geographical data from different resources as described below.

5.2.1. Domesday Book watermills

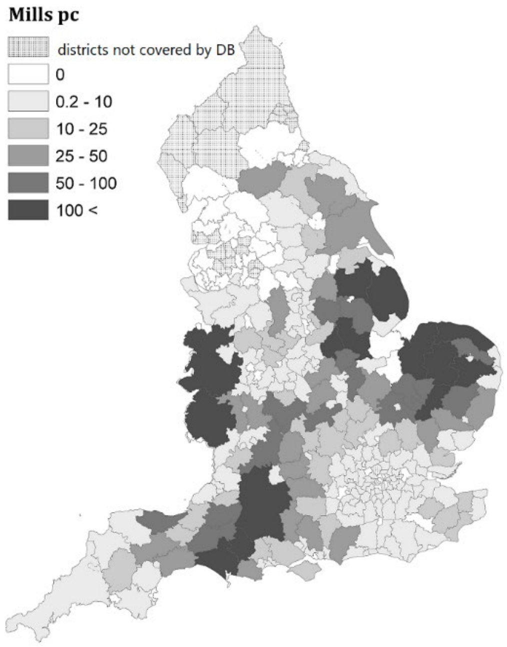
We use evidence from *Domesday Book* on the spatial distribution of watermills in 1086, when they were used for grain grinding.[31][32] It documents all the resources on English landholdings

[31] From an electronic edition of Domesday Book (Palmer, 2010). For the assumption that all mills mentioned in Domesday were corn mills see footnote 8.

[32] Domesday Book is a unique historical survey ordered by William *the Conqueror* in the eleventh century to assess the value and rights over landholdings in England (contains information on more than 13,000 *vilis*).

in 1086, including the extent of arable land, woodland, meadows, farmers (different types of legal statutes), the number of watermills and the total taxable value of the landholding. Domesday covers the English counties with some exceptions. It does not include the cities of London and Winchester, nor Bristol and Tamworth. Coverage of the north west of England is limited. The counties of Durham and Northumberland are omitted, and the coverage of Cumberland, Westmorland and Lancashire is limited. Using the Domesday mills in our econometric analysis therefore limits us to 298 districts.

Figure9. The Domesday Mills per capita 1086



Source: Palmer, J. (2010)

Figure 9 shows the distribution of Domesday watermills per capita. Interestingly, the number of mills used for grinding remained quite stable since Domesday, even though some of the mills were converted to become either tide mills or wind mills where the geographical conditions were favorable for these technologies (Langdon 2004). Furthermore, some mills were converted to industrial mills, and few other fulling mills were constructed. The information in Domesday Book also allows us to control for other economic and institutional characteristics of the different districts, including the share of lands owned by the king and the church, other properties in the district and their economic value and other economic characteristics that we use in our analysis.

4.3.1. Geographical Characteristics

4.3.1.1. Wheat suitability

The estimates for potential wheat yield (measured in tons, per hectare, per year), for each of $5' \times 5'$ degrees (i.e., about 100 squared km) cell are provided by the Global-Agro-Ecological Zones of the Food and Agriculture Organization (FAO). These measures are based on agro-climatic estimates, under low level of inputs and rain-fed agriculture, capturing conditions that prevailed in early stages of development.[33] We calculate the average potential yield in each district as a measure of the district's wheat suitability. Furthermore, the measures of wheat suitability are given in a scale from 1 to 8 (highly suitable). We define that a cell is highly suitable for wheat cultivation if it receives a measure of at least 5. Finally, we define that a district is highly suitable for wheat cultivation if at least 75% of its land is highly suitable for wheat cultivation (that is, at least 75% of its area ranks is at least 5 according to FAO ranking of suitability for wheat cultivation).

4.3.1.2. River suitability

To provide a measure for the suitability of a river for watermill construction we calculate the length of rivers with moderate levels of ruggedness in each district. Since topographic variation is highly correlated with many patterns in catchment-related hydrological responses driving the flow direction and water runoff velocity, we use the Terrain Ruggedness Index (TRI) for our purpose. TRI is a quantitative measurement of terrain heterogeneity devised by Riley et al. (1999) to express the amount of elevation difference between adjacent cells of a digital elevation grid.[34] Our TRI value calculation was based on data provided by HydroSHEDS at 15 arc-second (approximately 500 meters around the equator) resolution and is measured in hundreds of meters of elevation difference.[35] We sum the total length of rivers that have adequate ruggedness levels for constructing grinding mills given the technology of the time

[33] GAEZ provides estimates for crop yield based on three alternative levels of inputs – high, medium, and low - and two possible sources of water supply – rain-fed and irrigation. Moreover, for each input-water source category, it provides two separate estimates for crop yield, based on agro-climatic conditions, that are arguably unaffected by human intervention, and agro-ecological constraints, that could potentially reflect human intervention.

[34] TRI is calculated as the difference in elevation values from a center cell and the eight cells immediately surrounding it. Then it squares each of the eight elevation difference values to make them all positive and averages the squares. The terrain ruggedness index is then derived by taking the square root of this average.

[35] Elevations are from USGC DEM (US Geological Survey, Digital Elevation Model) - a global elevation data set developed through a collaborative international effort led by staff at the US Geological Survey's Center for Earth Resources Observation and Science (EROS). Data provided by HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales).

(i.e. too low flows were less regular and required higher setup costs of the water supply system, while too strong flows could damage the mill, which was rather delicate in this period).[36] Figure 4 shows how the English district differ with respect to the length of rivers with adequate levels of ruggedness.

Figure10. Wheat Suitability

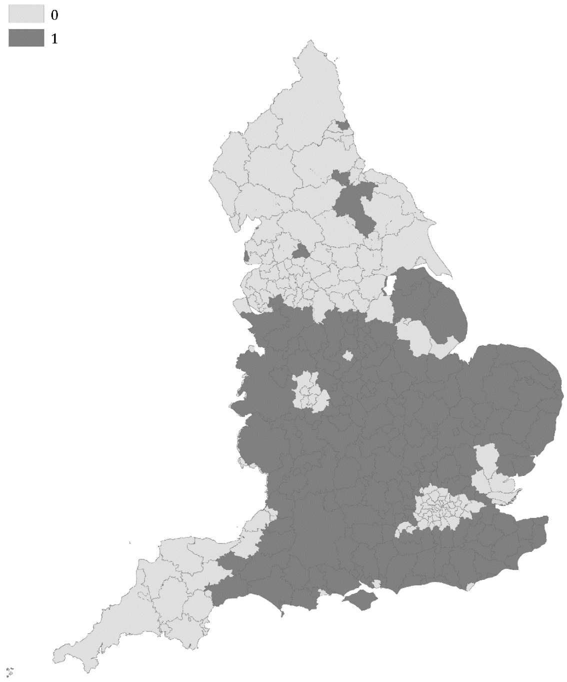
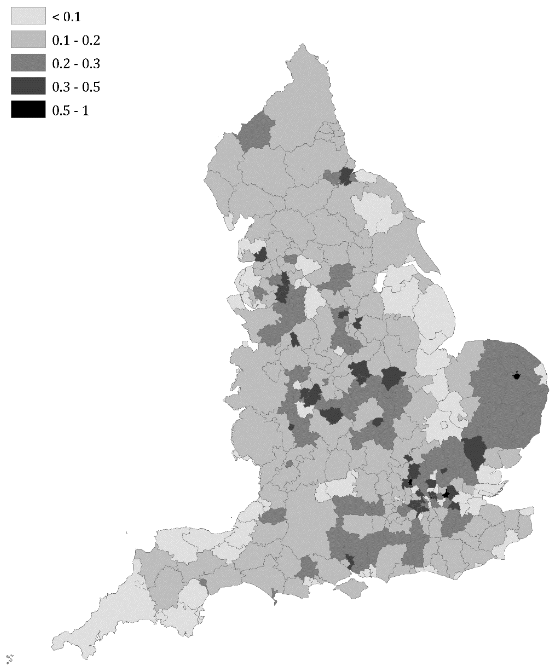


Figure11. River Suitability



Source: see text.

4.3.2. Additional Confounding Factors

We also account for different potentially confounding effects of a wide range of geographical and economic factors in each district, which may have affected the location of the textile industry. Since the climate of any particular place is influenced by a host of interacting factors, we account in our analysis for absolute latitude, elevation (also from HydroSHEDS), area, agricultural suitability (based on data from Ramankutty et. al (2001)), the district's average level of suitability for pasture cultivation, average precipitation and temperature, as well as the district proximity to London and to major harbors in eighteenth century England.[37]

[36] The authors propose the following breakdown for the values obtained for the index where: 0-80 m is considered to represent a level terrain surface; 81-116 m represents nearly level surface; 117-161 m a slightly rugged surface; 162-239 m an intermediately rugged surface; 240-497 m a moderately rugged; 498-958 m a highly rugged; and 959-4367 m an extremely rugged surface. In our analysis we used ruggedness levels between 200-300 meters, however, Appendix D shows that our results are not sensitive to these specific values, neither for the ruggedness levels, nor the share of area highly suitable for wheat cultivation.

[37] Average precipitation and temperature are calculated for each district based on data from Fick and Hijmans (2017), which provide gridded data of approximately 1 km^2 for monthly average temperature and precipitation for the period 1970-2000.

5. Empirical Analysis

Our core estimation examines textile production and the availability of mechanical skills in the years 1710-50. We have apprenticeship data on various occupational group for this period. This enables as to estimate a regression of the form:

$$(1) \quad O_d = \beta_0 + \beta_1 W_d + \sum_j \gamma_j X_{j,d} + \varepsilon_d$$

Where, O_d is the number of apprentices in occupation O in district d, and the occupations we estimate are drapers, weavers and smiths, all measured in per capita terms, W_d is the number of wright apprentices per capita in district d (henceforth, *wrights*), $\{X_{j,d}\}$ is a set of potentially confounding geographical, institutional and economical characteristics of district d, and ε_d is a district-specific error term. Our coefficient of interest, β, describes the correlation of initial wrights and industrial production (mainly textile, but also iron-make products).

5.1. Identification Strategy

The relationship between the number of drapers and the number of wrights may be endogenous due to reverse causality and possibly also to omitted variables (institutional, geographical, economic and human characteristics). Since wrights specialized in all types of machinery with similar mechanics as watermills, their numbers in the eighteenth century may have also been a response to the expansion in textile production, and not only its cause. To mitigate this concern, we first use the spatial distribution of historical watermills registered in Domesday Book (1086) as an instrument for the availability of wrights. Since the Domesday mills were only used for grain grinding at the time and wrights, who specialized in their construction and mechanics, resided in areas with high concentrations of mills, they were available in these areas long before the textile industry adopted the mechanics of the watermills. We also account for spatial auto-correlation and control for a wide range of geographical factors that may have affected the emergence of the textile industry (such as absolute latitude, mean ruggedness, mean precipitation and temperature and the total length

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For each variable we calculate the average yearly value for each grid cell, and then find the average in the district. Distances and absolute latitude are measured from the district's centroid.

of rivers), as well as economic factors such as agricultural suitability, the distance from London and from the main English ports at the beginning of the eighteenth century.

To mitigate any concern that districts from the same county are not independent, in all the regressions, all observations are clustered at the county level, thus correcting for any dependency at the county level. Reassuringly, our results are robust to this correction. Secondly, to exclude the possibility that the location of the Domesday mills was biased by some omitted unobservable characteristic, and, since the Domesday survey does not cover all the districts, we also instrument wrights with a geographical instrument that was constructed to capture the suitability of a district for the construction of *grain* watermills. For this purpose, we use the length of rivers in the district that have moderate levels of ruggedness, interacted with districts that are highly suitable for wheat cultivation.[38] This approach captures the exogenous variation of the potential of having wrights in the district before the introduction of industrial mills.

In addition, since the correlation between drapers and wrights may reflect a broader association between different industries, we perform two placebo tests, which explore two different issues: First, they examine whether our instrument is associated to draper apprentices via other occupations; Second, they explore whether wright apprentices are associated with other occupations; our analysis reveals that this is not the case. These two tests lend credence that our instrument satisfies the exclusion restriction.

6. Results

6.1. OLS Relationship between drapers and wrights 1710-50

Table 2 explores the association between the number of drapers and the number of wrights in a district for the pre-industrial period of 1710-1750. As established in column (1), the unconditional correlation between the number of draper apprentices per capita and wright apprentices per capita is positive and economically and statistically significant at the 1% level, suggesting that an increase in the number of wright per capita by one apprentice is associated with an increase of 0.43 drapers in the same district. Furthermore, as column (2) shows, the estimated relationship declines only slightly when we account for the potentially confounding

[38] A detailed explanation as to the construction of our geographical IV is provided in section 6.

effects of the geographical characteristics (latitude of the district's centroid, area, average level of ruggedness, and elevation).

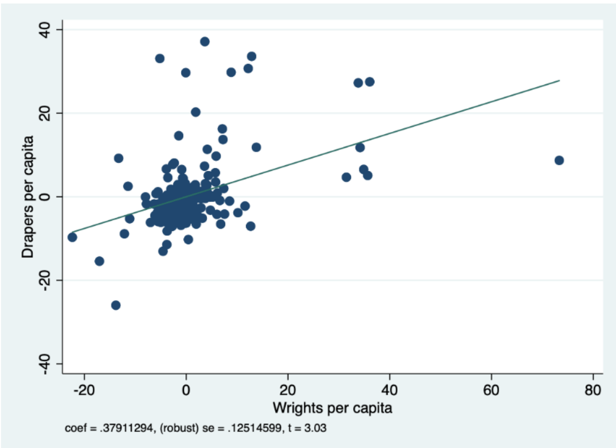
Table2. OLS Relationship between drapers and wright 1710-50

	No. of Draper Apprentices per Capita				
	(1)	(2)	(3)	(4)	(5)
Wrights (per capita)	0.43***	0.35***	0.37***	0.37***	0.38***
	(0.13)	(0.11)	(0.12)	(0.12)	(0.13)
Area (sq. km)		0.00	0.00	0.00	-0.00
		(0.00)	(0.00)	(0.00)	(0.00)
Latitude		-1.20**	-0.80*	-1.34*	-4.08***
		(0.52)	(0.41)	(0.79)	(1.30)
Ruggedness		0.50	0.22	-0.01	-0.17
		(0.35)	(0.43)	(0.47)	(0.42)
Elevation (mean)		0.29	0.83	-0.26	0.67
		(0.57)	(0.78)	(1.11)	(1.14)
Total River Length (km)		-0.00	0.00	0.01	0.01
		(0.02)	(0.02)	(0.02)	(0.02)
Agricultural Suitability			1.50	4.40**	2.92*
			(1.58)	(1.92)	(1.67)
Wheat suitability			-0.33	-0.13	-0.22
			(0.74)	(0.82)	(0.83)
Grass Suitability			0.79	-0.07	-2.08**
			(0.62)	(0.72)	(0.91)
Precipitation (mean)				2.13*	1.09
				(1.07)	(0.98)
Temperature (mean)				0.05	1.53
				(1.05)	(1.12)
Dist. to Nearest Harbor					-61.87
					(39.96)
Dist. from London					0.04***
					(0.01)
Adjusted-R^2	0.27	0.35	0.35	0.35	0.38
Observations	325	325	325	325	325

Notes: This table establishes the positive and economically and statistically significant association of the number of wright apprentices per capita in a district on the number of draper apprentices per capita for the period 1710-1750, controlling for population size, the area of the district, its average distance from London and major eighteenth century harbors and geographical controls. Specifically, the analysis suggests that an increase in the number of one wright apprentice per capita is associated with approximately one third of a draper apprentice in the district. All observations are clustered at the county level. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

In column (3) we add the district's wheat suitability (as calculated from the FAO GAEZ project), and agricultural suitability (as calculated from Ramankutty et al., 2001) to control for districts' land fertility as a possible channel for more intensive economic activity (*e.g.* markets, trade, etc.), Furthermore, both the textile industry and the location of mechanical skilled workers may have been potentially affected by specific geographical characteristics (the textile industry may have been affected by the amount of grass grown in the area for feeding sheep, whereas mechanical skilled workers may have been potentially affected by the amount of wheat grown in the district). [39] Yet, even after controlling for these potential effects and other climatic characteristics (mean precipitation and temperature), the estimated relation remains stable. Specifically, the analysis suggests that after controlling for these confounding effects, an increase of one wright apprentice per capita in a district is associated with an increase of 0.35 draper apprentice per capita.

Figure 12. Partial Correlation between drapers per capita and wrights per capita 1710-50



Finally, the estimated relation may have been affected by economic forces such as trade. Thus, in column (5) we control also for two potential channels through which trade may have affected the number of drapers: the proximity to London and the proximity to major harbors in the Eighteenth century. However, the estimated relation remains stable even when we control for these potential confounding effects and the relationship is statistically significant at the 1%, suggesting that an increase of one wright apprentice in a district is associated with an increase on 0.38 draper apprentices. Figure 12 depicts the partial correlation between draper

[39] Due to high transportation costs, milling was done on a local level, and thus there is a higher concentration of mills in places that were more suitable for wheat cultivation (van der Beek, 2010b, p.20). For more details see section 6.2.

apprentices and wright apprentices as captured in column (5). It shows that our results do not rely on any outlier.

6.2. Historical Grinding Mills and the Initial Location of Wrights

The results presented in Table 2 lend credence to our hypothesis that the location of the textile industry was affected by the location of mechanical skilled workers, because they provided a comparative advantage for implementing new technologies that used similar mechanics in the textile industry. Yet this analysis may suffer from reversed causality. To infer that the above-mentioned relationship between drapers and wrights is causal, we instrument the number of wrights in 1710 by the number of historical watermills registered in Domesday Book (1086) as an instrument for their availability 600 year later. The strong correlation between the two variables is clear from the results of the 1st stage analysis presented in table 3. Indeed, it seems that wrights in 1710-50 were more abundant in regions that had a high concentration of grinding mills in 1086.

Table3. Domesday mills (1086) and wrights (1710-50)

	No. of Wright Apprentices per Capita				
	(1)	(2)	(3)	(4)	(5)
Watermills (per capita)	0.15***	0.14***	0.13***	0.13***	0.13***
	(0.02)	(0.03)	(0.03)	(0.03)	(0.02)
Geographical controls	No	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes
Economic controls	No	No	No	No	Yes
Adjusted-R^2	0.57	0.58	0.58	0.58	0.59
Observations	298	298	298	298	298

Notes: This table establishes the poitive and statistically and economically significant effect of the number of water mills in a district as documented in the Domesday Book on the number of wright apprentices in the district, controlling for the district's population, area, suitability for cultivating wheat and other geographical controls. Specifically an increase in one hundred mills in the district is associated with an increase of eight wright apprentices, on average, per year in the period of 1710-1750. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Column (1) shows that the unconditional correlation between the number of mills and the number of wrights in a district is positive and statistically and economically significant at the 1% level, suggesting that an increase in one grinding mill in 1086 is associated with a 0.15 increase in the number of wrights in the district 600 years later. As columns (2)-(5) show, adding the geographical, climatic, agricultural and economic controls (identical to the ones in Table 1) hardly affects this result. Note that this analysis is limited to 298 districts due to the coverage of the Domesday survey.

Table4. IV Estimation of the Relationship between drapers and wright 1710-50 (Using DB Mills)

	No. of Draper Apprentices per capita					
	OLS	IV	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)
Wrights (per capita)	0.44***	0.57**	0.42***	0.56**	0.44***	0.55**
	(0.14)	(0.25)	(0.14)	(0.26)	(0.13)	(0.23)
Geographical controls	No	No	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	Yes	Yes	Yes	Yes
Economic controls	No	No	No	No	Yes	Yes
First-stage F-statistic		36.55		26.09		29.28
Adjusted-R^2	0.27	0.25	0.37	0.35	0.42	0.41
Observations	298	298	298	298	298	298

Notes: This table establishes the statistically and economically positive effect of the number of wright apprentices in a district on the number of draper apprentices, controlling for population size, geographical controls (latitude, area, mean temperature, mean precipitation, mean slope) and the distance from main eighteenth century harbors, navigable rivers, Roman roads and The City of London. To mitigate endogeneity problems, the analysis uses the number of watermills as reported in Domesday Book (1086) as an IV for the number of wright apprentices per capita. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table 4 presents the results of the OLS and the IV regressions, using Domesday Book (DB) mills as an IV.[40] Note that the number of observations is now limited to 298 districts due to the missing values for the DB mills.[41] In columns (1) and (2) we show the relationship between drapers and wrights using OLS and IV, respectively. As can be seen, the IV estimator is higher than the OLS estimator, and is economically and statistically significant. Moreover, the F-statistic suggests that it is strong enough an instrument, as it equals 36.55. The IV coefficient remain stable and significant when we replicate the analysis in columns (3) and (4) after adding

[40] Results of the 1st stage regressions appear in columns (1), (4) and (5) in table 3).

[41] Our OLS regression were estimated on the limited sample of 307 districts for matter of comparison. Thus, the estimators differ from those in Table 2.

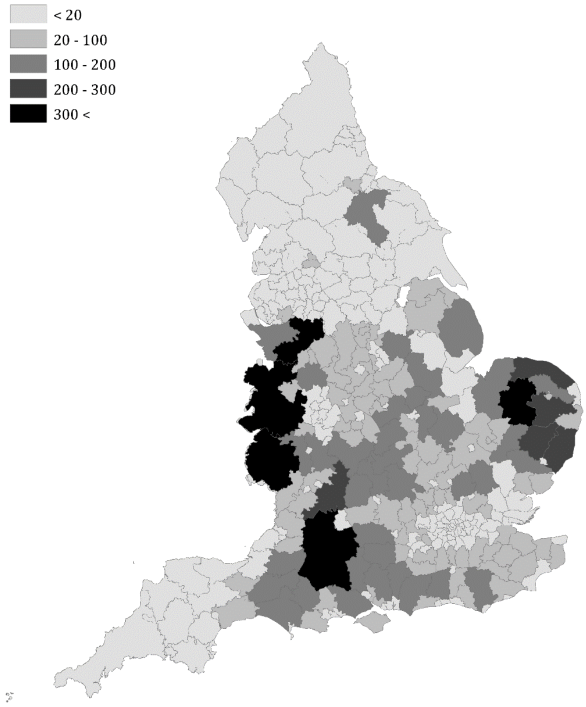
the geographical, climatic and agricultural controls, and finally, as well as in columns (5) and (6) where we add the economic characteristics of the district. The F-statistic in the last regression is higher than in column (2) and equals to 26.28. Thus, controlling for all characteristics, our analysis suggests that an additional wright generates an average increase of 0.55 drapers in a district.

6.3. Geographical Instrument for grinding Mill Suitability

It is possible that our IV, the number of Domesday mills in a district, is correlated with some omitted unobservable variables that may correlate with industrial production. For that reasons we construct a geographical variable that captures the locations with the best potential for construction of grinding mills in the early middle ages. The construction of a watermill was capital intensive. It was expensive both to construct and to maintain and was therefore constructed in locations where it was profitable (van der Beek, 2010a, 2010b). Profitability required that two conditions were met: First, that wheat was grown in a relatively large amount to cover the high construction and maintenance costs, and second, that river streams should be adequate for constructing grinding mills given the technology of the time. Thus, too low a flow was less regular and required higher setup costs of the water supply system, and too strong a flow could damage the mill, which was rather delicate in this period. As described in detail in section 4.3.1, our geographical IV is calculated as the interaction of a dummy variable for districts with large shares of land with high suitability for wheat growing, and the districts' length of rivers with moderate flows.[42] The resulting variable, *Mill Suitability,* is plotted on the map in Figure 13.

[42] Note that this instrument is similar in spirit to the one used in Caprettini and Voth (2017). They instrument the adoption of threshing machines in nineteenth century England using the interaction between the mean flow in a parish and the parish's degree of suitability to wheat cultivation. They argue that threshing machines were used mainly for wheat and were powered by water, and thus their instrument captures the exogenous variation between parishes in the potential for adopting threshing machines. Our instruments is different in two ways: First, because we are interested in capturing water mills constructed in earlier periods, we restrict the level of flow. Second, we use the length of rivers with moderate levels of ruggedness rather than the average accumulation of water. Ashraf et al. (2018) apply a similar approach for controlling for moderate river flows: They instrument the number of mills in a district in Prussia using the average level of ruggedness squared. They, however, look at possibly more modern mills (established until the beginning of the nineteenth century).

Figure13. Suitability for Grinding Mills as an IV for the availability of Wrights



Source: Authors' calculations. The sources for the calculations are explained in detail in the data section.

The results in table 5 provide support to our interpretation of the geographical IV as reflecting the potential of different locations for the construction of watermills in the early middle ages. It shows that such places were both suitable for wheat growing and had the "right" level of water flow. While, column (1) shows that high suitability for wheat cultivation and medium levels of river flows are both, independently, associated with the number of mills, once the interaction between the two is added in column (2), the coefficient of high suitability for wheat cultivation ceases to be significant, suggesting that indeed high suitability for wheat cultivation is important mainly in regions that have the adequate river flows for establishing water mills. Furthermore, the interaction increases the explained variation by more than 0.1. This analysis is robust to adding more geographical controls (columns (3) and (4)), and other agricultural and economical controls (columns (5) and (6)). In particular, as can be seen in column (6), an additional km of river with the adequate level of ruggedness in a district which is highly suitable for wheat cultivation is associated with an increase of about 0.44 water mills per thousand people in the district. This result is robust at the 1% level of significance, and once this interaction is included as an explanatory variable, both separate components of the interaction term – high suitability for wheat cultivation and adequate river flows – become statistically significant, but *negatively* associated with the number of mills, suggesting that once one of these conditions is not fulfilled, the number of mills in the district is lower.

Table5. Geographical Suitability for Grain Mills and Wrights (1710-50)

	No. of Domesday Watermills per Capita					
	(1)	(2)	(3)	(4)	(5)	(6)
Mill Suitability		0.46***		0.40***		0.44***
		(0.10)		(0.08)		(0.08)
Ruggedness Suitability	0.39***	0.07**	0.52***	0.18**	0.51***	0.13*
	(0.09)	(0.03)	(0.13)	(0.07)	(0.12)	(0.07)
Wheat suitability	12.49**	-13.48***	14.33**	-7.89**	9.63*	-15.69***
	(5.36)	(4.44)	(5.51)	(3.17)	(4.81)	(5.28)
Area			-0.00**	-0.00	-0.00**	-0.00
			(0.00)	(0.00)	(0.00)	(0.00)
Latitude			4.21	3.79	3.11	-3.22
			(5.53)	(4.64)	(9.97)	(8.61)
Ruggedness (mean)			-0.60	0.34	1.55	3.01
			(1.73)	(1.51)	(2.98)	(2.37)
Elevation (mean)			-0.08	-0.09	-0.13	-0.14
			(0.09)	(0.06)	(0.13)	(0.09)
Precipitation (mean)			0.27	0.21	0.68	0.58
			(0.33)	(0.28)	(0.59)	(0.43)
Temperature (mean)			15.36	6.88	27.63**	24.87***
			(9.80)	(7.12)	(12.15)	(8.92)
Agricultural Suitability					15.49	10.03
					(13.75)	(9.12)
Grass Suitability (mean)					-0.14	-0.25***
					(0.08)	(0.07)
Dist. to Nearest Harbor					0.13	0.15
					(0.13)	(0.12)
Dist. from London					0.03	0.10
					(0.09)	(0.08)
Dist to Nearest Roman Road					-0.28*	-0.27*
					(0.15)	(0.14)
Distance to Nearest Navigable River					6.29	4.79
					(6.38)	(8.83)
Adjusted-R^2	0.43	0.54	0.48	0.55	0.48	0.57
Observations	298	298	298	298	298	298

Notes: This table establishes the importance of both wheat suitability and rivers with adequate levels of ruggedness to the number of mills per capita in the district. Specifically, it shows that both wheat suitability and the total length of the rivers with low levels of ruggedness are positively associated with the number mills per capita, but once the interaction between the two is the explanatory variable, the former two become either either lose their economic significane, or even become negatively associated with the number of mills per capita in the district. All observations are clustered at the county level. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Table6. IV Estimation of the Relationship between drapers and wright 1710-50 (Using Geographical IV)

	No. of Draper Apprentices per capita					
	OLS	IV	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)	(5)	(6)
Wrights (per capita)	0.32**	0.66*	0.36***	0.70**	0.40***	0.73**
	(0.13)	(0.36)	(0.13)	(0.33)	(0.13)	(0.30)
Wheat suitability	-0.08	-1.21	-0.11	-0.99	0.13	-0.42
	(0.71)	(0.79)	(1.05)	(0.95)	(1.08)	(0.98)
Ruggedness Suitability	0.02	-0.00	0.01	-0.01	0.01	-0.01
	(0.01)	(0.02)	(0.01)	(0.02)	(0.01)	(0.02)
Geographical controls	No	No	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	Yes	Yes	Yes	Yes
Economic controls	No	No	No	No	Yes	Yes
First-stage F-statistic		12.08		13.69		15.04
Adjusted-R^2	0.30	0.19	0.36	0.25	0.41	0.31
Observations	325	325	325	325	325	325

Notes: This table establishes the statistically and economically positive effect of the number of wright apprentices per capita in a district on the number of draper apprentices per capita, controlling for population size, geographical controls (latitude, mean temperature, mean precipitation, mean slope and area) as well as the distance from main eighteenth century harbors, The City of London historical Roman roads and a navigable river. To mitigate endogeneity problems, the analysis uses an IV for the number of wright apprentices, which is based on the interaction of a dummy that indicates if the district is highly suitable for wheat cultivation and the length of rivers with a ruggedness level suitable for contructing watermills in Early Medieval times. Thus, the analysis also controls for these two varaiables separately. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

The estimation of the relationship between the availability of wrights in the district and textile production, based on our geographical suitability IV is presented in Table 6. Since the components of the IV, high wheat suitability and moderate ruggedness, may explain textile production, we add them to the regression separately. Columns (1) and (2) show the relationship between draper apprentices per capita and wright apprentices per capita controlling for the suitability of rivers in the district (i.e. the length of rivers with medium levels of ruggedness) and the wheat suitability of the district (i.e. suitability for wheat cultivation), using OLS and IV, respectively. As can be seen, the IV estimator is higher than the OLS estimator, and is economically and statistically significant at the 10%. The F-statistic suggests that it is strong enough an instrument, as it equals 12.08. We replicate the analysis in columns (3) and (4), where we also control for geographical, climatic and agricultural controls, and the results are even stronger: the IV estimator grows in its magnitude and is significant at the 5%. Finally, we control in columns (5) and (6) also for economic characteristics of the district. As can be seen in column (6), the instrument is even stronger, as the F-statistic equals 15.04. Furthermore, controlling for all characteristics, the analysis suggests that an increase of one wright apprentice per capita in a district generates an increase of 0.73 draper apprentices per capita.

6.4. The Relationship between Iron-Works and Mechanical Skills

In this subsection we replicate our result about the textile industry to the iron-makes industry. In particular, Table 7 replicates Tables 2, 3 and 6. Column (1) provides the

Table7. IV Estimation of the Relationship between smiths and wright 1710-50 (Using Geographical IV)

	No. of Smith Apprentices per Capita								
	OLS	IV Watermills	IV Mill Suit.	OLS	IV Watermills	IV Mill Suit.	OLS	IV Watermills	IV Mill Suit.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wrights (per capita)	0.41***	0.51***	0.34*	0.31***	0.46***	0.41**	0.31***	0.46***	0.41**
	(0.07)	(0.08)	(0.18)	(0.05)	(0.06)	(0.19)	(0.06)	(0.06)	(0.18)
Ruggedness Suitability			0.02**			-0.00			-0.00
			(0.01)			(0.02)			(0.02)
Wheat suitability			-0.36	0.63	0.27	0.36	0.57	0.36	0.41
			(0.46)	(0.43)	(0.47)	(0.47)	(0.44)	(0.44)	(0.35)
Geographical controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	No	No	No	No	No	No	Yes	Yes	Yes
First-stage F-statistic		36.55	12.08		15.49	17.26		16.67	18.17
Adjusted-R^2	0.57	0.53	0.67	0.69	0.60	0.66	0.68	0.60	0.66
Observations	325	298	325	325	298	325	325	298	325

Notes: This table replicates the results obtained about draper apprentices, but this time on smilh apprentices. In particular, it establishes the statistically and economically positive effect of the number of wright apprentices in a district on the number of smith apprentices, controlling for population size, geographical and climatic controls (latitude, area, mean temperature, mean precipitation, mean ruggedness) and the distance from main eighteenth century harbors, The City of London, historical Roman roads and navigable rivers. To mitigate endogeneity problems, the analysis uses the number of watermills (in columns (2), (5) and (8)) as reported in Domesday Book (1086) as an IV for the number of smith apprentices per capita, and the suitability for constructing grinding mills in early Medieval times (in columns (3), (6) and (9). Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

unconditional correlation between smith apprentices and wright apprentices, both in per capita terms. The correlation is statistically and economically significant at the 1%, suggesting that an increase of one wright apprentice in the district is associated with a 0.41 increase in smith apprentice per capita in the district. Columns (2) and (3) instrument wright apprentices per capita by the number of Domesday watermills per capita and mill suitability, respectively. Consistent with our hypothesis, both instruments are statistically and economically significant at the 1%, suggesting that an increase of one wright apprentice per capita in a district generates an increase of 0.51 and 0.34 smith apprentices per capita, depending on the instrument.

In columns (4)-(6) we add the main geographical controls geographical and the results are quite stable. Finally, in columns (7)-(9) we add all other controls, and our results remain significant at the 1%, suggesting an increase of one wright apprentices per capita generates an increase of 0.31 smith apprentices in our OLS estimations, 0.46 smith apprentices per capita when we use Domesday watermills as an IV, and 0.41 smith apprentices per capita when we use the geographical characteristic of mill suitability as an IV. These results lend further credence that wrights attracted industrial clusters to reside in close proximity to their knowledge.

6.5. Placebo Tests: Other Industries and Skills

6.5.1. Other Industries and Wrights

We discussed above the validity of our instrument. In this subsection we run two placebo tests, which provide additional evidence that wright apprentices affect only industries that adopted the watermill technology. Table 8 provides evidence that the number of wright apprentices in a district affects mainly the number of draper apprentices in the district, as well as other apprentices in the textile and iron-makes industries. As a benchmark, columns (1)-(4) replicates the last column on Table 7 for drapers, weavers, smiths and blacksmiths.[43] Columns (5) to (12) replicate columns (1)-(4), except that in each column the dependent variable is replaced by the number of apprentices of in other occupations in our dataset, which did not use watermills technologies in their production processes. Interestingly, none of these other apprentice variables is statistically significant, suggesting that an increase in the number of wright apprentices per capita does not affect the number of apprentices in these occupations. This table thus lends credence to our hypothesis, that wright apprentices had the know-how to advance the textile industry and other industries that used watermills in their production processes, and thus

[43] We already showed that our results hold for smiths, and in the appendix we use different occupations to proxy the textile industry (weavers) and iron-makes (blacksmith) to show that our results are robust to different occupations from the same industry. In this table we add these occupations.

Table8. IV Estimation of the Relationship between smiths and wright 1710-50 (Using Geographical IV)

	No. of Apprentices										
	Drapers	Weavers	Smith	Blacksmith	Carpenter	Joiner	Mason	Butcher	Leather	Attorney	Surgeon
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Wrights (per capita)	0.73**	1.45**	0.36**	0.89***	1.00	0.06	0.15	1.05	2.89	0.98	0.17
	(0.30)	(0.61)	(0.18)	(0.14)	(0.76)	(0.71)	(0.11)	(1.01)	(4.17)	(0.67)	(0.21)
Wheat suitability	-0.42	4.82	0.45	0.68	2.36**	2.01	0.76*	2.53*	12.31**	0.66	0.13
	(0.98)	(4.00)	(0.35)	(0.68)	(1.03)	(1.23)	(0.43)	(1.40)	(6.04)	(0.76)	(0.41)
Ruggedness Suitability	-0.01	0.07**	0.02	0.05***	0.12**	0.12**	0.01	0.16**	0.76**	0.05	0.05***
	(0.02)	(0.03)	(0.01)	(0.01)	(0.05)	(0.06)	(0.01)	(0.08)	(0.36)	(0.05)	(0.01)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	15.04	15.04	15.04	15.04	15.04	15.04	15.04	15.04	15.04	15.04	15.04
Adjusted-R^2	0.31	0.16	0.66	0.73	0.67	0.57	0.28	0.65	0.74	0.57	0.61
Observations	325	325	325	325	325	325	325	325	325	325	325

Notes: This table establishes that the number of wright apprentices mainly affects the number of draper, weaver, smith and blacksmith apprentices, rather than other occupation apprentices. It does so by instrumenting the number of wright apprentices per capita by the geographical IV described above, and controlling for all geographic, climatic, agricultural and economic characteristics in all previous tables. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

these textile industries, and hardly any other industry, resided in the same locations where the wrights resided.

Table9. IV Estimation of the Relationship between smiths and wright 1710-50 (Using Geographical IV)

	No. of Draper Apprentices							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Wrights (per capita)	0.73**							
	(0.30)							
Carpenter (per capita)		0.73						
		(0.74)						
Joiner (per capita)			13.25					
			(173.74)					
Mason (per capita)				4.95				
				(4.11)				
Butcher (per capita)					0.70			
					(0.82)			
Leather (per capita)						0.25		
						(0.43)		
Attorney (per capita)							0.74	
							(0.59)	
Surgeon (per capita)								4.30
								(6.52)
Wheat suitability	-0.42	-2.14	-27.07	-4.19	-2.09	-3.54	-0.91	-0.98
	(0.98)	(2.36)	(356.51)	(4.24)	(3.07)	(6.47)	(1.26)	(2.59)
Ruggedness Suitability	-0.01	-0.10	-1.60	-0.07	-0.13	-0.21	-0.05	-0.23
	(0.02)	(0.13)	(21.53)	(0.10)	(0.19)	(0.42)	(0.06)	(0.39)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	15.04	1.12	0.01	1.72	0.87	0.38	1.72	0.49
Adjusted-R^2	0.31	-1.57	-268.01	-3.65	-1.36	-2.12	-0.32	-6.77
Observations	325	325	325	325	325	325	325	325

Notes: This table establishes that the number of draper apprentices is not affected by the number of other apprentices, rather than wright apprentices. It does so by instrumenting the number of each type of apprentices per capita by the geographical IV described above. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

6.5.2. Drapers and Other Apprentices

Table 9 provides the results of a second placebo that shows that textile production was not affected by almost any other occupational group rather than wrights. This result lends more credence both to the idea that our instrument indeed holds the exclusion restriction, and to our hypothesis that the location of wright apprentices was important to the location of the textile industry in particular and other industries that passed an industrialization phase in general. In column (1), as a benchmark, we replicate the last column of Table 7, just like the previous table. In columns (2) to (9), we replace our instrumented apprentices – the wright apprentices – with other apprentices (the same ones as in Table 8). As can be seen in the table, none of the other apprentices seems to correlate with the number of draper apprentices. Furthermore, it seems that not only do they not correlated with the number of draper apprentices, but also the F-statistic of the first stage is very low, suggesting that our instrument is not a good instrument to other apprentices other than wright apprentices. We conclude from this table, that indeed our instrument holds the exclusion restriction, and that wright apprentices are the only type of apprentices that affected the number of draper apprentices.

7. Robustness

The previous tables lend credence to our hypothesis that at the eve of the First Industrial Revolution the mechanically skilled craftsmen trained as wrights assisted other industries which could use water power to flourish. Nevertheless, the results might be biased due to omitted institutional and human characteristics, or due to specific choice of occupations and levels of ruggedness and wheat suitability. The rest of this subsection establishes robustness results for (i) spatial autocorrelation; (ii) the availability of coal; (iii) biases due to the choice of occupations; (iv) reliance on specific levels of wheat suitability or ruggedness of rivers; (v) bias due to the effect of London

7.1.1. Spatial Autocorrelation

One concern in spatial regressions as we estimate is that the independence assumption is violated. Indeed, the Moran's I in our main variables is statistically different from zero, as it is close to 0.05. Though this means that the observations are weakly positively spatially correlated, the Moran I statistic is highly significant, receiving a z-score around 8. We perform different exercises to show that our results are not biased due to spatial autocorrelation. First, we correct the standard errors based on Conley (1999). Table A.1 provides the results of these estimations, and shows that our results are not affected by this correction.

Nevertheless, Kelly (2019) showed that where spatial autocorrelation is severe, Conley (1999) correction is not enough, as the t-statistics might still be inflated. Hence, following Kelly (2019), we perform Monte Carlo simulations with 5000 repetitions, where in each we generate spatially autocorrelated white noise. The spatial auto-correlation is calculated in a radius of 55km, which provides in 5000 simulations a spatial auto-correlation in levels similar to the one we calculated in our data. In each repetition, we run two placebo tests: First, we simulate our model where the spatially autocorrelated white noise replaces our explanatory variable: the number of wrights per capita. The results are presented in Table A.2. Reassuringly, none of the simulations generates a statistically significant coefficient. In the second placebo test we simulate our model, but this time the spatially autocorrelated white noise substitutes our dependent variable: the number of draper apprentices per capita. The results are presented in Table A.3. Again, none of the simulations yields a statistically significant coefficient. We conclude from the three tests that our results are not biased due to spatial autocorrelation.

7.1.2. Robustness to the availability of coal

Many studies concentrate on the availability of coal as an explanation for the location of the Industrial Revolution. In this paper we show that the availability of coal did not affect the location of the textile (and iron making) centers prior to industrialization, and became relevant only after the mid eighteenth century. To account for the availability coal we use a dummy for the presence of carboniferous rock strata in the district, which is used in studies to measure the district's potential for coal. The data was taken from *the 1:5 Million International Geological Map of Europe and Adjacent Areas* (IGME 5000) project.[44] The results in Appendix Table B1 show that the potential for coal does not have a significant effect on the location of textile centers in the first half of the eighteenth century when we control for other geographical and climatic characteristics of the district, and, it does not have an effect on our main result.

7.1.3. Robustness to the LHS choice of occupation

Appendix Tables C.1. and C.2. provide evidence that our results are robust to proxying the textile industry with weaver apprentices per capita rather than draper apprentices per capita,

[44] The data was collected by BGR (German Federal Institute for Geosciences and Natural Resources) for a project that mapped the European geological landscape.

and proxying iron-making with blacksmith apprentices per capita rather than smith apprentices per capita. In particular, Table C.1. replicates the results of Tables 2, 4 and 6, but using weaver apprentices per capita instead of draper apprentices per capita as a proxy of the textile industry. In all specifications, the number of wright apprentices per capita is positively associated and statistically and economically significant. Furthermore, both our two IV approaches suggest that an increase of one wright apprentice per capita causes an increase of about 1.45, 2.34 weaver apprentices per capita in the district, depending on the IV. These results lend credence to our hypothesis that the textile industry resided in regions where wrights and their human capital were abundant.

Table C.2. replicates Table 7, but uses blacksmith apprentices per capita instead of smith apprentices per capita as a proxy for the iron-makings industry. In all the specifications, OLS and IV alike, the number of wright apprentices per capita is positive and statistically and economically significant. Furthermore, our two IV approaches suggest that an increase of one wright apprentice per capita in the district causes an increase of 0.9, or 1.3 blacksmith apprentices per capita in the district, depending on the IV. Again, these results strengthen our confidence that industries that used water power in their production processes resided in regions with wrights, who could embed these technologies in different industries.

7.1.4. Robustness to Other Specifications of the Instrument Variable

One concern is how sensitive our results are to changes in the construction of our instrument variable. Recall that our instrument is the interaction of the length of the river with adequate levels of ruggedness (as a proxy for the flow of water) and a definition of the district as highly suitable for wheat cultivating. In particular, in our results presented above, we assume that the adequate levels of ruggedness are between two and three, and a district is considered to be highly suitable for wheat growing if at least 75% of its area is highly suitable for wheat growing.[45]

Appendix Tables D.1 and D.2 provide evidence that the results are not sensitive to these values. Table D.1 shows the results of the last column in Table 7 with different levels of ruggedness. Column (1) replicates the last column of Table 7 as a benchmark. Then, in column (2) and column (9) we replace the ruggedness levels with too low levels and too high levels of

[45] See footnote 32 for discussion of the relevant ruggedness levels.

ruggedness, respectively. As can be seen in these two columns, while the effect of wright apprentices per capita on draper apprentices per capita is still significant, the first stage F-statistics is too low, suggesting that these levels are not adequate for constructing water-powered plants. On the contrary, columns (3)-(8) show how using different medium levels of ruggedness in the instrument does not change the direct effect of wright apprentices on draper apprentices. Thus, our results are robust to different medium levels of ruggedness.

Table D.2 provides further evidence that our instrument is robust to different levels of suitability for wheat growing. Recall (from Section 4) that we define a district as highly suitable for wheat growing if at least 75% of its area is highly suitable for wheat growing. Table D.2 Shows that our instrument is valid also if the area highly suitable for wheat growing is between 40% and 90% of the area of district. In particular, in column (1) we replicate the last column in Table 7 as a benchmark. Then, on columns (2)-(8), we replace the share of area highly suitable for wheat growth in our instrument (and the controls). As can be seen, if we define the district as highly suitable for wheat growing for too low levels of area that indeed are suitable for wheat cultivation (see columns (2) and (3) for 10% and 25% of the area, respectively), both the effect of the number of wright apprentices per capita on the number of draper apprentices per capita is not statistically significant, and the first stage F-statistic is too low. Furthermore, if we use higher shares of area that are highly suitable for wheat cultivation, our results seem qualitatively similar to our instrument. We conclude from this table that while we use one level of the share of area that is highly suitable for wheat cultivation in our analysis, our instrument is robust to a range of values which we can use.

7.1.5. The Effect of London

A possible concern could be that proximity to London, as a vast commercial, demographic, and political center, could bias our results. To overcome this problem, we first control in all our tables the distance from London. To further show that London does not affect our results, we replicate Table 7, once for draper apprentices per capita as our dependent variable and once for smith apprentices per capita as our dependent variable, omitting The City of London from the sample. These tables can be found in Appendix E. , The tables show almost identical results to the results obtained in Tables 2, 4, 6 and 7.

8. Conclusions

The growing attention to persistence in the economic history literature has pointed to a considerable number of cultural and institutional features of pre-modern societies that explain variations in interesting outcome variables many generations later. In all those studies it has been critical to identify a mechanism that can account for such a persistence. In the analysis of the occurrence and dissemination of technological change, persistence has been linked in recent years, directly to the presence of Upper Tail Human Capital and the useful knowledge of an artisanal or intellectual elite (Squicciarini and Voigtländer 2015; Boerner, Rubin and Severgnini, 2019). The quality and competence of workers in the top few percent of the distribution of technical and mechanical ability mattered more to technological advances than the capabilities of the average worker. In that context, what was crucial to innovation and technological leadership in the centuries before and the early stages of the British Industrial Revolution was the supply of top-quality artisanal skill.

Our paper presents a powerful illustration of this persistence. What the data show is that certain forms of economically significant human capital such as local mechanical competence tended to persist over time and help determine the location of textile industries in the eighteenth century. This paper highlights one small but significant segment of England’s best and brightest craftsmen, namely millwrights and engineers. The presence of geographical conditions that favored the construction of water mills engaged in grain milling created a class of highly-trained millwrights whose skills spilled over to the woolen industries. The prevalence of these industries were a first step in the path of England becoming an industrial nation. It is no accident that the term “mill” became synonymous with “factory” in the early stages of the Industrial Revolution as the role of water mills in textile manufacturing remained central for many decades in the eighteenth century, before they were eventually superseded by steam engines.

The association between pre-existing mechanical skills thanks to millwrights and subsequent industrialization is obvious from the data, but a direct identification of the effects of this form of human capital is hard to establish because of the obvious confounding effects of reverse causality and the presence of unobservables, which may make it difficult to test the model with precision. To resolve this, we have employed both history and geography to tease out a better-identified statistical relation. Using both the 1086 Domesday book and a host of geographical variables as instruments, we have established that skilled millwrights were indeed an important factor in the location of the English woolen industry.

Did these locational patterns matter in any way to what happened after 1750? The importance of the woolen industry in the Industrial Revolution has been traditionally overshadowed by the spectacular growth of the cotton industry, but we should not forget that wool kept growing during the Industrial Revolution at a more than respectable rate and "the wool industry did not allow itself to be outshone" (Jenkins and Ponting, 1982, p. 296). Many of the technological breakthroughs in cotton carried over to wool and vice versa, and both industries benefitted immeasurably from the high level of competence of British craftsmen and mechanics (Kelly, Mokyr and Ó Gráda, 2019). Millwrights were a component of this class, but so were many others: clockmakers, mechanics, colliers, toymakers, ironmongers, and many manufacturers of up-market consumer goods all played a role.

We hasten to add that there was no simple mapping from the pre-existence of a high-skilled labor force to the acceleration of technological progress during the Industrial Revolution. The Midlands and London were able to transform these skills in rapid growth. But the traditional areas of woolen manufacturing in the West Country and East Anglia ended up slowly ceding their industrial base to Yorkshire. As Jones (2010, p.8) has pointed out, the failure of the English South to industrialize may seem surprising. More than anything else, they may have followed the rules of regional specialization as declining transportation costs and market integration overwhelmed the traditional aptitudes in woolen manufacturing in these areas. As Jones (2010, p. 66) observes, despite its relative decline, the Gloucestershire woolen industry was quite capable of mechanization.

At the end of the day, our research helps to restore the place of human capital in Britain's technological leadership. To see this, we need to shed modern habits of looking at human capital in "modern" terms of schooling and literacy, or even in terms of the social conditioning and drilling that educational institutions in this era instilled in their students. Instead, we should look at tacit skills, technical competence passed on from master to apprentice through informal personal contact. The great historian of the technology of the

Industrial Revolution, John R. Harris, realized this when he noted that "so much knowledge was breathed in by the workman with the sooty atmosphere in which he lived rather than ever consciously learnt" (Harris, 1992, p. 30). The same was true for Britain's millwrights, some of whom morphed into and trained a class of mechanical engineers in the nineteenth century. Their crucial role in the Industrial Revolution and thus in the Great Enrichment overall richly deserves our recognition.

9. References

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10. Appendices

Appendix A Robustness to Spatial Auto-Correlation

TableA1. Number of Draper Apprentices per Capita and Wright Apprentices per Capita
Robustness to Spatial Auto-Correlation

	No. of Draper Apprentices per Capita				
	(1)	(2)	(3)	(4)	(5)
Wrights (per capita)	0.43***	0.39***	0.40***	0.41***	0.43***
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)
Geographical controls	No	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes
Economic controls	No	No	No	No	Yes
Observations	325	325	325	325	325

Notes: This table establishes the positive and economically and statistically significant association of the number of wright apprentices per capita in a district on the number of draper apprentices per capita for the period 1710-1750, controlling for population size, the area of the district, its average distance from London, major eighteenth century harbors, historical Roman roads and navigable rivers, as well as geographical controls. Specifically, it uses Morna's I to calculate spatial autocrrelation, and shows that the results in table 2 are robust to this concern. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

TableA2. Draper Apprentices and Wright Apprentices: Placebo for Spatial Autocorrelation: Autocorrelated White Noise as a Dependent Variable

	Spatial auto-correlated white noise				
	(1)	(2)	(3)	(4)	(5)
Wrights (per capita)	0.00	0.00	0.00	0.00	0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Area		-0.00	0.00	0.00	-0.00
		(0.00)	(0.00)	(0.00)	(0.00)
Latitude		0.01	-0.02***	-0.02*	-0.03*
		(0.00)	(0.01)	(0.01)	(0.02)
Ruggedness (mean)		-0.01	-0.00	-0.00	-0.01
		(0.00)	(0.01)	(0.01)	(0.01)
Elevation (mean)		-0.00	-0.02*	-0.02**	-0.03**
		(0.01)	(0.01)	(0.01)	(0.01)
Agricultural			-0.06**	-0.04	-0.03
Suitability			(0.02)	(0.02)	(0.02)
Wheat suitability			-0.02**	-0.02	-0.00
			(0.01)	(0.01)	(0.01)
Grass Suitability			-0.03***	-0.04***	-0.04***
(mean)			(0.01)	(0.01)	(0.01)
Precipitation (mean)				0.02	0.02*
				(0.01)	(0.01)
Temperature (mean)				0.01	-0.02
				(0.01)	(0.01)
Dist. to Nearest					-0.00***
Harbor					(0.00)
Dist. from London					-0.00
					(0.00)
Dist to Nearest					0.00***
Roman Road					(0.00)
Distance to Nearest					0.05***
Navigable River					(0.02)
Adjusted-R^2	0.00	0.04	0.13	0.13	0.23
Observations	325	325	325	325	325

Notes: This table replicates Table 2, but as in Kelly (2019), we run our regression model, with autocorrelated white noise as our dependent variable. The Moran's I in this variable equals 0.075 with a z-score of 13.98. This index is higher than the one in our data (0.043 with a z-score of 8.344). The table suggests that spatial auto-correlation does not drive our results. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

TableA3. Draper Apprentices and Spatial Autocorrelated White Noise

	Number of Draper Apprentices per Capita				
	(1)	(2)	(3)	(4)	(5)
Autocorrelated white noise	-7.83	-2.38	-3.00	-4.10	-3.64
	(8.33)	(8.02)	(8.70)	(9.17)	(11.47)
Area		0.00*	0.00*	0.00*	0.00
		(0.00)	(0.00)	(0.00)	(0.00)
Latitude		-0.62	-0.80	-1.81	-6.21**
		(0.50)	(0.60)	(1.27)	(2.46)
Ruggedness (mean)		-0.00	0.43	0.22	-0.04
		(0.49)	(0.60)	(0.62)	(0.64)
Elevation (mean)		0.35	-0.32	-1.59	-0.86
		(0.80)	(1.03)	(1.17)	(1.30)
Agricultural			-0.23	2.07	2.07
Suitability			(2.23)	(1.98)	(2.09)
Wheat suitability			1.12	0.82	0.56
			(0.97)	(1.14)	(1.23)
Grass Suitability			-0.75	-1.38	-4.04***
(mean)			(0.83)	(0.97)	(1.24)
Precipitation (mean)				1.58	0.75
				(0.98)	(1.04)
Temperature (mean)				-0.97	0.69
				(1.60)	(1.75)
Dist. to Nearest					-0.03
Harbor					(0.03)
Dist. from London					0.05**
					(0.02)
Dist to Nearest					-0.08
Roman Road					(0.06)
Distance to Nearest					1.33
Navigable River					(2.45)
Adjusted-R^2	0.00	0.15	0.15	0.16	0.19
Observations	325	325	325	325	325

Notes: This table replicates Table 2, but uses spatial autocorrelated white noise as the main explanatory variable. The Moran's I in this variable is 0.075 with a z-score of 13.98. This index is higher than the one in our data for wrights per capita (0.053 and a z-score of 10.348). Ths table suggests that spatial autocorrelation does not drive our results. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Appendix B: Robustness to the availability of coal in the district

TableB1. Estimation of the relationship between drapers and wright 1710-50: controlling for the potential for of coal

	No. of Draper Apprentices per Capita								
	OLS	IV Watermills	IV Mill Suit.	OLS	IV Watermills	IV Mill Suit.	OLS	IV Watermills	IV Mill Suit.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wrights (per capita)	0.43***	0.60**	0.68*	0.40***	0.57**	0.70**	0.43***	0.56**	0.73**
	(0.14)	(0.28)	(0.37)	(0.13)	(0.28)	(0.33)	(0.13)	(0.25)	(0.30)
Carboniferous Strata	0.91	1.63**	1.10	-0.40	-0.59	-0.18	-0.87	-0.90	-0.84
	(0.62)	(0.77)	(0.94)	(0.94)	(1.06)	(1.01)	(1.17)	(1.24)	(1.29)
Ruggedness Suitability			-0.00			-0.01			-0.02
			(0.02)			(0.02)			(0.02)
Wheat suitability			-0.95	-0.23	-0.83	-1.01	0.00	-0.30	-0.47
			(0.71)	(1.06)	(1.05)	(0.94)	(1.07)	(1.06)	(0.97)
Geographical controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	No	No	No	No	No	No	Yes	Yes	Yes
First-stage F-statistic		30.99	12.18		20.61	13.40		23.75	14.73
Adjusted-R^2	0.27	0.24	0.18	0.35	0.34	0.25	0.41	0.41	0.31
Observations	325	307	325	325	307	325	325	307	325

Notes: This table establishes a robustness check that the results are not the consequece of having carbon in the district. It replicates the results obtained about draper apprentices oincluding a dummy variable, which indicates if the districts has a carboniferous layer in its soil. In particular, it establishes the statistically and economically positive effect of the number of wright apprentices in a district on the number of draper apprentices, controlling for population size, geographical and climatic controls (latitude, area, mean temperature, mean precipitation, mean ruggedness), the existence of carboniferous layer in the district, and the distance from main eighteenth century harbors, navigable rivers, historical Roman roads and The City of London. To mitigate endogeneity problems, the analysis uses the number of watermills (in columns (2), (5) and (8)) as reported in Domesday Book (1086) as an IV for the number of smith apprentices per capita, and the geographical suitability for constructing grinding mills (in columns (3), (6) and (9). Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Appendix C: Robustness to the choice of occupations

TableC1. Estimation of the relationship between weavers and wright 1710-50

	No. of Weaver Apprentices per Capita								
	OLS	IV	IV	OLS	IV	IV	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wrights (per capita)	1.73***	2.18***	0.98*	1.71***	2.29***	1.06**	1.65***	2.34***	1.45**
	(0.44)	(0.26)	(0.51)	(0.40)	(0.21)	(0.53)	(0.31)	(0.25)	(0.61)
Ruggedness Suitability			0.06***			0.08**			0.07**
			(0.02)			(0.03)			(0.03)
Wheat suitability			3.70	6.63	5.27	8.17	4.15	3.52	4.82
			(4.03)	(6.64)	(6.91)	(7.07)	(4.44)	(4.41)	(4.00)
Geographical controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	No	No	No	No	No	No	Yes	Yes	Yes
First-stage F-statistic		31.08	12.08		20.55	13.69		23.59	15.04
Adjusted-R^2	0.14	0.13	0.13	0.13	0.11	0.13	0.15	0.13	0.16
Observations	325	307	325	325	307	325	325	307	325

Notes: This table replicates the results obtained about draper apprentices, but this time on weaver apprentices. In particular, it establishes the statistically and economically positive effect of the number of wright apprentices in a district on the number of weaver apprentices, controlling for population size, geographical and climatic controls (latitude, area, mean temperature, mean precipitation, mean ruggedness) and the distance from main eighteenth century harbors, navigable rivers, historical Roman roads and The City of London. To mitigate endogeneity problems, the analysis uses the number of watermills (in columns (2), (5) and (8)) as reported in Domesday Book (1086) as an IV for the number of smith apprentices per capita, and the geographical suitability for constructing grinding mills (in columns (3), (6) and (9). Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

TableC2. Estimation of the relationship between blacksmiths and wright 1710-50

	No. of Blacksmith Apprentices per Capita								
	OLS	IV	IV	OLS	IV	IV	OLS	IV	IV
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wrights (per capita)	1.08***	1.29***	0.84***	1.04***	1.30***	0.88***	1.04***	1.31***	0.89***
	(0.08)	(0.09)	(0.16)	(0.09)	(0.09)	(0.14)	(0.09)	(0.08)	(0.14)
Ruggedness Suitability			0.05***			0.05***			0.05***
			(0.01)			(0.01)			(0.01)
Wheat suitability			-0.46	0.18	-0.48	0.49	0.20	0.03	0.68
			(0.41)	(0.72)	(0.79)	(0.62)	(0.89)	(0.87)	(0.68)
Geographical controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	No	No	No	No	No	No	Yes	Yes	Yes
First-stage F-statistic		31.08	12.08		20.55	13.69		23.59	15.04
Adjusted-R^2	0.66	0.62	0.73	0.69	0.64	0.74	0.69	0.64	0.73
Observations	325	307	325	325	307	325	325	307	325

Notes: This table replicates the results obtained about smith apprentices, but this time on blacksmilh apprentices. In particular, it establishes the statistically and economically positive effect of the number of wright apprentices in a district on the number of blacksmith apprentices, controlling for population size, geographical and climatic controls (latitude, area, mean temperature, mean precipitation, mean ruggedness) and the distance from main eighteenth century harbors, navigable rivers, historic Roman roads and The City of London. To mitigate endogeneity problems, the analysis uses the number of watermills (in columns (2), (5) and (8)) as reported in Domesday Book (1086) as an IV for the number of smith apprentices per capita, and the geographical suitability for constructing grinding mills (in columns (3), (6) and (9). Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Appendix D: Robustness to Other Specifications of the Instrument Variable

TableD1. IV estimation of the relationship between drapers and wright 1710-50: for different levels of ruggedness

	No. of Draper Apprentices per capita							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	(2-3)	(0-1)	(2-4)	(2-5)	(1-3)	(1-4)	(1-5)	(7-20)
Wrights (per capita)	0.73**	0.80**	0.77***	0.79***	0.77**	0.78**	0.79**	0.93***
	(0.30)	(0.33)	(0.30)	(0.29)	(0.33)	(0.32)	(0.31)	(0.21)
Wheat suitability	-0.42	-0.42	-0.48	-0.51	-0.40	-0.44	-0.46	-0.87
	(0.98)	(0.99)	(1.00)	(1.00)	(0.98)	(0.99)	(0.99)	(1.12)
Ruggedness Suitability (2-3)	-0.01							
	(0.02)							
Ruggedness Suitability (0-1)		-0.00						
		(0.00)						
Ruggedness Suitability (2-4)			-0.01					
			(0.01)					
Ruggedness Suitability (2-5)				-0.01				
				(0.01)				
Ruggedness Suitability (1-3)					-0.01			
					(0.01)			
Ruggedness Suitability (1-4)						-0.00		
						(0.01)		
Ruggedness Suitability (1-5)							-0.00	
							(0.00)	
Ruggedness Suitability (7-20)								-0.01
								(0.01)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	15.04	7.76	14.84	15.32	13.36	14.56	15.34	15.11
Adjusted-R^2	0.31	0.25	0.28	0.27	0.29	0.27	0.27	0.12
Observations	325	325	325	325	325	325	325	325

Notes: This table establishes the robustness of our instrument. In particular, it replicates the last column of Tsble 6 with different levels of ruggedness that fit the establishment of plants using water power. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

TableD2. IV estimation of the relationship between drapers and wright 1710-50: for different levels of wheat suitability

	No. of Draper Apprentices per capita							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Share of Land Highly Suitable for Wheat Growing	(0.75)	(0.1)	(0.25)	(0.4)	(0.5)	(0.6)	(0.8)	(0.9)
Wrights (per capita)	0.73**	-0.20	1.16**	0.90**	1.03**	0.96***	0.76**	0.83**
	(0.30)	(1.87)	(0.51)	(0.35)	(0.40)	(0.34)	(0.31)	(0.32)
Ruggedness Suitability	-0.01	0.05	-0.04	-0.03	-0.03*	-0.03*	-0.02	-0.02
	(0.02)	(0.13)	(0.04)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Wheat suitability (0.75)	-0.42							
	(0.98)							
Wheat suitability (0.1)		-1.81						
		(2.01)						
Wheat suitability (0.25)			0.32					
			(1.57)					
Wheat suitability (0.4)				-1.13				
				(1.18)				
Wheat suitability (0.5)					-0.38			
					(0.99)			
Wheat suitability (0.6)						0.71		
						(0.69)		
Wheat suitability (0.8)							-0.17	
							(0.91)	
Wheat suitability (0.9)								-0.04
								(1.00)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	15.04	1.16	6.93	12.84	10.08	12.23	14.29	12.40
Adjusted-R^2	0.31	0.11	-0.09	0.19	0.07	0.14	0.30	0.25
Observations	325	325	325	325	325	325	325	325

Notes: This table establishes the robustness of our instrument. In particular, it replicates the last column of Tsble 6 with different levels of wheat suitability in the district. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

Appendix E: The Effect of London

TableE1 Estimation of the relationship between drapers and wright 1710-50:

Using different levels of ruggedness

	No. of Draper Apprentices per Capita								
	OLS	IV Watermills	IV Mill Suit.	OLS	IV Watermills	IV Mill Suit.	OLS	IV Watermills	IV Mill Suit.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wrights (per capita)	0.43***	0.60**	0.66*	0.40***	0.58**	0.70**	0.42***	0.57**	0.73**
	(0.14)	(0.27)	(0.36)	(0.13)	(0.29)	(0.33)	(0.12)	(0.25)	(0.30)
Ruggedness Suitability			-0.00			-0.01			-0.01
			(0.02)			(0.02)			(0.02)
Wheat suitability			-1.14	-0.25	-0.85	-1.02	-0.01	-0.31	-0.47
			(0.80)	(1.07)	(1.06)	(0.95)	(1.08)	(1.06)	(0.98)
Geographical controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	No	No	No	No	No	No	Yes	Yes	Yes
First-stage F-statistic		31.16	12.01		20.45	13.57		23.43	14.94
Adjusted-R^2	0.27	0.24	0.19	0.35	0.34	0.25	0.41	0.41	0.32
Observations	324	306	324	324	306	324	324	306	324

Notes: This table establishes a robustness check that the results do not depend on London as a commercial center of eighteenth century England. It replicates the results obtained about draper apprentices omitting The City of London from the sample. In particular, it establishes the statistically and economically positive effect of the number of wright apprentices in a district on the number of draper apprentices, controlling for population size, geographical and climatic controls (latitude, area, mean temperature, mean precipitation, mean ruggedness) and the distance from main eighteenth century harbors, navigable rivers, historical Roman roads and The City of London. To mitigate endogeneity problems, the analysis uses the number of watermills (in columns (2), (5) and (8)) as reported in Domesday Book (1086) as an IV for the number of smith apprentices per capita, and the geographical suitability for constructing grinding mills (in columns (3), (6) and (9). Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.

TableE2. Estimation of the relationship between smiths and wright 1710-50: Excluding London

	No. of Smith Apprentices per Capita								
	OLS	IV Watermills	IV Mill Suit.	OLS	IV Watermills	IV Mill Suit.	OLS	IV Watermills	IV Mill Suit.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wrights (per capita)	0.41***	0.52***	0.34*	0.39***	0.52***	0.36*	0.39***	0.52***	0.36**
	(0.07)	(0.10)	(0.18)	(0.06)	(0.10)	(0.19)	(0.06)	(0.10)	(0.18)
Ruggedness Suitability			0.02**			0.02			0.02
			(0.01)			(0.01)			(0.01)
Wheat suitability			-0.37	0.38	0.10	0.41	0.43	0.23	0.45
			(0.47)	(0.41)	(0.37)	(0.46)	(0.41)	(0.35)	(0.35)
Geographical controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Economic controls	No	No	No	No	No	No	Yes	Yes	Yes
First-stage F-statistic		31.16	12.01		20.45	13.57		24.89	15.17
Adjusted-R^2	0.57	0.52	0.67	0.62	0.55	0.67	0.62	0.55	0.67
Observations	324	306	324	324	306	324	324	306	324

Notes: This table establishes a robustness check that the results do not depend on London as a commercial center of eighteenth century England. It replicates the results obtained about smith apprentices omitting The City of London from the sample. In particular, it establishes the statistically and economically positive effect of the number of wright apprentices in a district on the number of smith apprentices, controlling for population size, geographical and climatic controls (latitude, area, mean temperature, mean precipitation, mean ruggedness) and the distance from main eighteenth century harbors, navigable rivers, historical Roman roads and The City of London. To mitigate endogeneity problems, the analysis uses the number of watermills (in columns (2), (5) and (8)) as reported in Domesday Book (1086) as an IV for the number of smith apprentices per capita, and the suitability for constructing grinding mills (in columns (3), (6) and (9). Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests; All regressions include a constant.