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THE WHEELS OF CHANGE: TECHNOLOGY ADOPTION, MILLWRIGHTS AND THE PERSISTENCE IN BRITAIN'S INDUSTRIALISATION*

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This paper examines the effect of the early adoption of technology on the evolution of human capital and industrialisation. We argue that mechanical skills and competence were a main determinant of the location of industry on the eve of the Industrial Revolution. It concentrates on the case of millwrights, eighteenth-century specialists in advanced carpentry and hydraulic machinery. Millwrights were a key part of the upper tail of the distribution of mechanical abilities. Their emergence was determined by the early adoption of watermills in the Middle Ages as recorded in the Domesday Book survey (1086). Their location displays considerable persistence.

The key role of human capital in the process of innovation and economic growth has been emphasised by economists for more than half a century and has since become a central component in many growth-theory studies (e.g., Lucas, 1988; Galor and Weil, 1999; 2000; Acemoglu, 2003; Galor, 2011). Our paper follows recent studies that suggest modifications to our thinking about the role of human capital during the British Industrial Revolution. This new approach argues, in brief, that in the early stages of industrialisation technical competence mattered much more than schooling and literacy. The key factor in this view was the supply of upper-tail artisanal human capital: the manufacturing and maintenance of relatively sophisticated devices using high-quality materials required top-quality mechanical competence (Mokyr, 2009; Kelly *et al.*, 2014; 2020; 2021). The paper focuses on a particular group of highly skilled mechanical craftsmen known as *wrights*, to demonstrate the important role played by the supply of such top-quality artisans in the first half of the eighteenth century and points to the roots of their formation in the medieval economy. These were highly skilled carpenters and engineers specialised in the planning, construction, improvement and maintenance of water-powered machinery. We can think of them as the engineers of the pre-industrial era.

The evidence that British craftsmen as a whole were of superior quality during the Industrial Revolution has been presented elsewhere (Kelly *et al.*, 2014; 2020; 2021), but until recently

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its causes and historical roots have been little explored. There are a number of complementary hypotheses explaining the superior quality of British artisans. One focuses on the flexibility and effectiveness of the institutions that supported apprenticeship and the supply of high-skill labour in Britain (Mokyr, 2019).[1] A second view sees certain specific features of British geography as facilitating the demand for skills and focusing devices (Mokyr, 2009, pp.114–15). A third explanation, and one we will propose here, is the persistence and heritage of the medieval English economy, which was technically more advanced and sophisticated than is commonly believed.

Our hypothesis is that the formation of human capital was a persistent process driven by the choice of initial production technologies determined by geographical factors. Once in place, skilled artisans produced not only sophisticated devices, but also produced more artisans. The growth of water mills in the early Middle Ages had unintended long-run consequences. In the case of England, the demand for workers with high mechanical skills originated from the adoption of water-powered mills for grain grinding. The growth of these mills led to the rise of a group of millwrights specialised in advanced carpentry and hydraulic machinery.

We argue that the wrights' growing competence in the construction, maintenance and improvement of the machinery generated an advantage for the adoption of complementary water-powered machinery in other industrial uses (e.g., fulling mills in textile, blowing mills in tin smelting, water-raising mills in mines, and forging mills in ironworks) in the same locations where possible. This symbiotic relationship was most pronounced in the textile sector in which fulling mills were widely adopted by the beginning of the fourteenth century. The industry shifted its location in the thirteenth and fourteenth centuries from the urban centres of the Eastern plains to the hilly northern and western rural districts (Carus-Wilson, 1941; Lucas, 2005). In the following centuries, the number of wrights continued to grow hand-in-hand with the technological changes that were taking place and the expanding use of machinery (Feldman and Van der Beek, 2016).

This process continued at least until late in the eighteenth century when the steam engine began to replace the waterwheel as a source of energy. Engineers—a profession that in part grew out of the skilled millwrights of the pre-Industrial Revolution era—became the newly demanded skill and became one of the key parts of the upper tail of the skill distribution and thus one of the main drivers of the Industrial Revolution (Musson and Robinson, 1960; MacLeod and Nuvolari, 2009; De Pleijt *et al.*, 2020; Hanlon, 2020). Thus, the adoption of grinding mills was important as a source of motive energy, as a stimulus to skill accumulation that spilled over to other industries and as a focusing device for more innovation.

To test our hypothesis of the central role that the skills and technical competence of England's millwrights played in its technological evolution, we use district-level data on England's government area districts, containing information from various sources. Mainly, we use the *Apprentice Tax Registers* to proxy for the numbers of *wrights* in every district, by employing the number of apprentices to masters in the relevant occupations in the decades before the onset of the Industrial Revolution (1710–50).[2] To measure the extent of textile manufacturing in the district, we use

[1] The agility and effectiveness of England's apprenticeship system (notwithstanding the 1562 law) was one of the underlying causes that explain Britain's advantage in terms of high-skilled mechanics (Ben Zeev *et al.*, 2017; De la Croix *et al.*, 2018; Kelly *et al.*, 2020). Here we zoom in on one particular occupation that played an important role in the creation of these skills.

[2] Board of Stamps (n.d.) *Apprenticeship Books*, Series IR 1.

the number of apprentices to masters in the categories of *drapers* and/or *clothiers*, who had a pivotal role in the organisation of cloth manufacturing during the first half of the eighteenth century.

Our exogenous source of variation for the availability of wrights in a district is based on the listings of mills in the early Middle Ages as registered in the Domesday Book (henceforth DB) in 1086.[3] By 1700 the supply and demand side for waterpower had changed sufficiently to make the 1086 mills plausibly exogenous. Thus, we can identify the districts in which the number of wrights grew in response to the adoption of grinding mills before the introduction of industrial mills, and thus overcome the simultaneity of the numbers of wrights and mills in the eighteenth century. The obvious objection to this procedure is that geographical suitability of sites for watermills (a time invariant feature) drove their location, and that the same conditions explain the prevalence of millwrights six centuries later. To isolate non-geographical factors such as millwright skills we introduce a large number of geographical controls as well as a number of other econometric procedures to ensure that physical geography and similar variables such as population size and distance to London do not create a spurious statistical relation. All these corrections hardly affect the correlation between the location of DB mills in 1086 and the prevalence of millwrights in the eighteenth century. Something else besides geography must have been at play here.

Furthermore, we test the robustness of our results by taking advantage of two historical events. One is the Black Death, which devastated England to rather different degrees, and hence led to the abandonment of some mills that had existed in 1086. Consistent with our hypothesis, only a few of those mills came back, indicating that the topographical environment did not wholly drive their location. A closer look at one county (Hampshire) confirms this finding. We also utilise the location of worsted producers. Worsted relied on combed rather than carded wool and, unlike wool, rarely depended on water mills as worsted cloth did not require fulling. We show that in the first half of the eighteenth century, worsted production was not located where mills were. However, worsteds were easier to adapt to the new spinning technologies developed for cotton than for wool. Hence, in the second half of the eighteenth century worsted producers switched to locations where DB mills were located. Worsteds did not use these mills much, but needed increasingly complex machinery (some of it waterpowered). This suggests that the presence of wrights and their skills is what in part drove this relocation.

Our results provide empirical evidence for a strong and persistent capital skill complementarity between the location of DB mills and the spatial distribution of wrights across England more than 600 years later. Controlling for a wide range of geographic, climatic and agricultural variables, we show that one additional mill per ten thousand people in a district in 1086 is associated with an average increase of 0.14 wright apprentices per 10,000 people in 1710–50. To address the concern that the estimators we obtain may be biased due to some omitted unobservable geographical characteristic of the sites where mills were located in the early Middle Ages, we also estimate the regressions instrumenting DB mills with a geographical IV capturing the suitability of a site to constructing grinding rather than industrial mills.

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

We then proceed to provide evidence for the role of wrights in the process of early industrialisation. We show that the existence of DB mills in a district predicts the spatial distribution of the textile and iron-making industries on the eve of the British Industrial Revolution. These industries adopted a growing numbers of water-powered machines since the late thirteenth century. In contrast, the spatial distribution of other industries, which did not adopt such machinery, cannot be explained by the existence of DB mills. Again, in these placebo regressions we use a considerable number of geographical controls and other tests to reduce the concern for spurious correlation. To reinforce this finding, we conduct a horserace between the density of mills and wrights in the entire Domesday sample that indicates that the mills alone are much less important once wrights are taken into account. Moreover, to further rule out the 'pure' effect of topography, we perform a mediation analysis that directly separates the geographical elements from other sources of persistence. This analysis suggests that wrights are responsible for 30%–70% of the total effect of mills on industrialisation. We also test whether the results could be biased due to unobservables, and the standard procedures we employ suggest that such a bias is small.

Our paper does not purport to explain directly the location of the Industrial Revolution as its main dependent variable pertains to the period 1710–50, whereas the standard accounts place the Industrial Revolution in the second half of the eighteenth century. By highlighting the importance of artisanal skills, however, it sheds light on a central factor in the Industrial Revolution that has hitherto not received sufficient attention, which is the superiority of Britain in mechanical competence, its significance and its historical origins (Kelly *et al.*, 2020; Mokyr, 2021).

In what follows, we briefly survey the related literature in Section 1 and provide the historical background in Section 2. Section 3 describes our data. In Section 4, the heart of our paper, we present our main results, followed by robustness tests in Section 5. Section 6 concludes. The tables supporting the robustness tests and a more detailed historical background are provided in the appendices.

1. Related Literature

This paper relates to the wide-ranging empirical literature concerned with the role of human capital in economic growth. There is still controversy surrounding empirical evidence for the positive effect of schooling measures as a proxy for human capital and its subsequent effect on economic performance. There is even more room for scepticism in the context of Britain's industrialisation (Mitch, 1992; Crafts, 1996; Allen, 2003; Clark, 2005). Since the seminal work of David Mitch (1999), showing that schooling and literacy in Britain were not exceptionally favourable, more studies have focused on schooling and literacy rates and reached similar conclusions as to the role of traditional human capital, e.g., Lindert (2004).

This paper focuses on artisanal mechanical skills, rather than on formal schooling, and connects to a growing literature that places artisans at centre stage in explaining the Industrial Revolution (Harris, 1992; Berg, 1994; 2007; Kelly *et al.*, 2020). In recent years, the emergence and dissemination of technological change has been linked directly to the presence of upper-tail human capital and the useful knowledge of an artisanal or intellectual elite (Mokyr, 2009, pp.121–2;

Kelly *et al.*, 2014; Hanlon, 2020).[4] It is also related to the large (and growing) literature on the role of persistence in economic and social phenomena (for a survey, see Voth, 2021). This literature has pointed to a considerable number of cultural and institutional features of pre-modern societies that explain variations in later generations.

Our study is concerned with the effects of geography on industrialisation, highlighted by many scholars and specifically the central role of coal. Unlike most studies of the location of mechanised factories that look at coal field location, we examine the location of manufacturing prior to the application of steam power. We show that coal did not matter to the location of textile manufacturing (which required motive power rather than heat) before the Industrial Revolution (Online Appendix D). A possible explanation for the subsequent shift of textile manufacturing to areas close to coalfields is that collieries were also a source of high-skill labour.[5] Another explanation offered by Sugden *et al.* (2018) is the lower cost of living due to cheaper coal for heating in the late seventeenth century (see also Crafts and Wolf, 2014).

2. Mills and Skills

Mechanical engineering was one of the unsung heroes of the Industrial Revolution. Most scholars writing about the origins of engineering during the Industrial Revolution have recognised that 'millwrights can be considered the most direct ancestors of professional engineers' (MacLeod and Nuvolari, 2009, p.229; see also Musson and Robinson, 1960; Hanlon, 2020). The upper tail of the distribution of wrights on the eve of the Industrial Revolution included some of the finest artisans found anywhere in Europe at that time and the most distinguished of them have found their way into modern accounts of the Industrial Revolution and compilations such as the *Oxford Dictionary of National Biography*. 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.[6] As we show in Online Appendix G, many of the major inventors of the Industrial Revolution were trained by master millwrights.

Millwrights in the medieval and early modern era may not have been sophisticated 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, a familiarity with the properties of timber and iron, and some informal, but workable, notions of force and velocity (even if they used a different vocabulary). Through their apprentices, this knowledge was

[4] 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. Squicciarini and Voigtländer (2015) examined the density of subscribers to the famous Encyclopédie in mid-eighteenth-century France, and have shown it is a strong predictor of city growth after the onset of French industrialisation. Boerner and Severgnini (2019) show that the early adoption of clocks can explain variations in growth rates among European cities between 1500 and 1700.

[5] In this regard watermills and coal mines are similar in that they provided a focusing device and thus a major source of innovation and skilled engineers who played major roles in generating a host of inventions that spilled over to other sectors, not least the steam engine itself (Kelly *et al.*, 2021).

[6] Some of the best-known civil engineers of the Industrial Revolution originally apprenticed as millwrights. Two famous examples were James Brindley, the great builder of canals during the early canal era after 1750, and John Rennie, the co-inventor of the path-breaking breast-wheel water mill (with John Smeaton) and the designer of the first steam-driven flour mills, as well as Waterloo and Southwark bridges in London.

passed on from generation to generation. Moreover, medieval millwrights were flexible enough to adapt to new demands on their competence as windmills were introduced besides water mills, and vertical wheels replaced horizontal ones.

In the pre-Industrial Revolution years, millwrights were much like building contractors today. They negotiated with the client, designed the mill, secured the workmen and materials employed to build it and supervised the construction (Langdon, 2004, p.252). The perception of the millwright as an all-round technically competent craftsman remained paramount during the Industrial Revolution. The nineteenth century 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’ (Fairbairn, 1861, p.v). Textile engineering installations categorised their equipment as either ‘millwright’s work’ or ‘clockmaker’s work’ and these concepts ‘were soon enshrined in insurance policies’ (Cookson, 2018, p.68). The exact meaning of the term ‘millwright’ evolved, 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.

The Industrial Revolution changed millwrights’ roles in the industrialising regions, and the profession morphed into something that today would be called mechanical engineering (MacLeod and Nuvolari, 2009). Engineers were a critical component of innovation in the Industrial Revolution and accounted for a large proportion of patents (Hanlon, 2020). More details on the transition from ‘millwright’ to ‘engineer’ are provided in Online Appendix G, which contains a more detailed historical background.

2.1. *Mills, Wrights and the Location of the Textile Industry*

An early manifestation of the persistent effect of the location of medieval watermills for grinding was in the late thirteenth century, when the location of textile manufacturing shifted from the urban centres of the eastern plains to the hilly northern and western countryside (Carus-Wilson, 1941; Pelham, 1944). Carus-Wilson famously argued that the new locations were determined by their suitability for the newly adopted water-powered fulling mills.[7] The locations identified by Carus-Wilson and Pelham persisted well into the fifteenth century and remained England’s main textile manufacturing centres until the eighteenth century, as can be observed in the maps provided by Darby (1973).[8] The main pulling forces of these locations were both the availability of a physical environment and topography suitable for mill construction and the presence of workmen specialised in the construction and in the inner workings of mills, elements which constituted an important advantage for setting up a cloth manufacturing centre based on mechanical fulling.

The complementarity between the technologies of the grain-grinding mills and the other industrial mills was obviously high, as the latter evolved from the former. The set-up of the water control system, depending on the type of mill, and the waterwheel were similar, and the inner

[7] Worsted manufacturing, which did not require fulling, widely diffused to West Riding later, by 1700–20 (Clapham, 1907, p.71; Darby, 1973, pp.90–1).

[8] Darby (1973) provides a map of the cloth industry circa 1500 in figure 49 (p.224) and for 1720 in figure 77 (p.359).

workings of the two machines were based on the same mechanical principles.[9] Whether the mills were used for grinding, fulling or for other industrial uses, their construction was carried out by the same artisans. Millwrights were a major force behind machinery improvement centuries earlier.[10]

In the closing decades of the Middle Ages the mechanical principles of watermills were increasingly adopted to other industrial uses besides fulling, such as forging mills in iron making, tin mills for crushing tin-ore, blowing mills for smelting, tanning mills in leatherworking, 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% between the years 1300 and 1540 (Langdon, 2004, p.41, fig. 2.8). Their share of the total number of mills increased as well and represented almost a quarter of the mills by the end of the fifteenth century (Langdon, 2004, pp.43–4). The connection of millwrights' skills to industrial mills must have run 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 were traditionally the preserve of the millwright (Cookson, 1994, p.19).

A drive towards mechanisation in textile manufacturing in the early eighteenth century characterised the entire textile industry.[11] By the eighteenth century, millwrights were hired to build early factories (known, of course, as 'mills'). Cookson stresses that cases in which millwrights constructed the textile equipment from top to bottom were rather unusual and that other skilled artisans were equally likely to have been 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). Where millwrights may have been more important is as technical consultants to entrepreneurs or in selling some textile machinery to the rapidly evolving new mills (Tann, 1974, pp.82, 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.[12] For more historical details on the role of millwrights in engineering the Industrial Revolution, see Online Appendix G.

3. Description of the Data

Our empirical analysis is based on a cross-sectional dataset on 325 of England's government area districts between 1710 and 1750.[13] The dataset contains historical information about occupations,

[9] Most medieval mills worked from cams or wooden projections set into the mill axle, which 'tripped' various devices, such as vertical stamps, horizontal hammers, bellows and saws (Langdon, 2004, p.98). The different types of mills were, for instance, leat mills, wear-and-leat mills and millpond mills.

[10] Such was the case with the fulling mill, which, according to John Luccock, a woolstapler who wrote about England's woollen industry in 1805 (Luccock, 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 œconomy in the use of time and labor which augurs well for the interest of the manufacture.'

[11] 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 elaborated 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, 2002, p.643).

[12] 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).

[13] We restrict our research to England. There are 326 districts, however, due to missing data on population in the Isles of Scilly in the HYDE project, we are left with 325 districts.

Table 1. *Summary Statistics.*

Variable	Mean	SD	Min.	Max.	N
Watermills (per capita)	18.922	48.382	0	412.601	298
Wrights (per capita)	3.76	9.121	0	85.926	325
Drapers (per capita)	2.809	7.534	0	58.264	325
Weaver (per capita)	9.441	40.624	0	645.552	325
Smith (per capita)	1.853	5.007	0	48.167	325
Blacksmith (per capita)	5.336	12.093	0	93.546	325
Longitude	461.164	85.217	199.192	647.806	325
Latitude	265.819	124.544	54.276	594.137	325
Ruggedness (mean)	2.876	1.609	0.527	9.856	325
Elevation (mean)	0.825	0.62	0.016	3.563	325
Agricultural suitability	0.756	0.205	0.112	0.981	325
Pasture suitability (mean)	7.727	0.6	6.267	9.947	325
Precipitation (mean)	0.592	0.136	0.408	1.176	325
Temperature (mean)	9.700	0.691	7.547	11.104	325
Minimal distance to a Roman road	0.016	0.044	0	0.352	325
Minimal distance to a navigable river	0.009	0.098	0	1.54	325
Minimal distance to an important harbour	0.504	0.371	0	1.629	325
Distance to London	0.141	0.105	0	0.406	325
Area	0.409	0.560	0.003	5.078	325
Population (mean) 1710–50	7.696	12.958	0.107	67.493	325
Population (mean) 1750–1800	101.952	172.674	1.448	872.631	325
Population change	−2.812	2.488	−11.476	3.451	325
Population (1086)	0.86	1.194	0	9.390	298
Worsted weavers 1710–50	2.315	24.424	0	419.768	325
Worsted weavers 1750–1800	3.651	33.538	0	563.981	325
Woollen weavers 1700–50	6.478	17.472	0	225.784	325
Woollen weavers 1750–1800	7.111	23.999	0	247.885	325
Textile usage of engines	0.809	4.365	0	57	325
Carboniferous strata	0.342	0.475	0	1	325
Non-fulling district	0.138	0.346	0	1	325
Lord's share of arable land	0.238	0.114	0	0.818	298
King's Vill share	0.095	0.156	0	1	298
Ecclesiastical Vill share	0.14	0.161	0	1	298

Notes: King's vill: share of royal holdings of land.

geographical features and production factors in 10,201 locations gathered from various sources, geolocated in the districts. The sources and construction of our main variables is described in detail in Online Appendix H. A brief list of the data used is provided below and Table 1 presents summary statistics for all the variables in our dataset.

3.1. *Occupational variables*

To approximate the size of various skilled occupational groups as well as of industrial sectors in England during the first half of the eighteenth century (1710–50), we make use of the information included in the Apprenticeship Stamp Tax registers. This approximation relies on the assumption that most skilled occupations in Britain required some form of apprenticeship that involved a formal contract. The entries in these 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. They begin in 1710, following the introduction of a stamp duty payment on apprenticeship contracts (such that indentures were void without the stamp), and contain information on the masters' trade, location, and on the premium paid. The location of masters (where the apprenticeship took place) was matched to locations as they appear in TownsList (https://www.townslist.co.uk), the most comprehensive database of locations of cities, towns, and villages in the United Kingdom. Apprentices were found in 10,201 of the 36,144 English locations in the TownsList and in all the other places their number was set to zero. The number of apprentices in each occupation was then aggregated to the district level and divided by the average population in the district during the same period (1710–50) in per capita (per 10,000) terms. To measure the extent of textile manufacturing in the district, we used the number of apprentices to masters we refer to here as *drapers*. This occupational category is composed of 4,359 people apprenticed to masters in the categories of drapers and/or *clothiers*, who had a pivotal role in the organisation of cloth manufacturing during the first half of the eighteenth century. We also use the number of apprentices to master *weavers* as an alternative proxy, to avoid biases that may arise from changes in the organisation of textile manufacturing in the second half of the century (see Online Appendix H). To proxy for the districts' level of high-skill artisanal human capital, we use the number of apprentices to masters we refer to as *wrights*. Our definition of wrights consists mainly of apprentices to millwrights, wheelwrights, or simply, 'wrights'. Millwrights were engaged in the heavy mechanisms of the mill, the fulling stocks, the water wheels, and the transition gears. Wheelwrights, whose skills were ranked below those of millwrights, were nevertheless highly involved in the making of textile machinery, e.g., spinning wheels and other machines (Cookson, 2018, p.30). They also appear as part of the trades connected with cotton manufacture in Lancashire in the population returns for 1831 (Baines, 1835, p.424).

3.2. *Domesday mills*

The famous medieval survey known as the Domesday Book, commissioned by William the Conqueror, contains data on the location of mills in 1086. The survey documented all the landholdings and resources in England: plough teams including arable land, woodland, meadows, farmers (different types of legal statutes) and mills (about 5,600 mills in more than 3,000 locations). We use this source mainly to gather evidence on the location of watermills which were used for grain grinding at the time. The survey covers England with the exception of the cities of London, Winchester, Bristol and Tamworth and the coverage of the northwest is limited: the counties of Durham and Northumberland are omitted, and the coverage of Cumberland, Westmorland and Lancashire is partial. Thus, using the Domesday mills in our analysis limits us to 298 districts. The survey simply refers to water-powered mills as 'mills', most of which were used for grain grinding.

3.3. *Geographic controls*

We use a large number of geographic and demographic controls, including topographical characteristics to measure suitability for water mills, suitability for wheat (ground in flour mills), latitude, distance from ports, Roman roads and London, as well as population estimates in 1086, 1700 and 1750. The data rely on a variety of sources, detailed in Online Appendix A. Among them are estimates for potential wheat yield (measured in tonnes, per hectare, per year), for each of 5 arc minutes by 5 arc minutes degrees (i.e., about 100 square km) cell provided by the Global-Agro-Ecological Zones (GAEZ) of the Food and Agriculture Organization (FAO). We also rely on the Terrain Ruggedness Index (TRI), a quantitative measurement of terrain heterogeneity devised by Riley *et al.* (1999) to express the elevation difference between adjacent cells of a digital elevation grid.

4. Empirical Analysis

Our analysis is divided into two parts. We begin by examining, in Subsection 4.1, the persistent association between early medieval flour mills and the distribution of wrights in the eighteenth century through capital–skill complementarity. In this manner we establish that, once we control for geographical factors, an old tradition of skilled wrights led to the concentration of textiles and iron in areas where such skills could be found. While there is anecdotal evidence to support this notion, ours is the first to provide systematic evidence for the hypothesis.[14] We then proceed in Subsection 4.2 to substantiate the significance of the role played by wrights in early industrialisation.

4.1. *The Persistence of Skills*

The benchmark regression in this part of the analysis is as follows:

$$w_i = \beta mills_i + \boldsymbol{X}'\gamma + \varepsilon_i, \tag{1}$$

where w_i is the number of wright apprentices per capita in district i, $Mills_i$ is the number of Domesday mills per capita, the matrix X contains our control variables (i.e., a set of geographical, institutional and economic characteristics of the district), and ε_i is the district-specific error term. Our coefficient of interest, β, represents the correlation between early medieval grinding mills and the supply of wrights 600 years later in the early eighteenth century. To mitigate any concern that dependence between districts within 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).

4.1.1. *Identification strategy*

Given that the watermills in the analysis were constructed (at least) 600 years before the existence of the wright apprentices on the left-hand side of the regression, there is no concern for simultaneity between the two. We use a wide set of geographical control variables in order to isolate the non-geographical effect of mills on spatial persistence. The relationship may, however, still be spurious due to the possibility of omitted unobservable variables (institutional, geographical, economic and human characteristics). The size of the population does not pose a problem: Table A.1 in the Online Appendix shows that the correlation between the population of 1086 and that of 1710–50 is weakly negatively correlated. Hence, even if there were some conditions that were conducive to population growth in early Middle Ages, they did not affect population size 600 years later. We also normalise both the number of Domesday mills and the number of wrights

[14] The eighteenth-century engineer and scientist John T. Desaguliers pointed out that although Thomas Newcomen was originally working in Cornwall, he could not get his atmospheric machine to work in the mines there until ‘being near Birmingham, and having the assistance of so many admirable and ingenious workmen, they came, about 1712, to the method of making the pump valves, clacks, and buckets, whereas they had but an imperfect notion of them before’ (Desaguliers, 1744, p.533).

to per capita terms, based on the mean district population in the years 1710–50.[15] Yet to exclude the possibility that the location of Domesday mills was biased by some omitted unobservable characteristic, we construct a geographical instrument that captures the suitability of a district for the construction of grain grinding watermills in the Middle Ages.

4.1.2. *Results*

Table 2 presents the results of ordinary least squares (OLS) regressions between the number of Domesday mills per capita and the number of apprentices to wrights in 1710–50 (per capita). As established in column (1), the unconditional correlation between the two is positive and economically and statistically significant at the 1% level, suggesting that one more mill per capita in a district in 1086 was associated with an increase of 0.15 wright apprentices in the same district in the early eighteenth century. Nevertheless, it seems logical to object that this correlation is spurious and reflects no more than the simple fact that geographical suitability to waterpower determined the location of water mills in the eleventh century and their location in the eighteenth century, and that millwright apprentices located to where the mills were.

We therefore control for a full array of geographic characteristics. These characteristics are: latitude and longitude of the district's centroid, mean level of ruggedness and elevation. As column (2) shows, when all these factors are accounted for the estimated relationship declines only slightly. In column (3) we add the measures of wheat suitability, suitability for pasture and agricultural suitability to control for districts' land fertility as a possible channel for more intensive economic activity (e.g., markets, trade, etc.). Even after controlling for all of these potential effects as well as other climatic characteristics (mean precipitation and temperature), the estimated relation remains stable. The resulting analysis suggests that after controlling for these geographical and topographical effects, an increase of one mill per capita in a district in 1086 is associated with an increase of 0.14 wright apprentices per capita in the eighteenth century, only slightly less than the raw correlation.

Furthermore, the estimated relationship may have been affected by non-topographical time invariant factors. Thus, in column (5) we control also for several potential channels through which trade may have affected the number of wrights: the proximity to London, the proximity to major harbours, the proximity to a navigable river and to a historical Roman road as well as the district's area. We also control for the district's population size. As the table shows, the estimated relationship remains stable after controlling for these effects and is statistically significant at the 1% level, suggesting that one additional mill per 10,000 people in a district is associated with an increase of 0.12 wright apprentices. Figure 1 depicts the partial correlation between Domesday mills per capita and wright apprentices per capita as captured in column (5). It shows that our results do not rely on outliers.

However, it is still possible that the location of mills in 1086 was endogenous to unobserved time invariant features that affected the location of wrights in the eighteenth century. For that reason, we employ an instrumental variables strategy, which captures the exogenous variation in the suitability of a district for the construction of grinding mills in the early Middle Ages, reported in Table 3. The IV 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. We take

[15] We also control for the district's population size with two controls; the mean population size in 1710–50, as calculated from the HYDE project, and the land suitability for agriculture, as calculated from Ramankutty *et al.* (2002).

Table 2. *Number of Wright Apprentices per Capita and Domesday Book Mills per Capita.*

	No. of wright apprentices per capita				
	(1)	(2)	(3)	(4)	(5)
Watermills (per capita)	0.15***	0.14***	0.14***	0.14***	0.12***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)
Latitude		0.01	0.01	0.00	0.01
		(0.00)	(0.01)	(0.01)	(0.01)
Longitude		0.02**	0.02**	0.02**	0.03*
		(0.01)	(0.01)	(0.01)	(0.01)
Ruggedness (mean)		0.04	−0.13	−0.27	−0.41
		(0.33)	(0.33)	(0.36)	(0.41)
Elevation (mean)		0.26	0.60	−0.57	0.84
		(1.11)	(1.19)	(1.22)	(1.48)
Agricultural suitability			−4.05	−3.23	−4.85*
			(2.59)	(2.65)	(2.41)
Wheat suitability			1.89**	1.50	1.23
			(0.82)	(0.94)	(0.97)
Pasture suitability (mean)			0.98	0.94	0.63
			(1.20)	(1.24)	(1.59)
Precipitation (mean)				4.55	5.03
				(7.68)	(6.66)
Temperature (mean)				−1.70	1.76
				(1.26)	(1.95)
Population (mean) 1710–50					−0.02
					(0.03)
Minimal distance to an important harbor					2.97**
					(1.29)
Distance to London					1.04
					(16.19)
Minimal distance to a Roman road					−8.80*
					(5.15)
Minimal distance to a navigable river					0.59
					(1.51)
Area					3.34*
					(1.89)
Adjusted R^2	0.57	0.58	0.59	0.59	0.61
Observations	298	298	298	298	298

Notes: This table establishes the positive and economically and statistically significant association of the number of mills per capita in a district, as documented in Domesday Book (1086), and the number of wright apprentices per capita for the period 1710–50, controlling for the district's longitude, latitude, mean elevation, ruggedness, temperature and precipitation, as well as agricultural suitability, pasture suitability, wheat suitability, the area of the district, its distance from London, major eighteenth-century harbours, navigable rivers and a historical Roman road. Specifically, the analysis suggests that an increase in the number of one mill per capita is associated with an increase of approximately 0.12 wright apprentice per capita in the district. All observations are clustered at the historical county level. Heteroscedasticity 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.

advantage of the fact that the construction of grinding mills in the early Middle Ages, in contrast with later industrial mills, depended on a high potential for wheat growing and the availability of suitable hydraulic conditions. Our instrument was therefore constructed to capture the suitability of a district for the construction of grinding watermills. In the results presented below, we assume that the adequate levels of terrain ruggedness are between 2 and 6 (which is a range of gentle to moderate degrees of undulation), and a district is considered highly suitable for wheat growing if the mean wheat suitability 'category' of the district is lower than, or equal to 5 (the lower, the more suitable).

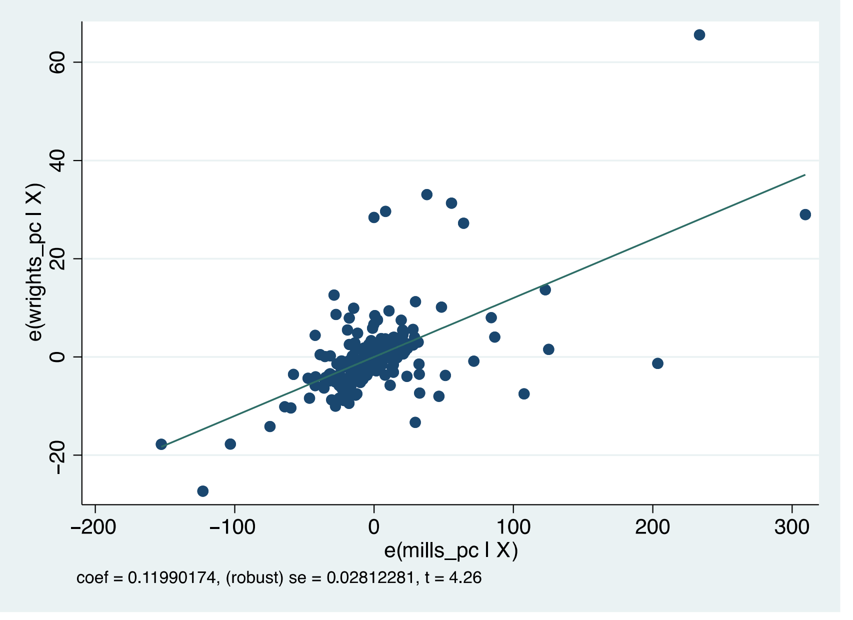

Fig. 1. *The Number of Wrights and Domesday Book Watermills: Partial Correlation.*
Source. Specification as in Table 2 column (5).

Table 3. *Wright Apprentices per Capita and the Number of Domesday Mills per Capita.*

	No. of wright apprentices per capita					
	OLS (1)	IV (2)	OLS (3)	IV (4)	OLS (5)	IV (6)
Watermills (per capita)	0.15***	0.16***	0.14***	0.15***	0.12***	0.16***
	(0.02)	(0.04)	(0.02)	(0.04)	(0.03)	(0.04)
River suitability		2.28		5.06	13.90	11.35
		(3.65)		(5.01)	(10.08)	(10.51)
Wheat suitability		1.18*		1.34	1.17	0.91
		(0.70)		(0.86)	(0.94)	(0.86)
Main geographic controls	No	No	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	Yes	Yes	Yes	Yes
Other geographic controls	No	No	No	No	Yes	Yes
First-stage *F*-statistic		19.90		16.96		16.17
Adjusted R^2	0.57	0.57	0.59	0.59	0.62	0.59
Observations	298	298	298	298	298	298

Notes: This table establishes the statistically and economically positive effect of the number of Domesday mills in a district on the number of wright apprentices, controlling for the district's population, main geographic controls (longitude, latitude mean ruggedness, mean elevation), agricultural controls (agricultural suitability, suitability to grow pasture and wheat), climatic controls (mean precipitation and temperature) and other geographical controls (distance from London, main eighteenth-century harbours, a historical Roman road and a navigable river, and the district's area). To mitigate endogeneity problems, the analysis uses the geographical suitability for establishing grain griding mills as an IV for the number of Domesday mills. Heteroscedasticity 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 identifying logic here is that late eleventh-century mills, which were largely used for grinding cereals, would be set up in locations that had a terrain suitable for water mills on the supply side and grew a lot of wheat on the demand side (see Subsection 4.1.1). Watermills were costly in terms of the fixed cost of the construction and heavy annual maintenance and repairs costs. To cover these expenses, large amounts of wheat had to be brought to the mill to be ground into flour. Because grain was costly to transport over long distances during the early Middle Ages, and flour could not be preserved for long, grains were brought to the mill on a daily basis for grinding. Mills were therefore mostly constructed in the countryside in the vicinity of wheat fields and not necessarily close to larger concentrations of population. In addition, as noted, their construction required reasonably adequate river streams. Processing mills were normally situated near the areas where the crops they used were grown; the same was true for rapeseed oil mills (Brace, 1960, p.18).

Given that industrial mills were not used for wheat grinding, the only way that the instrument affects the location of eighteenth-century millwright apprentices, controlling for all other geographic characteristics, is through the persistent effect of Domesday mills, so that the IV meets the exclusion restriction. Our IV approach is constructed in a way that will identify the construction of older mills, rather than more modern and industrial mills, leading us to identify the persistence of mill location over longer periods of time. It should be noted that the two variables that make up our IV, wheat suitability and 'river suitability', are uncorrelated, as can be verified from Online Appendix Figure E.1.

Table 3 presents the results of our IV estimation (in columns (2), (4) and (6)).[16] For ease of comparison, they are presented along with our OLS estimations. As can be seen in column (2), using our instrument increases the coefficient only slightly (comparing to the OLS estimation). This suggests that the unobservables do not seriously confound the estimation. Despite this finding, we perform a test on the possible bias due to the unobservable (see Subsection 5.4). Furthermore, the first-stage F-statistic equals 19.90, assuring that the instrument is strong enough. These results hardly change when we add the same controls as in Table 2. As can be seen in columns (4) and (6), once these controls are added an increase of one watermill per capita is associated with an increase of 0.15 wright apprentices (per capita) and the first-stage F-statistic remains strong: 16.96 and 16.17, respectively. According to the hypothesis presented in this paper, the availability of highly skilled mechanical labour in districts with many watermills during the Domesday Book survey, *ceteris paribus* played an important role in the persistence of these locations for later industrial activities.

4.1.3. *Eighteenth-century wrights and the Black Death*

To provide further support to this claim we show that districts that experienced the disappearance of more grinding mills in the fourteenth century due to the Black Death and the epidemics that followed, had fewer wrights in 1710–50. Thus, if the death toll varied randomly between districts, the abandonment of mills was independent of the geographical characteristics of their location and we can thus conclude that the persistence identified implies that there were fewer wrights in 1700–50 in districts that were hit harder by the Black Death.

[16] Online Appendix Table D.1 presents the coefficients of the full specification. Online Appendix Table E.4 (panel a) presents the first-stage estimation of columns (2), (4) and (6), and Online Appendix Table E.4 (panel b) presents the reduced form of these columns.

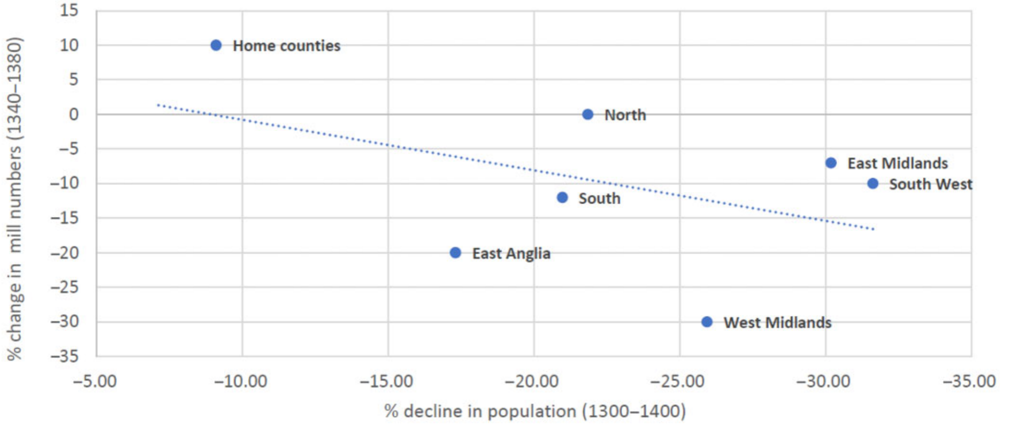

Fig. 2. *Population Decline and Changes in Mill Numbers: 1300–1400.*
Sources. Changes in mill numbers from Langdon (2004,[17] p.32, fig. 2.3); for more details see Online Appendix H.

The Black Death in 1348–50 eliminated between a third and half of England's population. The sharp decline in population and the rise in wages triggered a shift in land use from arable to pastoral farming.[18] This shift from 'corn to horn' was a European-wide phenomenon (Voigtländer and Voth, 2013). The decline in grain production resulted in the disappearance of hundreds of grinding mills.[19] As shown in Figure 2, greater decline in a region's population led, *ceteris paribus*, to the destruction of more grinding mills. The shift from corn to horn may have increased investment in fulling mills and offset some of the decline in grinding mills. In fact, in many cases grain watermills were converted to fulling mills. Yet, because grain mills remained the lion's share of mills, the overall number of mills which declined only a little in the immediate aftermath of the Black Death experienced something of a 'bubble bursting' in around 1390 and had fallen by more than 20% by 1440. It had not fully recovered by the mid-sixteenth century (Langdon, 2004, pp.28–30).

4.1.4. *The mills of Winchester district*

The death toll and destruction brought about by late fourteenth-century plagues varied much throughout England.[20] According to the HYDE project historical population estimates, England's population declined by 22.4% between 1300 and 1400 on average, with a high of as much as 49% decline in Craven district (North Yorkshire), and a low of almost 15% increase in population in

[17] Broadberry *et al*. (2011) reconstruct land use in 1290 on the basis of the arable land acreage in 1871 when a first systematic national survey of farmland and farm output has been conducted. They do so by considering variations in population density, the location of drainage schemes, the density of deserted medieval villages and the effects of urbanisation. Arable land is defined in these calculations as land sown with grain (wheat, barley, rye, oats), field legumes (beans, peas, vetches), root crops (potatoes, turnips, swedes, mangold), green crops (cabbage, kohlrabi, rape, Lucerne), industrial crops (flax, hemp, madder, saffron, hops, tobacco), small fruit, lay crops (clover, sainfoin), and bare fallow. Excluded are gardens, permanent grassland and woodland.

[18] Campbell (2000) estimates a 15% decline in land for grain growing.

[19] According to Langdon (2004), grain mill numbers declined by about 15% of what they had been in the beginning of the century, due to the 'lack of tenants or to deaths among the holders or operators of the mills themselves' (p.28).

[20] More serious plague epidemics erupted in England in 1361–2, 1369, 1379–83, 1389–93.

Islington district (in Greater London) (Klein Goldewijk *et al.*, 2011). This section will concentrate on Winchester district in Hampshire where the population declined by 33.2% on average, among the country's highest.

Domesday Book mentions almost 70 mills in 30 locations on the main rivers that flow through Winchester district: River Meon (32 mills) and River Itchen (about 36.5 mills). Situated at the source of River Hamble, between the two main rivers, was the market town Bishop's Waltham, one of the largest towns in Hampshire. Death and destruction by the plagues in this region varied.[21] Bishop's Waltham was also among the places that were strongly hit. Its population declined by 65% as a result of the Black Death according to Titow, looking at the whole century the decline was estimated at 44.7% (cited by Mullan, 2007, p.8).

The rich accounts of the bishops of Winchester, known as the Winchester pipe rolls, enable us to get a closer look at the effect of the plague on agriculture and as a corollary, on the distribution of water mills. As in the rest of England, the impact on economic life caused by the Black Death and the epidemics that followed in the Winchester district was huge. Trade and other economic activities practically ceased and there were not enough people to farm the land. This led to patterns similar to those identified by Bruce Campbell on the national level, i.e., an increased emphasis on the more valuable crops, 'wheat rather than barley for bread, barley rather than oats for ale, and an increase in pastoral farming at the expense of arable' (Hare, 2006, p.202).

The detailed information on arable and livestock on manors in the vicinity of our two rivers provides a good illustration of the effect of high mortality on agriculture and mill construction. In Bishop's Waltham, where the death toll from the plagues was relatively high, the sown arable acreage declined sharply from 365 acres in 1300–24 to 189 in 1325–49 (45%). Considering the share of wheat, wheat-sown land declined by 98.7 acres (65%). At the same time the total number of sheep increased from 637 in 1302 to 776 in 1366 and to 864 towards the end of the century. The situation in other manors east of the River Itchen was different. In Crawley, to the north-west of Winchester, where population decline was slightly below the district's average (32.4%), wheat-sown acreage increased by 12% and the number of sheep by 5% (from 1,276 in 1302 to 1,345 in 1357). In Littleton, where population declined slightly above the average (35%), total sown land hardly changed, wheat-sown land declined by 20% and the number of sheep increased by about 9% (from 1,042 to 1,134 at the end of the century).[22]

The strong negative effect of the plagues on the economy of Bishop's Waltham, the largest settlement in the area, resulted in a contraction of wheat growing in its vicinity and, as a result, on mill construction over the River Meon (see Table 4). Thus, mills could be observed in 1759 in only three of the nine locations where there had been mills in Domesday. In the vicinity of the River Itchen, however, there was almost no change. Winchester, the largest city in that district was relatively lightly hit in terms of population decline, as well as most of the locations on the

[21] On the Meon River, of the nine locations that had mills in 1086, the population of two locations declined by more than 60% between 1300 and 1400 (Exton and Meonstoke). The population of three other locations by 50–60% (Warnford, Droxford and Wickham), and of the four others by 40–50% (Hambledon, Corhampton, West Meon and Soberton). The situation in the 14 locations on the River Itchen was a little bit better. Population decline exceeded 50% only in Twyford. In four locations population declined by 40–50% (Headbourne Worthy, Easton, Martyr Worthy and Chilcomb), four locations by 30–40%, and Winchester by 25.4% (for the last three we do not have information).

[22] Population estimates are from the HYDE project. Arable acreage from Hare (2006, p.193, table 1); Wheat-sawn land is the multiplication of the share of wheat given in Hare (2006, p.196, table 2) and the total arable acreage in Hare (2006, table 1) and sheep from Hare (2006, p.198, table 3).

Table 4. *Locations with Mills in Winchester District: 1086 versus 1710–60.*

River	(1) Locations with mills 1086	(2) Population 1300–1400 (average)	(3) Locations with mills 1759 vs. 1086	(4) People per mill 1759	(5) Locations with wrights (vicinity) 1710–60	(6) Mills per wright 1710–60
Meon	9	−52%	0.22	11,187.92	2	1.5
Itchen	14	−40%	0.64	3,184.50	12	1.1

Notes: Population estimates are from the Hyde 3.1 project; mill numbers in 1759, from Taylor's map of Hampshire. Locations with wrights in vicinity are locations located within 5 miles from the river. The sources and calculations are provided in detail in Appendix H.

banks of the river. Meanwhile, in the manors of Littleton and Crawley, wheat-sown land remained almost unaffected by the plagues. As shown in Table 4, the number of mills in 1759 declined significantly less (relative to DB) than on the River Meon.[23] Furthermore, while the relative number of mills per wrights seems fixed at around 1–2 mills per wright in 1710–60, the number of mills relative to the population size in the settlements near these rivers was significantly lower over the Meon.

4.1.5. *Empirical analysis*

To test whether, indeed, the impact of the Black Death to a district's grain milling industry led to a lower number of wrights later on in the first half of the eighteenth century, we estimate the following model:

$$w_i = \delta_1\, mills_i + \delta_2 dpop_{13001400,i} + \delta_3 dpop_{13001400,i} \times mills_i + \gamma \boldsymbol{X'} + \omega_i, \qquad (2)$$

where, as in (1), w_i is the number of apprentices to wrights per capita in district i, $mills_i$ is the number of Domesday mills per capita, $dpop_i$ is the (negative) growth in population in district i between 1300 and 1400 ($dpop_{13001400,i}$) $\times$ $mills_i$ is the interaction of the change in the population with the number of Domesday mills, the matrix X contains our control variables, and, ω_i is the district-specific error term. Our coefficient of interest, δ_3, is the mean number of additional wrights per capita associated with a population decline of 1% given the number of mills in the district. This effect is net of both the effects of population change and the number of Domesday mills. According to our hypothesis, this coefficient should be positive. Table 5 present the results of our (OLS) estimation of (2). Column (1) presents the estimate for the effect of Domesday mills on the number of wrights per capita in the district in 1710–50 controlling for geographical characteristics and omitting the effect of the Black Death. The effect is positive and significant. Once we add the change in population during the fourteenth century, to proxy for the level of destruction during the Black Death, and add its interaction with mills, we find that, *ceteris paribus*, a larger decline in population resulted in fewer wrights in 1710–50. In columns (3) and (4) we perform a placebo test in which we distinguish between districts that experienced a relatively large decline in population (column (3)) and those that experienced a relatively small decline (column (4)) and find that the coefficient is much larger in column (4) as we expect (0.2).

[23] The numbers of mills in the 1750s were calculated from a map of Hampshire, which was engraved by Isaac Taylor and dedicated to Charles Powlett, fifth Duke of Bolton in 1759 (Taylor, 1759). It is available online (as well as in the British Archives).

Table 5. *The Black Death and the Number of Wrights: OLS.*

	No. of wright apprentices (per capita)			
	Mills (1)	Mills and pop. change (2)	Larger pop. decline (3)	Small pop. changes (4)
Watermills (per capita) × Pop. change		0.03***	0.03**	0.20***
		(0.01)	(0.01)	(0.07)
Watermills (per capita)	0.12***	0.19***	0.24***	0.50***
	(0.03)	(0.03)	(0.08)	(0.14)
Pop. change		0.27	−0.14	0.14
		(0.22)	(0.39)	(0.29)
Geographical controls	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes
Other geographic controls	Yes	Yes	Yes	Yes
Adjusted R^2	0.61	0.66	0.63	0.83
Observations	298	298	187	111

Notes: This table provides suggestive evidence that the formation of skills in the early eighteenth century depended on the persistence effect of DB mills. Specifically, it shows that districts that were harmed more severely from the Black Death, conditional on the number of DB mills, had fewer wrights 350 years later. Geographic, climatic and agricultural characteristics are controlled for. Heteroscedasticity 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.

4.2. *Capital-Skill Complementarity and Early Industrialisation*

We conclude from these results that the data are consistent with strong persistence in the location of what Gimpel (1976) has called the 'medieval machine', and that the mechanism is the high level of artisanal competence that they required. The question we now want to tackle is: did it matter for the location of manufacturing centres in the eighteenth-century industrialisation? We have shown that early water-powered machinery led to the emergence of a large cadre of millwrights. We now turn to the hypothesis that wrights, once in place, helped determine the location of the textile and metal industries, which, while independent of flour mills, also used water-powered machinery. The analysis presented in this section will show that the location of Domesday mills, through the mechanical ability of their millwrights, helped determine the location of the textile and iron-making industries in the mid-eighteenth century. We show that regions that underwent industrial progress relatively early in the Industrial Revolution can be predicted by the location of Domesday mills. To do so, we estimate the following equation:

$$Ind_i = \pi w_i + \mathbf{Z}'\delta + \mu_i, \qquad (3)$$

where Ind_i is a proxy for the extent of production of an industry per capita in district i, and w_i as before is the relative number of millwright apprentices. These industries include textiles (proxied by the number of apprentices to cloth merchants, clothiers and weavers) and iron making (proxied by the number of apprentices to smiths and blacksmiths). $\mathbf{Z}$ is a matrix containing our control variables, and μ_i is the error term. To address 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.

4.2.1. *Empirical strategy*

Equation (2) cannot be estimated consistently by OLS due to reverse causality. Wrights specialised in all types of machinery with similar mechanics as watermills. Their numbers in the eighteenth century may therefore have been a response to the expansion in textile production and not just its cause. The model may also produce spurious correlations due to omitted variables (above all geographical, but also institutional, economic and human characteristics). Thus, we estimate (1), but instead of estimating the effect of existing mills on the number of wright apprentices per capita, we estimate the effect of mills in 1086 on the number of apprentices in the textile industry (drapers and clothiers as well as weavers) and iron-making industry (smith and blacksmith apprentices). The textile (woollen and worsted) and iron industries were already slowly transforming in the eighteenth century and the existence of millwrights facilitated that progress. We estimate (1) with the same IV technique, using a handful of other occupations that were not mechanised, and show that indeed they cannot be predicted by the number of Domesday mills.

Our main contention is that the availability of wrights (but not mills as such) in a district had a positive effect on the emergence of industrial activities in the more progressive manufacturing industries. The industrial history of England can be described as a narrative in which technology and skills affected each other's evolution over many centuries. Mill location was determined by initial geographical conditions that favoured the specific technology of watermills, but skills through intergenerational transmission became localised. As wrights were elite mechanics, they were the channel through which new mechanical techniques spilled over into other industries.

To lend credence to this hypothesis, we perform two different exercises. First, we run a mediation test, which analyzes how much of the direct effect of mills on the emergence of different industries was mediated through wrights. This analysis is based on a procedure proposed by Imai *et al*. (2010) and Imai *et al*. (2010; 2011). We show that wrights mediated 39%–69% of the effect of the location of mills on the analyzed industries (depending on the industry). Second, we show that the evolution of one key textile industry, worsteds, is perfectly consistent with our view about the importance of skilled mechanics trained by and as millwrights. Worsteds had little need for waterpower before 1750 and, indeed, were spread all over England. After 1750, though, they experienced a rapid mechanisation and, as a result, relocated to districts where mills were abundant.

4.2.2. *Results*

Table 6 presents the simple association between the textile industry, as proxied by the number of apprentices to drapers and clothiers per capita in a district, and the number of apprentices to wrights in the same district. Column (1) presents the unconditional correlation between the two. It shows a statistically and economically significant correlation between the two, as an increase of one wright apprentice per capita is associated with an increase of 0.43 draper apprentices per capita, and the coefficient is statistically significant at the 1% level. Adding all the controls does not affect the result much: as can be seen in column (5), the coefficient remains stable and highly significant at the 1% level. To overcome selection bias problems, we restrict our analysis in column (6) to the districts covered in the Domesday Book (so the sample size declines by c.9%), but the strong association is hardly affected: the coefficient declines to 0.38 and remains significant at the 1% level.

The results in Table 6 suggest that indeed wrights played a role in early industrialisation. One concern again would be possible unobserved topographical characteristics, which might

Table 6. *Number of Draper Apprentices per Capita and Wright Apprentices per Capita.*

	No. of draper apprentices per capita					
	All sample					DB sample
	(1)	(2)	(3)	(4)	(5)	(6)
Wrights (per capita)	0.43***	0.48***	0.47***	0.47***	0.41***	0.38***
	(0.14)	(0.13)	(0.13)	(0.13)	(0.13)	(0.13)
Geographical controls	No	Yes	Yes	Yes	Yes	Yes
Agricultural controls	No	No	Yes	Yes	Yes	Yes
Climatic controls	No	No	No	Yes	Yes	Yes
Other economic controls	No	No	No	No	Yes	Yes
Adjusted R^2	0.27	0.36	0.37	0.37	0.41	0.45
Observations	325	325	325	325	325	298

Notes: This table establishes the positive and economically and statistically significant association of the number of wrights per capita in a district, and the number of draper apprentices per capita for the period 1710–50, controlling for the area of the district, its distance from London, major eighteenth-century harbours, navigable rivers and a historical Roman road, as well as geographical controls (longitude, latitude, mean elevation, ruggedness, temperature and precipitation, agricultural suitability, pasture suitability and wheat suitability). Specifically, the analysis suggests that an increase in the number of one wright per capita is associated with an increase of approximately 0.41 draper apprentice per capita in the district. All observations are clustered at the historical county level. Heteroscedasticity 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.

create a spurious effect as they are naturally persistent. Table 7 presents the effect of Domesday mills on industrialisation in early eighteenth century, instrumenting the Domesday mills by the geographical instrument used in Table 3. As in Table 3, the suitability to construct medieval watermills, which we capture by the interaction between wheat suitability and the adequate river water flows, allows us to overcome endogeneity problems. A natural way to see this is to emphasise that the wrights who resided near the mills predicted by this instrument were in these districts not because of the existing textile industries there, but rather due to the suitability of the site to construct flour mills 600 years before. In columns (1)–(4), we present the second-stage regressions showing the effect of the number of Domesday mills in a district on the number of apprentices in the textile industry (drapers and clothiers in column (1) and weavers in column (2)), and on the iron-making industry (proxied by the number of smith and blacksmith apprentices). These industries were among the first to mechanise during the Industrial Revolution, and their dependence on high-skill labour was strong. Note that the effect of the number of mills in 1086 is positive and economically and statistically significant for both industries, suggesting that indeed the location of the Domesday mills had an effect on early industrialisation more than 600 years after the Domesday survey was conducted. The concern that the correlation may be spurious because textiles and iron required water for their production process is addressed by the geographical controls included.

Furthermore, river suitability and wheat suitability were orthogonal to one another as shown in Online Appendix Figure E.1. This implies that industries that required water could have been located also in districts that were not suitable for wheat cultivation. In this case, our IV should not predict their location. If, however, we find that our IV predicts where they resided, they must have done so because these regions provided them something else other than rivers and water.

One concern with these results is that the location of the mills could have affected all industries, either because these locations were for some reason more attractive for living in them, or because other industries were also affected by the same geographical characteristics and thus grew in

Table 7. *Industrial versus Other Apprentices and DB Mills.*

	No. of apprentices per capita									
	Draper (1)	Weaver (2)	Smith (3)	Blacksmith (4)	Joiner (5)	Trader (6)	Butcher (7)	Attorney (8)	Surgeon (9)	Apothecary (10)
Watermills (per capita)	0.12***	0.21***	0.09**	0.14***	0.15	−0.01	0.28	0.14	0.06	0.11
	(0.03)	(0.08)	(0.04)	(0.04)	(0.10)	(0.40)	(0.17)	(0.12)	(0.04)	(0.09)
Wheat suitability	0.25	6.52	0.42	0.37	0.56	42.83	−1.95	−0.45	−0.85	−0.59
	(0.63)	(4.31)	(0.37)	(0.58)	(0.94)	(41.18)	(1.75)	(1.05)	(0.52)	(0.81)
River suitability	10.75	70.82*	1.19	19.22*	21.80**	210.45	5.19	36.82***	11.77**	19.22*
	(10.28)	(38.89)	(4.70)	(10.39)	(9.56)	(201.09)	(17.63)	(12.85)	(5.86)	(9.90)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	16.17	16.17	16.17	16.17	16.17	16.17	16.17	16.17	16.17	16.17
Adjusted R^2	0.31	0.17	0.55	0.64	0.41	0.03	0.60	0.51	0.51	0.38
Observations	298	298	298	298	298	298	298	298	298	298

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. Heteroscedasticity 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.

areas where mills were built during the Middle Ages. If, for instance, population was denser in these districts, and there were economies of scale or agglomeration in milling and manufacturing, this could produce a spurious correlation. However, as Online Appendix Table A.1 shows, even if the mills were built in more populated areas during the Middle Ages, these districts were on average less populated in the eighteenth century.

Most telling, however, is that the effects of millwrights can be discerned only for more dynamic industries that required high-skilled artisans and engineers. In columns (5)–(10) of Table 7 we present placebo tests that show that the Domesday mills do not have any effect on occupations that were not mechanised at this time. These occupations include similar occupations to wrights (such as the joiners), other rural occupations (such as butchers), other traders not in the textile industry (column (6)) and occupations which should reside in more heavily populated areas (attorneys, surgeons and apothecaries). We conclude from this table that the mills generated industrial clusters in textiles and iron industries, but not more generally for manufacturing.

4.2.3. *Geography and skills compared: Horse race and mediation analysis*

A different way to show that the driver of industry location was the millwrights and not the mills themselves is to conduct a horse race between mills and wrights as explanatory variable for each occupation as reported in Table 8: drapers (columns (1)–(3)), clothiers (columns (4)–(6)), smiths (columns (7)–(9)), and blacksmiths (columns (10)–(12)). In each triplet, the first column displays the results of a regression in which only wrights are used as explanatory variable. The second column of each triplet displays the results of a regression in which only mills are used as explanatory variables. Finally, the third column of each triplet represents the regression in which *both* are used as explanatory variables. As can be seen in the table, once both wrights and mills are explanatory variables (columns (3), (6), (9) and (12)), the coefficient of the mills drops significantly, losing 35%–68% of its size. Moreover, in the case of drapers, it also loses its significance. The coefficient of wrights, however, loses much less (13%–25%) once we add the mills. More formally, we execute a mediation analysis, which measures how much of the total effect of mills on each occupation is mediated through the wrights.[24] The results of the mediation analysis are presented at the bottom of Table 8. Interestingly, it shows that the wrights per capita mediate between 31% and 68% of the effect of mills per capita on the number of apprentices per capita in each occupation.[25]

4.2.4. *The case of worsteds*

We can also use the case of the worsted or combed wool industry to demonstrate the validity of our hypothesis. Worsted manufacturing had thrived in East Anglia in the fourteenth century (Allison, 1960). There are important differences between woollens and worsteds. For our purposes, the important difference is that worsteds did not go through the process of fulling, the most heavily mechanised process in the textile industry, until the second half of the eighteenth century. This implies that while the location of wool cloth manufacturing could have been determined by the

[24] The mediation analysis is based on Imai *et al*. (2010) and Imai *et al*. (2010; 2011). The idea behind mediation analysis is to estimate how much of the total effect mills have on each occupation directly, and how much is indirect and mediated through wrights. The results of this analysis are obtained by predicting the value of the wrights per capita for different values of mills per capita, and then using these predictions to estimate the effect of both the mills and the predicted values of wrights on the different occupations. The analysis repeats this procedure a thousand times, sampling each time different values of mills to predict the values of wrights.

[25] A hypothetical analysis, in which the mills mediate the effect of the wrights yields much lower numbers, ranging between 15% and 27% (available on request).

Table 8. *Wright Apprentices and DB Mills Mediation Analysis.*

	No. of apprentices per capita											
	Drapers			Weavers			Smiths			Blacksmiths		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Wrights (per capita)	0.38***		0.32**	1.32***		0.73***	0.32***		0.23***	0.90***		0.67***
	(0.13)		(0.13)	(0.26)		(0.26)	(0.06)		(0.08)	(0.09)		(0.16)
Watermills (per capita)		0.06**	0.02		0.28***	0.19***		0.06***	0.03**		0.15***	0.07**
		(0.03)	(0.03)		(0.06)	(0.06)		(0.01)	(0.01)		(0.03)	(0.03)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Other geographic controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mediation percentage			0.68			0.31			0.49			0.52
Adjusted R^2	0.45	0.39	0.45	0.15	0.16	0.17	0.65	0.60	0.68	0.70	0.63	0.74
Observations	298	298	298	298	298	298	298	298	298	298	298	298

Notes: This table shows the results of a mediation analysis based on Imai *et al.* (2010) and Imai *et al.* (2010; 2011). It shows that the direct effect of mills on drapers (69%), clothiers (51%), smiths (49%) and blacksmiths (56%) is mainly mediated via wrights. Heteroscedasticity 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 9. *Worsted versus Woollen Weaver Apprentics.*

	No. weaver apprentices per capita					
	1710–50		1750–1800			
	(1)	(2)	(3)	(4)	(5)	(6)
Watermills (per capita)	0.12***	0.06	0.46***	0.15**	0.13**	
	(0.03)	(0.04)	(0.14)	(0.07)	(0.06)	
Wrights (per capita)						0.90**
						(0.37)
Non-fulling district					15.28	16.08
					(13.31)	(13.58)
Carboniferous strata					5.76	2.75
					(5.27)	(4.08)
Textile usage of engines					−0.36	−0.29
					(0.38)	(0.33)
River suitability	36.11**	30.93	48.48*	43.74	40.49	24.86
	(15.44)	(22.67)	(25.31)	(33.64)	(30.63)	(24.57)
Wheat suitability	2.81	3.69	2.14	4.95	5.40	3.92
	(1.86)	(2.69)	(2.36)	(3.77)	(4.10)	(3.39)
Geographical controls	Yes	Yes	Yes	Yes	Yes	Yes
Agricultural controls	Yes	Yes	Yes	Yes	Yes	Yes
Climatic controls	Yes	Yes	Yes	Yes	Yes	Yes
Other geographic controls	Yes	Yes	Yes	Yes	Yes	Yes
First-stage F-statistic	16.17	16.17	16.23	16.23	16.53	16.37
Adjusted R^2	0.28	0.09	0.23	0.12	0.14	0.15
Observations	298	298	298	298	298	325

Notes: This table establishes the positive effect of wright apprentices on the location of the worsted industry, before and after the mechanisation process it experienced during the second half of the eighteenth century. In particular, it shows that during the first half of the eighteenth century, the location of the mills affects the location of the woollen industry (due to fulling), but not of worsted. After spinning machinery was adopted by the worsted industry, wright apprentices affect the location of the worsted industry, while the effect on the woollen industry is economically small. The table uses the geographical IV presented above in this paper. Furthermore, the result is robust also for controlling for the existence of carboniferous strata in the district, the number of engines used in the textile industry by 1800 and a dummy variable that indicates that the district was a textile centre for yarns that were not fulled (and thus historically did not use waterpower). Heteroscedasticity 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.

'mill aspect' of the existence of medieval mills for the construction of fulling mills, the location of worsted manufacturing was not, at least not until the middle of the eighteenth century.

In the second half of the century, when spinning machinery was introduced, the differences between the type of machinery used in the two branches increased, mainly due to the differences in the nature of the fibre. The worsted branch adopted the more complex technology of the Arkwright type of water-frames (i.e., spinning machines operated by waterpower and later by steam), which were widely used in large-scale production factories. The first worsted spinning mill in Yorkshire was established in 1787, and by 1820 the domestic spinning of worsted yarn was almost extinct (Clapham, 1906, p.517).

In short, in the second half of the eighteenth century this industry, which had had little use for waterpower before, moved to areas where it was abundant. Table 9 demonstrates this transition: whereas in the first half of the eighteenth century only woollens were located in areas with waterpower, this changes to both woollens and worsted after 1750.[26] The results of estimating the effect of Domesday mills on the location of weavers in the years 1710–50 is presented in

[26] As discussed earlier, as we cannot use our variable *draper* as a consistent proxy for the extent of textile production in 1710–50 and in 1750–1800, when the shift to the factory system changes the organisation of the industry, we use *weavers per capita*, an occupation that remained relatively independent of the factory system at this stage, as a proxy. We

columns (1)–(2), and the years 1750–1800 is presented in columns (3)–(4). As expected, the effect on woollen manufacturing is highly significant in both periods, mainly due to the dependence on water-powered fulling. However, it is also due to the industry's need for wrights and other skilled mechanics following the adoption of jennies in workshops. As for the location of worsted manufacturing, Domesday mills had no significant effect on its location in the first half of the century when it was relatively modest and mostly manual. It becomes, however, significant in the second half of the century following the expansion and mechanisation of worsteds. As Table 9 shows, in columns (5) and (6), the argument survives all geographical controls. Moreover, in Online Appendix Figure E.1, we show that river suitability and wheat suitability are independent. The fact that after 1750 we find worsted producers mainly where wheat can be cultivated (as well, of course, areas where rivers had adequate flows) implies that they moved to where mills were. Given that before 1750 worsteds did not use DB mills, it must have been the presence of skilled wrights that made it advantageous for them to move there. We interpret the significant effect of the existence of medieval mills on the extent of worsted manufacturing in 1750–1800, as a dependence on human capital rather than on physical capital.[27]

As can be seen in column (5), the effect of historical mills on the location of manufacturing declines, but remains significant even in the presence of additional controls. Lastly, in column (6), we replace Domesday mills with the number of wright apprentices in 1710–50 and test its effect on the location of worsted. Note that the use of the geographical IV as an instrument for wrights in this specification does not violate the exclusion restriction, because worsted did not depend on waterpower until the second half of the century.

Consistent with our hypothesis, the results show that the availability of wrights has a positive and significant effect on the location of worsted. Thus, our results confirm that wrights clearly played a role in the first phases of industrialisation.

5. Robustness

A number of concerns can be raised as to various threats to our results given the inevitable problems with the data available. This section establishes that our main results are robust to (i) spatial autocorrelation; (ii) the availability of coal; (iii) bias due to the effect of London; (iv) different levels of our IV components and (v) Domesday Book institutional differences.

5.1. *Spatial Correlation*

One concern in spatial regressions, like the ones presented in this paper, is that the independence assumption is violated. According to our Moran's I statistics (Online Appendix, Table B.1), our results may, indeed, be affected by spatial autocorrelation and, thus, our statistical significance may be an artefact of spatial autocorrelation (Moran's I statistics in our main variables are significant, receiving z-scores around 8–10). Therefore, we first correct the standard errors based on Conley (1999). Online Appendix Table B.2 provides the results of these estimations, for

therefore estimate the effect of the per capita number of Domesday mills in the district (instrumented by our geographical IV) separately on the number of woollen weavers per capita and on the number of worsted weavers per capita.

[27] Support for this view can also be found in Edward Baines's words in 1859: 'I apprehend that the principal advantages of the West Riding over Gloucestershire, Wiltshire, and Norfolk consist, first, in the greater cheapness of coal and iron; secondly, in the larger body of men skilled in the making and working of machinery; and thirdly, in the facility of access to the great ports of Liverpool and Hull' (Baines, 1859, p.16).

wrights and mills, and Online Appendix Tables B.3, B.4, B.5 and B.6 for drapers and wrights, weavers and wrights, smiths and wrights, and blacksmiths and wrights, respectively. Each of these tables display the results of our full specification, with all the controls, and corrects the standard errors by clustering all neighbouring observations for different distances (30 km, 45 km, 75 km, 90 km, and 100 km). These tables show that our results are not affected by this correction. Furthermore, following Kelly (2020), we perform Monte Carlo simulations with 5,000 repetitions, where in each we generate spatially autocorrelated white noise, and show that white noise cannot explain our dependent variables. Finally, we perform a new method suggested by Colella *et al.* (2019) for correcting the standard errors in case of spatial data in a 2SLS estimation. We therefore replicate our estimations correcting the standard errors based on their methodology for 30 km, 60 km, 90 km, 120 km and 180 km. Online Appendix Table B.3 presents the results, and as can be seen in the table, our results are immune to this correction. We conclude from all these estimations that our results are robust to spatial autocorrelation. Full details and tables can be found in Online Appendix B.

5.2. *The Effect of London*

A possible concern could be that proximity to London, as a vast commercial, demographic and political centre, could bias our results. To overcome this problem, we controlled in all our estimations for the distance from London. To show further that London does not affect our results, we replicate our main Tables 3, 7 and 8 while omitting London from the sample. These tables can be found in Online Appendix C. The tables show that the results remain nearly unchanged.

5.3. *Robustness to the Availability of Coal*

Did the availability of coal affect the location of the textile (and iron-making) centres prior to industrialisation? Full details on the sources used and the statistical tests can be found in Online Appendix D. The results show that the potential for coal does not have a significant effect on the location of mechanically skilled workers (Table D.1) on the location of textile centres in the first half of the eighteenth century (Table D.2) or the location of the iron industry (Table D.3) when we control for other geographical and climatic characteristics of the district. In other words, we can rule out the presence of coal as a powerful alternative in explaining the location of the most dynamic industries before the Industrial Revolution. Instead, the presence of mechanical skills seems more important.

5.4. *Robustness to Selection on Observables and Unobservables*

The results in Table 2 lend credence to our hypothesis, that the availability of medieval mills set into motion a long-term process in skill formation, which persisted at least until the first half of the eighteenth century. While we control for observable characteristics to mitigate identification concerns, our results may still suffer from a selection on unobservables problem.

Online Appendix Table F.7 explores the potential bias that could be generated by omitted variables. In particular, using statistics on selection on observables and unobservables (Altonji *et al.*, 2005; Oster, 2019), it establishes that the degree of omitted variable bias is relatively low and is unlikely to explain the magnitude of the estimated association between DB mills and the number of wright apprentices. In particular, omitted factors would need to be 4.85 times (based on Altonji *et al.*, 2005) and 0.7 times (based on Oster, 2019) more correlated with the number of mills per capita, in order to account for the estimated association between DB mills per capita and the number of wrights per capita. While the results using the Oster (2019) procedure are somewhat weaker, this result is driven by us having added the area of the district as a control variable; omitting it raises Oster's δ-parameter to 2.05, suggesting that the area of the district may play a role in selection on unobservables.

5.5. *Robustness to Other Specifications of the Instrument Variable*

In this section we examine the sensitivity of our results to changes in the construction of our instrument.

5.5.1. *Balance of the instrument*

A concern may be that our instrument is correlated with (unobserved) pre-existing conditions, and thus its validity is in question. That is, any correlation between the instrument and mills (and thus wrights and other occupations) may merely reflect the correlation with some unobserved variables. While, by assumption, we cannot show that our instrument is (un)correlated with unobserved characteristics. Indeed, Online Appendix Table E.1 shows that some of the observed characteristics are correlated with the instrument, raising concerns about the validity of the instrument. To overcome this problem, we execute several steps. First, given that we test the correlation between the instrument and all the control variables that we use in this paper and the instrument, the hypotheses of the coefficients between each control variable and the instrument are not independent, it might also be that some of the hypotheses we test are mistakenly rejected. Thus, we correct the standard errors (and the *p*-values) using different methods of multiple hypothesis testing. These *p*-values are reported in Online Appendix Table E1 and, indeed, these corrections reduce the number of controls that are correlated with our instrument.

Second, we run different tests that elucidate how biased would be the coefficient of our instrument on the number of wrights per capita, given that (i) the exclusion restriction does not necessarily hold and (ii) the correlation between unobserved characteristics and the instrument is not necessarily zero. To test (i), we use the methodology from Conley *et al.* (2012), and to test (ii), we use the methodology used in Nevo and Rosen (2012). We further correct our standard errors.

Online Appendix Table E.1 presents the results of estimating regressions in which the dependent variables are all the variables that we used in the paper, and the explanatory variable is the instrument, controlling for the two components of the instrument. As can be seen, several controls we use in the paper indeed correlate with the instrument, raising a concern that the instrument is not valid. Nevertheless, we correct the standard errors of these estimation using different methods of multiple hypotheses testing. Specifically, we use the Westfall and Young (W&Y) (1993) and Romano–Wolf (R&W) (Romano and Wolf, 2005a,b) methods. As can be seen in the table, only two control variables remain statistically significant at the 10% (mean precipitation and the district's distance from London). This slightly alleviates the results of the independent hypothesis testing.

Nevertheless, due to the correlations we do find in Online Appendix Table E.1, we perform two further exercises to measure how seriously biased the coefficient of the instrument would be if the exclusion restriction does not hold, based on procedures outlined in Conley *et al.* (2012) and Nevo and Rosen (2012).

As can be seen in Online Appendix Figure E.2, the estimation of the effect of mills per capita on the number of wrights per capita is always positive and remains statistically significant at the 10% level if the direct effect of the instrument on the number of wrights per capita reaches the value of 12.5, that is, if it is 0.43 times the direct effect of 29.26 reported in Online Appendix Table E.4. This strongly supports our conclusion that our IV estimates of the association between DB mills and millwrights are valid.

5.5.2. *Sensitivity to different levels of ruggedness*

Recall that our instrument is the interaction of the length of rivers with adequate levels of ruggedness (as a proxy for the flow of water) and whether a district is suitable for wheat cultivation. In particular, in the results presented above, we assume that the adequate levels of ruggedness are between 2 and 6, and a district is considered suitable for wheat cultivation if the mean wheat suitability in the district is not higher than 5. Online Appendix E provides evidence that the results are not sensitive to these values and shows the balance of the instrument.

5.5.3. *High levels of ruggedness*

One concern that may arise is that the instrument is constructed on relatively moderate water flows, whereas perhaps more powerful water flows could have been adequate for constructing medieval mills as well. There is some historical reason to suspect it was not. Highly rugged terrain required overshot mills to function well, and while these machines were known in the Middle Ages, the sources showed none before the thirteenth century (Reynolds, 1983, pp.99, 172). The last columns in Online Appendix Tables E.2 and F.4 show similarly that very rugged terrain conditions weaken the connection between millwrights and Domesday mills. The last column of Online Appendix Table F.4 replicates the last column of Table 3, only with ruggedness levels between 10 and 20. As can be seen, the first-stage F-statistic is very weak (1.30), and while mills per capita are correlated with wrights per capita, the significance of this correlation is very weak.

Moreover, Online Appendix Table F.4 further explores the relation between mills, wrights and high water flows. The first three columns present the results of the first stage, only with different controls, and the next three columns present the reduced form estimations. As can be seen in the table, the number of mills per capita is not statistically significant in any of these columns. We conclude from these columns that the relation of wrights per capita and high water flows is not robust. Finally, the last three columns show the results when we estimate the relation between wrights and mills using 2SLS. The coefficient of the mills is significant when we control only for the two components of the instrument; it is insignificant when we control for the main geographic, climatic, and agricultural controls; and it is marginally significant in the full specification. Furthermore, the first-stage F-statistic is very low in all three columns, suggesting that the instrument is robust when taking into account high water flows.

5.5.4. *Sensitivity to different levels of wheat suitability*

Online Appendix Table E.3 provides further evidence that our instrument is robust to different levels of suitability for wheat growing. It shows that our instrument is valid if the mean wheat suitability 'category' of a district is either lower than any value between 4.8 and 5.9, but not for higher levels of wheat suitability (recall that category 8 implies that the district has a low value of the suitability index and thus is not suitable for wheat cultivation). The results suggest that moving about 45% of the sample from a control group (that is, low wheat suitability) to the treatment group (that is, high wheat suitability) or vice versa does not change our results.

5.5.5 *Robustness to DB institutions*
Finally, our results may be driven by some historical institutions that affected both the location of DB mills and historical wrights, which in turn affected the location of wrights during the eighteenth century. In Online Appendix Table A.2 we show that the share of royal holdings (King's Vill), the share of ecclesiastical holdings, and the share of arable land held by the lords did not have a significant effect on the location of DB mills. Online Appendix Table F.6 confirms that indeed these institutions do not affect our results.

6. Conclusion

The results presented above lend credence to the hypothesis that on the eve of the first Industrial Revolution, the spatial distribution of mechanically skilled millwrights was the outcome of a persistent process, which began in the early Middle Ages when water mills (invented in Roman times) came into wide use. As Marc Bloch (1966, p.150) memorably put it, by the time of Charlemagne in Gaul and Domesday Book in England, 'for all of those with ears to hear, [these regions] are loud with the music of the millwheel'. The technical demands on building these mills played a key role in the formation of skilled craftsmen. In turn, the mechanically skilled craftsmen trained as wrights assisted other industries that could use waterpower to flourish. This paper presents a test of the persistence that these skills generated.

We highlighted one small but significant segment of England's best and brightest artisans, namely millwrights and engineers. The presence of geographical conditions that favoured the construction of medieval watermills engaged in grain milling created a class of highly trained millwrights whose skills eventually spilled over to the woollen and iron industries. The prevalence of these industries was 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 waterpower in textile manufacturing remained central for many decades in the eighteenth and early nineteenth centuries, before they were eventually superseded by steam power.

The importance of the woollen 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).

We can regard millwrights as a *pars pro toto* of Britain's superior skilled artisans. As detailed in Online Appendix G, millwrights were in the class of highly competent British mechanics, but so were many others: clock- and watchmakers, lens grinders, colliers, locksmiths, toymakers, ironmongers, instrument makers and many manufacturers of up-market consumer goods—all played a role (Kelly *et al.*, 2021).

Were millwrights more important in Britain than elsewhere in Europe? Mills and millwrights by themselves could not, of course, lead to an Industrial Revolution and were hardly a sufficient condition for further progress. Mills were found everywhere in eighteenth-century Europe, if perhaps not quite at the intensity we observe in Britain. In the Netherlands we observe a very high concentration of windmills in some regions, both for hydraulic and industrial purposes. The Dutch published sophisticated and detailed technical descriptions of the mechanics of their mills, such as in the *Groot Volkomen Moolenboek* (1734), an early example of the detailed technical descriptions of handicrafts and production techniques we see later in Enlightenment compilations such as the *Grande Encyclopédie*, and even more in the *Descriptions des Arts et Métiers* (1761–88). But as Davids (2008, vol. 2, p.453) points out, despite the relative openness of Dutch society, the skills of millwrights were 'segmented by specialty' and their skills did not carry over to other industries. In eighteenth-century France, given its heavy dependence of water and wind power, there must have been a great number of millwrights. Yet it is striking that the 80 volumes of the *Descriptions* do not contain a separate volume on millwrighting, despite volumes on wig-making, embroidery, pin-making, anchor-making, and the manufacture of tobacco pipes. The *Grande Encyclopédie* did contain a long and well-illustrated essay on watermills and windmills, but, significantly, it was classified under 'agriculture and rural economy'. Continental Enlightenment scientists were deeply interested in theoretical hydraulics and contributed a great deal to the formal mathematical analysis of hydraulics (Reynolds, 1983). The British Enlightenment, however, was far more down-to-earth and pragmatic than that of the continent, and this difference extended to the effects of its watermills on industries requiring skilled mechanics[28] (see Online Appendix G for details).

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 instill 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 technology during the Industrial Revolution, John R. Harris, realised 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 (MacLeod and Nuvolari, 2009). The crucial role of mechanically trained and highly competent craftsmen in the Industrial Revolution, and thus in the Great Enrichment overall, richly deserves our recognition.

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Additional Supporting Information may be found in the online version of this article:

Online Appendix
Replication Package

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[28] A typical British scientist contributing to hydraulics was John Smeaton, a thoroughly practical experimentalist and engineer, whose breast wheel combined the advantages of over- and undershot mills. But following Smeaton was a large number of engineers trained as millwrights with extensive practical skills, who invented, improved and tweaked water mills and other machinery.

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