# Technology Adoption and Productivity Growth: Evidence from Industrialization in France*

Réka Juhász
(UBC, NBER, and CEPR)

Mara P. Squicciarini
(Bocconi and CEPR)

Nico Voigtländer
(UCLA, NBER, and CEPR)

First version: December 2019
This version: October 2023

### Abstract

New technologies tend to be adopted slowly and – even after being adopted – take time to be reflected in higher aggregate productivity. One prominent explanation for these patterns is the need to reorganize production, which often goes hand-in-hand with major technological breakthroughs. We study a unique setting that allows us to examine the empirical relevance of this explanation: the adoption of mechanized cotton spinning during the First Industrial Revolution in France. The new technology required reorganizing production by moving workers from their homes to the newly-formed factories. Using a novel hand-collected *plant-level* dataset from French archival sources, we show that productivity growth in mechanized cotton spinning was driven by the disappearance of plants in the lower tail – in contrast to other sectors that did not need to reorganize when new technologies were introduced. We provide evidence that this was driven by organizational challenges such as developing optimal plant layout. A process of 'trial and error' led to initially low and widely dispersed productivity, and – in the subsequent decades – to high productivity growth as knowledge diffused through the economy and new entrants adopted improved methods of organizing production.

*JEL: F63, O14*

*Keywords: Industrialization, Technology Adoption, Productivity*

> [T]here were strong pairwise complementary relations between factory organization and machinery [...] employers needed to simultaneously determine the choice of technique, the level of worker effort, and the way incentives were set up and communications and decisions flowed through the firm hierarchy. [...] Factories were the repositories of useful knowledge ... but they were also the places in which experimentation took place. – Mokyr (2010, pp. 345-46)

# 1   Introduction

The diffusion of innovation is at the core of aggregate productivity growth in the long run. Yet, many technologies that ended up being widely adopted were slow to diffuse across firms (Griliches, 1957; Mansfield, 1961; Rosenberg, 1976; Hall, 2004; Comin and Hobijn, 2010). This slow adoption is particularly puzzling given that new technology can provide a substantial boost to firm productivity (Syverson, 2011; Bloom, Eifert, Mahajan, McKenzie, and Roberts, 2013; Giorcelli, 2019). There is also a second, well-documented puzzle: When major innovations such as information technology (IT) or electricity spread across firms, the widely expected boost in aggregate productivity has proved hard to document in the data. This prompted Robert Solow to remark in 1987 that "You can see the computer age everywhere but in the productivity statistics" (*The New York Times, July 12, 1987*).

One prominent explanation for both puzzles is the need to modify and reorganize the production process when adopting major breakthrough technologies (David, 1990; Brynjolfsson, 1993; Brynjolfsson and Hitt, 2000; Hall and Khan, 2003; Brynjolfsson, Rock, and Syverson, 2021). Initially, many firms operate the new technology inefficiently – often because complementary organizational innovations are missing. If these challenges are indeed important during the early phase of technology adoption, we expect them to be reflected in a highly dispersed productivity distribution – due to a lack of standardized organizational knowledge that adopting firms can draw from. However, empirical evidence on this mechanism is scarce, as measuring the productivity distribution specific to new adopters is challenging for numerous reasons. First, standard data sources rarely make it possible to observe the use of specific technologies. Second, it is difficult to observe whether an adopting plant has also reorganized production. Third, productivity under the old and new technology are typically correlated.

This paper shows how the need to reorganize production affects the productivity distribution of adopting plants during the diffusion of a major new technology. We bypass the typical challenges by studying a unique historical setting – the adoption of mechanized cotton spinning in France during the 19th century. Importantly, the macro-inventions that mechanized cotton spinning (the famous spinning jenny, the water-frame, and the mule) went hand-in-hand with the need to reorganize production on a revolutionary scale. Prior to mechanization, workers produced in their homes in a cottage-industry setting. Adopting the new technology required setting up factories from scratch, and moving workers there from their homes because of the reliance on inanimate

power sources and the need to monitor workers more closely (Williamson, 1980; Szostak, 1989). This led to one of the most dramatic shifts in the organization of production in economic history (Mokyr, 2011). While the key elements of the new spinning technology itself were well-known across France (Horn, 2006), and multiple domestic producers supplied firms with the machinery (Chassagne, 1991), its adoption occurred in the absence of complementary knowledge on how the new cotton spinning plants should be organized (Pollard, 1965).

A number of features of this setting allow us to isolate the productivity distribution of adopters and study its evolution over a long time horizon (three decades), making headway on the typical empirical challenges faced by the literature. In particular, the sharp break in the *location* of production due to its organization in plants makes it possible to distinguish adopters of the new technology from old producers. This addresses the first two empirical challenges mentioned above. Moreover, the first generation of mechanized cotton spinners did not typically have a background in the old technology, suggesting that productivity under the two technologies were not systematically related, which addresses the third challenge.

Our empirical analysis is based on a novel, hand-collected plant-level dataset from historical surveys covering three sectors (mechanized cotton spinning, metallurgy, and paper milling) at two points in time, around 1800 and in the 1840s. To help distinguish the effect of reorganization from broader trends such as general productivity growth, political and institutional change, or enhanced regional integration, we compare the evolution of the plant productivity distribution in mechanized cotton spinning to two comparison sectors (metallurgy and paper milling). This is similar in spirit to a difference-in-differences strategy. Crucially, in both comparison sectors, production was already organized in plants for centuries before the Industrial Revolution because of their reliance on water power and high-fixed-cost machinery. As a consequence, these sectors possessed fairly standardized knowledge about how to organize plant-based production. Moreover, during our sample period, all three sectors witnessed the arrival of new technologies that could be introduced fairly seamlessly into the *existing* organization of production.[1] Thus, while all three sectors were adopting new technologies, only mechanized cotton spinning had to adapt to a radically reorganized production process.

We document four main findings for mechanized cotton spinning plants: 1) we observe a highly dispersed productivity distribution in the initial period (1806) relative to 1840; 2) we estimate that the industry underwent a substantial (82%) increase in plant productivity between 1806 and 1840 *after* mechanization had already been adopted; 3) this aggregate productivity growth was largely

---

[1]In mechanized cotton spinning, there were improvements to the existing vintages of machinery and in preparatory processes (Allen, 2009). In paper milling, one part of the production process was mechanized (André, 1996) and in metallurgy, charcoal was replaced with coal as the source of fuel (Pounds and Parker, 1957). As we discuss in more detail below, the three industries shared important similarities in adopting these new technologies during our sample period. This supports our implicit assumption that technological additions to the *existing* production setups did not lead to differential productivity trends.

driven by the disappearance of plants in the lower tail of the distribution (which we refer to as 'lower-tail bias' of productivity growth); 4) the disappearance of the lower tail took place almost exclusively through plant exit and entry. Inefficient producers were replaced by more efficient entrants. In the comparison sectors, we also find a sizeable increase in plant productivity during the sample period (68% in metallurgy and 33% in paper milling). However, the lower-tail bias of productivity growth is unique to mechanized cotton spinning. In contrast, in the comparison sectors, the entire productivity distribution shifted right. Taken together, we interpret these results as suggestive of a link between the lower-tail bias of productivity growth and the feature unique to the mechanized cotton spinning industry – the need to reorganize production.

The second part of the paper examines why the need to reorganize production would lead to a lower-tail bias in productivity growth. Central to our argument is the fact that, at early stages of technology adoption, plants need to learn about optimal organizational forms. To fix ideas, we provide a simple framework in which plants endogenously learn about the optimal organization of *multiple* inputs or tasks in the spirit of Perla and Tonetti (2014). These tasks reflect organizational challenges such as optimal plant layout, and they exhibit complementarities in the production function. We show that these features initially, when plants have little knowledge about the optimal ways to perform these tasks, lead to a fat lower tail in the plant productivity distribution. Over time, as plants learn about the efficient organization of inputs, the lower tail disappears. We present both historical and empirical evidence consistent with this.

According to the historical literature, there were two broad classes of challenges that early cotton spinning mills faced. First, they needed to contend with a range of issues related to mill layout and design. As Allen (2009, p.184) writes: "The cotton mill, in other words, had to be invented as well as the spinning machinery *per se*." Second, a set of labor management innovations were required for setting up and operating spinning mills at a scale not seen elsewhere in the economy (Pollard, 1965). We examine the data for evidence consistent with the spread of organizational practices. We provide evidence for the spatial diffusion of knowledge during the early phase of industrialization, by showing that cotton plants located closer to high-productivity peers were themselves more productive. Strikingly, this spatial productivity pattern is not present in the comparison sectors, where plant-based production methods were more mature, nor in cotton spinning in the long-run, once organizational knowledge had diffused. We show, using a rich set of controls and placebo tests, that these results are unlikely to be driven either by selection into productive locations or by omitted variables.

While these results are suggestive of a role for the spatial diffusion of knowledge, they do not distinguish between learning about the new technology itself (i.e., how to operate and maintain the new machines) and learning about efficient organizational forms. We provide direct evidence for the latter using detailed metrics on cotton spinning plant design from our sample period. We

find that during the early phase of adoption, two key design features (number of floors and square-ness of its layout) were chosen almost at random – consistent with plants experimenting with how to organize the factory floor optimally. Later, as best-practice knowledge spread, these metrics converged towards much narrower distributions around the optimum. We provide additional complementary evidence that helps us to distinguish the two forms of learning. If plants were learning mostly how to operate the newly adopted technologies, we would expect incumbents to have an advantage relative to newer entrants. On the other hand, if organizational knowledge on plant design diffused over time, we would expect later adopters to have an advantage in setting up their factories. Two features in the data point to the latter: First, cotton spinning plants that entered the market *later* had higher productivity during the initial phase of adoption. This holds even after controlling for newer capital vintages, and it does not hold for the comparison sectors or for cotton spinning in later periods. Second, the exit rate of plants in mechanized cotton spinning was substantially higher than in other sectors between 1800 and 1840, and buildings were also abandoned for use by the industry at higher rates. These findings suggest that knowledge of how to set up and organize cotton plants spread over time (and space), giving an edge to new entrants.

We examine alternative explanations that could account for our results. While our DID-style evidence based on the comparison sectors addresses many potential concerns, it is possible that some alternative channels affected mechanized spinning *differentially*. We control for a large set of these directly, showing that the lower-tail bias of productivity growth remains robust. For example, our results hold with region fixed effects, suggesting that the sorting of cotton plants into areas with better location fundamentals, better market access, or better input markets are unlikely to drive our results. Region fixed effects also make it unlikely that the Napoleonic Blockade, which had a regionally differential effect across France in mechanized cotton spinning (Juhász, 2018), drives our findings. We also account for possible more localized confounders, such as battles during the Napoleonic Wars or location-specific market access. Finally, plant-specific features such as size, output quality, capital deepening, and plant life-cycle characteristics do not confound our results, and they are also robust to excluding all plants that could be smaller 'spinning workshops' (which shared some, but not all characteristics of mature factory-based production). For a systematic overview of alternative mechanisms and the corresponding robustness, we refer the reader to the summary table in Appendix F.

*Related Literature and Contribution.* Our paper is closely related to a literature on innovation and technology adoption in manufacturing – particularly the strand that has studied the productivity effects of the adoption of IT.[2] Interestingly, some of the patterns we document for mechanized cotton spinning have been found in other settings. For example, Syverson (2011) discusses that the

---

[2]See Hall and Khan (2003) and Hall (2004) for an overview of the literature on technology diffusion. Brynjolfsson and Hitt (2000) and Syverson (2011) discuss the literature on the productivity effects of IT.

adoption of IT capital is associated with increased within-industry productivity dispersion. Foster, Grim, Haltiwanger, and Wolf (2018) provide empirical support for the argument by Gort and Klepper (1982) that periods of rapid innovation are associated with a surge in firm entry, followed by a period where experience with the new technology is accumulated, eventually leading to a shakeout where unsuccessful firms (or plants) exit. Brynjolfsson and Hitt (2000) conjecture that the surge in aggregate productivity in the 1990s was explained in part as a return on the large, intangible complementary organizational innovations that firms had undertaken in prior decades to make efficient use of IT. Our paper contributes to this literature in two ways. First, we provide evidence that these patterns generalize to other settings in which major new technologies are adopted. Second, our unique setting allows us to more closely tie these patterns to the need to reorganize production that often accompanies major technological change. In particular, initial information disparities about the optimal organization of production can help to explain why breakthrough technologies tend to be adopted slowly and – even after being adopted – take time to be reflected in higher aggregate productivity. Along this dimension, our paper relates to recent work that documents how a variety of organizational barriers can impede technology adoption (Atkin, Chaudhry, Chaudry, Khandelwal, and Verhoogen, 2017; Feigenbaum and Gross, 2021).

In addition, our paper brings the insights of the firm productivity literature to the most important structural break in economic history – the First Industrial Revolution, which saw unprecedented growth in manufacturing productivity (Crafts, 1985; Crafts and Harley, 1992; Galor, 2011). So far, productivity growth during this period has been studied mostly at the country level, or – in some cases – at the aggregate sectoral level.[3] Our paper is the first to study the contribution of plant dynamics to manufacturing productivity improvements during the Industrial Revolution. Our focus on the overall plant productivity distribution allows us to shed new light on how productivity growth evolved during this important period.[4] In particular, we isolate and track the productivity distribution of newly created adopting plants in cotton spinning. This goes beyond previous work (including with modern data), where major new technologies are typically introduced by existing producers, so that the changes in the productivity distribution reflect *both* the productivity differential of the new technology and subsequent gains due to organizational improvements. We are also the first to show that the extensive margin of plant entry and exit contributed decisively to productivity growth during the Industrial Revolution. Finally, we complement a rich historical literature by providing the first systematic empirical evidence for the importance of organizational innovations in driving productivity growth during the Industrial Revolution (Pollard, 1965; Sokoloff,

---

[3]Closely related, Clark (1987) studies cross-country differences in the productivity of mechanized cotton spinning, but only at the sectoral level. Braguinsky, Ohyama, Okazaki, and Syverson (2015) study the Japanese cotton spinning industry in the late 19th century and early 20th century. Rather than technology adoption, their paper focuses on the effects of acquisitions on acquired plants.

[4]In related work, Braguinsky, Ohyama, Okazaki, and Syverson (2021) study how cotton firms grow by innovating vertically and horizontally in Japan's Meiji period in the late 19th and early 20th century.

1984, 1986).

The paper is structured as follows. The next section discusses the historical context. Section 3 describes the data, while Section 4 presents and discusses our empirical results. Section 5 sheds light on the underlying mechanism, and Section 6 concludes.

## 2 Historical Background

In this section we describe the key features of the historical setting. First, we discuss why mechanized cotton spinning and its adoption in France presents a well-suited setting to examine the productivity effects of major technological breakthroughs. Second, we introduce the three sectors that we analyze in the paper. We first describe the process of mechanization in cotton spinning and discuss the reorganization of production that it entailed. Finally, we introduce our two comparison sectors. We summarize the most important aspects in the main text. Appendix A contains a more extensive discussion.

### 2.1 The Industrial Revolution in Britain and its Spread to France

Early nineteenth century France presents an opportune setting for our study of technology adoption. First, the development of mechanized cotton spinning during this time period is widely seen as a macro-invention (or general purpose technology), whose effects on the economy were similar to the development of the steam engine, electrification, or the information technology (IT) revolution.[5] Mechanized cotton spinning belongs in this category partly because its path-breaking innovations enabled the subsequent mechanization in other branches of the textile industry such as wool, linen, and silk (c.f. Jenkins, 2003). Freeman and Louçã (2001) include innovations in the cotton textile industry among the first major wave of industrialization, with steam power and railways fueling the second wave, and electrification, the third. As Freeman and Louçã (2001, p. 156) put it: "many of the organizational as well as technical innovations in cotton were followed later by other branches of the textile industry and by manufacturing more generally." Similarly, Pollard (1965); Mokyr (2016) emphasize that mechanization in cotton spinning was the birth of the modern factory system, which fundamentally altered the organization of production – first in this industry itself, and later in manufacturing more broadly.

Second, studying mechanized cotton spinning in France – a follower country – allows us to focus on technology *adoption*, as opposed to *innovation*. As is well-known, the flagship inventions of the Industrial Revolution – most notably the spinning jenny and the coke-fired blast furnace – were developed in Britain. While England was the first country to industrialize, France was an early follower. The latest estimates for France find an acceleration in economic growth around 1800,

---

[5]Macro-inventions, or general purpose technologies, are typically defined as generic products, processes or organizational forms (Lipsey, Carlaw, and Bekar, 2005) that generate spillovers across sectors and set in motion a whole stream of advances that result in large productivity improvements (Bresnahan and Trajtenberg, 1995; Lipsey et al., 2005; Allen, 2009). See Dudley (2010) for a discussion.

well after growth in England took off (Ridolfi and Nuvolari, 2021). During the initial phase of French industrialization, new technologies arrived from Britain (Mokyr, 2021). The processes of innovation and adoption differed in the two countries. While Britain may have had a comparative advantage in *developing* commercially viable machines and mills due to its highly skilled workers (artisans, engineers, millwrights), France was arguably the world leader in science (Gillispie, 2004), which may have facilitated technology adoption. Indeed, Nuvolari, Tortorici, and Vasta (2023) use patent data to show that France was able to effectively absorb key technologies from Britain in this period. However, the mere adoption of these technologies was only one step. Their integration in factory settings and efficient operation presented major challenges (Mokyr, 2021). The tacit, non-codified aspect of British industrial know-how is important in this context, as it explains why the French needed to undertake costly experimentation to efficiently operate the technology. Appendix A.1 contains further details about the Industrial Revolution in France.

## 2.2  Cotton Spinning: Mechanization and Reorganization of Production

This section discusses the main historical features and challenges in the transition to mechanized cotton spinning. Appendix A.2 and A.3 provide further detail.

*Development of mechanized spinning.*  Cotton textiles was the flagship industry of the First Industrial Revolution, contributing one-quarter of TFP growth in Britain during the period 1780-1860 (Crafts, 1985). Cotton spinning is the process by which raw cotton fiber is twisted into yarn. Traditionally, this task was performed mostly by women in their homes, using a simple spinning wheel (see Figure A.1 in the appendix). With this old technology, each spinner was able to spin only one thread of yarn at a time. The industry was rurally organized and generally centered around a local merchant-manufacturer who would supply spinners with the raw cotton, collect their output, take care of the marketing, and who often also owned the spinning wheels (Huberman, 1996).

The breakthrough 'macro-inventions' in spinning were forged in Britain in the 1760s and 1770s, when three new vintages of machinery (the spinning jenny, the water-frame and the mule) were developed in quick succession. The left panel in Figure A.2 depicts the mule; Allen (2009) provides an in-depth discussion of each vintage. These new machines made it possible to spin multiple threads simultaneously, as twist was imparted to the fibre not by using the workers' hands, but rather by using spindles. These innovations required production to move from workers' homes to the factory floor for two reasons. First, the machines almost always used inanimate power sources (typically water power), which led to the concentration of production in one location. Second, mechanized production increased the need for monitoring workers because of the complementarity of their tasks, but also because the machinery with which they worked was both more complex and more expensive (Williamson, 1980; Geraghty, 2007; Mokyr, 2010).

The productivity effect of these innovations was enormous. Allen (2009) estimates that the first vintage of the spinning jenny alone led to a threefold improvement in labor productivity.

Correspondingly, the price of yarn declined rapidly in the late 18th century (see Appendix Figure A.3), especially for the highest-quality yarn, where prices declined from 1,091 pence per pound to 76 pence per pound in real terms between 1785 and 1800 (Harley, 1998).

During the early decades of the 19th century, the mechanized cotton-spinning industry was characterized by a steady stream of micro-inventions (Allen, 2009, p. 206). Importantly, the next major innovation, the self-acting mule (a completely new vintage of spinning machinery), did not spread widely until the 1840s, i.e., until after our sample period (Huberman, 1996). Thus, there was no major technology switching during our period of study, but rather a steady stream of inventions that improved existing vintages.

*Adoption of mechanized spinning in France.* Mechanized spinning was adopted with some lag in France. Efforts to adopt the technology had begun with state support during the *Ancien Régime*. By the time of our first cotton spinning survey in 1806, the large-scale expansion of the industry documented in Juhász (2018) had just begun. The existence of the technology was known throughout the country (Horn, 2006), and a number of domestic spinning machine-makers had been established (Chassagne, 1991). The spinning machinery itself was produced locally (using British blueprints) because of a ban on exporting machinery (and the emigration of engineers and skilled workers) from Britain until 1843 (Saxonhouse and Wright, 2004). All three vintages (the spinning-jenny, the water-frame, and the mule) were used in France. Importantly, when widespread adoption in France began, the technology – and in particular its optimal organization – was far from being mature in Britain. Thus, while France was a follower country, it could not copy a 'mature' technology, as we discuss in more detail below.

*The challenging transition to factory-based production in cotton spinning.* The transition of workers from their homes to the factory floor has been characterized as "one of the most dramatic sea changes in economic history" (Mokyr, 2010, p. 339). It fundamentally altered people's lives and, importantly for our setting, posed a host of challenges for the first generation of large-scale factories.

In the case of cotton spinning, adopting the first generation of mechanized spinning machinery went hand-in-hand with the need to organize production in plants rather than homes. While cotton spinning was not the first sector to organize production in plants, the industry faced challenges for which a standard set of solutions did not exist at the time. Partly, this was because the knowledge required was largely technical and hence industry-specific (Pollard, 1965, p. 158). In addition, mechanized cotton spinning mills pioneered *flow production* – that is, the production of standardized goods in huge quantities at low unit costs by "arranging machines and equipment in line sequence to process goods continuously through a sequence of specialized operations" (Chapman, 1974, p. 470). This led to a finer division of labor and larger-scale plants than what had been seen before in other sectors, raising novel challenges (Chapman, 1974).

Flow production meant that machines and equipment had to be spatially organized and co-ordinated such that the "continuous (twenty-four hours a day) synchronisation of a sequence of highly specialised machines" (Chapman, 1974, p. 472) could be achieved. This organizational innovation, pioneered in cotton spinning, distinguishes 'proto-factories' from the 'factory proper' (Chapman, 1974; Markus, 2013). Under the former, older, system, "several batch processes are centralised into a large unit with a systematic grouping of machines, with or without water power, without linked semi-automatic processes" (Markus, 2013, p. 262). In the factory proper, "power and automatic machinery are organised for flow production in 24-hour operation. Water or steam power is a necessary but not sufficient defining feature" (Markus, 2013, p. 262).

Mechanized cotton spinning firms needed to resolve a range of issues related to mill layout and design. Allen (2009, p. 202) discusses some of the key challenges in developing the first mills in Britain: "...design issues emerged regarding the spatial location of the various machines, the flow of materials from one to the next, and the provision of power throughout a multi-story building." It is useful to highlight three complementary aspects of mill design challenges that spinners faced. First, as we have seen, flow production meant that the production line needed to be synchronized so that the layout (i.e., the floorplan) of the building became important. For example, factories needed to be sufficiently wide for a mule operative to work two mules alternately, which were placed back to back in pairs (see Markus, 2013, p. 265, also illustrated on the right-hand side of Figure A.2). Second, flow production relied on the mechanization of each step of the production process (Chapman, 1974), which meant that power needed to be continuously distributed throughout the building. In Britain, Chapman (1970, p. 239) claims that there were only a handful of millwrights, *qualified from experience*, capable of undertaking the construction of the gearing for the new cotton mills. Third, a mechanized production line at this scale introduced a host of structural challenges. For example, building structures needed to withstand the stress they faced from the vibrations of machines (Chassagne, 1991, p. 435). Iron rods with plates held beams to the masonry walls to prevent the vibrations of machines from shaking the walls apart (Langenbach, 2013). Similarly, buildings had to be well-lit, which created design challenges to let as much daylight as possible reach the spindles, and it implied massive fire hazards when gas lights were used, due to the highly inflammable cotton dust (Markus, 2013).

These were novel, complementary challenges for which a standard set of solutions did not exist at the time. The industry experimented through a process of trial and error. Successful mill designs in England were observed and copied (Chapman, 1970, p. 239). It took time for design defects to be improved; for example, contemporaries were aware of ventilation problems in the Arkwright-style mills, but continued to use the same layout regardless (Fitton and Wadsworth, 1958, p. 98). Appendix A.3 provides further detail on the process of trial and error in developing solutions to building design challenges.

In addition to design-related organizational challenges, a large set of management innovations were required to run spinning mills efficiently. In the 'Genesis of Modern Management,' Pollard (1965, p. 160) described the development of efficient labor management practices as the primary management challenge facing early factories. There were three salient aspects of this for cotton spinning mills; i) how to get workers, who were used to the independence of the domestic system, to adapt to the rhythm and hierarchy of factory work, ii) how to coordinate and implement a fine division of labor, and iii) how to solve monitoring problems. Appendix A.3 discusses these challenges in more detail. Here, we give one illustrative example.

Renumeration in the pre-industrial home spinning system was characterized by piece rates. This made sense, given that the merchant had no way to monitor worker effort. The move to continuous flow production made piece rates unworkable. The speed of production was controlled by the entire production line, not individual workers. This is illustrated by Karl Marx, who quoted a large cotton manufacturer, Henry Ashworth: "When a laborer lays down his spade, he renders useless for that period, a capital worth eighteen pence. When one of our people leaves the mill he renders useless a capital that cost *£100,000*" (Clark, 1994, p. 129). Piece rates became impractical because the teamwork inherent to flow production made it difficult to determine the contribution of individual workers (Mokyr, 2016, p. 344). The alternative, a time wage, raised incentive issues because monitoring individual worker effort was difficult in cotton mills (Huberman, 1996). The solution was not obvious, and it was context-specific. In cotton mills, employers experimented with a variety of techniques: some paid the entire team (which in turn created issues with the internal distribution within teams); other early factories solved the team production issue by hiring entire families as a work unit and paying them a piece rate (Mokyr, 2016). Huberman (1996) estimates that it took two generations for efficient labor management practices to be developed in cotton spinning. Finally, around 1830, the industry in Britain settled on efficiency wages (Huberman, 1996).

The first generation of mechanized cotton spinners faced these complementary design and management challenges all at once. Not only did best-practice solutions emerge slowly, but it also took time for this new body of knowledge to coalesce. According to Pollard (1965), the process was more or less complete around 1830 in Britain: "a cotton mill was so closely circumscribed by its standard machinery, and there was so much less scope for individual design, skill or new solutions to new problems, by 1830, at least, ... that little originality in internal layout was required from any but a handful of leaders" (Pollard, 1965, p. 90).

*Knowledge diffusion in mechanized cotton spinning.* How did the first generation of mechanized cotton spinners learn the solution to these organizational challenges? Given our discussion above, it is unlikely that there were important spillovers from home spinning to mechanized plants. The sharp break in organizational form under the new technology rendered experience with the old

technology effectively useless. Chassagne (1991, p.274) presents suggestive evidence to support this assertion: According to data on owners of 148 mechanized cotton spinning establishments between 1785-1815 in France, "traders, bankers and commercial employees" accounted for the vast majority (62.5%) of entrepreneurs. While these figures have to be interpreted with caution (they probably oversample larger, better-known plants), they point to the importance of commercial knowledge as opposed to previous experience with handspinning in setting up cotton spinning factories. This suggests that productivity under the old and new technology were not systematically related.

Knowledge spillovers *across* sectors are also unlikely to have played an important role. As we discussed above, mechanized cotton spinners had to contend with new challenges that had not been encountered in other sectors, even those that were organized as 'proto-factories' in 1800. For example, André (1996) notes that there were no standardized mill designs in paper milling (one of our comparison sectors) – arguably because it did not feature flow production, making it less crucial that all production steps were efficiently integrated. Moreover, much knowledge was highly industry-specific (Pollard, 1965). Again, Chassagne (1991) presents suggestive evidence to support this pattern. Only 10% of early cotton spinners in his sample had a background in another industry – of these, most came from cotton printing, a relatively close industry, and almost none came from other sectors whose production was organized in plants (Chassagne, 1991, p. 274).

For French cotton spinners, the most important source of knowledge about plant design and organization was Britain. However, spillovers from Britain were limited for a number of reasons: It wasn't until the 1830s that the British began to codify best practice in manuals (Pollard, 1965), and even that was limited because a lot of the industry's knowledge was tacit (Mokyr, 2001, 2010). In addition, there were British bans on knowledge transfer (Horn, 2006; Chassagne, 1991). Finally, the best practice that the British industry eventually converged to was not necessarily applicable to plants in France, as local conditions were different. For example, the abundance of water power meant that French spinners mostly relied on hydropower throughout our sample period, in contrast to the British reliance on steam power (Cameron, 1985). Chassagne (1991) notes that the French solution eventually developed for mitigating fire hazards in cotton mills was to build factories with fewer floors. This may have been possible in France as water power allowed the industry to remain more rural than was the case in Britain, where the industry moved into dense, urban environments.

When knowledge about plant design diffused, this often occurred in spatial proximity. For both Britain and France, the historical record is full of examples of knowledge diffusion embodied in engineers and other skilled workers, who were hired by local entrepreneurs to design and build plants (Chapman, 1970; Chassagne, 1991). For example, English engineers were recruited in Toulouse (circumventing legal bans) to build a cotton spinning plant. Once they had finished, a number of them were hired by other local entrepreneurs, and some set up their own mills nearby

(Chassagne, 1991, pp. 243-244). Additionally, the French (local and central) government often incentivized the diffusion of knowledge. Horn (2006, pp. 83-84) describes how the Bureau of Encouragement at Amiens (in Picardy) provided capital for an English machine-builder to install machines for one French plant. In exchange, the firm had to commit to sharing "their techniques and technical know-how" with other firms. Other entrepreneurs in Picardy came to the plant in Amiens to study their machines and processes. The technology transfer that took place was not passive. Local workers tinkered with the machines installed by the English and improved on their designs in various ways, adapting them to local needs (Horn, 2006).

## 2.3 Comparison Sectors: Metallurgy and Paper Milling

We have highlighted the challenges in reorganizing production in mechanized cotton spinning. To distinguish these from other, broader, trends at the time, we examine two sectors that did not need to reorganize production during this period – our 'comparison sectors.' We summarize the most important characteristics of these industries for our purposes below. Appendix A.4 contains a more detailed discussion.

Metallurgy, the sector that supplied iron and steel to the rest of the economy, was a flagship industry of the Industrial Revolution. Paper milling – while not particularly important for other sectors – also underwent mechanization, which renders it a useful comparison sector. Despite the obvious differences in the production processes, metallurgy and paper milling share an important characteristic that differentiates them from mechanized cotton spinning.

*Difference with cotton spinning: plant production before 1800.* Both metallurgy and paper milling had already organized production in plants since well before the Industrial Revolution. In metallurgy, plant production was mostly due to a reliance on high fixed-cost machinery such as the furnaces used both in smelting and refining. In paper milling, production was organized in plants because of a reliance on water power. The early start to plant-based production meant that these sectors had already accumulated industry-specific expertise in building design and labor management. Thus, both comparison sectors fit well the characterization of 'proto-factories' described above. Appendix A.5 uses *Encyclopédie* plates to show that best-practice methods and codified knowledge already existed for the two comparison sectors in the late 18th century. These plates illustrate crafts, processes, and inventions, thus representing a unique source of information to study the existence of codified manufacturing knowledge at the time. As André (1996, p. 21) writes about the entries referring to paper milling, "The classic reference for technical descriptions of paper milling is Diderot and D'Alambert's famous 18th century *Grande Encyclopédie* ... [Here], one will find the different practices, with the terminology used in different provinces..." For metallurgy and paper milling, there were many *Encyclopédie* plates illustrating information on plant organization and production technology, while there are no such plates for mechanized cotton spinning (Figure A.9). Note that the absence of plates on mechanized cotton spinning is not surprising,

12

since this technology had just been invented; the most important take-away from these data is that codified knowledge was indeed available for our two comparison sectors in the late 18th century.

*Similarities between the comparison sectors and mechanized cotton spinning.* Once cotton spinning had mechanized and shifted to plant production, the subsequent development shares important similarities with the comparison sectors. All three experienced a steady flow of productivity-enhancing 'micro'-inventions over our sample period, and in all cases, these were integrated into *existing* plants. In each sector, workers needed to be retrained to work with the new equipment (Gille, 1968; Horn, 2006; André, 1996). However, there was no need to re-organize production, as the plant setup was not affected.

The source country of the technology in each case was Britain. Thus, similar barriers to diffusion applied to all sectors, and machines were typically built in France because of the ban on exports from Britain. Appendix A.6 presents patenting data from Britain, showing that all three sectors witnessed the consistent arrival of patents during our sample period. Spinning was the third-most patent intensive out of the 146 categories; metallurgy ranked ninth, and paper milling twenty-first. It should be noted that spinning patents include those for all textile fibers, so that patent intensity in *cotton* spinning was actually closer to those in the comparison sectors.

In what follows, we briefly discuss the most important innovations in the comparison sectors, showing that they were integrated in the existing plant settings. In paper milling, the main technological innovation was the mechanization of forming paper with the Fourdrinier machine (one step in the production process). This invention still forms the basis of paper making today. Changes in the factory layout were not required to introduce the Fourdrinier machine (see Figures A.6 and A.7). It was thus uncommon to establish new plants for the sole purpose of mechanization. Modifications and enlargements of existing plants were often undertaken without having to substantially modify other parts of the production process, and – in contrast to flow production in cotton milling – different parts of the paper milling process could be hosted in different buildings. For example, when plants adopted the Fourdrinier machine, they typically merely reconstructed the two sections hosting the cylinders and the machine, while re-using the buildings previously devoted to the other operations (André, 1996, p. 178). Similarly, while workers had to be trained to operate the new technologies, there is little surviving record of substantial labor conflicts or management challenges (André, 1996, p. 246).

Metallurgy in France also witnessed technology adoption in *existing* plants (Gille, 1968), suggesting that major reorganization of production was not necessary. The most prominent innovation was the switch from charcoal to coal. Given that the new equipment itself was similar to the older one (Pollard, 1965), its introduction merely required modification or replacement of existing machines and ovens (see the illustration in Figures A.4 and A.5). The main reason for setting up new plants was not technological, but to locate closer to coal sources.

In summary, the three industries share important similarities in adopting new technologies during our sample period. However, the need to reorganize production, and the introduction of flow production, was unique to cotton spinning.

## 3   Data

Our analysis is based on a novel, plant-level dataset for the initial phase of industrialization in France. The data have a panel-like structure covering three industries: mechanized cotton spinning, metallurgy, and paper milling. We observe plants in these sectors at two points in time: around 1800 and around 1840. We construct the dataset from four main sources that we describe below. We also discuss the construction of the main variables in our analysis: plant-level labor productivity, plant location, and plant survival for all sectors. Appendix B contains further information on data sources and processing.

### 3.1   Plant-Level Industrial Surveys

Detailed, plant-level industrial surveys form the basis of our dataset. We build on large-scale data collections by the French state over the period 1789-1815. France's innovations in data gathering during this period are frequently praised as the basis of modern statistical data collection (Perrot and Woolf, 1984). We use data from three industry-specific surveys conducted around 1800 and link these to the first manufacturing census in France, 1839-47.

The survey for paper milling was implemented in 1794 during the French Revolution; it contains data on 520 plants. The most important survey for our analysis – mechanized cotton spinning – was conducted by the Napoleonic regime in 1806, covering 340 plants. The survey in metallurgy in 1811 covers 470 plants. Finally, the first manufacturing census in France was initiated in 1839, and the results were published in 1847. While this census covers all manufacturing establishments, we only use data for cotton spinning (528 plants), metallurgy (896 plants), and paper milling (347 plants). For simplicity, we use "1800" throughout the paper to refer to the period of the three early surveys, and "1840" to refer to the later manufacturing census.

The quality of our data sources is high. Each has been scrutinized by economic historians (Bonin and Langlois, 1987; Chanut, Heffer, Mairesse, and Postel-Vinay, 2000; Chassagne, 1976; Woronoff, 1984), allowing us to understand their strengths, as well as their limitations. The three industrial surveys and the first industrial census were conducted in a similar way. The central government sent detailed, standardized questionnaires to local government officials (usually prefects at the département level). The officials and their subordinates (subprefects and mayors) were tasked with identifying and enumerating the relevant plants in their jurisdiction. Plants themselves typically submitted the requested information to local officials, who were also tasked with validating that the submitted records were correct (Ministère de l'Agriculture et du Commerce, 1847, p. xviii). In all cases, the motivation for collecting the data was to gather statistical information as

opposed to tax collection.

The fact that the surveys were carried out by local officials contributed to the high data quality, as they were able to cross-check the responses against other sources and use expert guidance (Perrot and Woolf, 1984, p. 161).[6] Furthermore, France had experience in conducting industrial surveys dating back to the *ancien régime*. Thus, in many cases officials merely needed to update existing knowledge as opposed to starting from scratch (Chassagne, 1976; Ministère de l'Agriculture et du Commerce, 1847). For all surveys, the geographic coverage is close to complete, with only a handful of *départements* failing to submit returns. These surveys have been characterized as a true administrative feat of the French government (Chassagne, 1976, p. 350).[7] Figure A.14 shows the spatial distribution of plants around 1800 and in 1840 for the three industries. Although plants are more concentrated in some regions than others, we have broad coverage across all of modern-day France. For the three industry-specific surveys from the 1800s, the data that have survived are the handwritten returns submitted by the *département* and located in the National Archives in Paris. These are at the plant level in all cases, but were not cleaned or harmonized by the central authorities in any way at the time. We use the data assembled by Juhász (2018) for the mechanized cotton spinning industry. For the other two sectors, we collected, digitized, cleaned, and harmonized the handwritten surveys. For the manufacturing census from 1840, the data were cleaned, harmonized, and organized centrally. The results were published by the Ministry of Agriculture and Commerce in four volumes in 1847 *"(Statistique de La France: Industrie)"*. These volumes served as the raw data for the digitization undertaken by Chanut et al. (2000). We use the latter source for our analysis.

Appendix B describes the specific context for each individual survey and assesses their quality along a number of dimensions. A limitation of our overall setup arises from the different years in which the initial surveys were carried out across the three sectors (1794, 1806 and 1811). This may present a challenge if the economic environment changed over this period. We confront this issue by examining the robustness of our results to some of the most important shocks in this period (in particular, the Napoleonic blockade and the Napoleonic Wars).

## 3.2 Main Data Construction Steps

In what follows, we discuss the most important steps in the construction of our dataset.

---

[6]For example, Perrot (1975, p. 161) writes; "Woronoff has demonstrated the high level of reliability of the statistics on mines and forges, where the visitations by engineers corresponded to the sophisticated elaboration of questionnaires calculated to trap forge owners into revealing accurate figures."

[7]In particular, Chassagne (1976, pp. 350-351) describes the mechanized cotton survey as follows: "the survey obviously testifies first of all to the efficiency of the prefectural system. Of the 109 prefects questioned, 107 responded [...]. This represents a real administrative performance, since none of the prefects had the information immediately available to respond to requests from the central administration. The realization of this work certainly made it possible, at all levels of the administrative hierarchy, to appreciate the competence and to stimulate the zeal of the civil servants, who were always candidates for a promotion."

### 3.2.1 Estimating labor productivity

Our main variable of interest is plant-level labor productivity, defined as log revenues per worker. We use this measure in our baseline estimates because it can be constructed for all sectors and in both time periods. For mechanized cotton spinning, we can also construct plant-level TFP. We face two challenges in constructing consistent productivity measures across plants and time. First, while the surveys for the three sectors around 1800 report output *quantity* (and some information on product-specific prices and quality), the census in 1840 reports plant-specific *revenues* (but not output quantities). To render productivity measures comparable over time, we have to construct revenues for 1800. Second, worker categories are not consistently reported across all plants in 1800 in metallurgy and paper milling. We describe how we deal with each of these issues below.

### 3.2.2 Estimating plant revenues in 1800

*In cotton spinning*, the 1806 survey reports the quantity of yarn spun as well as the minimum and maximum count of yarn spun – where the count of yarn is the standardized measure of quality in the sector.[8] We construct plant-level revenue by multiplying the quantity of plant-level output by the price of the average quality of yarn produced by the plant. We use a schedule of prices for different counts of yarn reported by the French government (*Archives Nationales, F12/533*). In practice, the adjustment in price for the different qualities produced is not crucial for our results (which we confirm with a battery of robustness checks). The reason for this is that the quality produced by the majority of plants is fairly similar. The interquartile range (25th to 75th percentile) for the average quality of yarn produced by the plants in our sample is 20 – 47.5. That is, most plants produced relatively low quality cotton yarn in this period (high count yarns typically start around 100). This is consistent with the British experience (Harley, 1998).

*In metallurgy*, the 1811 survey asked for the quantity of output produced (by product, e.g., pig iron, natural steel, etc.), as well as the price charged by the plant, by product type. While product-specific output quantity is reported by all plants, the product-specific price is only reported by a subset of plants. We compute the average price for each product using the subset of plants where the price information is available. We obtain plant revenues by multiplying product-specific plant output by the average price for the respective product, and summing across products of a given plant.

*In paper milling*, the 1794 survey reports the total quantity of paper products produced, but it does not provide plant-specific output prices. To construct revenues, we multiply plants' output quantity with the average price of paper products as reported in the *Tableaux du Maximum* – a data source compiled in 1794 during the French Revolution that provides detailed data on goods prices and

---

[8]We use the (unweighted) average of the minimum and maximum count of the yarn produced by the plant as a proxy for its average output quality. The maximum and minimum count is the only information that plants provided on the quality of yarn that they produced.

trade links across French regions.

Finally, to compare revenues in the earlier periods and in 1840, for all three sectors, we deflate revenue data using the wholesale price index for the respective survey years from Mitchell (2003). We note in passing that potential errors in the deflators would affect our estimates for *average* growth rates in the three sectors between 1800 and 1840, but they would not change the growth patterns over the plant distribution (e.g., the lower-tail bias in cotton spinning).

### 3.2.3 *Constructing consistent labor variables*

Next, we describe how we harmonize labor input in our two comparison sectors. In cotton spinning, we observe the total number of workers, so that no adjustment needs to be made.

*In metallurgy*, about 40% of the plants reported either 'internal' labor only, or both 'internal' and 'external' labor, separately. The remainder of plants reported only total labor, with no indication of whether this includes external labor.[9] To construct a consistent measure of labor input, we estimate the size of the internal labor force for the 60% of plants that reported only total labor. We use a matching procedure based on plant characteristics that is described in Appendix B.2. We also show below that our empirical results for metallurgy hold when we restrict the 1811 data to the 40% of plants with direct information on internal labor.

*In paper milling*, many plants only reported male labor in 1794, while the 1840 survey reports both male and total labor. In order to compare output per worker consistently, we need to impute total employment in 1794. We scale male labor in 1794 by the average proportion of total employees to male employees in 1840.[10] We show that our results are robust to using only male employees in both periods.

### 3.2.4 *Distinguishing plants from home production in cotton spinning*

Mechanized spinning was operated in centralized locations (plants), while the old technology relied on home production. We can thus identify the users of the new technology (i.e., all *plants* observed in our data). Consequently, we are able to isolate the productivity distribution for plants that used the new, mechanized technology under the new organizational form.

### 3.2.5 *Plant linking and plant survival*

We link plants across the two sample periods within communes based on two metrics: i) the plant had the same (or very similar) owner name in both periods; ii) there was only one plant in the

---

[9]Woronoff (1984, p. 138) describes external labor as only having very loose ties to the plant. These workers did not typically work at the location of the plant, their work was not supervised by the manager, and their identity was often not even formally known to the manager. They performed tasks such as driving, collecting charcoal for the plant, or performing other jobs without belonging to the hierarchy or reporting to superiors in the chain of command. Thus, external workers were unlikely to be considered formal salaried employees of the plant in the 1840 census.

[10]The validity of this method hinges on the assumption that the ratio of total employment to male employment was constant over time. We are able to check this using the 18 plants in 1794 that reported both types of labor. We find a ratio of 2.11 in 1794, which is very similar to the ratio of is 2.29 in 1840 (among all plants).

respective sector in the commune in 1800 and *at least* one plant in the same sector in 1840. In what follows, we describe each step of this process and the assumptions it entails.

All three surveys from around 1800, as well as the 1840 census, report the name of the owner and the location of the plant up to the commune, which is the lowest administrative unit in France. In bigger cities such as Paris, the *arrondissement* is also reported. We construct a consistent measure of plant location across surveys by assigning each plant to its modern-day commune, *département*, and region (as described in Appendix B.1 - B.4 for each respective survey).

*Linking plants.* We use two pieces of information to link plants over time. First, we match plants by their owner names in a given commune in the respective industry (see Appendix B.5 for detail on the implementation). Since the name of the owner may change even if the physical structure of the plant was the same, we also match by location in a second step. We match locations that had only *one* plant in the respective sector in 1800, and at least one plant active in the same sector in 1840. This turns out to be fairly common in the data. An obvious concern is whether this 'local matching' indeed identifies the same plant. This is likely, given a fortuitous feature across all three of our industries: their reliance on water power. Only a small number of locations in a typical commune were suitable for setting up a water-powered mill, as rapid stream flow was needed to yield sufficient power. Moreover, the backwater created by one mill meant that another mill could not be located in close proximity. Consistent with this, Crafts and Wolf (2014) argue that agglomeration in the cotton textile industry was not observed until steam became the common source of power in Britain. Consequently, our 'local matching' arguably identifies plants that had the same location within communes. Whether these were owned by the same entrepreneur (or their descendants), or whether they had passed on to a different owner is not crucial for our analysis.

*Plant survival.* Our main measure of plant survival is based on the combination of matching by owner name and 'local matching' that we described above. We define the survival rate as the percentage of plants from the initial period that survive into the later period. The numerator counts all plants that fulfill at least one of the following two conditions: i) the plant had the same owner in both periods; ii) there was only one plant in the respective sector in the location in the initial period and *at least* one plant in the same sector in 1840. The denominator is the sum of *all* plants in the given sector in the initial period. We provide a verification of this methodology in Appendix B.5.

Note that our baseline measure of plant survival does not adjust for the fact that the number of plants located in communes that had only one plant varies across the three sectors in our sample.[11] Thus, we may mechanically find higher survival rates in a sector where single-plant communes were relatively more frequent. To address this issue, we also construct the 'restricted sample'

---

[11]Among the 520 plants in paper milling in 1794, 211 (40.6%) were the only plants active in their commune in this sector. For cotton spinning in 1806, the proportion is 25.6% (87 out of the 340 plants), and in metallurgy in 1811, 69% (324 out of 470 plants).

survival rate as a robustness check. This measure is based solely on single-plant locations. The numerator of the 'restricted sample' survival rate counts the number of communes that had only one plant in the respective sector in the initial period, and at least one plant in 1840. The denominator is the set of all single-plant communes in 1800.

### 3.3 Descriptive Statistics

Tables A.2-A.4 contain descriptive statistics for all variables used in the analysis. Several important features of the data stand out. First, the scale of plants (measured by the number of employees) is striking for cotton spinning plants (see Table A.2). The average spinning plant in 1806 had 64 employees. This is larger than metallurgy and paper milling, where plants had on average 23 and 13 employees, respectively. Second, between 1806 and 1840, the mechanized cotton spinning industry expanded substantially, and this expansion was accompanied by an increase in the number of plants active in the market (from 340 in 1806, to 528 in 1840). That is, for every plant that exited the market, more than one new plant entered. As such, the results we present below constitute more than a 'shake-out' of unsuccessful plants.

## 4 The Pattern of Productivity Growth

In this section, we study the evolution of the plant productivity distribution in mechanized cotton spinning after the new technology had been adopted. Similar in spirit to a difference-in-differences strategy, we contrast the observed patterns with those in the two comparison sectors – metallurgy and paper milling. This allows us to distinguish the unique feature in mechanized cotton spinning – the need to reorganize production – from other common factors that affected productivity growth in all three sectors over our sample period.

### 4.1 Average and Quantile Productivity Growth

We begin by examining average annual labor productivity growth. Column 1 in Table 1 shows that all three sectors experienced a significant increase in labor productivity between 1800 and 1840. This is consistent with the historical evidence that gradual innovations were incorporated in all three sectors during this time period. The largest productivity gains were achieved in cotton spinning (2.42% per year), followed by metallurgy (2.33%) and paper milling (0.72%).[12] It is noteworthy that the large productivity increase in spinning reflects improvements *within* the

---

[12]Given that we discount revenues using price indices, all our productivity calculations reflect price-adjusted revenue-based productivity. To obtain the average annual growth rates between the two time periods, we first regress log output per worker $lnProd$ on a dummy for 1840 (separately for each sector, including the data from both time periods). This coefficient measures the percentage growth in output per worker over the entire time period between the respective survey years. We then annualize these values (and corresponding standard errors) by dividing by the number of years between the surveys in each sector. Note that this method delivers average annual growth figures, not accounting for compound growth. In cotton spinning, the overall growth over the period 1806-40 amounts to 82% (2.42% per year x 34 years). In metallurgy, it is 68% (2.33% per year x 29 years), and in paper milling it is 33% (0.72% per year x 46 years).

mechanized technology.

In which part of the productivity distribution were these gains concentrated? Figure 1 plots the distribution of labor productivity in the three sectors at the beginning and at the end of our sample period, illustrating our main results. In cotton spinning, two features stand out. First, the initial dispersion in labor productivity was large in 1800 relative to that in 1840.[13] Second, the productivity gains are almost exclusively concentrated in the lower tail: The lower tail disappeared over our sample period, while increases in productivity at the upper tail were modest. In other words, productivity growth occurred largely due to the distribution shifting towards the productivity frontier. The contrast between cotton spinning and our two comparison sectors is striking. In metallurgy and paper milling, the entire productivity distribution shifted to the right between 1800 and 1840. Quantile regressions confirm this pattern. Columns 2-6 in Table 1 report these results for the three sectors, estimating regressions for productivity growth at different quantiles of the productivity distribution. Figure 2 displays the corresponding coefficients. In cotton spinning, the bias towards productivity growth in the lower tail is marked. Productivity growth at the 25th percentile was twice as large as that at the 75th percentile (3.3% per year relative to 1.65%), and the difference is fourfold between the 10th and the 90th percentile (3.9% and 1.0%, respectively). In the comparison sectors, productivity growth occurred relatively evenly across the distribution; if anything, growth was concentrated in the upper tail in metallurgy. These differences between cotton spinning and the comparison sectors constitute suggestive evidence that the aspect unique to mechanized spinning – the need to reorganize production – was associated with the lower tail bias in productivity growth.

## 4.2   Robustness of the Lower-Tail Bias to Construction of Productivity

Before we examine mechanisms behind the upper-tail bias in productivity growth in cotton spinning, we document that it is robust to using alternative measures of productivity.

*Output quality.*   Could the different productivity-growth pattern in cotton spinning be driven by differential trends in output quality? Recall that our data for cotton spinning in 1800 enable us to use quality-adjusted prices to compute revenues from output quantities. Panel B in Table A.5 in the appendix presents quantile regressions without quality-adjustments in 1800, i.e., using the same sector-level price across all plants in cotton spinning. The magnitude of the lower-tail bias is slightly smaller, but it still holds. Quality adjustment does not substantially alter the pattern of productivity growth because most plants produced yarn of a fairly similar (low) quality: The interquantile range for the quality of yarn produced in our data is 20 – 47.5; high-count yarns

---

[13]The 90-10 percentile productivity range (the difference in log output per worker between plants in the 90th and 10th percentile) decreased from 2.17 to 1.17. Thus, in 1800, 90th percentile cotton spinning plants were 8.7 times more productive than 10th-percentile plants, and this ratio fell to 3.2 in 1840. The latter is comparable to the average 90-10 percentile productivity ratio within 4-digit US manufacturing sectors in 1977, where this factor was about 4 (Syverson, 2004).

typically start around count 100 (Harley, 1998). The low quality output during the initial phase is consistent with the British experience (Harley, 1998).

*Mark-up heterogeneity.* In cotton spinning, our plant productivity measure in 1800 is computed from physical output (adjusted by quality-specific sector-level prices), while the 1840 values are based on *revenues*. The latter also reflect differences in markups across plants (Garcia-Marin and Voigtländer, 2019). If more productive plants also charged higher markups (De Loecker and Warzynski, 2012), the heterogeneity in markups would lead to a *more* dispersed productivity distribution in 1840. Thus, this data limitation – if quantitatively important – would work against our finding of a *tightening* productivity distribution.

*Robustness to measuring productivity as TFP.* Our baseline productivity measure is log output per worker. For cotton spinning, we can also compute TFP, using data on physical capital (number of spindles) – see Appendix E.1 for detail. Panel C in Table A.5 confirms the lower-tail bias of productivity growth in cotton spinning using TFP.

*Robustness to imputed variables in metallurgy and paper milling.* Appendix E.2 shows that our quantile regression results are robust to i) using only those plants in 1800 in metallurgy with direct information on internal labor (Table A.6, Panel B); ii) using the plant-product-specific prices for those metallurgy plants that reported them to construct productivity, while dropping the remaining metallurgy plants in 1800 (Table A.6, Panel C); iii) using only male labor in both periods in paper milling (Table A.7).

# 5 Mechanism: Learning About Best Practice in Factory-Based Production

We have documented that the lower-tail bias of productivity growth was present only in cotton spinning. The historical evidence in Section 2 suggests that the need to reorganize production was also unique to this sector. In what follows, we link these two features: the need for reorganization can explain the lower-tail bias. We first discuss a stylized framework that captures the key elements of the historical evidence. Then, we turn to examining the data for evidence compatible with the learning effects that reorganizing production entailed.

## 5.1 A Stylized Framework

We summarize the key features of our stylized model here; Appendix D provides detail and shows simulation results. The model features heterogeneous plants, and we distinguish three phases: Initial market entry, exit of particularly unproductive plants, and endogenous search for better technology among the surviving plants. To model the observed thick lower tail in the initial productivity distribution, we use a production function with multiple *complementary* inputs (tasks). We think of these as the organizational challenges discussed in Section 2.2 such as plant design, power supply, or management of workers. For each input, a plant receives a random efficiency

draw, reflecting the plant's organizational knowledge.[14] Due to the strong complementarity across the inputs, even having one bad draw (say, inappropriate factory layout) substantially reduces overall efficiency. This gives rise to the thick lower tail in the initial productivity distribution.

Our model then features two mechanisms that lead to the disappearance of the lower tail over time: First, exit of the least productive firms eliminates the lowest part. This standard mechanism (c.f. Hopenhayn, 1992) reflects the significant exit rates of cotton spinning firms in the early mechanization period. Second, motivated by the historical evidence on the diffusion of organizational practices, we model a process à la Perla and Tonetti (2014) whereby relatively unproductive firms can search and copy the organizational knowledge of more productive firms: Firms with productivity below an endogenously determined cutoff halt production and search for better organizational knowledge; they are matched to a randomly-drawn firm among the higher-productivity firms that continue production. Searching firms thus forego profits, but they expect higher profits in the future due to the improved organization of production. This process leads to the disappearance of the lower tail, while the productivity frontier remains unaffected.

Figure 3 illustrates the simulated productivity distributions over the three phases. The dashed line reflects the initial productivity distribution. In the first phase, firms with very low productivity draws exit. In the second phase, among the surviving firms, the relatively unproductive ones halt production and search for better organizational knowledge among the more productive firms, who continue to produce. This gives rise to the solid blue productivity distribution, where the initially fat lower tail has disappeared, while the productivity frontier (plants that already operate with high organizational efficiency) remains unchanged. This pattern of productivity growth mirrors the one for cotton spinning in the data (see Figure 1). Note also that the final productivity distribution resembles the one observed for our comparison sectors, where factory production had been adopted earlier, so that the process of exit and organizational learning had already occurred by 1800.[15]

While our stylized theoretical framework is not the only one that gives rise to lower-tail bias in productivity growth, it is a simple setup that represents the key features of the historical context. The empirical results below provide evidence for these mechanisms, suggesting that the diffusion of organizational practices across plants was an important dimension in the observed productivity dynamics.

---

[14]Of course, these draws can also be interpreted as technology. Our model is agnostic about the distinction between technological and organizational knowledge. However, our historical accounts and empirical evidence suggest an important role for the latter.

[15]Note that in order to replicate the right-shift of the whole productivity distribution over time in the comparison sectors, we would have to introduce productivity growth for *all* plants. In contrast, we do not need this additional feature to rationalize the dynamics in cotton spinning, i.e., learning from more productive plants is sufficient to deliver the observed lower-tail bias in productivity growth.

## 5.2 Learning About Re-Organizing Production

In what follows, we shed light on *what* plants needed to learn to re-organize production efficiently, followed by *how* plants went about learning. Through the lens of our stylized framework, plants initially had a wide array of efficiency draws, reflecting the fact that they largely experimented with different solutions, rather than having standardized answers to the organizational challenges of factory production. Over time, less productive plants either exited the market or they learned better organizational practices from their peers. We present evidence consistent with this initial experimentation and subsequent learning, using one central aspect in the move to factory-based production: optimal mill design.

*Building design.* The historical literature highlights building design as the foremost challenge faced by French mechanized cotton spinners (Bonin and Langlois, 1987). We are able to examine two aspects of mill design for a subset of 59 historical mechanized cotton spinning plants, using data on their floor plans. The data are from Chassagne (1991).[16] For each plant, we observe the length and width of the plant building, as well as the number of floors. The historical evidence suggests that both dimensions were important: A building with many floors presented a fire hazard, which is why over time, the French converged to buildings with fewer stories (Chassagne, 1991). In addition, a more rectangular (less 'square') building shape was more suitable for the optimal layout of machines (Markus, 2013, pp. 265-267).

In light of this, we examine the number of floors a building had, as well as its 'squareness' (defined as $S \equiv \frac{length \times width}{max\{length,width\}^2}$). This measure of squareness is size-invariant. That is, if buildings simply got bigger over time without changing their shape, our squareness measure would remain unchanged. In light of our model, we expect there to be an initially wide distribution of these dimensions, reflecting the dispersed initial draws. Over time, as plants learned about what worked, we expect convergence to best-practice designs. Importantly, the data contain information on the year in which a plant was set up. We thus split the sample into an 'early' experimental period (defined as plants set up before 1820) and a 'mature' period (defined as plants set up after 1820). Of the 59 plants for which we have building dimensions, 58 have a date of foundation ranging between 1789-1845. Exactly one-half of these plants are assigned to each period.

Figure 4 plots the estimated kernel densities for the number of floors (Panel A), and for building squareness (Panel B). Consistent with our model and the historical evidence, there is wide variation along both dimensions in the early period. Buildings had anywhere from 0-7 stories and all sorts of shapes ranging from a squareness measure of $S = 0.1$ (indicating very asymmetric width and length) to perfect squares ($S = 1$). Moreover, as the historical literature claims, over time, best

---

[16]Appendix E.3 contains a more detailed description of this source. It is important to note that the data are unlikely to be a representative sample as records of larger, more important plants were more likely to survive. However, note that this bias would likely lead us to *underestimate* the extent of initial experimentation, as we arguably undersample less successful plants with less efficient organizational draws.

practice converged to buildings with a moderate number of floors (around 3) and a more rectangular shape ($S \approx 0.5$).

Was better building layout correlated with productivity? Appendix E.3 explores this question. Since the Chassagne (1991) data do not include the necessary information to compute plant productivity, we examine a proxy: plant survival until the 1840 census (which collected plant data in 1839-47). Table A.8 regresses a dummy for plant survival on each of the two dimensions of plant layout, allowing for a non-linear relationship. We find a hump-shaped pattern. The estimated coefficients imply that the optimal number of floors was about 3.7, and the predicted optimal squareness was $S = 0.5$, which is close to what the industry converged to after 1820, according to Figure 4. These results on building design support the historical account as well as the mechanism outlined in our stylized framework: Cotton spinning plants initially experimented with a wide range of organizational practices, and as the industry matured, they converged to best-practice designs.

*Strikes.* Another organizational challenge that the historical literature highlights is that firms needed to develop new labor management practices (see Section 2.2). While we do not observe historical management practices, we follow recent work that points to a proxy: Bianchi and Giorcelli (2022) show that firms that improved their labor management as a result of a training intervention saw a significant decline in worker complaints and strikes. Historical evidence from our sample period in France also links key labor management challenges in factory-based cotton spinning to strike activity. Through the 1820s and 1830s, there were several strike episodes in France where workers demanded payment as a time wage as opposed to a piece-rate, as well as a decrease in the length of working hours (Chassagne, 1991). The former in particular is a key labor management challenge that we described in detail in Section 2.2. In stark contrast, André (1996, p. 246) notes that paper milling firms' records do not mention similar conflicts with labor during the mechanization process.

Based on this historical evidence, we examine whether strikes were more frequent in textiles relative to our comparison sectors that did not experience similar labor management challenges. Appendix E.4 provides suggestive evidence, using data on strike activity at the sector-*département* level. Table A.9 shows that the textile sector was subject to about 30% more frequent strike activity, relative to the comparison sectors – metallurgy and paper milling. This holds conditional on controlling for employment at the sector-*département* level, total manufacturing employment (across all sectors), and *département* fixed effects. Of course, factors other than management challenges may also be responsible for the differential strike activity in cotton spinning. We thus interpret the evidence from strikes with caution, and merely view it as complimentary to the historical record in pointing to labor management challenges in mechanized cotton spinning.

24

## 5.3 Spatial Diffusion of Knowledge

In what follows, we shed light on how learning about organizational practices took place. The historical background discussed in Section 2 showed that plants copied successful designs and setups of the production process from each other. To examine this channel, we estimate whether a plant's own productivity was higher in the proximity of other high-productivity plants. We use the following specification:

$$lnProd_{ij} = \beta_0 + \beta_1 lnDist_{ij}^{p90} + FE_j + \epsilon_{ij} \, ,$$

where $lnProd_{ij}$ is labor productivity (log output per worker) for plant $i$ located in *département* $j$; $lnDist_{ij}^{p90}$ is log distance to the nearest plant (in the same sector) with productivity in the 90th percentile (in the distribution of *all* plants in the sector across France). Plants that are themselves in the top productivity decile are excluded from the sample to avoid introducing a mechanical relationship. All specifications include *département* fixed effects ($FE_j$) to absorb unobserved location characteristics that may make all plants in a given area more productive, irrespective of local spillovers. Thus, the coefficient of interest, $\beta_1$, reflects the extent to which plants in the same *département* benefit from being located closer to a high-productivity plant (which may be located in the same or in another *département*). We do not interpret these correlations as causal effects, but as evidence that is compatible with spatial spillovers of knowledge. We estimate the specification separately for the three sectors, and in both time periods. Standard errors are clustered at the *département* level to account for spatial correlation.

Before presenting the results, we first examine the spatial distribution of high-productivity plants across our sectors and time periods. Figure A.17 plots the spatial distribution of cotton spinning, metallurgy, and paper milling plants, distinguishing those in the 90th percentile of the productivity distribution. Unsurprisingly, some regions have a larger concentration of high-productivity plants than others. Due to our use of *département* fixed effects, these regional differences do not affect our results.

Figure 5 visualizes our baseline results, and Table A.10 in the appendix reports the corresponding regressions. To allow for direct comparability, we report standardized beta coefficients of $lnDist^{p90}$ for all three sectors in the two periods. The estimated coefficient for cotton spinning in 1800 is negative, statistically significant and large in magnitude. A one-standard-deviation (std) increase in distance to a high productivity plant is associated with a 0.84 std decline in labor productivity. The pattern is much weaker in the two comparison sectors in 1800 – the coefficients are less than one-third in magnitude as compared to cotton spinning. In addition, in 1840, all three sectors show at best a muted relationship: The distance-coefficient for mechanized cotton spinning is reduced to less than one-fifth of its initial size, and it is only marginally statistically significant.

In the comparison sectors, the coefficients of interest are also further reduced slightly, and they are no longer statistically distinguishable from zero. Thus, proximity to high-productivity plants mattered the most in cotton spinning in 1800, i.e., in the period before knowledge about the optimal organization of production had spread widely. Distance mattered much less when organizational knowledge had diffused: In cotton spinning in 1840, and in the comparison sectors in both time periods. These findings are consistent with spatial learning during the early phase of mechanized cotton spinning.

*Alternative explanations for the distance results.* In Appendix E.5, we examine possible alternative explanations for the relationship between $lnDist^{p90}$ and productivity. While $FE_j$ capture unobserved differences that vary at the *département* level, they cannot account for unobserved differences at a finer spatial level. To address this possibility, we implement several additional checks. First, we control directly for prominent location fundamentals at the commune level such as the availability of fast-flowing streams (as a source of water power), proximity to coal (for steam power), and the share of forest cover (for access to charcoal – a major input in metallurgy). Table A.11 shows that our results are highly robust to these controls. Second, we check whether our results are affected by more general agglomeration externalities, as opposed to learning. In Table A.12, we control for the density of production at the commune level (measured as the log of total output in the sector, excluding a plant's own output). Our results are essentially unaffected by adding this control. Third, Table A.13 conducts a placebo exercise, showing that, in cotton spinning, plant productivity in 1800 was *not* related to the distance to high-productivity plants in 1840. This suggests that the large estimated coefficient in our baseline specification is not driven by persistent location fundamentals within *départements*. Fourth, we examine whether *ex-ante* high-productivity plants may have selected into 'productive locations' (i.e., chose to locate near existing high-productivity plants). Since we observe plant age in cotton spinning in 1806, we can examine selection patterns. Table A.14 shows that our result holds in a subsample of plants that entered *before* the nearest high-productivity plant, so that the timing of entry rules out the type of selection described above. Finally, we examine whether there is evidence for learning *across* sectors. Table A.15 shows that there is no consistent pattern in the data: Mechanized cotton spinning plants located closer to high-productivity metallurgy or paper milling plants in 1800 were not more productive.

In summary, the consistently larger distance coefficient estimated in cotton spinning in 1806, in combination with a series of robustness checks, points to the spatial diffusion of knowledge as one mechanism through which learning across plants took place. The historical accounts of spatial learning in Section 2.2 corroborate this interpretation.

## 5.4 Plant Layout vs. Technology: Evidence from Plant Survival and Age Profiles

Which type of knowledge diffused across space? The results presented above cannot distinguish between the spatial diffusion of knowledge about the technology itself (for example, how to operate and maintain the machines efficiently) and organizational knowledge (i.e., how to design mills and organize workers within the plant). We now present two patterns in the data that are more consistent with organizational learning.

*Productivity handicap of exiting plants.* If an important component of learning in mechanized cotton spinning occurred along the organizational dimension of factory design, we would expect initially low plant survival rates relative to the other two sectors. Building design and layout are either sunk at the time of building or costly to change, implying that plants who got this wrong were likely to exit the market. On the other hand, inefficient operation of the new technology itself could be adjusted within an existing factory so that, if anything, we would expect incumbents to have an edge over new entrants. The data speak in favor of the former. We find substantially larger exit rates in cotton spinning relative to the other two sectors. Table 2 reports plant survival rates over our sample period, using the two measures defined in Section 3.2 in each of the three sectors. Based on our baseline measure, survival rates in spinning (5%) were lower than in paper milling (10.8%) and much lower than in metallurgy (37.7%). Note that the actual difference in plant survival between spinning and paper milling was likely larger, because the survey for the latter was conducted in 1794, more than 10 years earlier than the cotton spinning survey (1806).

The 'restricted sample' survival rates in Table 2 allow a more direct look at the role of building layout and design in plant survival. By using only single-plant locations in the initial period, we are in effect testing whether a building used for production in a particular industry in 1800 continued to be used in the later period in the same industry (irrespective of who the owner was). The differences across the three sectors are even starker. By this measure, the survival rate in spinning (13%) is much lower than in the comparison sectors: 52.5% in metallurgy and 24.6% in paper milling (with the latter being an under-estimate, as discussed above). The low survival rate observed in cotton spinning means that many locations lost their (only) cotton mill – owners that had invested in a mill with poor layout had to exit the market, and the structure of the mill was not subsequently used by other plants in cotton spinning.

Appendix E.6 provides further results on plant survival. We first explain that the differential survival rates are not driven by the shift from water to steam power (which occurred more slowly in France than in Britain). Next, Table A.18 shows that exiting plants in mechanized cotton spinning were much less productive than those that survived. In the comparison sectors, the productivity handicap of exiting plants is also present, but less pronounced. In other words, early cotton plants that 'got it wrong' were particularly unproductive, which can explain the fat productivity lower tail in this sector. These plants eventually exited the market, and for many of them, the same building

was not used by another plant in the industry. This pattern is consistent with large organizational challenges and low initial guidance in switching to factory-based production in cotton spinning.

*Age profile of plant productivity.* To further distinguish the role of best-practice organizational methods as opposed to learning about technology, we now examine the age profile of plant productivity. For now, assume that spinning technology itself did not change over time (we relax this in the next subsection). Then, if learning how to use the (already installed) technology was the dominant dimension, we would expect older plants to have accumulated more experience and hence have a productivity advantage. On the other hand, if efficient organizational design of the plant was more important, younger plants had a larger pool of knowledge to draw from, as they set up their design later. This would render younger plants more productive than older plants that were locked into less efficient designs (see also our evidence on plant design in Section 5.2).

We exploit the richness of our data to test this in both 1800, when best-practice mill design was still evolving, and in 1840, when according to Pollard (1965), the industry had reached maturity – at least in Britain. The 1806 survey in cotton spinning contains the year of foundation of plants. This allows us to compute a dummy for 'young' plants, defined as below-median age (with the median age in 1806 being three years). Column 1 in Table 3 shows that 'young' plants were 58% more productive in 1806. This could be driven by mechanisms other than the one discusses above. For example, new entrants may have used the most recent vintage of capital, leading to higher physical productivity (Foster, Haltiwanger, and Syverson, 2008). To address this issue, we control for several important plant characteristics in columns 2-6 of Table 3. These include the capital intensity of the plant (measured as log spindles per worker), the number of workers in the plant, and the vintage of machinery (binary variables for the three main vintages of machinery, from oldest to newest).[17] The productivity advantage of 'young' plants remains quantitatively very similar and statistically highly significant when we add these controls.

Appendix E.6 explores the 'young' plant productivity differential further. Table A.19 shows that in 1840, when the mechanized cotton spinning technology had reached maturity, younger plants did not have a productivity advantage anymore. For comparison, we also examine the age-productivity pattern for metallurgy plants, where best-practice knowledge had already been established by 1800. Correspondingly, we find that younger metallurgy plants did not have a productivity advantage in either of the two periods (Tables A.20 and A.21). In paper milling, data limitations prevent us from examining these patterns.

In summary, the evidence on productivity-age profiles is in line with best-practice organizational methods in cotton spinning spreading slowly over time and space, so that newly constructed plants were more productive around 1800. This advantage eroded when organizational knowledge

---

[17]The three different vintages of machinery are the spinning jenny (oldest), the water-frame (throstle), and the mule-jenny (newest). These are not mutually exclusive categories, as some plants used multiple vintages. Young plants tended to be more capital intensive, employ fewer workers, and use the newest vintage of spinning machinery.

diffused more broadly by 1840.

## 5.5 Robustness to Alternative Explanations

In the final part of this section, we consider additional alternative mechanisms that could also explain our results. We examine these along a number of different dimensions.

*Gradual innovation and capital mix: Common patterns across all three sectors.* We observe the lower-tail bias in productivity growth only in cotton spinning, and not in the other two sectors. For this reason, it is unlikely that factors that also affected the comparison sectors in similar ways can explain our findings. For example, the fact that mechanized spinning experienced innovations during our sample period seems unlikely to explain the lower-tail bias, as both comparison sectors also witnessed the introduction of new technologies. In a similar vein, improvements to power sources (notably water power, which remained the dominant source of power in cotton spinning) affected the other two sectors similarly (see also Appendix E.6). Finally, all three sectors used a mix of different vintages of their core capital equipment, suggesting that the choice of capital itself is not a confounder. In fact, below, we show that the lower-tail bias of productivity growth remains intact if we remove all plants that used the earliest vintage of capital: the spinning jenny.[18]

*Regional differences in productivity distributions.* It is important to highlight the robustness of our results to using only within-region variation (see Appendix E.7). Table A.22 shows that the lower-tail bias of productivity growth in mechanized cotton spinning remains intact if we add fixed effects for 22 French regions.[19] The lower-tail bias of productivity growth is somewhat muted, but still striking. Productivity growth in cotton spinning is almost twice as high at the lowest relative to the highest decile. The inclusion of region fixed effects absorbs the effect of different regional fundamentals, input markets, market access, or institutions. In what follows, we examine possible alternative mechanisms at a finer geographic level, i.e., potentially even within regions.

*Market integration.* Could increased market integration in cotton spinning explain our results? As the French economy became more integrated over time, it is possible that lower-productivity plants faced tougher competition and had to exit the market.[20] We address this concern in Appendix E.8.

---

[18]In this regard, the metallurgy sector is a helpful comparison as we observe the use of different vintages of capital in 1811. Some plants used the so-called 'direct technology' widely known in France as the Catalan forge, while others used the 'indirect technology' which separates the production process into smelting and refining. The direct technology was gradually replaced by the indirect technology during our sample period (Pounds and Parker, 1957). See Appendix A.4 for further discussion.

[19]Regions are larger than *départements*: There are 22 regions in France and 86 *départements*. Our data in the three sectors do not have sufficiently many observations to include *département* fixed effects, i.e., to estimate meaningful productivity distributions within *départements*. In contrast, our results on spatial diffusion (Figure 5) do include *départements* fixed effects, because they examine the effect of proximity to high-productivity plants on the *average* productivity of plants, rather than on the full distribution.

[20]Market integration arguably increased during our sample period both for policy reasons such as the abolition of internal barriers to trade during the French Revolution (Daudin, 2010), and because of infrastructure improvements that reduced transport costs such as the introduction of railways in the late 1820s.

We first use data on trade flows in 1794 from Daudin (2010) to show that market integration was initially *higher* in cotton yarn than in our comparison sectors – cotton yarn (and textiles more generally) are high value-to-weight products, which made them more easily tradable over long distances than iron and steel, or paper (Figure A.18). Given its higher starting point, if anything, we expect further market integration after 1800 to have been *less* pronounced in cotton spinning than the comparison sectors. This renders it historically unlikely that differential (i.e., higher) growth of market integration in cotton yarn drives our results. We complement this argument by controlling for measures of market access (both within France and within Europe), as well as for access to overseas trade (Table A.23). The coefficients of interest change only marginally, and the lower-tail bias of productivity growth in cotton spinning remains strong.

*Napoleonic Blockade and Napoleonic Wars.* Juhász (2018) shows that temporarily higher trade protection from British competition shifted the location of the mechanized cotton spinning industry within France. Since our results hold within regions, where the pattern of protection was very similar, it is unlikely that they are affected by the Napoleonic Blockade (1806-14). Figure A.19 presents further evidence that varying trade protection does not drive our results, by splitting the sample into plants in northern and southern regions in France (corresponding to the main dimension along which protection varied). The productivity distributions in the north and south are remarkably similar, and in both regions, productivity growth until 1840 was due to a disappearing lower tail. Appendix E.9 provides further evidence and shows that i) the Napoleonic Blockade did not drive the differential plant survival in cotton spinning; ii) conscription of soldiers as well as battles on French soil during the Napoleonic Wars (1803-15) are not associated with cotton spinning plant productivity.

*Early spinning workshops.* Another potential concern is that our results may be driven by the disappearance of small cotton spinning plants (or 'workshops'). Indeed our data may include relatively small plants that operated early vintages of mechanized spinning jennies and did not necessarily need inanimate sources of power. This small-scale setup may have been inherently different from the larger-scale factories powered by inanimate power sources. While the move to factory-based production was swift, systematic differences of smaller mechanized cotton workshops could account for the lower-tail bias of productivity growth in this sector. Our data does not differentiate between these two types of plants, as we observe the capital vintage, but not the power source in the 1806 survey. However, we can examine the extent to which our results may be driven by these forces.

In Appendix E.10, we adopt a stricter definition of 'factory-production' and omit plants with fewer than 10 employees from all sector-year pairs. This should exclude the majority of the smaller workshops that may have been organized as factory-based production along some but not all dimensions. It also addresses the concern that that smaller plants were under-sampled in the 1840

manufacturing census (see Appendix B.4). Table A.27 shows that the lower-tail bias in productivity growth is robust to using only larger plants, and that it remains unique to mechanized cotton spinning. In other words, small plants are not responsible for the fat lower tail in 1806. In addition, we implement an even more conservative definition of factory production. We drop the 76 plants from the 1806 survey that used the earliest vintage of machinery – the spinning jenny. These were the types of machines that could, in principle, have been operated also in small workshops without inanimate power sources. Table A.28 shows that the lower-tail bias of productivity growth remains striking. Thus, early spinning workshops that shared some, but not all features of factory-based production do not confound our results.

*Plant scale.* Appendix E.11 shows that it is unlikely that increasing plant size drives our results, as all sectors witnessed an increase in scale. In addition, as the results in Table A.29 demonstrate, controlling for the number of workers (at the plant level, in all sectors and in both periods) does not alter our findings.

*Capital deepening.* Over time, spinning machines were equipped with more spindles, and hence less labor was needed to produce a unit of output. We address this in Appendix E.12, where Table A.30 shows that the lower-tail bias of productivity growth remains robust and similar in magnitude when we control for the capital-labor ratio at the plant level (measured as log spindles per employee).

*Machine quality.* Machine production, and even maintenance, was typically in the hands of external regional suppliers (see Appendix A.2 under 'Historical evidence about machinery producers'). Given that we find the lower-tail bias of productivity growth also within regions, it is unlikely that heterogeneity in machine quality was an important driver.

*Output quality.* In Section 4.2, we already examined whether cotton output quality could account for our core result by affecting the computation of productivity. This is not the case – the lower-tail bias of productivity growth continues to hold even when we use output prices in 1806 that do not account for quality differences across plants (see Panel B of Table A.5). In Appendix E.13, we provide one additional check. Output quality could still drive our results indirectly if it led to higher sales and thus larger plant size over time, leading to scale economies. To examine this possibility, we estimate the quantile regressions *not* adjusting for quality differences in prices across plants in 1806, and controlling for the number of workers. Table A.31 shows that the lower-tail bias of productivity growth continues to hold.

*Age profile of plants.* The median age of plants in mechanized spinning in 1806 was strikingly small (3 years). This is consistent with historical accounts that the period witnessed the birth of mechanized spinning in France. Could it be that young plants are always more dispersed in terms of productivity, and that this drives the fat lower tail? Our earlier results in Table 3 render this interpretation unlikely. We have shown that younger plants were substantially *more* productive

31

than older ones. Thus, if anything, a predominance of younger plants would tend to lead to a thicker *upper* tail.

Altogether, the findings of this section show multiple pieces of evidence that point to an important role for reorganizing production in explaining the unique lower-tail bias of productivity growth in mechanized cotton spinning. While this is not the only possible explanation, we have shown that numerous prominent alternative mechanisms are incompatible with the data. Together with the corroborating historical evidence, this leaves organizational challenges in technology adoption as the most promising candidate to explain the observed patterns in the data.

# 6   Conclusion

The unique setting examined in this paper allows us to shed new light on important open questions in the technology adoption literature. First, our findings speak directly to why the *aggregate* productivity effect of major technological breakthroughs, such as IT and electricity, may be hard to pin down in the data. As pointed out by David (1990), the full effects of a new technology may take significant time to materialize, as plants still need to learn how to organize production efficiently. In our context, adopting mechanized cotton spinning required producers to reorganize production from households to factories. Our results suggest that initially, many plants operated the new technology in combination with inefficient complementary organizational practices. This led to a widely dispersed productivity distribution and relatively low average productivity. Observers estimating the productivity effect of switching from handspinning to mechanized spinning would significantly underestimate the long-run aggregate productivity gain if they only looked at the initial data around 1800.

Second, our results also shed light on the slow adoption of major new technologies. When there is uncertainty about how to operate a new technology efficiently, and the organizational knowledge – once acquired – is observable to competitors, plants face a strategic incentive to delay adoption. The high exit rates observed in cotton spinning relative to other sectors, alongside the higher productivity observed for younger plants in 1806, suggest that plants that entered later were at an advantage. If plants understood the significant uncertainty they faced when setting up a spinning mill at early stages of adoption, they had an incentive to delay the switch to the new technology in order to take advantage of the learning externalities generated by other early adopters.

In summary, our unique setting allows us to speak to a dimension of productivity growth that is usually hidden. Productivity differences across plants reflect both the underlying technology and the complementary organizational practices with which the respective technology is used. Both features play important roles in the decision to adopt new technologies: What are the potential productivity gains of a new technology (i.e., its frontier), and is the organizational knowledge

needed to achieve these gains (i.e., operate at the frontier) readily available? Separating these features empirically is difficult because of data limitations. Our results suggest that the need to reorganize production is an important dimension of technology adoption. Approaching the frontier of a new technology via organizational improvements can take a long time, and it can explain some of the salient features in the adoption of major innovations.

Finally, our paper provides a first look at how the unprecedented growth in manufacturing productivity during the First Industrial Revolution played out at the plant level. We show that in mechanized cotton spinning – the flagship industry of the period – a substantial proportion of productivity growth materialized along the extensive margin of plant exit and entry. Our results suggest that throughout this process, organizational innovations (alongside the traditionally emphasized technological ones) were an important driver of productivity growth. Future research – building on the increasing availability of historical data – should examine whether these findings constitute a common feature of the structural transformation from agriculture to modern, factory-based manufacturing. Our paper lays the groundwork by using comparative historical analysis to deepen our understanding of why the diffusion of innovation is often a complex and slow process.

# References

Allen, R. C. (2009). *The British Industrial Revolution in Global Perspective*. Cambridge University Press.

André, L. (1996). *Machines à Papier: Innovation et Transformations de l'Industrie Papetière en France : 1798-1860.* Editions de l'Ecole des Hautes Études en Sciences Sociales.

Atkin, D., A. Chaudhry, S. Chaudry, A. K. Khandelwal, and E. Verhoogen (2017). Organizational Barriers to Technology Adoption: Evidence from Soccer-Ball Producers in Pakistan. *Quarterly Journal of Economics 132*(3), 1101–1164.

Bianchi, N. and M. Giorcelli (2022). The Dynamics and Spillovers of Management Interventions: Evidence from the TWI Program. *Journal of Political Economy 130*, 1630–75.

Bloom, N., B. Eifert, A. Mahajan, D. McKenzie, and J. Roberts (2013). Does Management Matter? Evidence from India. *Quarterly Journal of Economics 128*(1), 1–51.

Bonin, S. and C. Langlois (1987). *Atlas de la Révolution Française: Economie*, Volume 10. Editions de l'École des Hautes Études en Sciences Sociales, Paris.

Braguinsky, S., A. Ohyama, T. Okazaki, and C. Syverson (2015). Acquisitions, Productivity, and Profitability: Evidence from the Japanese Cotton Spinning Industry. *American Economic Review 105*(7), 2086–2119.

Braguinsky, S., A. Ohyama, T. Okazaki, and C. Syverson (2021). Product Innovation, Product Diversification, and Firm Growth: Evidence from Japan's Early Industrialization. *American Economic Review 111*(12), 3795–3826.

Bresnahan, T. F. and M. Trajtenberg (1995). General Purpose Technologies: 'Engines of Growth'? *Journal*

*of Econometrics 65*, 83 – 108.

Brynjolfsson, E. (1993). The Productivity Paradox of Information Technology. *Communications of the ACM 36*(12), 66–77.

Brynjolfsson, E. and L. M. Hitt (2000). Beyond Computation: Information Technology, Organizational Transformation and Business Performance. *Journal of Economic Perspectives 14*(4), 23–48.

Brynjolfsson, E., D. Rock, and C. Syverson (2021). The Productivity J-Curve: How Intangibles Complement General Purpose Technologies. *American Economic Journal: Macroeconomics 13*(1), 333–72.

Cameron, R. (1985). A New View of European Industrialization. *Economic History Review 38*(1), 1–23.

Chanut, J., J. Heffer, J. Mairesse, and G. Postel-Vinay (2000). *L'Industrie Française au Milieu du 19e Siècle: Les Enquêtes de la Statistique Générale de la France*. Editions de l'École des Hautes Études en Sciences Sociales, Paris.

Chapman, S. (1970). Fixed Capital Formation in the British Cotton Industry, 1770-1815. *Economic History Review 23*(2), 235–253.

Chapman, S. (1974). The Textile Factory Before Arkwright: A Typology of Factory Development. *Business History Review 48*(4), 451–478.

Chassagne, S. (1976). L'Enquête, dite de Champagny, sur la Situation de l'Industrie Cotonnière Française au Début de l'Empire (1805-1806). *Revue d'Histoire Économique et Sociale 54*(3), 336–370.

Chassagne, S. (1991). *Le Coton et ses Patrons: France 1760-1840*. Editions de l'Ecole des Hautes Etudes en Sciences Sociales.

Clark, G. (1987). Why Isn't the Whole World Developed? Lessons from the Cotton mills. *The Journal of Economic History 47*(1), 141 – 173.

Clark, G. (1994). Factory Discipline. *The Journal of Economic History 54*(1), 128–163.

Comin, D. and B. Hobijn (2010). An Exploration of Technology Diffusion. *American Economic Review 100*(5), 2031–59.

Crafts, N. (1985). *British Economic Growth During the Industrial Revolution*. Oxford: Oxford University Press.

Crafts, N. and K. Harley (1992). Output Growth and the British Industrial Revolution: A Restatement of the Crafts-Harley View. *Economic History Review 45*(4), 703–730.

Crafts, N. and N. Wolf (2014). The Location of the UK Cotton Textiles Industry in 1838: A Quantitative Analysis. *Journal of Economic History 74*(4), 1103–1139.

Daudin, G. (2010). Domestic Trade and Market Size in Late-Eighteenth-Century France. *Journal of Economic History 70*(3), 716–743.

David, P. (1990). The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox. *American Economic Review 80*(2), 355–361.

De Loecker, J. and F. Warzynski (2012). Markups and Firm-Level Export Status. *American Economic Review 102*(6), 2437–2471.

Dudley, L. (2010). General Purpose Technologies and the Industrial Revolution. Papers on Economics and Evolution No. 1011.

Feigenbaum, J. J. and D. P. Gross (2021). Organizational Frictions and Increasing Returns to Automation: Lessons from AT&T in the Twentieth Century. *National Bureau of Economic Research w29580*.

Fitton, R. and A. Wadsworth (1958). *The Strutts and the Arkwrights, 1758-1830: A Study of the Early*

*Factory System*. Manchester University Press.

Foster, L., C. Grim, J. Haltiwanger, and Z. Wolf (2018). Innovation, Productivity Dispersion, and Productivity Growth. NBER Working Paper 24420.

Foster, L., J. Haltiwanger, and C. Syverson (2008). Reallocation, Firm Turnover, and Efficiency: Selection on Productivity or Profitability? *American Economic Review 98*(1), 394–425.

Freeman, C. and F. Louçã (2001). *As Time Goes By: From the Industrial Revolutions to the Information Revolution*. Oxford University Press.

Galor, O. (2011). *Unified Growth Theory*. Princeton University Press.

Garcia-Marin, A. and N. Voigtländer (2019). Exporting and Plant-Level Efficiency Gains: It's in the Measure. *Journal of Political Economy 127*(4), 1777–1825.

Geraghty, T. (2007). The Factory System in the British Industrial Revolution: A Complementarity Thesis. *European Economic Review 51*(6), 1329–1350.

Gille, B. (1968). *La Sidérurgie Française au XIXe Siècle: Recherches Histioriques*. Librairie Droz.

Gillispie, C. C. (2004). *Science and polity in France: the revolutionary and Napoleonic years*. Princeton University Press.

Giorcelli, M. (2019). The Long-Term Effects of Management and Technology Transfers. *American Economic Review 109*(1), 1–33.

Gort, M. and S. Klepper (1982). Time Paths in the Diffusion of Product Innovations. *Economic Journal* (367), 630–653.

Griliches, Z. (1957). Hybrid Corn: An Exploration in the Economics of Technological Change. *Econometrica 25*(4), pp. 501–522.

Hall, B. (2004). Innovation and Diffusion. NBER Working Paper 10212.

Hall, B. and B. Khan (2003). Adoption of New Technology. NBER Working Paper 9730.

Harley, C. (1998). Cotton Textile Prices and the Industrial Revolution. *Economic History Review 51*(1), 49–83.

Hopenhayn, H. A. (1992). Entry, Exit, and Firm Dynamics in Long Run Equilibrium. *Econometrica 60*(5), 1127–1150.

Horn, J. (2006). *The Path Not Taken: French Industrialization in the Age of Revolution, 1750-1830*. Cambridge MA: MIT Press.

Huberman, M. (1996). *Escape from the Market*. Cambridge University Press.

Jenkins, D. T. (Ed.) (2003). *The Cambridge History of Western Textiles*. Cambridge University Press.

Juhász, R. (2018). Temporary Protection and Technology Adoption: Evidence from the Napoleonic Blockade. *American Economic Review 108*(11), 3339–76.

Langenbach, R. (2013). Better than Steel? Part 2: Tall Wooden Factories and the Invention of "Slow-burning" Heavy Timber Construction. Article URL accessed June 20, 2020.

Lipsey, R. G., K. I. Carlaw, and C. T. Bekar (2005). *Economic Transformations: General Purpose Technologies and Long-Term Economic Growth*. Oxford University Press.

Mansfield, E. (1961). Technical Change and the Rate of Imitation. *Econometrica 29*(4), 741–766.

Markus, T. A. (2013). *Buildings and Power: Freedom and Control in the Origin of Modern Building Types*. Routledge.

Ministère de l'Agriculture et du Commerce (1847). *Statistique de la France: Industrie*, Volume 1. Imprimerie Royale.

Mitchell, B. (2003). *International Historical Statistics. Europe, 1750-2000*. Palgrave Macmillan.

Mokyr, J. (2001). The Rise and Fall of the Factory System: Technology, Firms, and Households since the Industrial Revolution. *Carnegie-Rochester Conference Series on Public Policy 55*, 1–45.

Mokyr, J. (2010). *The Enlightened Economy: An Economic History of Britain 1700-1850*. Yale University Press.

Mokyr, J. (2011). The Economics of Being Jewish. *Critical Review 23*(1-2), 195–206.

Mokyr, J. (2016). *Culture of Growth: Origins of the Modern Economy*. Princeton University Press.

Mokyr, J. (2021). "The holy land of industrialism": Rethinking the Industrial Revolution. *Journal of the British Academy 9*, 223–47.

Nuvolari, A., G. Tortorici, and M. Vasta (2023). British-French Technology Transfer from the Revolution to Louis Philippe (1791–1844): Evidence from Patent Data. *The Journal of Economic History*, 1–41.

Perla, J. and C. Tonetti (2014). Equilibrium Imitation and Growth. *Journal of Political Economy 122*(1), 52–76.

Perrot, J. (1975). *L'ăge d'Or de la Statistique Régionale Française (An IV-1804)*. Paris: Société des Etudes Robespierristes.

Perrot, J. and S. Woolf (1984). *State and Statistics in France, 1789-1815*. Taylor & Francis.

Pollard, S. (1965). *The Genesis of Modern Management: A Study of the Industrial Revolution in Great Britain*. Harvard University Press.

Pounds, N. and W. Parker (1957). *Coal and Steel in Western Europe: The Influence of Resources and Techniques on Production*. Bloomington: Indiana University Press.

Ridolfi, L. and A. Nuvolari (2021). L'histoire immobile? A reappraisal of French economic growth using the demand-side approach, 1280–1850. *European Review of Economic History 25*(3), 405–428.

Rosenberg, N. (1976). Factors Affecting the Diffusion of Technology. *Explorations in Economic History 10*(1), 3–33.

Saxonhouse, G. and G. Wright (2004). Technological Evolution in Cotton Spinning. In D. Farnie and D. Jeremy (Eds.), *The Fibre that Changed the World: The Cotton Industry in International Perspective, 1600-1990s*, pp. 129–152. Oxford University Press.

Sokoloff, K. (1984). Was the Transition from the Artisanal Shop to the Nonmechanized Factory Associated with Gains in Efficiency? Evidence from the US Manufacturing Censuses of 1820 and 1850. *Explorations in Economic History 21*(4), 351–382.

Sokoloff, K. (1986). Productivity Growth in Manufacturing During Early Industrialization: Evidence from the American Northeast, 1820-1860. In *Long-Term Factors in American Economic Growth*, pp. 679–736. University of Chicago Press.

Syverson, C. (2004). Product Substitutability and Productivity Dispersion. *Review of Economics and Statistics* (2), 534–50.

Syverson, C. (2011). What Determines Productivity? *Journal of Economic Literature 49*(2), 326–365.

Szostak, R. (1989). The Organization of Work: The Emergence of the Factory Revisited. *Journal of Economic Behavior and Organization 11*(3), 343–358.

Williamson, O. (1980). The Organization of Work: A Comparative Institutional Assessment. *Journal of*

*Economic Behavior and Organization 1*(1), 5–38.

Woronoff, D. (1984). *L'Industrie Sidérurgique en France Pendant la Révolution et l'Empire.* Paris: École des Hautes Études en Sciences Sociales.
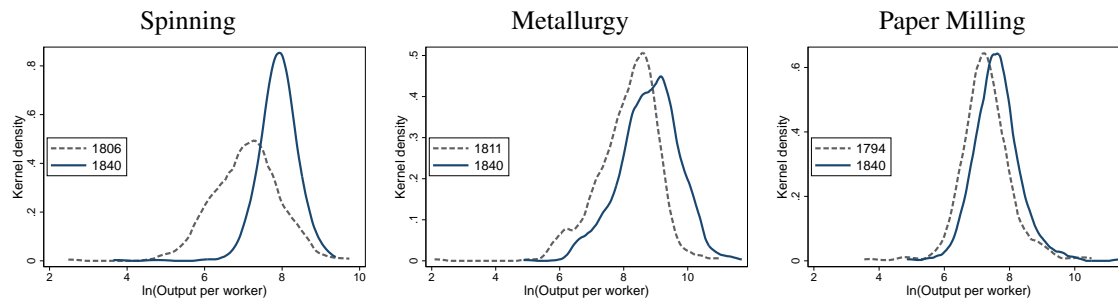
# FIGURES



Figure 1: Changes in the Productivity Distributions in the Three Sectors

*Notes*: The figure shows the distribution of log(output per worker) for the three sectors at the beginning of our sample period (around 1800) and in 1840. Productivity growth in spinning was mainly due to a disappearing lower tail. In contrast, in metallurgy and paper milling, the whole distribution shifted to the right.
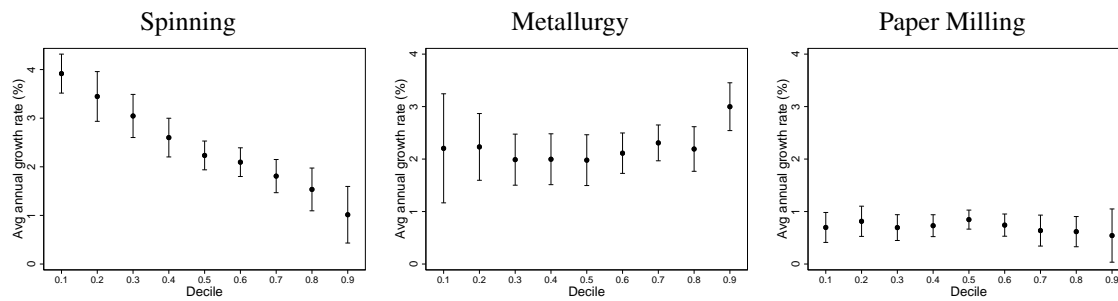


Figure 2: Productivity Growth at Different Quantiles of the Distribution

*Notes*: The figure visualizes the results of quantile regressions for growth in log(output per worker) for the three sectors, estimated at each decile. Productivity growth in spinning was concentrated in the lower tail of plant productivity. In contrast, in metallurgy and paper milling, productivity growth occurred relatively evenly across the distribution.
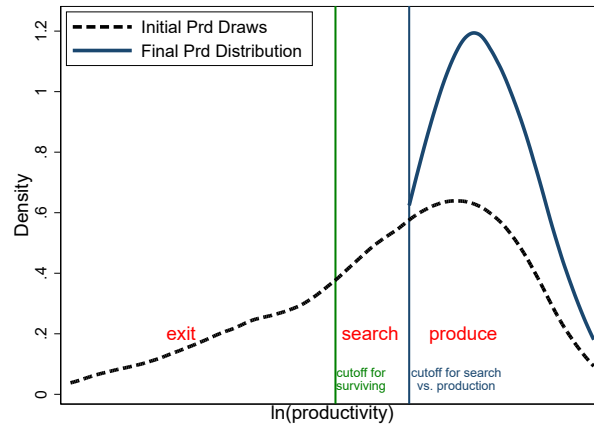
Figure 3: Productivity Dynamics in the Stylized Model

*Notes*: The figure illustrates the productivity dynamics in our stylized model: In the initial period, the least productive plants exit. Subsequently, in the innovation period, surviving plants decide whether to search for better organizational knowledge, foregoing production. The searching plants are randomly matched to continuing producers as in Perla and Tonetti (2014). In the final period, searching plants adopt the improved organizational knowledge from more productive producing plants. Thus, the lower tail of the productivity distribution disappears, and the mass shifts towards higher productivity draws. At the same time, the productivity frontier remains unchanged.
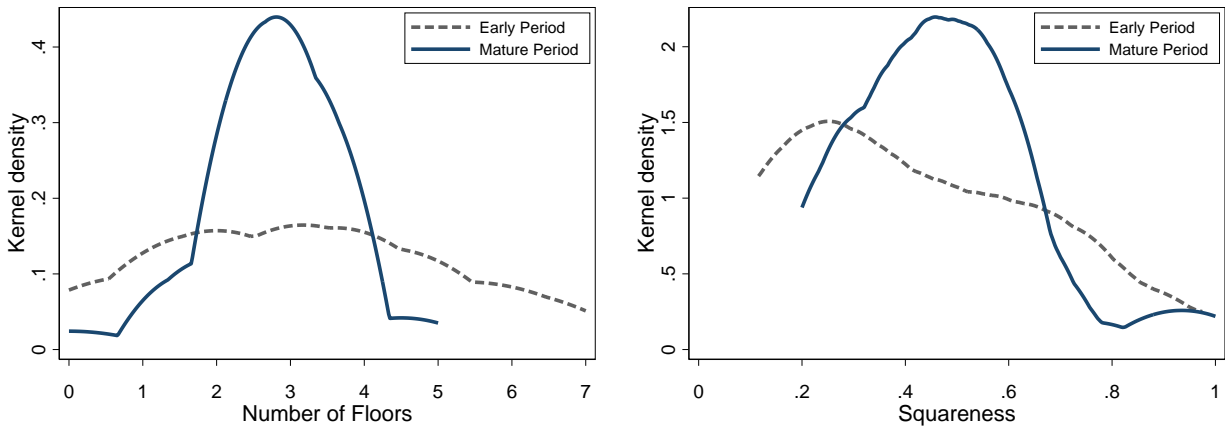


Figure 4: Experimentation and Convergence in Mill-Design for Cotton Spinning Plants

*Notes*: The figure shows the distributions of two important features of cotton mill design, in an 'early' experimental period (built before 1820) and a later 'mature' period (built after 1820). Panel A plots the distribution of the number of floors of cotton mills. Panel B plots the distribution of 'squareness,' as defined in Section 5.2. Data on the length, width, and number of floors of overall 59 cotton plants are from Chassagne (1991).
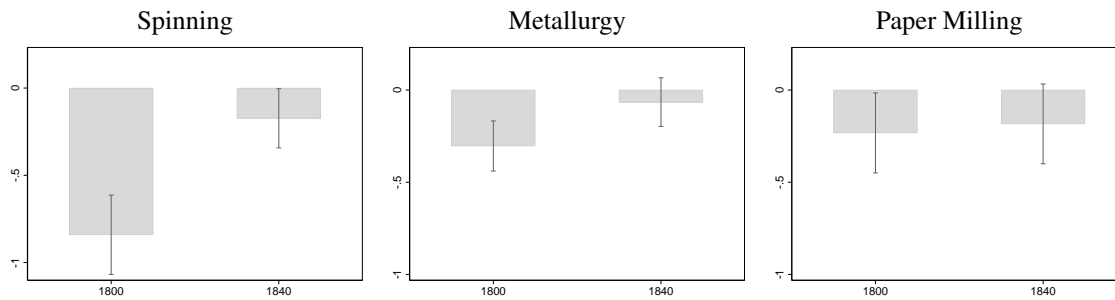
Figure 5: Proximity to High-Productivity Plants

*Notes*: The figure shows that proximity to high-productivity plants mattered the most in mechanized cotton spinning at the beginning of our sample period (around 1800), when the technology had just been introduced in France. The figures plot the standardized beta coefficients of $lnDist^{p90}$, which measures the log distance to the closest plant with productivity in the 90th percentile (in the same sector and in the same period – 1800 and in 1840, respectively). The dependent variable is log(output per worker). All regressions include *département* fixed effects (see Table A.10). Whiskers indicate 90% confidence intervals.

# TABLES

Table 1: Annual Productivity Growth (in %) at Different Quantiles of the Distribution

|  | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
|  | Average | At the following quantiles: | | | | | N |
|  |  | 0.1 | 0.25 | 0.5 | 0.75 | 0.9 |  |
| Spinning (1806-1840) | 2.420*** | 3.917*** | 3.293*** | 2.234*** | 1.651*** | 1.014*** | 868 |
|  | (0.154) | (0.204) | (0.229) | (0.151) | (0.167) | (0.297) |  |
| Metallurgy (1811-1840) | 2.328*** | 2.205*** | 2.068*** | 1.979*** | 2.285*** | 2.998*** | 1366 |
|  | (0.183) | (0.530) | (0.317) | (0.247) | (0.193) | (0.232) |  |
| Paper milling (1794-1840) | 0.719*** | 0.697*** | 0.717*** | 0.846*** | 0.691*** | 0.542** | 867 |
|  | (0.111) | (0.145) | (0.139) | (0.092) | (0.130) | (0.258) |  |

*Notes*: The table reports the average annual productivity growth (in %) between the initial sample period (around 1800) and 1840 for the three sectors (column 1), and annual productivity growth estimated at different quantiles (columns 2-6). Column 7 reports the number of observations. Robust standard errors in parentheses. Notation for statistical significance: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.


Table 2: Survival Rates Across Sectors

|  | Spinning | Metallurgy | Paper milling |
|---|---|---|---|
| Period | 1806-1840 | 1811-1840 | 1794-1840 |
| Survival rate | 5.0% | 37.7% | 10.8% |
| Number of plants | 340 | 470 | 520 |
| Restricted sample survival rate | 12.6% | 52.5% | 24.6% |
| Number of plants | 87 | 324 | 211 |

*Notes*: The "survival rate" is defined as the percentage of plants from the initial period that survived to the later period based on matching either by name or location (see Section 3.2). The "restricted sample survival rate" uses only the subset of plants located in communes that had only one plant in the initial period.

Table 3: Cotton Spinning in 1806: Productivity and Plants' Age Profile

Dependent variable: log(Output per worker)

|  | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Young plant | 0.575*** | 0.534*** | 0.608*** | 0.543*** | 0.575*** | 0.493*** |
|  | (0.088) | (0.085) | (0.086) | (0.083) | (0.089) | (0.085) |
| log(Spindles per worker) |  | 0.336*** |  |  |  |  |
|  |  | (0.070) |  |  |  |  |
| log(Workers) |  |  | 0.107*** |  |  |  |
|  |  |  | (0.025) |  |  |  |
| Spinning jenny |  |  |  | -0.626*** |  |  |
|  |  |  |  | (0.087) |  |  |
| Throstle |  |  |  |  | -0.003 |  |
|  |  |  |  |  | (0.092) |  |
| Mule jenny |  |  |  |  |  | 0.481*** |
|  |  |  |  |  |  | (0.086) |
| $R^2$ | 0.11 | 0.17 | 0.14 | 0.20 | 0.11 | 0.18 |
| N | 340 | 340 | 340 | 340 | 340 | 340 |

*Notes*: The table shows that mechanized cotton spinning plants that had just entered the market by 1806 had significantly higher productivity. 'Young' is a dummy variable equal to one for cotton spinning plants with below-median age (with the median age in 1806 being three years). The number of spindles is a standard measure of a spinning machine's production capacity, irrespective of vintage. Spinning-jenny, throstle and mule-jenny are binary indicators equal to one for plants using the earliest (spinning-jenny), intermediate (throstle), and latest (mule-jenny) vintage of spinning machinery, respectively. Robust standard errors in parentheses. Notation for statistical significance: *** p<0.01, ** p<0.05, * p<0.1.