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The Spinning Jenny and the Guillotine: Technological Diffusion at the Time of Revolutions

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The Spinning Jenny and the Guillotine: Technological Diffusion at the Time of Revolutions

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Abstract

Why was England the cradle of the Industrial Revolution? The present work shows that scale economies and demand, combined with the conditions of the relative prices of input factors, allow to provide a purely economic answer to this question. The labor-saving innovations of the Industrial Revolution were profitable only if, after their adoption, sales expanded enough to cover the upfront cost of capital. For some time, England was the only country in which sales exceeded the minimum threshold required to make adoption profitable. This fact is illustrated here by means of a detailed case study centered on the cotton industry and on the adoption of the spinning jenny in England and in France at the dawn of the Industrial Revolution. By then, the sufficiently large and relatively well-off English middle class could guarantee to cotton spinners a level of sales that was not viable in France, where income was lower and more concentrated in the hands of the upper classes.

Keywords: Industrial Revolution, income distribution, economies of scale, choice of technique, spinning jenny.
JEL classification: N00, N01, N70.

1 Introduction

For at least half a century the innovations at the roots of the Industrial Revolution originated and diffused almost exclusively in England. This fact leads to suppose that England, as compared to other countries, benefited from some unique features that were necessary to allow the invention and the diffusion of the new technologies. What, then, made the difference?

One answer argues that, while the cognitive *capability* to produce inventions was relatively widespread in Western Europe, England was comparatively more endowed of the practical *competences* that were necessary to implement and ameliorate such inventions. In this view, while everywhere progress depended on the notorious breakthroughs accomplished by a mechanical elite, England benefited also from the greater availability of skilled artisans capable to carry out the myriads of anonymous micro-inventions that allowed a wide diffusion of the new technologies. In particular, it is argued, this differential in human capital stemmed from the sharper inclination of the English culture toward useful and pragmatic knowledge, which in fact characterized the English declination of the Enlightenment.[1] In this sense, then, a cultural element would possibly constitute the differential factor that spurt a major economic change like the Industrial Revolution.

A partly competing answer, instead, argues in favor of a solely economic explanation of the Industrial Revolution. According to this view, England was only country in which the price of labor relative to capital was high enough to stimulate the adoption and invention of the new labor-saving technologies of the 18th century. In particular, English manufacturers were the only ones that could conveniently adopt these innovations, and consequently their inventors could not have a market anywhere else but in England. In this story, then, the conditions of the relative prices of input factors are considered sufficient to explain the unfolding of the Industrial Revolution. Moreover, the fact that England may have benefited from a greater availability of skilled labor is possibly seen as a consequence of the fact that advanced technical skills paid in England but not elsewhere, precisely because the widespread use of more advanced technologies was convenient only to the North of the channel.[2]

Also the present work provides a strictly economic account of the Industrial Revolution, but it also shows that demand conditions can predict its location and timing much more accurately than relative prices. Possibly for the same reasons described by Allen, by the mid 18th century England was benefiting from a higher level and a

[1] Mokyr (2009, pp. 99–123).
[2] See Allen (2009a, pp. 8–11 and 238–271) and Broadberry and Gupta (2009).

more even distribution of average real income, as compared to its "most similar country", France.[3] While giving stronger incentives to substitute labor with capital, higher real wages generated also more consumption and thus more sales per manufacturer. Indeed, both factors entailed a higher profitability of the new technologies in England relative to France. On the one hand, the higher sales of the average English manufacturer allowed her to exceed the minimum output threshold that was necessary to cover the fixed costs of new technologies, while the average French manufacturer was forced below the critical level. On the other hand, the more favorable English relative prices implied a lower critical output threshold in England as compared to France. Although in general both factors could have a role, demand was likely more decisive than relative prices. To put it loosely, inverting the sales of the average English manufacturer with those of her French counterpart would have inverted the industrial fortunes of the two countries; conversely, an inversion of relative prices would have left history unchanged. By the same token, the timing of industrialization in each country is matched very poorly by the evolution of relative prices, while it is accurately predicted by the evolution of demand. In this perspective, also the reorganization of labor that characterized the Industrial Revolution comes to make sense: indeed, there was a clear incentive to expand the size of productive units.

The general argument outlined above is conducted here focusing on the cotton industry, which was the first to industrialize. In particular, a detailed case study is developed on the diffusion of the spinning jenny in England and France during the 18th century. As it will be discussed, the spinning jenny is an especially significant case study, for at least two reasons. First, it can well be regarded as one of the very first technologies of the Industrial Revolution; thus, it allows to focus the analysis on the very embryonic phases of this historical discontinuity. Second, the relatively limited fixed cost entailed by the jenny guarantees that scale effects were small as compared to the technologies that followed. Hence, if scale effects mattered for the jenny, they must have mattered *a fortiori* also for the subsequent technologies: in this sense, using the jenny as an example allows, to some extent, to generalize the conclusions that are to be presented here.

2 Cotton market

By the mid 18th century society and markets in Western European countries looked quite different from what they were about to become shortly after. Until then, technological breakthroughs had been very infrequent within the manufacturing sector, which employed only a minority of the labor force. For instance, the processing of cotton might have employed less than one percent of the population, and an activity like spinning was still essentially based on a centuries-old technology such as the spinning wheel.

This stable technological environment was coupled with — and partly responsible of — a great rigidity in the market structure, essentially due to limited price competition. On the one hand, it was precisely "to prevent this reduction of price [...] by restraining that free competition which would most certainly occasion it, that all corporations, and the greater part of corporation laws, [had] been established."[4] On the other hand, the fact that all manufacturers used an identical and stable technology did not allow any of them to have substantially different costs from their rivals; hence, there was a strong lower limit to the possibility of cutting prices. In this sense, strategic competition was probably not the custom of the time. Possibly because of this, when new technologies appeared, those entrepreneurs who attempted to use them in order to undercut competitors and expand output were systematically sanctioned. Typically, their machines got wrecked and their stocks of raw materials burned by those manufacturers who either lost their jobs or were forced to lower their living standard, due to the attempt to decrease the prices of the manufactured goods.[5] The cotton market was no exception. Records of machine-breaking riots date as far back in time as 1738, when "a large body of weavers [...] assembled in a tumultuous manner, and cut all the chains in the looms belonging to Mr Coulthurst [...] on account of his lowering of the prices".[6] Similarly, Hargreaves' spinning jennies and furnitures were attacked and destroyed in 1767, 1769, and 1779, when also Arkwright-type of factories were assaulted.[7] Overall, then, corporative, technological and social reasons jointly contributed to limit severely the use of price competition among manufacturers.

Hence, the cotton spinner of the pre-industrial era was not likely to reason strategically. In particular, she probably carried out her decisions considering the demand she already had in hand, rather than the potential demand she could have had by lowering price. In this sense, it is not the *total* demand for yarn that mattered to her, but rather the slice of it that she faced *individually.* Given the absence of domestic cotton plantations, a proxy of the average demand per spinner within each country, Q, can be obtained by dividing the total net imports of raw cotton by the number of spinners: that is $Q \equiv Q_{tot}/sN$, where Q_{tot} are total net imports of raw cotton, s is the share of spinners, and N is the total population. From here it is straightforward to derive an

[3]See Allen (2009a, pp. 23–131) for an explanation of why English wages were higher.
[4]Smith (1776, Book I, Chapter 10, p. 101).
[5]See Hobsbawm (1952) and Horn (2005) for an account of machine-breaking riots during the 18th century in England and France.
[6]Gentleman's Magazine (1738, p. 658).
[7]See Allen (2009b, p. 906), Hobsbawm (1952, p. 62), Horn (2005, p. 163), and Nuvolari (2002, p. 393).

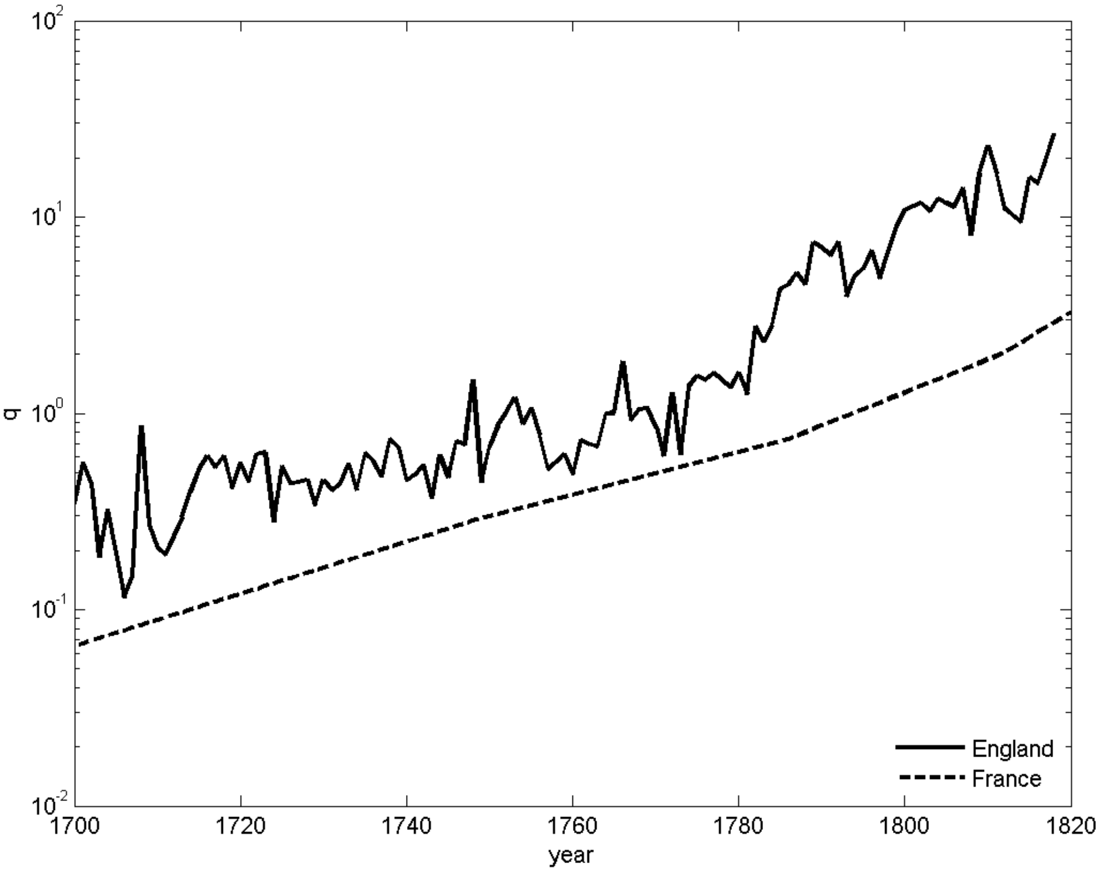

Figure 1: Imports of raw cotton per spinner (logarithmic scale).

Source: Figures for each country in each year are obtained by interpolation of the available data. English data on imports of raw cotton for each single year in the span 1700–1820 are taken from Mitchell and Deane (1971, p. 177). English population estimates come from Mitchell and Deane (1971, p. 5): these data are available at a decennial frequency in the span 1700–80, then every five years in the span 1780–1800, and again at a decennial frequency in the span 1800–20. French data on imports of raw cotton come from: Mulhall (1892, p. 160), for years 1688 and 1750; Crouzet (1966, p. 267), for year 1786; Chaptal (1819, p. 15), for year 1812; Baines (1835, p. 525), for year 1822. French population data come from: Maddison (2010), for years 1700 and 1820; Morrisson and Snyder (2000, p. 66), for year 1788.

index describing the evolution of the demand per spinner with respect to a reference year:

$$q \equiv \frac{Q}{Q_0} \equiv \frac{Q_{tot}/sN}{Q_{tot_0}/s_0 N_0} \tag{1}$$

where the subscript 0 indicates the base period. Equation (1) can be further adapted to the specific context of the early-industrial era considering that the share of spinners in the population kept roughly constant over time, due to the limits to market entry discussed before. Formally, this corresponds to assuming $s \approx s_0$, so that the index of the demand per spinner simplifies to $q \approx (Q_{tot}/N)/(Q_{tot_0}/N_0)$. Naturally, this assumption becomes less accurate as the barriers to entry become negligible, but in the early-industrial era this certainly was not the case. Moreover, irrespective of the degree of market competition, the population share employed in a given sector changes slowly enough to make $s \approx s_0$ an adequate approximation in the short term, which will actually be the focus of the present analysis. Thus, Figure 1 shows the evolution of q in England and France over the 18th century, assuming $s \approx s_0$ and using as Q_{tot_0} the net imports of raw cotton recorded in England in 1764–65 (i.e. the year of invention of the spinning jenny).

According to Figure 1, the average cotton demand per spinner was systematically higher in England relative to France. For instance, q is at least three times as high in England relative to France in almost all observations. Clearly, the different tendency to fluctuate of the two lines reflects the greater scantiness of French data relative to English ones. Despite this limitation, however, Figure 1 does not seem to leave doubts about the fact that the demand per spinner was higher in England relative to France throughout the 18th century.

Could this differential derive from foreign markets? It would seem unlikely. During the 18th century, exports of yarn and manufactured cotton were negligible compared to their domestic consumption, both for England

Table 1: Respectable subsistence basket in England (1759) and France (1788).

ITEM	QUANTITY *(p.c.)* (Yearly)	UNIT PRICE *(gs.)* (Base year)	COST PER HOUSEHOLD *(gs.)* London (1759)	Paris (1788)
Bread	182.0 *kg.*	0.693		
Beans/peas	52.0 *l.*	0.477		
Meat	26.0 *kg.*	2.213		
Butter	5.2 *kg.*	3.470		
Cheese	5.2 *kg.*	2.843		
Eggs	52.0 *each*	0.010		
Beer	182.0 *l.*	0.470		
Soap	2.6 *kg.*	2.880		
Linen	5.0 *m.*	4.369		
Candles	2.6 *kg.*	4.980		
Lamp oil	2.6 *l.*	7.545		
Fuel	5.0 *MBTUb.*	4.164		
Total of the above		414.899	1704.000	1991.500
Rent London (1769)		556.800	497.579	
Rent Paris (1788)				225.648
Total cost			2201.579	2217.148

Source: All monetary values are expressed in grams of silver *(gs.)* at the conversion rates $1d. = 0.464gs.$ and $1livre = 4.701gs.$, as taken from Allen (2011a). Apart for data on rent, the base year price of each good (column 3) is the average of its price in Strasbourg over the span 1745–54. In columns 4 and 5, the total value at current prices of the basket per household (excluding rent) is obtained using the following expression: $414.899 \times CPI \times$ *consumers per household*. The consumer price index (CPI) of London and Paris at the relevant years come respectively from the files `London` and `Paris` available on Allen's web site, `http://www.nuffield.ox.ac.uk/General/Members/allen.aspx`, and discussed in Allen (2001). The number of consumers per household is set to 3, assuming that the average household size was 4 and the two children consumed each half the quantities of an adult, similarly to Allen (2001, p. 426). For what concerns the cost at current prices of rent, the original English datum for 1769 has been deflated to its current value in 1759, while the original French datum was already expressed in its 1788 current value. Apart for the cost of rent, all data on single items are taken from Allen (2001, p. 421). The cost of rent in London in 1769 comes from Young (1770, p. 438): the rent in Kensington was used for the calculations. The cost of rent in Paris in 1788 comes from Young (1794, p. 450): the rent in Isle of France was used for the calculations.

and France.[8] Moreover, given that most of the exports were directed to colonies, until the late 1780s England and France had similar international markets; therefore, if a difference existed in the level of demand faced by the average spinner of each country, it was unlikely to be due to international markets.[9]

Could the differential derive from domestic markets? The combination of the level of real income per capita with the distribution of income in each country seems to provide a positive answer. To fully appreciate this point it is sufficient to think of a rather "classical" type of consumer: one who aims first at attaining a respectable subsistence level, and then spends her extra income by scrolling down a list of gradually more superfluous goods coming in fixed quantities. No item on the list can be bought before all the previous ones have been purchased. It follows that the consumption basket of the richer will differ from the one of the poorer by including more items on the list, rather than greater quantities of the same items. Moreover, if all consumers have the same list, the demand for a certain item will be represented by the share of people earning enough to buy all the previous items on the list plus the one of interest, which instead cannot be afforded by poorer people. Therefore, due to their underlying differences in income distribution, two countries with the same aggregate income and equal preferences may express different levels of demand for a given item.[10] This would then determine a cross-country differential in the market size for the item. For example, the market size for extreme luxury items would tend to be higher where income is more concentrated, since a greater share of the population will be rich enough to buy them. Vice versa, a mass-good in the country with a more equal income distribution may well become an upper-class good in the other country. Now suppose that cotton was the first-ranked good on the list of consumers after the respectable subsistence basket: then, the eligible cotton customers are represented by the share of the population whose income is above the respectable subsistence threshold.

[8] Baines (1835, pp. 109–112, 522–525).

[9] The same argument has been recalled and used by Daudin (2010, p. 738). However, such work does not identify any decisive role of market size during the Industrial Revolution precisely because it takes in consideration the total market size rather than the portion of demand addressed to single spinners.

[10] See Murphy et al. (1989, pp. 540–41) for a more formal definition of the utility function sketched informally here.

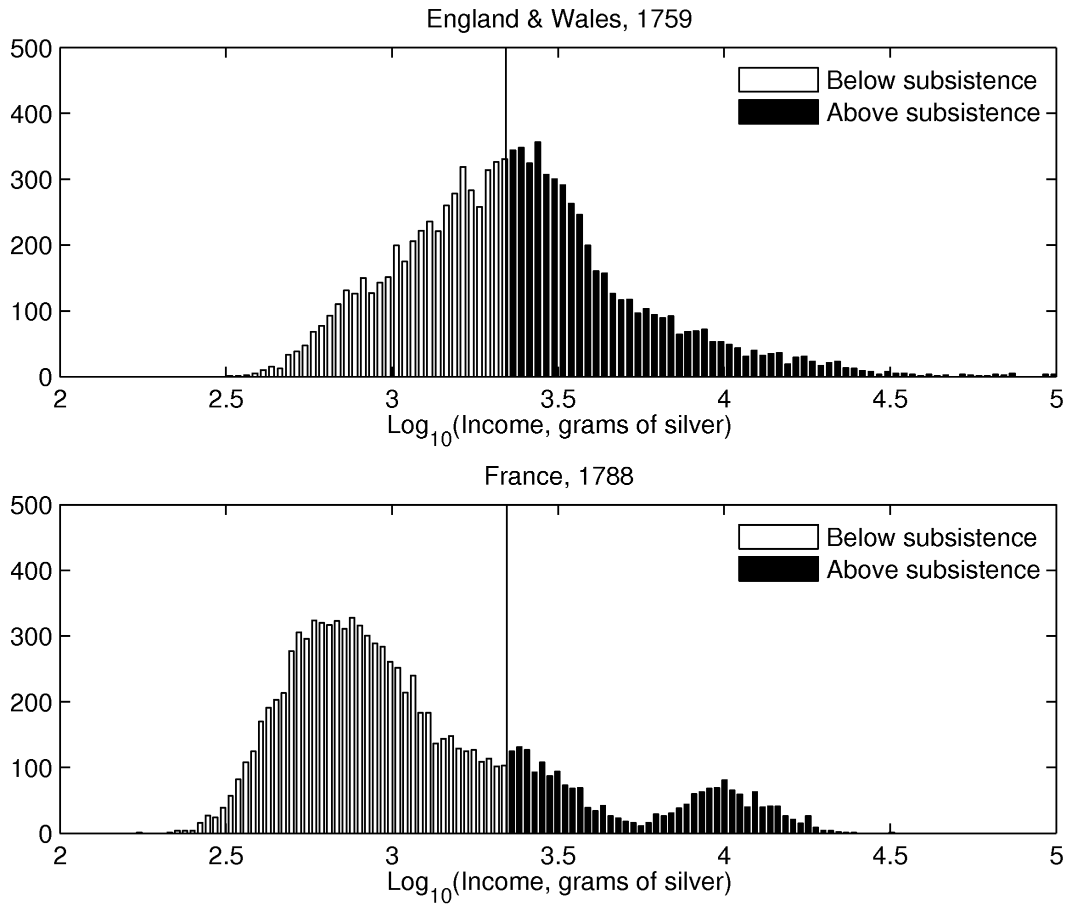

Figure 2: Income distributions per household in England (1759) and France (1788).

Source: All data have been downloaded from the web site `http://gpih.ucdavis.edu/Distribution.htm`, of the the Global Price and Income History Group (GPIHP). The GPIHP files quote the following sources: income distribution data for England are taken from Lindert and Williamson (1982); population data for England are taken from Mitchell (1988); income distribution and population data for France are taken from Morrisson and Snyder (2000). A log-normal smoothing has been applied to each class for purely aesthetical purposes.

Looking at income data through this lens reveals that English customers could buy more cotton than French ones. To begin with, average real income per household was higher in England than it was in France, respectively in 1759 and 1788. This can be deduced by comparing the mean values of the nominal income distributions shown in Figure 2 with the cost of the subsistence basket in each country reported in Table 1 at current prices. The subsistence basket of Table 1 corresponds to the respectable subsistence basket defined by Allen (2001) but for the addition of rent, which is here included since this datum is reliably available for each of the two countries taken in consideration. Yearly average nominal income per household amounted to 3381.1 grams of silver in England and only 2021.6 grams of silver in France, while the cost of Allen's respectable subsistence basket was actually slightly higher in France ($2217 g.s.$) than it was in England ($2201 g.s.$).[11] Yet, according to the consumption model sketched above, the sole average real income per household would be insufficient to infer anything about the size of the cotton market faced by the average spinner: income could be concentrated in the hands of a few, thus implying that only a relatively small portion of the population could actually demand a non-subsistence good like cotton. In this respect, it is in fact worth noting that the subsistence basket defined in Table 1 accounts for basic clothing necessities by including the consumption of linen, while the need for a finer textile like cotton is plausibly excluded from subsistence. Hence, income distributions have to be considered, and doing so further confirms that a greater share of people could afford cotton in England relative to France. Thanks to the more even income distribution the Gini coefficient in England was 0.48 in 1759, while in France it was 0.56 in 1788.[12] As a consequence, the fraction of the population earning more than the respectable

[11] The fact that average real income per capita was higher in England than in France has been discussed at greater depth by Allen (2009a, pp. 25–26).

[12] Notice that the difference between England and France in terms of income distribution is even more striking when the "inequality extraction ratio" (IER) is considered rather than the sole Gini coefficient, as discussed by Milanovic et al. (2011). The IER is

subsistence level was 51% in England and only 22% in France: these shares are represented by the bars to the right of the vertical line in Figure 2. Then, considering as equal the ratio of spinners per person, the level and the distribution of income can well explain why the demand faced by the average cotton spinner was higher in England than it was in France at the dawn of the Industrial Revolution.

Two remarks are worth noting. First, the percentage of people who earned, for instance, four times the income necessary to attain subsistence was higher in France than it was in England. Therefore, despite the lower average income, the demand for extreme luxury goods was possibly higher in France than it was in England. Second, the consumption model that was sketched here to put forward an explanation of demand differentials does not rely at any stage on a variation of consumer tastes. This does not mean that the tastes of consumers did not actually change, possibly in favor of "new goods" like cotton: all it implies is that changes in tastes are not a necessary ingredient for the story that will be told here.[13]

Crucially, the fact that the sales of the average cotton spinner were higher in England than in France is not sufficient to regard demand as the trigger of the "wave of gadgets [that] swept over England" by 1760.[14] In particular, although possibly lower than the English ones, the sales of the average French spinner might have been already high enough to make profitable the adoption of the new technologies; vice versa, these could turn out being profitable in England even if the sales of the average English spinner had been as low as the French one. In these cases, demand would not help to explain technological diffusion during the Industrial Revolution. Otherwise, if sales had to grow in order to render adoption profitable, demand would hold an essential role. In parallel, demand was central, also income distribution may have mattered in the way discussed above. In this perspective, the famous motto ascribed to the French Revolution, "Liberté, *egalité*, fraternité", may well have found some economic justifications especially with respect to the promotion of greater equality in terms of income. This, however, does not imply at all that the intentions of the motto were coherently followed by the revolutionary actions: how much, if at all, and in favor of whom wealth moved after the French Revolution remains an entirely empirical issue beyond the scope of the present analysis.

3 Profitability of adopting spinning machinery

Had the sales of the average French spinner been as high as those of her English counterpart, would a new technology like the spinning jenny find reasons to diffuse also in France rather than only in England? And vice versa, had the English average spinner spun as much cotton as the French one, would the jenny not diffuse in England? One way to address these questions is to evaluate technological diffusion in terms of the profitability of adoption. A potential user must evaluate whether the revenues obtainable by producing with the new technology would exceed costs by an amount superior to the profit generated by the old technology. Only in this case the new technology would be preferred to the old one and thus diffuse.

When the new technology operates at constant returns to scale (CRS), adoption depends solely on the relative prices of input factors. The new technology will be convenient as long as it saves on dearer inputs by substituting them with cheaper ones, *regardless* of the output quantity to be produced. Instead, when the new technology operates at increasing returns to scale (IRS), both the relative prices of input factors and the output quantity matter in deciding the profitability of adoption: in fact, as average and marginal costs vary with the scale of production, so do returns to adoption. In general, then, an IRS technology is profitable only above a certain output threshold. And when the minimum output level required by a new technology is higher than the level attained historically until then, the innovation can be profitably adopted only if sales expand above the critical threshold. In this sense, demand matters.

In a world in which capital cannot be rented, the upfront cost of productive equipment is sufficient to generate economies of scale. Yet, the extent to which they are actually relevant to technological adoption depends upon the magnitude of the upfront capital investment: the higher the fixed cost, the higher will be the minimum output threshold needed to make the technology profitable. With this consideration in mind, the present work focuses on a specific technology, the spinning jenny, which entailed an especially low upfront cost of capital relative to the other major inventions of the Industrial Revolution. By choosing the spinning jenny as a case study, it is ensured that any scale effect acting upon the profitability of adoption would have been even stronger for the other contemporary technologies.

The most profitable between two alternative techniques of production is the one generating a higher net present value. The invention of the jenny in 1764 allowed spinners to evaluate the profits that had been granted until then by the spinning wheel against those that could be granted from then on by the jenny.

computed by subtracting the cost of the subsistence basket from each income class to then compute the Gini coefficient on the remaining income levels. The computations made by Milanovic et al. (2011, pp. 263–264, Table 2) show that the IER amounted to 55.4% in England and 76.1% in France, respectively in 1759 and 1788.

[13] See De Vries (1994, especially pp. 255–57) and Berg (2004, especially pp. 91–95) for interpretations of the Industrial Revolution based on generalized shifts in consumer tastes.

[14] Ashton (1955, p. 42).

Accordingly, a general formula for the profitability of the jenny (superscripted by J) relative to the spinning wheel (superscripted by S) would read:

$$K^J = \sum_{t'=t+1}^{t+T} \frac{p(Q^J_{t'} - Q^S_{t'}) - w(L^J_{t'} - L^S_{t'}) - m^J}{(1+r)^{t'-t}} , \tag{2}$$

where t identifies the year of the adoption choice, K is the upfront cost of capital, m its yearly maintenance cost, w is the daily wage paid for each of the $L_{t'}$ work days in the year t', p is the price obtained for each of the $Q_{t'}$ units of output sold in that year, T is the life time of the jenny, and finally the unknown r is the rate of return from choosing the jenny over the spinning wheel. Equation (2) neglects the upfront cost and the maintenance cost of the spinning wheel just to simplify the notation: the spinning wheel cost only one shilling and such amount does not affect any of the results presented here.[15] Given the data summarized in Table 2, the computation of equation (2) can be made viable through different assumptions, of which one fits especially well the purpose of this work. Before moving to them, it is necessary to introduce the following notation. Define the labor input coefficients α^S and α^J such that $Q^S = L^S/\alpha^S$ and $Q^J = L^J/\alpha^J$: it follows that α^{-1} is labor productivity, and the term $\eta \equiv \alpha^S/\alpha^J$ indicates the labor productivity of the jenny relative to the spinning wheel.

One possibility to allow the computation of equation (2) is to assume that output stays constant across technologies and over time, thus forcing labor to decrease with adoption by a share equal to the productivity gain. This implies that the price drop determined by the productivity gain would not reflect into greater sales: demand would thus be assumed to be perfectly inelastic. Hence, any effect of demand on profitability would be ruled out *ex hypothesis*. An alternative assumption is to consider labor as constant over time and across technologies. This corresponds to a situation in which the decrease in labor that would be allowed by the productivity gain is exactly offset by the labor increase required by the expansion in output. In this case, the productivity gain would reflect entirely on output through price: demand would thus be assumed to be unitary elastic with respect to productivity.[16] As a third possibility, *a priori* assumptions on demand elasticity can be avoided entirely in favor of a more empirical approach. This is the strategy that will be adopted here in order to ensure a more agnostic starting point on demand, which is precisely the issue at stake. Profitability will be computed directly as a function of Q assuming only that $Q^J_{t'} = Q^S_{t'} = Q_{t'}$, while allowing $Q_{t'}$ to change over time. Labeling as L^S_0 the base-year quantity of labor associated with the base-year output quantity Q_0, labor will vary with output according to

$$L^S = \frac{L^S_0 Q}{Q_0} = L^S_0 q , \tag{3}$$

$$L^J = \frac{L^S}{\eta} = \frac{L^S_0 Q}{\eta Q_0} = \frac{L^S_0}{\eta} q . \tag{4}$$

In particular, the base-period labor input will be set to $L_0 = 100$ days per year, which was estimated by Allen to be the characteristic working time of an English spinner prior to the introduction of the jenny.[17] The values of q are instead those reported in Figure 1.

As a first exercise, in this Section Q will be assumed constant over the life of the jenny but possibly different from Q_0. Summing this to the assumptions mentioned above, equation (2) can be rewritten as

$$K^J = \sum_{t'=t+1}^{t+T} \frac{w L^S_0 q \left(1 - \frac{1}{\eta}\right) - m^J}{(1+r)^{t'-t}} , \tag{5}$$

recalling that $q \equiv Q/Q_0$. Given the parameter values, equation (5) allows to plot the value of r as a function of the relative output q. Figure 3 carries out this operation using as parameter values those proposed by Allen (2009b, p. 916) and summarized in Table 2. In Figure 3, England and France are each associated to a specific profitability curve, and these differ one from the other due to the different underlying levels of w and K^J. Figure 3 also takes in consideration that investors did not have necessarily to put money on spinning; in fact, since the average rate of return on economic activities was 15% (represented in Figure 3 by the horizontal line), investment in the jenny would not have taken place unless it guaranteed a greater or equal rate of return.[18] In order to evaluate the profitability of the jenny at a given point in time, Figure 3 highlights also the value of r associated to the level of q recorded in England and France in 1766–67, that is right after the invention of the jenny: the corresponding values are labeled q_E and q_F, respectively for England and France, and they are taken directly from Figure 1. At least three important results emerge from Figure 3.

[15] The cost of the spinning wheel is reported by Allen (2009b, p. 916).
[16] See Gragnolati et al. (2011); Allen (2011b) for further details on these two scenarios.
[17] Allen (2009b, p. 916).
[18] The 15% value is taken from Allen (2009b, p. 917).

Table 2: Data for England and France.

Variable	England	France
w	6.25 *d.* per day	9.00 *st.* per day
L_0^S	100 days per year	100 days per year
K^J	840 *d.*	2800 *st.*
μ	0.1	0.1
m^J	84 *d.*	280 *st.*
T	10 years	10 years
η	3	3

Note: Money values are expressed in pence *(d.)* and sous tournois *(st.)*. The variables summarized in the table are the following: w, daily wage; L_0^S, full working days of a wheel spinner in a year; K^J, purchase price of the jenny; μ, yearly maintenance rate; $m^J = \mu \cdot K^J$, yearly maintenance cost of the jenny; T, years of life of the jenny; η, labor productivity of the jenny relative to the spinning wheel. *Source*: All data come from Allen (2009b, p. 916).

First, the simple profitability computations presented here can provide an economic explanation to why the jenny diffused in England but not in France. Namely, at the output levels existing in each country right after the invention of the jenny, it was profitable to adopt in England but not in France: the value of r associated to the English relative output, q_E, is above 15%, while the one associated to the French relative output, q_F, is far below.

Second, the value of r is always higher in England than it is in France thanks to the more favorable relative prices of input factors, w/K. As reported in Table 2, the ratio between wages and the cost of capital was higher in England than in France; therefore, since the jenny was labor-saving relative to the spinning wheel, its rate of return results to be always higher where labor was dearer. In this sense, English spinners had a stronger incentive than French ones to substitute labor with capital. Yet, by affecting the level of r, relative prices play also a role in determining the critical output threshold above which the jenny was convenient. Again, an higher cost of labor relative to capital implied a lower critical threshold in England as compared to France.

Third, demand mattered to adoption choices *regardless* of the relative prices of input factors. A relative output level equal to q_E would have made the jenny profitable also for French spinners, despite the adverse relative prices they faced. Vice versa, if at the same moment English spinners had to restrain their relative output to q_F, the jenny would have been unprofitable for them in spite of the favorable relative prices they faced. In this sense, demand mattered regardless of relative prices, and the questions that were posed at the beginning of this Section are now answered.

All the results presented so far in terms of the index number q can be referred to the output per spinner Q by assigning a value to s, the share of population employed as a spinner. In the attempt to give a numerical example, s can be assumed to be equal to 1%. In this case, the output per spinner Q_E and Q_F corresponding to the points q_E and q_F in Figure 3 would be about 74*lbs* and 24*lbs* respectively. Such quantities would represent the average output per spinner, respectively in England and France, in 1766–67. Similarly, it is possible to characterize precisely the critical output threshold in each country, that is the output per spinner above which r is higher than 15%. Assuming $s = 1\%$, the critical level would be about 32*lbs* and 74*lbs* respectively in England and France.[19]

The results shown here seem to make the case for increasing returns in manufacturing even at the early stage of the Industrial Revolution.[20] Relatedly, also the evidence on the possible relevance of demand in deciding the diffusion of the spinning jenny starts now to be more binding. Nonetheless, a source of skepticism could regard the link between demand conditions and the timing of industrialization. Given the relative prices of input factors, it could turn out that the minimum amount of sales needed for adoption was reached in England and France at a different timing from the actual start of industrialization in each country. Vice versa, given an amount of sales, it could turn out that the relative prices of input factors allowing for adoption in each country were reached way before or way too late with respect to the actual pace of industrialization. Overall, then, it is necessary to assess the extent to which demand and relative prices can match with history.

[19] Notice that, assuming, $s = 1\%$ produces an estimate of the typical Q for England that is quite close to the one proposed by Allen (2009a,b), that is 100*lbs*. As discussed by Bythell (1964), obtaining reliable figures for the number of workers employed in the cotton industry during the 18th century is particularly difficult. Precisely for this reason the present work has adopted a methodology that allows to largely prescind from that information. In any case, just to have a rough idea of the weight of cotton in terms of employment, also Bythell (1964, p. 344) reports multiple sources estimating the number of weavers in England to be between 200,000 and 250,000 before 1833: that corresponded approximately to 1% percent of the population. Clearly, this percentage would grow if also spinners were included, but on the other hand the cotton industry was already much bigger by 1833 than it was by the mid 18th century.

[20] To the contrary, Mokyr (1977, p. 995) claimed that "it is not an easy task to substantiate the case for increasing returns in manufacturing anywhere before, say, 1870".

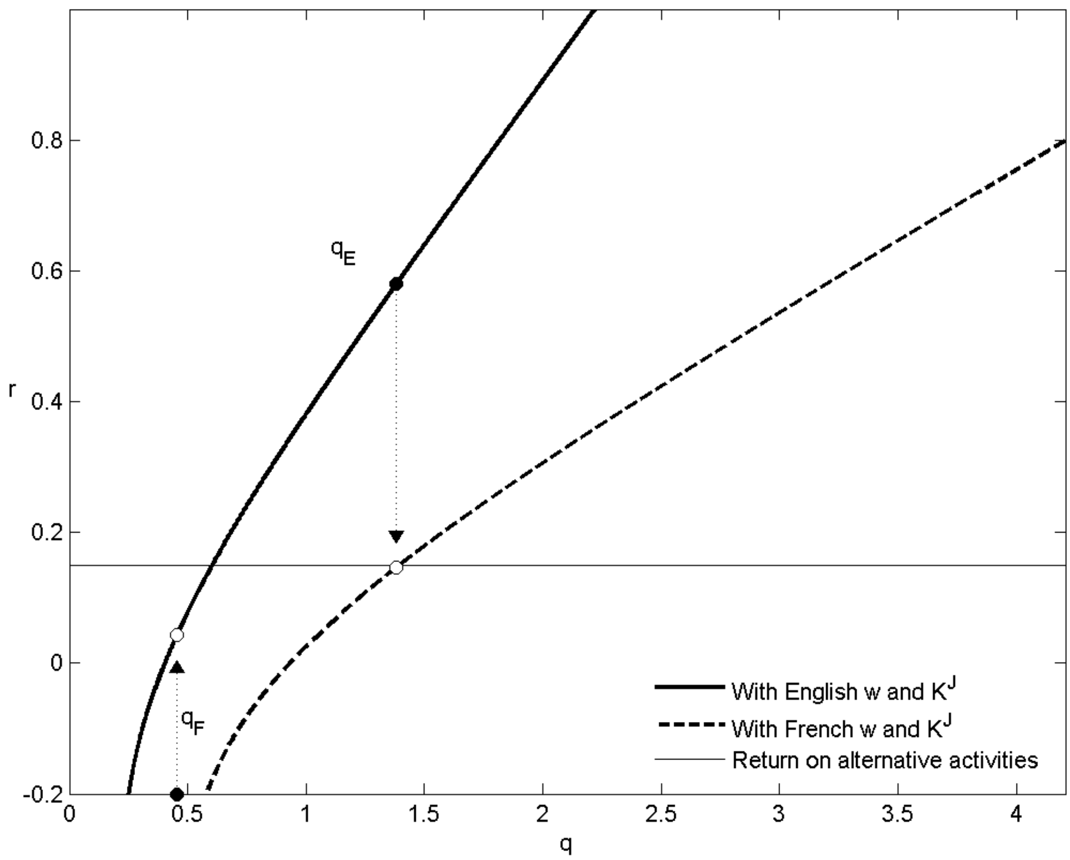

Figure 3: r as a function of q.

4 Timing of adoption of the new technologies

So far it was shown that the adoption of a representative Industrial Revolution technology like the jenny was not viable in France *at the same time* as it was in England, due to differences in demand and relative prices. Now the relevant question becomes another one, namely: given either demand or relative prices, *since when* was the adoption of the jenny viable in each country?

The first counterfactual exercise consists in fixing relative prices while allowing the amount of sales to vary. In particular, relative prices are fixed at the year of invention of the jenny, while the output for each year, $q_{t'}$, is set at the corresponding value of q reported in Figure 1. This allows to evaluate how the profitability of the jenny changed over time according to the evolution the requests faced by the average spinner. In order to do so, it is sufficient to include explicitly a year index for q in equation (5), so that it becomes

$$K^J = \sum_{t'=t+1}^{t+T} \frac{wL_0^S q_{t'}\left(1-\frac{1}{\eta}\right)-m^J}{(1+r)^{t'-t}} . \quad (6)$$

The value of r as computed with equation (6) is plotted in Figure 4 at the English and French 1764–65 relative prices, taken from the values of w and K reported in Table 2. The plot shows that a technology like the jenny would have been profitable since 1740 in England, and after 1790 in France. Considering the ideal beginning of industrialization to be 1760 and 1810 respectively in England and France, the estimates on the timing of adoption provided by equation (6) are reasonably lagged backwards by 20 years. In the case of England, this discrepancy may be justified by the fact that inventions need time to become marketable. For instance, the first major (but unsuccessful) attempt to mechanize cotton spinning is surprisingly close in time to 1740: namely, Lewis Paul patented for the first time his roller spinning machine in 1738 and then obtained a second patent for a perfected version in 1758.[21] Similarly, the jenny underwent a possibly significant period of experimentation

[21] See English (1973) and Hills (1979) for two detailed technical assessments of the roller spinning and of its timing of invention.

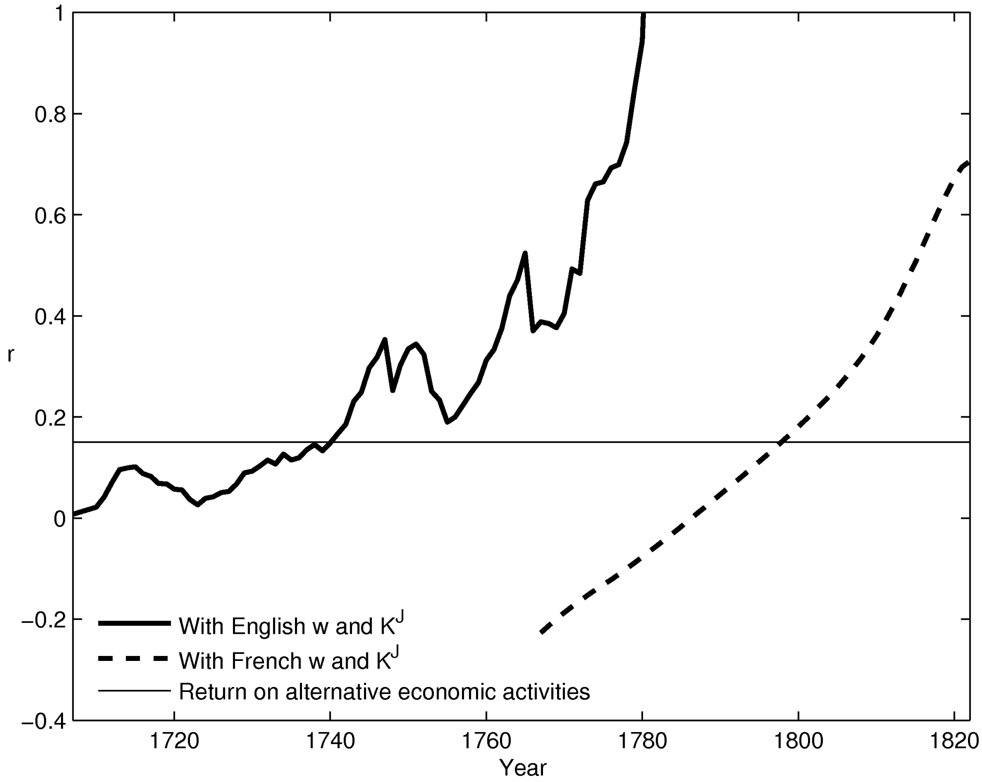

Figure 4: r as a function of $q_{t'}$.

and improvement before it reached the minimum efficiency that was necessary to make it profitably adoptable and thus marketable. As for what concerns France, it may seem that the discrepancy between the economic prediction and history does not concern only the time lag but also the very fact that the jenny did not diffuse much in France after 1790.[22] By that time, however, the jenny had already been superseded by the spinning mule, which in fact started to spread also in France: that is why the diffusion of the jenny in France cannot be observed.[23] Overall, then, demand variations seem to explain quite accurately the timing of industrialization.

The second counterfactual exercise consists in fixing the amount of sales while allowing the relative prices of input factors to vary. When output is fixed so that $Q_{t'} = Q_0$, recalling that $m^J/K^J = \mu$ and dividing both terms in (5) by K^J allows to write

$$1 = \sum_{t'=t+1}^{t+T} \frac{\left(\frac{w}{K^J}\right)_{t_0} z_{t'} L_0^S \left(1 - \frac{1}{\eta}\right) - \mu}{(1+r)^{t'-t}}, \tag{7}$$

Given $(w/K^J)_{t_0}$, equation (7) reveals how the value of r changes according the variation of relative prices of input factors, which are summarized by the index $z = \left(w/K^J\right)_{t'} \left(K^J/w\right)_{t_0}$. In England, setting $(w/K^J)_{t_0}$ to its 1764–65 level reported in Table 2, r turns out being greater than 15% for any $z > 0.6$. According to the time series on relative prices elaborated by Allen, this condition was attained in the English economy since 1650.[24] But the jenny was invented and adopted one century later! Therefore, the time accuracy obtained with a varying amount of sales cannot be replicated by allowing the relative prices of input factors to vary instead. In this sense, it seems possible to claim, at least, that demand explains the timing of adoption of the jenny much more accurately than relative prices do.

[22]According to Allen (2009a, p. 193), by 1790 there were 900 jennies in France and 20,000 in England.

[23]For instance, Chaptal (1819, p. 5) describes the technological state of the French cotton industry by 1819 as follows: "L'état actuel de nos filatures par les mécaniques dites *mull-jennys* et *continues*, nous permet de fournir par an à la fabrication des tissus ou de la bonneterie plus de 25 millions de livres de fil de coton, indépendamment de ce qui se file encore au rouet ou à la main dans les montagnes: la filature est aussi parfaite qu'on peut le désirer; et si jusqu'ici on a paru négliger de filer les numros les plus fins, c'est qu'on a préféré ceux dont le débit et la consommation étoient plus assurés et plus étendus".

[24]See Allen (2009a, p. 139, Figure 6.1) for the time series of the price of labor relative to capital. See instead Crafts (2010, pp. 158–59) for an assessment similar to the one presented here.

Then, demand has likely played an important role in deciding the 'when', 'where', and 'how fast' of the Industrial Revolution. Nevertheless, it could reasonably be argued that an "explanation" of an event needs to be consistent with the facts that preceded it and with those that followed. In particular, the industrial one was a "revolution" not only because it increased enormously output, but also because it drastically changed the way in which labor was organized. Then, it is necessary to verify whether the analytical framework presented here can be consistent also with the major changes in the organization of labor that followed the diffusion of a technology like the jenny.

5 From cottages to factories

Up to now it was explained why, *given* a certain organization of labor and a certain market structure, an IRS technology like the jenny might diffuse. Yet, it is equally important to understand how the diffusion of IRS technologies ended up affecting the organization of labor and the market structure within the cotton industry. In this respect, the general fact to be explained is the transformation from a landscape of small cottagers to an industry of factories. Which mechanisms governed this transformation? And how do they fit in the analytical framework proposed here?

In the pre-industrial era the manufacturing of cotton was not highly specialized. Typically, cotton spinners carried out *all* the activities that were necessary to turn raw cotton into yarn, and then they sold the finished product to a merchant. Indeed, spinning was only one of the several activities involved in the process, and the remaining ones occupied a non negligible share of time. Moreover, since it was often women from the countryside that spun cotton, a considerable share of the employment in the industry devoted to cotton only a limited part of their day, as the rest was taken by other domestic activities. By the same token, labor could be hard to find in rural areas because the other women of the village were also busy in their own business and household, while men carried out other activities.[25] Thus, labor scarcity tended to keep production on a small scale.

In contrast with this "traditional" picture, by the end of the 18th century England saw a growing presence of big productive units, often located near cities, and always characterized by a much finer division of labor. The factories of the Industrial Revolution contributed to moving the barycenter of economic production from the countryside toward urban centers, and contemporaneously they brought a major change in the organization of labor and society. How did this change come about?[26]

An answer to this question can be given by analyzing the evolution of labor input requirements in the cotton industry, especially during the very early phases of industrialization.[27] Recalling that spinners traditionally carried out more than one activity to turn raw cotton into yarn, the *total* labor input requirement is obtained by adding the time needed *only* for spinning to the time required *only* by activities other than spinning. According to Allen, the amount of time required to clean, card, reel, and make rovings of a pound of cotton was 1.067 days.[28] Using this estimate, the total labor input required by the technology $i = \{S, J\}$, will simply be $L^i_{TOT} = L^i + 1.067 \cdot Q$, where L^i is the labor input required only for spinning with a given technology as computed with equations (3) and (4). Taking the values of q reported in Figure 1 and applying a filter to remove high frequency changes, the resulting values of L^i_{TOT} for the average English spinner are those shown in Figure 5. The corresponding French values are instead omitted to simplify the exposition: since they are just delayed with respect to the corresponding English levels, what applies to England applies also to France but simply later on in time. A number of considerations emerge from Figure 5.[29]

To begin with, for quite some time after the introduction of the jenny, a spinner who had adopted it could work less than what she did with the spinning wheel. As shown in Figure 5, somebody who had immediately adopted the jenny in England in 1764 could decrease straight away her total working time from point A to point B; then, as compared to point A, she would continue to spare time until point C was reached in 1778. The 14-year distance between A and C means that the amount of sales kept small enough for long enough, so as to not require any extra labor throughout the whole life time of the jenny (i.e. $T = 10$ years in Table 2) and beyond. Therefore, the adoption decision concerning the jenny was not initially affected by the aforementioned constraints on the availability of labor, since no extra labor was needed; nor would the spinner have to sacrifice some of the time she devoted to leisure or to other activities, since the working time taken by the processing of cotton initially reduced.[30] But soon things had to change.

[25] Allen (2009a, p. 185) and Allen (2011b, p. 462).

[26] For an overview of the literature on the transition toward factory productions see Mokyr (2001).

[27] Note that, being the *first* IRS technology for spinning after a whole history of CRS technologies, the jenny turns out again to be an especially interesting case study to focus on the early moments of the industrializing English economy.

[28] Allen (2009a, p. 185) and Allen (2011b, p. 462).

[29] In order to simplify the exposition, Figure 5 was obtained under the assumption that all spinners used either the spinning wheel to the jenny, but not the two technologies contemporaneously.

[30] Incidentally, this fact shows that the concerns raised by Allen (2011b) about leisure/work decisions and labor availability are not stringent in the case of the jenny. It is indeed for this reason that the labor equations (3) and (4) were used without imposing

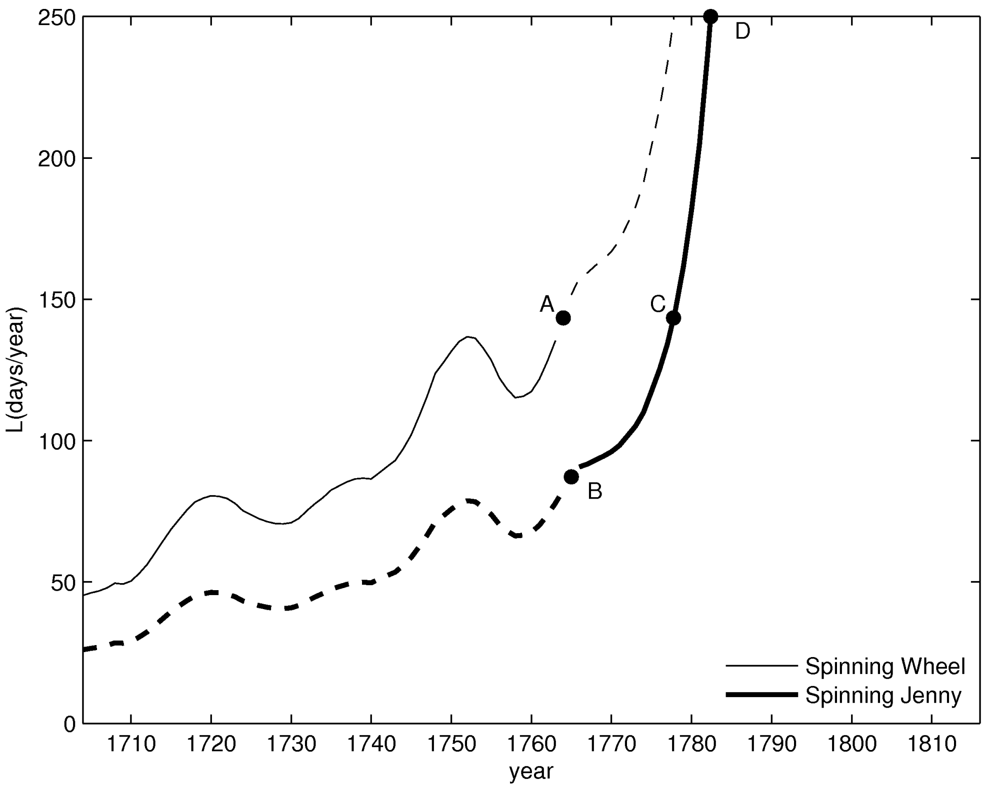

Figure 5: Evolution of L^S_{TOT} and L^J_{TOT} during the 18th century in England.

As the requests from the market kept growing, much more labor became necessary. Indeed, the attainment of point C was closely followed by the requirement of a full working year for the processing of cotton, as represented by point D in Figure 5.[31] And those two points were already in the middle of an exponential growth in labor requirement. Hence, even supposing that the spinner actually decided to work more on the processing of cotton, her own working time would anyway become soon insufficient to keep up with the market requests. She could recover some of the extra time that was needed by specializing only on spinning, while abandoning the other activities involved in the processing of cotton: in this sense, then, an IRS technology like the jenny could induce specialization simply because its user was involved in parallel in other CRS activities, which offered comparatively lower returns after the jenny was adopted. But the time saving granted by specialization would certainly not suffice to keep up with the exponential growth rate of requests shown in Figure 1. Much more labor was needed. And if, until then, labor might have been hard to find, now IRS technologies offered an economic escape from the bottleneck. The owner of a machine working under IRS could offer a wage above the average in order to attract workers from other industries; in turn, and within a certain limit, this would allow to increase output substantially, push scale economies further, and finally obtain higher rates of return. In this way, scale economies allowed the employer to rise wages and hire workers, while contemporaneously obtaining a return above the average.

As a result, if until then the work force in the cotton industry was substantially constituted by households that operated on a very small scale, now a clear pressure and possibility emerged to organize production on a larger scale. As scale grew, it also became convenient to adopt technologies that had contemporaneously even stronger IRS and an higher upfront cost than the jenny. Not surprisingly, then, if the earlier vintages of the jenny had 12–24 spindles and were used by cottagers, by 1780 the standard design contemplated 80 spindles and was typically adopted in workshops.[32] By the same token, the water frame found a market although the licenses for its 1769 patent design were restricted to units of a thousand spindles, which ruled out adoption from cottagers and made it convenient to set up factories.[33]

any constraint on L.

[31] The quantification of a full working year in 250 days comes from Allen (2009b, p. 916).

[32] Allen (2009b, p. 906).

[33] See Hills (1979, p. 123). In this respect, it is worth noting that it was technically possible to build small cottage water frames that could be used as a domestic spinning machine rather than inside factories; yet, the Arkwright partnership decided to build

Within this process of change, the co-evolution of technology and society was not necessarily peaceful. The innovations of the Industrial Revolution and the consequent emergence of the factory system were heavily contrasted as soon as they ate into the established socio-economic order. For example, during the Lancashire riots of 1778-1780, machine-wreckers demolished the larger workshop jennies with more than 24 spindles and spared the smaller ones, which were consistent with the traditional organization of cottagers in the cotton the industry.[34] By the same token, Arkwright-type of factories were assaulted in 1779.[35] Overall, riots against the new machines and factories persisted for a long time and reached their most intense phase during the Luddites riots of 1811–1813. How was it, then, that technological inertia was finally broken and a new order came into being? The fact is that the political support to mechanization changed radically and played a decisive role. As the new technologies appeared, the English government increasingly identified its interests with those of the "innovative entrepreneurs": in 1769, a new law was passed which made the destruction of machinery an offense punishable by death; in 1780, the Parliament denied a petition of cotton spinners against the new machines; and, finally, the Luddites outbreaks were quelled by an army of 12,000 men.[36] In this sense, repression from the "liberal state" has likely favored the unfolding of the Industrial Revolution.

6 Conclusion

The present work has documented the essential role played by demand in deciding the diffusion of a representative Industrial Revolution technology like the spinning jenny. Both the average income level and its distribution were shown to be plausible reasons for which the typical English spinner would face more requests as compared to its French counterpart. England could count on a sufficiently vast and well-off portion of the population capable to express a sufficiently ample demand for a non-subsistence good like cotton; to the contrary, the fact that income was lower and more concentrated in France blocked a considerable share of the French population from participating to the formation of the demand for cotton. If the typical French spinner had accomplished as many sales as her English counterpart, the jenny would have been profitable to adopt also in France despite the unfavorable relative prices; vice versa, had the output of a typical English spinner been restrained to the level of its French equivalent, the jenny would not have been profitable even under the favorable English relative prices. By the same token, the evolution of cotton demand over the 18th century turns out matching both the early start of England and the late arrival of France in the race toward industrialization. These results are based on the specific case of the spinning jenny, yet they are likely to contain broader implications regarding also the other textile technologies of the Industrial Revolution. In fact, the spinning jenny entailed smaller upfront capital costs as compared to the other textile innovations that followed; consequently, if scale effects acted on the profitability of adopting the jenny, they possibly had an even greater impact for the more capital-intensive textile technologies that followed. These conclusions bear three main messages in relation to other contributions in the literature.

First, and contrarily to the argument made by Allen (2009a,b, 2011c) and Broadberry and Gupta (2009), although being an ingredient of the story, the relative prices of input factors alone seem insufficient to explain the Industrial Revolution. This was shown through the various counterfactual exercises on the profitability of adoption: if only relative prices mattered, a technology like the jenny should have been invented one century before its actual invention. Why did history run otherwise? Whatever the possible reason, it implies that some other piece of an explanation needs to be added to the relative prices of input factors, if they are to be used to account for the Industrial Revolution. This extra piece can well be demand.

Second, and in contrast with the claim made by Mokyr (1977), demand did matter during the Industrial Revolution due to the interaction between scale effects and market size.[37] As a consequence, the analysis of supply conditions should go hand in hand with the analysis of demand, rather than walking alone.

Third, and in relation to the recent debate emerging from Allen (2009a) and Mokyr (2009), the market for the early inventions of the Industrial Revolution could exist in England but not in France, notwithstanding the level of technical competence of the two countries.[38] For instance, any effort to invent and sell the jenny to French spinners would have normally failed, even if French inventors and engineers had had the same technical competence as their English counterparts. In this perspective, it may be possible that the reason why England had a higher level of technical competences was precisely because such competences paid in England but not elsewhere.

only bigger frames in order to prevent losing control of the patent, since "everyone would have copied it and built their own machines in the privacy of their own homes" (*ibid*).

[34] Wadsworth and Mann (1931, p. 499–500).

[35] See Nuvolari (2002, p. 393) and Horn (2005, p. 143).

[36] See Mokyr (1990, p. 257).

[37] The reference is to Mokyr (1977, p. 1005): "[T]he traditional notion that supply and demand were somehow symmetric in the industrialization process is unfounded. The determination of 'when', 'where', and 'how fast' are to be sought first and foremost in supply, not demand related processes".

[38] See Mokyr (2009, pp. 99–123) and Allen (2009a, pp. 8–11 and 238–271), as a reference to the two sides of the debate. See Crafts (2010) for an insightful assessment of each of the two sides.

To conclude, it is important to notice that the story which has been told here has all the ingredients to answer an apparently critical question. Namely, if demand for final goods was decisive, why was a machine like the jenny not invented in the richest country of the mid 18th century, the Netherlands? Two facts are possibly relevant to provide an answer. First, by 1732, only 33% of the Dutch population earned more than subsistence.[39] That percentage is higher than it was in France in 1788 (22%), but it is still much lower than the English one in 1759 (51%); hence, domestic demand might have been insufficient to render the jenny convenient for the average Dutch spinner. Second, by the mid 18th century, the Dutch population was about one sixth of the English one, and consequently also the number of cotton spinners was proportionately lower in the Netherlands. It follows that the *inventor* of the spinning jenny had a much bigger potential market in England as compared to the Netherlands. Therefore, somebody like Hargreaves had a greater probability to appear north of the channel, where the highly uncertain sunk cost entailed by research and development activities were easier to cover, as discussed by Allen (2011c, p. 14).

[39]This number is obtained using exactly the same procedure described in Section 2. The income distribution data for Holland in 1732 come from the GPIHP web site `http://gpih.ucdavis.edu/Distribution.htm`, which quotes Milanovic et al. (2007) as the source of the data. The 1732 value at current prices of the respectable consumption basket in Amsterdam is obtained exactly as in Table 1: the corresponding CPI value is again taken from the file `Amesterdam` on Allen's web site, `http://www.nuffield.ox.ac.uk/General/Members/allen.aspx`.

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