ESSAYS ON THE ORIGINS OF MODERN ECONOMIC GROWTH

by

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ABSTRACT

This thesis is concerned with the origins of modern economic growth, dealing with a fundamental discontinuity in the process of world economic development: the Industrial Revolution and the emergence of modern economic growth.

The first chapter argues that, in spite of slow economic growth, the Industrial Revolution was a period in which there was a discontinuity in the driving forces of modern economic growth. Nevertheless, empirical evidence indicates that temporary growth spurts occurred in several pre-industrial economies. Micro and macro data also suggest that there was another discontinuity in the driving forces of the demographic transition and modern economic growth, involving a change in fertility decisions. Cross-country regressions indicate that improvements in human capital were fundamental for the emergence of modern economic growth.

The second chapter uses an endogenous structural breaks procedure that allows us to confront two alternative views of the Industrial Revolution. The tests are carried out for two periods: 1700-1800 and 1800-1850. The empirical results show that structural breaks occurred in most industries throughout the period, suggesting that growth was pervasive during the period and not localized in the iron and cotton industries. The econometric results also indicate that, for the period 1700-1800 the population variables underwent structural breaks earlier than the industrial variables. A vector autoregression (VAR), impulse response functions and causality tests are used in order to further understand the relationship between industrial output and population.

The third chapter argues that the fundamental feature of the first Industrial Revolution was a reorganization of the British economy originated by the development of an organizational general purpose technology, the factory system. During the Industrial Revolution there was both slow per capita GDP growth and pervasive innovation because it took time for the investment in organizational capital to be fully realized and a process of social learning to be completed. In spite of low rates of growth, the organizational revolution was crucial for the emergence of modern economic growth.

DEDICATION

To my wife, Isabel, my parents, and my son Tiago, who will also enjoy the benefits of modern economic growth

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Chapter 1

When Did Modern Economic Growth Really Start?[1]

The Empirics of Malthus to Solow

Abstract

This chapter argues that, in spite of slow economic growth, the Industrial Revolution was a period in which there was a discontinuity in the driving forces of modern economic growth. Nevertheless, empirical evidence indicates that temporary growth spurts occurred in several pre-industrial economies. Micro and macro data also suggest that there was another discontinuity in the driving forces of the demographic transition and modern economic growth, involving a change in fertility decisions. Cross-country regressions indicate that improvements in human capital were fundamental for the emergence of modern economic growth.

JEL Classification: N10, O11, O14

Keywords: Malthus to Solow, stylized facts, modern economic growth

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1. Introduction

Following the developments of endogenous growth theory in the 1990s, the macroeconomics literature has recently focused on the transition from "Malthus to Solow" (Artrouni and Komlos 1985, Goodfriend and McDermott 1995, Hansen and Prescott 1999, Galor and Weil 2000, Galor and Moav 2002, Carlaw and Lipsey 2001), as well on the Industrial Revolution (Lucas 2002, Jones 2001). This literature emphasizes that there are fundamental differences between Malthusian and modern economies, and the Industrial Revolution is seen as a watershed in world economic development after which sustained growth started. This renewed interest in the transition from Malthus to Solow was mainly caused by the lingering inconsistencies between the Malthusian and the neoclassical theories of economic development. Although the Malthusian theory accounts relatively well for most of pre-industrial history and the modern growth theory can explain many features of modern economic development, there was no unifying theory linking both theories until the recent literature on the transition Malthus to Solow (Lucas 2002).

This interest of macroeconomists in the process of long-term economic growth has coincided with the revisionist movement in economic history, which has reconsidered long-held views on world development. An "old" perspective maintained that the first Industrial Revolution marked a brave new era, after which diminishing returns and the Malthusian checking forces were finally defeated and growth triumphed. In this view, the advent of industrialization unleashed the forces of modern economic growth (Kuznets 1966), which then allowed for a massive increase in population and urbanization at the

same time that income and consumption per capita trended sharply upwards (Deane and Cole 1969).

More recently, several studies have cast doubt on some of the premises of this traditional view. It is now clear that the Industrial Revolution was much less sudden and less dramatic than previously thought (Harley 1982, Crafts 1985, Crafts and Harley 1992, Clark 2001). Due to the slow rates of both GDP and per capita GDP growth[2], the Industrial Revolution has been depicted as a mere growth spurt, not very different from others in the past (Clark 2001, Goldstone 2002). In addition, there is also a growing debate on whether or not the Industrial Revolution was really necessary for the emergence of modern economic growth. For instance, de Vries and Woulde (1997) have argued that the 17th century Dutch economy had many features of a "modern" economy, such as high urbanization (around 35 percent by 1650), and relatively high income per capita. Since international trade and secure property rights were the main sources of growth during this Dutch "golden age", de Vries (2001) contends that industrialization was not the sole path to modern economic growth. In overview, the revisionists argue that the Industrial Revolution should be seen as an episode, albeit important, in the trajectory of world economic development, but not as a marked discontinuity.

In sum, after years of neglect, macroeconomists have renewed their interest in the Industrial Revolution and the transition from Malthus to Solow, whereas mainstream economic historians have increasingly downplayed the role of the Industrial Revolution, preferring to emphasize continuity instead of structural breaks in the process of world economic development.

[2] GDP per capita grew at an average rate of less than 1 per cent per year from 1760 to 1830.

This chapter attempts to bridge the gap between the two literatures by providing some empirical evidence on the transition from Malthus to Solow. The empirical results support the view that modern economic growth started with the Industrial Revolution. Namely, the results indicate that permanent "symptoms of modernity" emerged during this period. The chapter also argues that although the results of the growth process in countries such as Britain exhibit a certain continuity (as Crafts and Harley (1992) have shown), the Industrial Revolution entailed a discontinuity in the driving forces of the same growth process. Thus, although the aggregate indices do not seem to indicate a sharp discontinuity in the evolution of GDP and per capita GDP, the underlying forces of modern economic growth were already in full swing during this period. However, as many have argued before[3], the emergence of modern economic growth during the Industrial Revolution does not imply that intensive growth was nonexistent in the previous centuries. Indeed, the empirical results of this chapter also suggest that growth spurts occurred in several pre-industrial economies, indicating that the latter were much more dynamic than suggested by the traditional modeling of Malthusian economies.

This chapter also presents additional evidence that there were discontinuities in other driving forces typically associated with modern economic growth as well as with the demographic transition. Namely, the micro data for some early European developers suggests that there was a change in fertility decisions in the early 19th century (as suggested by many "Malthus to Solow" models). Nevertheless, the empirical evidence also indicates the fall in birth rates is highly correlated with the decline in mortality rates, which decreased due to improvements in health technology.

[3] See, for instance, Jones (1988), Snooks (1994), de Vries (2001).

Finally, the empirical results from several macro cross-country regressions suggest that: 1) literacy was highly correlated with economic development in the 19th century, 2) the average number of children was negatively correlated with per capita GDP growth as well as literacy rates, 3) Protestantism and urbanization were positively correlated with literacy, and 4) there was a strong negative relationship between mortality rates and literacy rates.

The chapter proceeds as follows. The next section describes the three main features of the Malthus to Solow literature: intensive versus extensive growth, the relationship between real wages and population, and the child quantity-quality trade-off. The following subsections present empirical evidence on each of these features. The last section concludes.

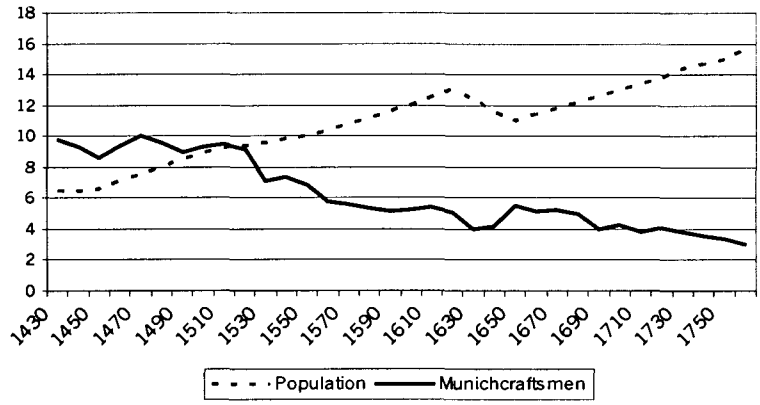
2. From Malthus to Solow

The Malthus to Solow models contain three central ideas. First, in Malthusian economies, income gains were mainly translated into additional population. Consequently, income per capita was almost constant (Galor and Weil 2000). In contrast, in modern economies, productivity improvements sustained by technical change enabled population and standards of living to increase simultaneously.

Second, since technical change was largely absent in Malthusian economies, labour supply shocks were much more common than labour demand shocks. Typically, increases in population led to a rise in the labour supply, putting downward pressure on real wages. Since the shift in labour supply was not matched by a shift in labour demand, population increases were associated with a decrease in real wages. By the same token, wages increased during periods of population decline (e.g. after the Black Death in the 14th

century). Figure 1 presents a typical example of the inverse relationship between real wages (in grams of silver) and population (in millions) in pre-industrial economies. In modern economies, wages and population are no longer inversely related, due to sustained improvements in labour productivity, which offset increases in the labour supply. Therefore, one "symptom" that an economy is no longer Malthusian is a *permanent* disappearance of the inverse relationship between wages and population.

Figure 1_ Munich Craftsmen Real Wages Vs German Population, 1460-1750



Source: real wages from Allen (2001), population from McEvedy and Jones (1978)

Third, the decline in fertility initiated sometime in the late 18th century was chiefly caused by parents' preferences over their children's education. According to Becker, Murphy and Tamura (1990), Galor and Weil (2000) and Lucas (2002), the returns to education were low in the mostly-agricultural Malthusian economies, and hence parents preferred to invest in child quantity. Over time, technology raised the returns to human capital, and parents started investing in the quality of their children, initiating a demographic transition.

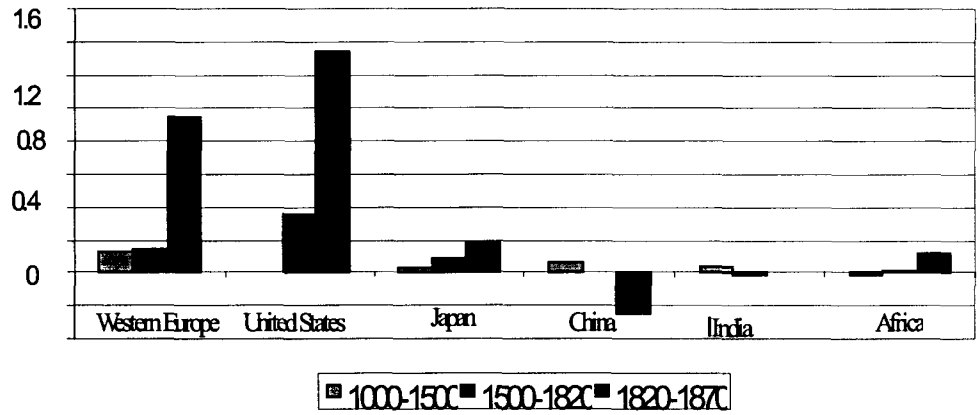
These three characteristics of the transition from Malthus to Solow allow us to observe the process of economic development by looking at "symptoms of modernity" in terms of intensive versus extensive growth, the relationship between real wages and

population, and the child quality-quantity trade-off. The next sections present some empirical evidence on these "symptoms of modernity".

Extensive Versus Intensive Growth

The greatest difference between modern and pre-modern economies was not the existence of growth, but the nature of growth. In pre-industrial economies intensive growth (GDP per capita growth) was almost negligible (figure 2). Although average standards of living in pre-industrial economies showed little trend (Hansen and Prescott 1999), many pre-industrial economies sporadically experienced periods of relatively fast growth, such as in Sung China (Jones 1988), 14th century Italy (Clark 2001), or 17th century Holland (de Vries and Woulde 1997). However, these growth episodes were then mostly reflected into a higher population, an expansion of urbanization, or an improvement in the living standards of the ruling elites.

Figure 2_Per Capita GDP growth rates: 1000-1870



Source: Maddison (2001)

Furthermore, not only was intensive growth rather uneventful in pre-industrial economies, but also extensive growth was not impressive by today's standards (Livi-Bacci 1989). In contrast, in the last 200 years both intensive and extensive growth

accelerated considerably. In spite of a dramatic rise in population, output per person has also increased at an unprecedented pace, increasing by more than a factor of 13 in the most developed countries (Lucas 2002).

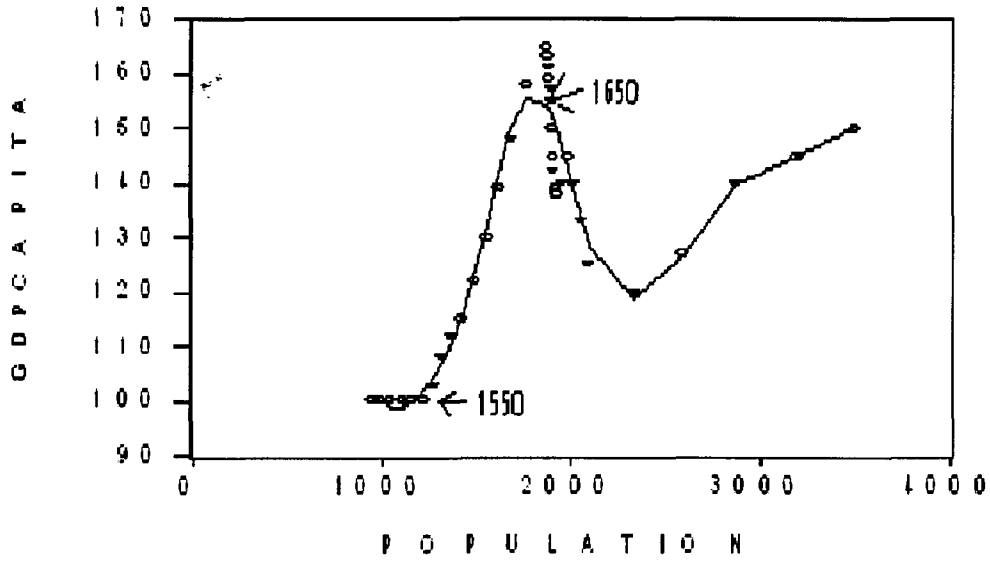
Other features of the transition from Malthus to Solow can also be observed from cross-country data, although before 1800 the data are often made of rough guess-estimates (and thus are subject to significant measurement error). GDP and GDP per capita figures from Maddison (2001) for a sample of 23 countries and territories[4] show that, by the year 1000, GDP per capita was remarkably similar for the great majority of the countries and territories, since most of them were still at the subsistence level of $400 (1990 international dollars). Between 1000 and 1800, the level of income per capita increased for most countries and territories in the sample. Namely, by 1800, most countries and territories in the sample were in a better position than 300 years earlier. Although these rates of GDP per capita growth are small by today's standards, from 1500 onwards there was already an important difference between Western Europe and most other countries: the former was growing at about 0.1 percent per year whereas the latter grew on average at 0.01 percent. At these rates European living standards doubled each 700 years, whereas for the rest of the world it would take about 7,000 years to double income. Thus, these small rates were sufficient to open up a sizeable gap between Europe and the rest of the world in a few centuries.

The impact of intensive growth can also be grasped in individual countries, although the scarcity of high-frequency data raises several difficulties to cross-country

[4] The countries and territories include Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Sweden, Switzerland, United Kingdom, Portugal, Spain, Eastern Europe, Russia, the United States, Mexico, Japan, China, India, Other Asia, and Africa.

comparisons. Most data start only in the 18th or 19th centuries, and often the existing figures are incomplete and unreliable. Nevertheless, we do have some data for some of the most advanced countries in Europe, and some scattered data for many of the other countries of different regions. More importantly, we have data for the two early developers in Western Europe, Holland and England, which allows us to compare the development trajectory of these two countries. Data on the Dutch population data are from McEvedy and Jones (1978) and de Vries and Woude (1997). The GDP data were obtained from de Vries (2000) and from de Vries and Woude (1997). Figure 3 shows the relationship between Dutch GDP per capita (in 1720-44 guilders) and the Dutch population (in thousands) from 1500 to 1900, adjusted by an Epanechnikov Kernel fit[5].

Figure 3 _ Dutch GDP per capita Vs Population: 1500-1860



[5] The Epanechnikov Kernel was used due to its versatility and optimality in comparison to other parametric and nonparametric approaches. According to Härdle (1990), there are four main advantages of the nonparametric kernel-fit approach to estimating a regression curve: 1) versatility of exploring a relationship between two variables, 2) prediction of observations without having to use a fixed parametric model, 3) it is a tool for finding spurious observations, 4) it is a method for interpolating or substituting for missing values

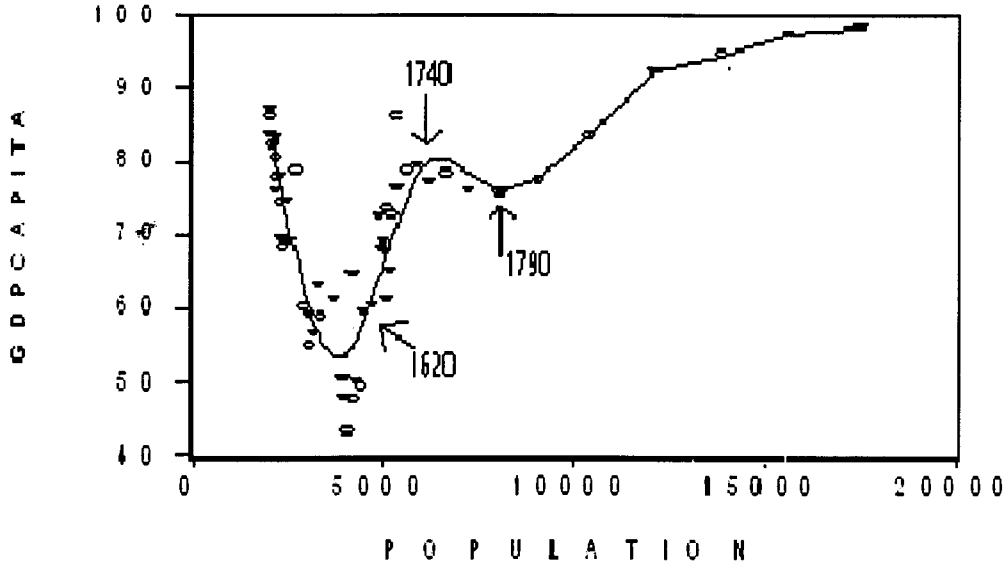
During the period 1550-1650, the Dutch economy exhibited some "symptoms of modernity", as de Vries and Woude (1997) claim. During this Dutch "golden age", trade-based or Smithian growth fuelled GDP per capita and enabled a considerable increase in population. However, these signs of modernity were only temporary. After 1650, population growth stagnated, and GDP per capita fell. Consequently, the Kernel fit polynomial relating both variables becomes negatively sloped. Only after 1800 did both population and GDP per capita increase simultaneously once again. The wage data in the next section also suggests the same pattern of development. Since the increases in both standards of living and population did not become permanent or self-sustaining, the Dutch Golden Age should be seen more as a growth spurt rather than the start of the modern economic growth, as Goldstone (2002) argues.

For England, I obtained data on GDP per capita from Clark (2001), as well as population data from Hatcher (1977) and Wrigley and Schofield (1981). Figure 4 plots an index of English GDP per capita against population (in thousands). The figure shows that GDP per capita was inversely related to population until around the 17th century[6]. From about 1620 until around 1740, there is an increase in both population and GDP per capita, which indicates that the English economy was experiencing an intensive growth spurt. North and Thomas (1973) attribute much of the significant income gains during this period to the establishment of well-defined property rights (North and Thomas 1973) as well as gains from international trade. However, this growth spurt did not become self-sustaining because it was based on Smithian growth, which, according to Mokyr (1990),

[6] The considerable decrease in GDP per capita observed in the Clark (2001) data was a consequence of rise in incomes to the survivors of the Black Death. The sharp fall in population in the 14th century led to a considerable rise in real wages as well as capital per capita. Per capita GDP fell in the following centuries due to the increase in population.

is subject to diminishing returns. Between 1740 and 1790, population continued to expand considerably, but GDP per capita declined slightly. Consequently, during this period both variables became temporarily inversely related. After 1790, and in spite of an unprecedented increase in population, the productivity improvements associated with the Industrial Revolution allowed for both GDP per capita and population to clearly trend upwards. Contrary to previous growth spurts, growth from the Industrial Revolution did not peter out, because it was largely based on sustained technological and organizational change or Schumpeterian growth (Mokyr 1990).

Figure 4 _ English GDP per capita Vs Population: 1400-1860



Source: Clark (2001), Hatcher (1977), Wrigley and Schofielld (1981)

In short, by comparing the two most developed countries in the world after the 16th century we can see that pre-industrial economies were much more dynamic than suggested by the models of the transition from Malthus to Solow. The data show that pre-industrial economies underwent *temporary* growth spurts, in which both population and GDP per capita grew. These findings are consistent with the recent historical literature (de

Vries and Woulde 1997, de Vries 2000, Clark 2001, Goldstone 2002), which emphasize temporary growth episodes in some pre-industrial economies. Nevertheless, the data also suggest that *permanent* increases occurring simultaneously in both population and GDP per capita happened only after the Industrial Revolution. Thus, whereas in previous periods growth petered out, the technological and organizational changes of the Industrial Revolution allowed for the emergence of modern economic growth. In this sense, and in spite of slow per capita GDP growth, the Industrial Revolution was indeed a discontinuity in the process of world development (which is consistent with the Malthus to Solow literature). The same conclusions are obtained by analyzing the relationship between real wages and population.

Real Wages and Population

As mentioned above, wages and population are inversely related in Malthusian economies, whereas in modern economies sustained productivity improvements enable simultaneous increases of wages and population. This section analyzes the wage-population relationship for some European countries (Austria, Belgium, England, France, Germany, Italy, the Netherlands, Poland and Spain). Most population data are from McEvedy and Jones (1978). Whenever possible, these data are complemented by other sources, such as Hatcher (1977), Wrigley and Schofield (1981), de Vries and Woulde (1997), and de Vries (2000). The existing wage data are for representative professions (chiefly labourers and craftsmen) that can proxy for the behaviour of overall real wages. Since most of the wage data are for urban professions, a great percentage of the population is not accounted for in the analysis. Nevertheless, Clark (2001) provides evidence that for England at least, urban wages provide a good proxy for the general

wage trend during the period analyzed since his real wages for farm labourer's are highly correlated with both craftsmen's and labourer's wages. Most data on real wages are from Allen (2001). Allen provides an invaluable collection of annual data for series of nominal wages, consumer prices indexes, real wages and welfare ratios for several European cities in a uniform measure, grams of silver[7]. English real wage data was also obtained from Clark (2001). The data are mostly from 1400 to 1900[8]. Figures 5-8 present the wage-population relationship adjusted by an Epanechnikov Kernel fit of a polynomial of degree 2. As expected, for most countries, there is a strong inverse relationship between real wages and population until the 19th century. After the mid-14th century, real wages became relatively high throughout Europe after a plethora of plagues (such as the notorious Black Death), wars and famines. After that shock to population, real wages gradually declined with the recovery of the European population.

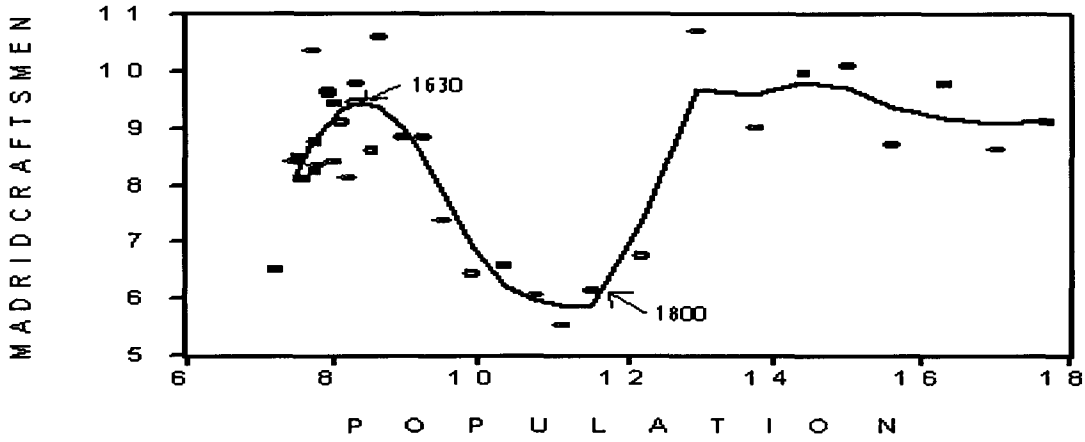
However, as argued before, pre-industrial economies were by no means static. Several European economies underwent temporary growth spurts throughout the period. In Spain, the revenues from the empire and the gains from international trade enabled real wages to grow at the same time as population during the early 16th century (figure 5). The wage data for Valencia craftsmen and labourers also show that the Spanish growth spurt was experienced in other regions outside Madrid (figure 8h). Nevertheless, after 1630, the relationship between real wages and population became once again negative until early in

[7] The data are available in the website: www.econ.ox.ac.uk/Members/robert.allen

[8] The Allen data used are the following: Austria (Vienna from 1400 to 1800), Belgium (Antwerp: 1400-1900), England (London and Oxford, 1400-1900), France (Paris and Strasbourg: from 1395 to 1900, with missing observations from 1790 to 1840), Germany (Munich 1430-1760, Leipzig 1600-1800, and Augsburg 1500-1770), Holland (Amsterdam: 1400 to 1900), Italy (Florence 1340-1900, and Milan 1600-1900), Poland (Krakow and Warsaw: 1400-1900), Spain (Madrid: 1550-1900, and Valencia: 1410 to 1790).

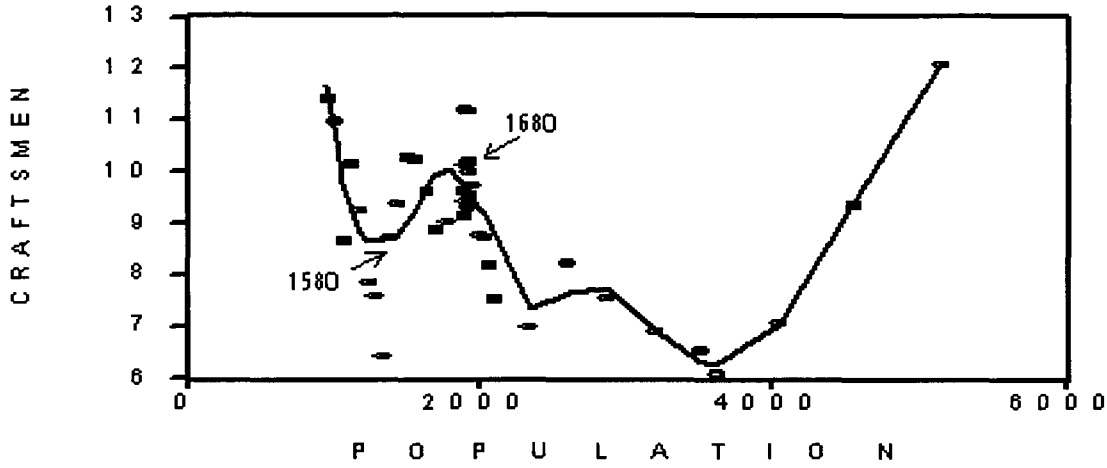
the 19th century. All in all, a growth spurt fuelled by Smithian growth enabled the Spanish economy to temporarily experience simultaneous increases in real wages and population. However, after the growth spurt ended, real wages and population reverted to their previous inverse relationship.

Figure 5 _ Madrid Craftsmen Real Wages vs. Population (1550-1900)



As the previous section indicated, an important growth spurt also occurred in the Netherlands from around the mid 16th century until about 1670. The Dutch and Belgium graphs (figures 6, 8b and 8c) show that during the so-called Dutch golden age real wages and population were no longer inversely related. During this period, there were simultaneous increases in population and real wages (for craftsmen and labourers). This is consistent with de Vries and Woude (1997), who asserted that the Dutch economy exhibited some signs of "modernity" during this period. Thus, the Golden Age allowed the Dutch economy to *temporarily* escape the traditional negative relationship between real wages and population. Nevertheless, after this growth spurt ended, the inverse relationship between wages and population emerged once again, persisting until the 19th century.

Figure 6 _ Amsterdam Craftsmen Real Wages Vs. Population (1400-1900)



There is also evidence suggesting the existence of growth spurts in England before the Industrial Revolution. The wage-population data indicate that, between 1620 and the early decades of the 18th century, the English economy started exhibiting some symptoms of modernity. The 17th century growth spurt enabled both population and real wages to trend upwards. However, this growth spurt in the English economy was not self-sustaining, since by 1720 real wages declined whereas population continued to increase. This trend persisted until the start of the Industrial Revolution, after which the relationship between real wages and population became *permanently* positive. Both the data from Allen (2001) and from Clark (2001) support the findings.

Figure 7 _ London Craftsmen Real Wages vs. Population (1300-1900)

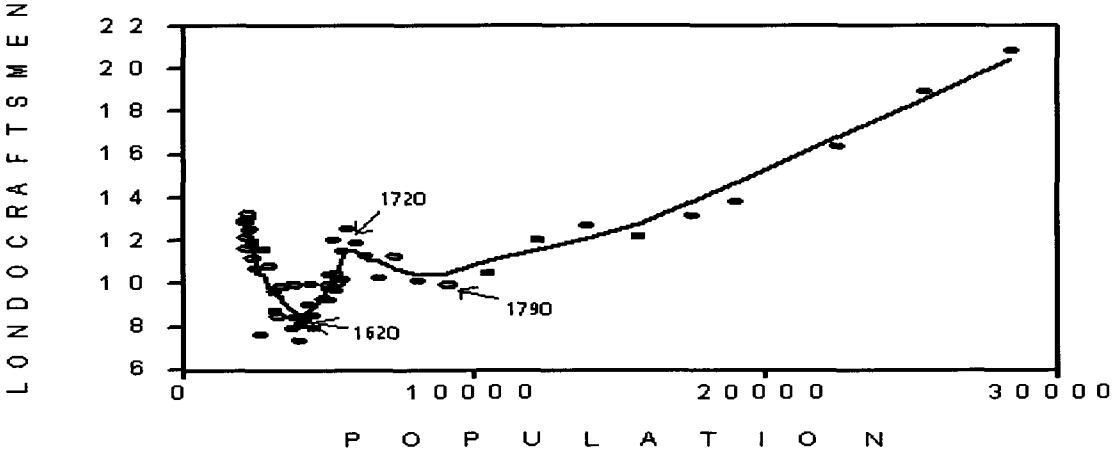
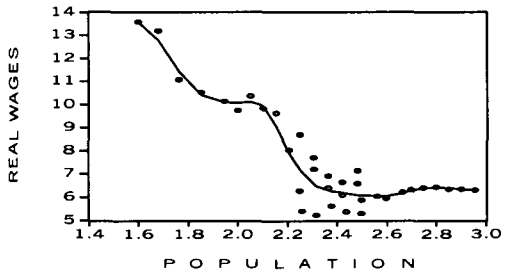


Figure 8 _ Wages Vs Population in Europe

Figure 8a _ AUSTRIA

Vienna Craftsmen 1490-1800



Vienna Labourer 1490-1800

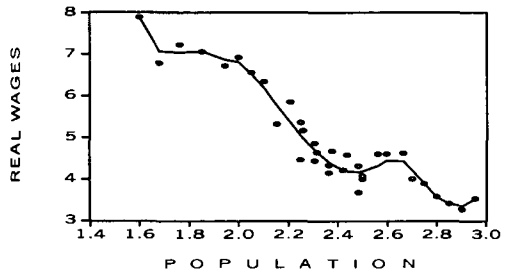
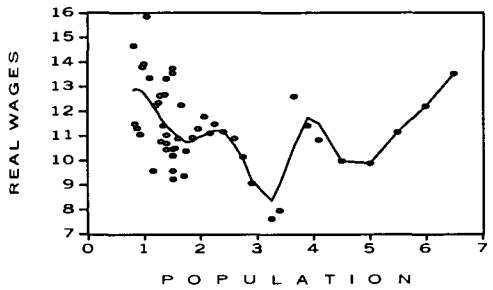


Figure 8b _*BELGIUM*

Antwerp Craftsmen 1400-1900



Antwerp Labourer 1400-1900

Figure 8c _ *NETHERLANDS*

Amsterdam Labourer 1400-1900

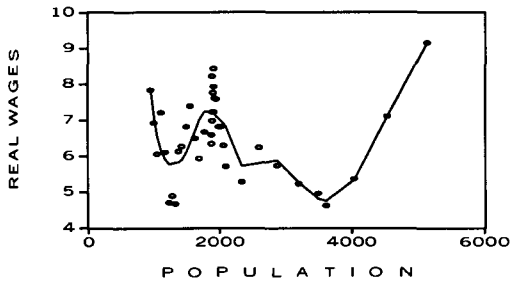


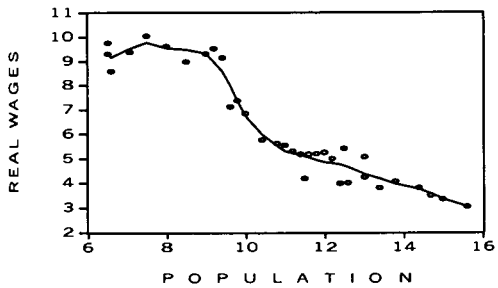
Figure 8d _*ITALY*

Florence Craftsmen 1340-1900

Milan Labourer 1600-1900

Figure 8e _*GERMANY*

Munich Craftsmen 1430-1760



Leipzig Labourer 1600-1800

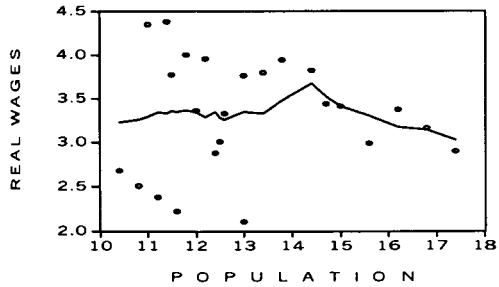
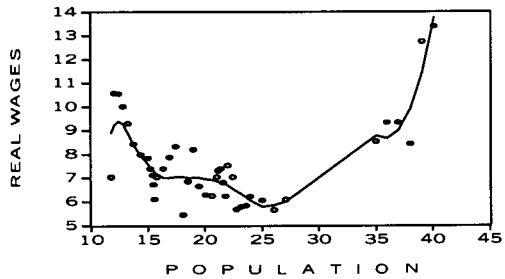


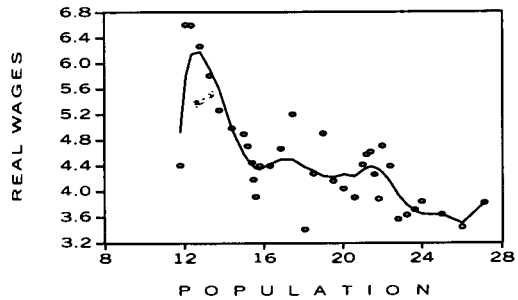
Figure 8f _*FRANCE*

Paris Craftsmen 1390-1870



Strasbourg Craftsmen 1390-1860

Paris Labourer 1430-1790



Strasbourg Labourer 1390-1860

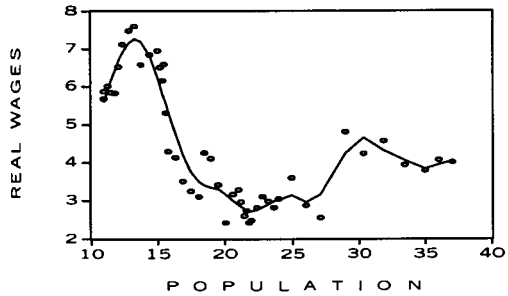
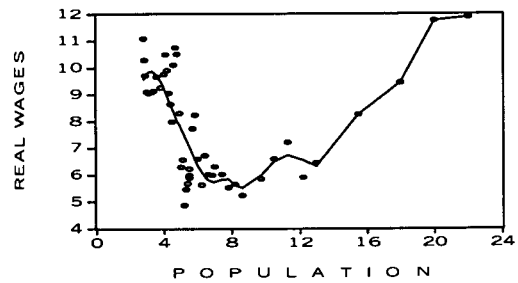


Figure 8g _*POLAND*

Krakow craftsmen 1410-1900



Krakow labourer 1410-1900

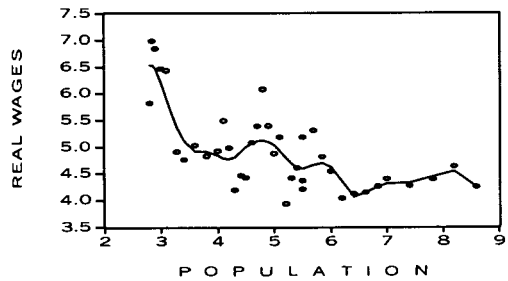
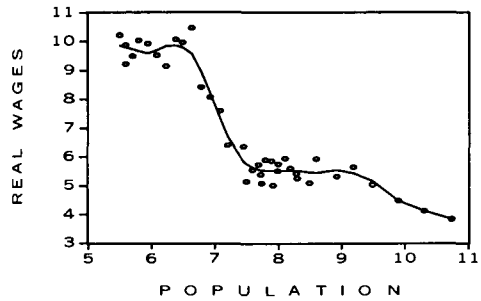


Figure 8h _*SPAIN*

Valencia craftsmen 1410-1790



Valencia labourer 1410-1790

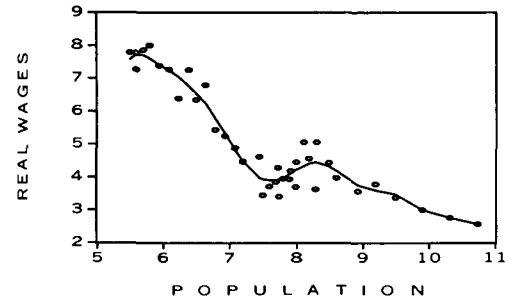
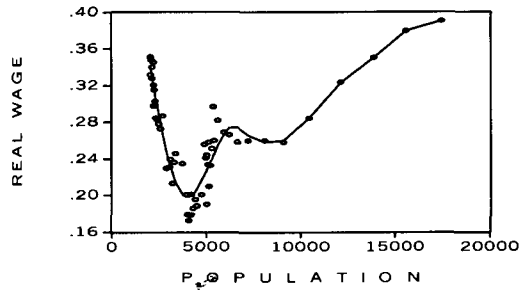


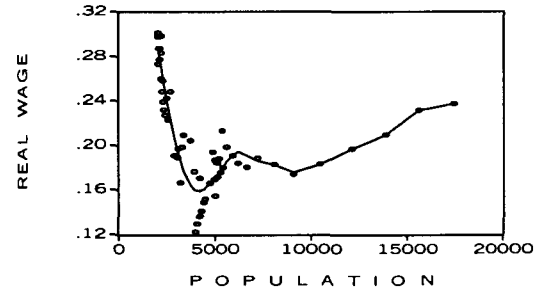
Figure 8i _*ENGLAND*[9]

Clark data

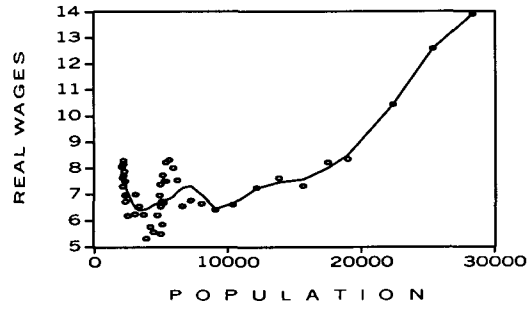
Overall Wage Vs Population 1400-1860



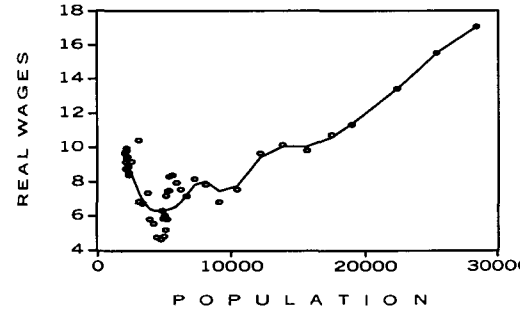
Farmer's Real Wage 1400-1860



London Labourers Vs Population 1541-1850



Oxford Craftsmen Vs Population 1541-1850



[9] It could be argued that the temporary negative relationship between real wages and population from about 1720 until 1790 is due to the measurement error inherent to these historical data. Nevertheless, the magnitude of the increases in population and real wages after the Industrial Revolution suggest that there was indeed a discontinuity in the wage-population relationship during this period.

All in all, there is evidence that growth spurts occurred in some European economies before 1800, allowing for a temporary inversion of the typical negative relationship between wages and population that was typical in pre-industrial societies. However, it is only after the Industrial Revolution that the relationship between real wages and population becomes positive in a *permanent* basis, a clear "symptom" of modern economic growth. Therefore, the findings on the wages-population indicate not only that pre-industrial economies were much more dynamic than suggested by a simple division "Malthus to Solow", but also there is strong evidence that the Industrial Revolution was indeed a discontinuity in the process of world economic development. The difference between the Industrial Revolution and previous growth spurts might have been a question of degree, but the irreversibility of events show that, as Mokyr (1999) emphasizes, "degree was everything".

Shocks to Wages and Population: a VAR approach

The findings in this section suggest that the Industrial Revolution also induced very different types of shocks to wages and population from those of the pre-industrial period. Contrary to previous growth spurts, after 1770, the negative response of population to shocks in real wages suggests that the Industrial Revolution induced parents to alter their fertility decisions.

The dynamic relationship between real wages and population can be further observed by estimating a vector autoregression (VAR) and calculating impulse response functions. Namely, the following VAR of order q was estimated:

$$W_t = \beta_{10} + \gamma_{1j} \sum_{j=1}^{q} W_{t-q} + \gamma_{1j} \sum_{j=1}^{q} POP_{t-q} + e_{1t} \quad (1)$$

$$POP_t = \beta_{20} + \gamma_{2j} \sum_{j=1}^{q} W_{t-q} + \gamma_{2j} \sum_{j=1}^{q} POP_{t-q} + e_{2t} \quad (2)$$

where W represents real wages and POP denotes population, and it is assumed that both disturbances are white noise with standard deviations of σ_W and σ_{POP}. In more compact notation, a multivariate VAR of order q can be written as:

$$x_t = A_o + A_1 x_{t-1} + A_2 x_{t-2} + \ldots + A_q x_{t-q} + e_t \quad (3)$$

where x_t is an (n x 1) vector of variables, A_0 is an (n x 1) vector of intercept terms, A_i is a (n x n) matrix of coefficients and e_t is an (n x 1) vector of error terms.

The order of the VAR was determined by the usual lag selection criteria. Since the coefficients of the estimated VARs often alternate in sign and are difficult to interpret, I follow the usual procedure of estimating impulse response functions. The latter provide the response of the dependent variable to shocks in the error terms (also known as innovations or impulses). In terms of the transition to modern economic growth, we should expect the following results from the impulse response functions: 1) in traditional Malthusian economies, population should increase after a shock to real wages, and 2) after modern growth emerges, population should respond negatively to a positive shock in real wages since higher incomes are associated with lower fertility. Formally, the impulse responses can be obtained from the vector-moving average representation of (3):

$$x_t = \mu + \sum_{j=0}^{\infty} \phi_i \varepsilon_{t-j} \quad (4)$$ [10]

[10] e_i are the white-noise disturbances for a VAR in standard form, whereas ε_i are the errors terms for a structural VAR. Chapter 2 presents the formal relationship between them for a VAR of order 1.

For instance, in a VAR of order 1, we have:

$$\begin{bmatrix} W_t \\ POP_t \end{bmatrix} = \begin{bmatrix} \overline{W} \\ \overline{POP} \end{bmatrix} + \sum_{j=0}^{\infty} \begin{bmatrix} \phi_{11}^{(i)} & \phi_{12}^{(i)} \\ \phi_{21}^{(i)} & \phi_{22}^{(i)} \end{bmatrix} \begin{bmatrix} \varepsilon_{Wt-j} \\ \varepsilon_{POPt-j} \end{bmatrix} \tag{5}$$

where $\phi_{11}^{(i)}$ is the expected one-period response of a one-unit change in ε_{Wt-1} on real wages W, and $\phi_{12}^{(i)}$ is the expected one-period response of a one-unit change in ε_{Wt} on POP. $\phi_{21}^{(i)}$ and $\phi_{22}^{(i)}$ denote the responses to ε_{POPt} shocks.

Due to the correlation between the error terms ε_{Wt-j} and ε_{POPt-j} in (5), it is likely that if ε_{Wt-j} changes then ε_{POPt-j} will be affected, and hence POP_t will also be altered. Therefore, we need to undertake orthogonalization, in which $e_{1t} = \varepsilon_{Wt} - b_{12}\varepsilon_{POPt}$, and $e_{2t}=\varepsilon_{POPt}$. Assuming that the structural disturbances have a recursive structure, the structural parameters are recovered using the Choleski decomposition of the reduced form covariance matrix, which constrains the system such that there are no contemporaneous effects of W_t on POP_t. Impulse response functions were then estimated for combinations of real wages and population for all the countries described above[11]. Figures 9a-9e report the impulse response functions for the two early European developers, England and Holland in several periods. In the figures 9a-9e, the horizontal axis represents the number of years after the shock took place, whereas the vertical axis shows the magnitude of the shock on different variables.

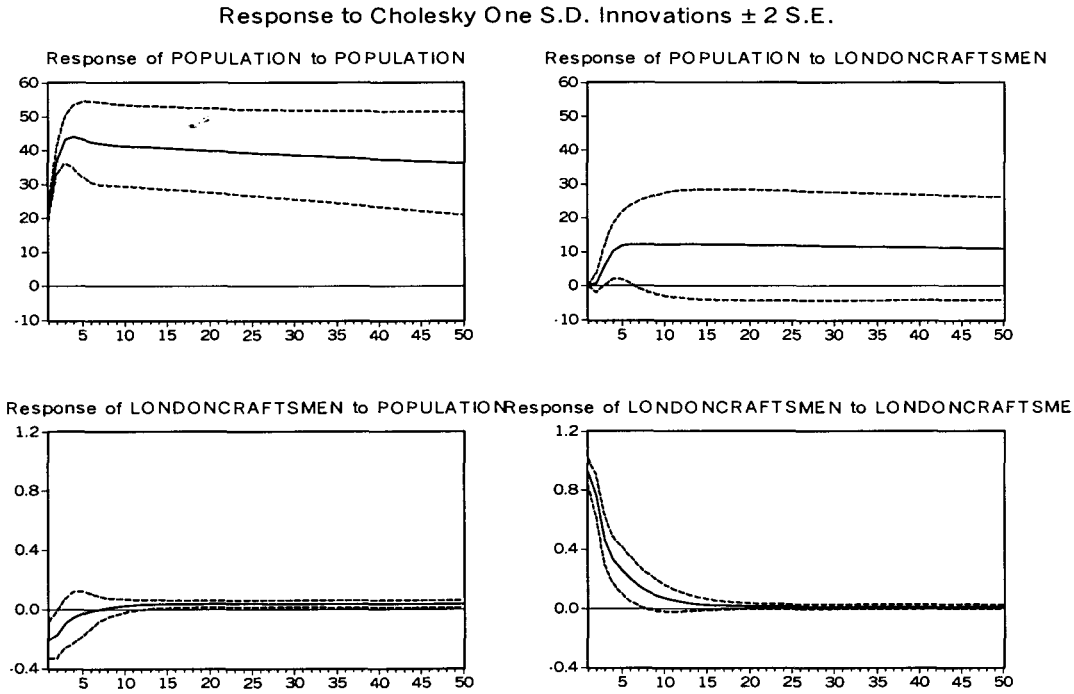
For England, the model above was estimated for two broad periods: before the Industrial Revolution (1541-1770) and after (1770-1850)[12]. As we can see in Figure 9a,

[11] Due to data limitations, for most countries, the data are decennial. For England, we also have annual data for both real wages and population after 1541. In addition, following Sims (1982) methodology, the data used for the estimation of the VARs are raw or untreated data

[12] Allen's data in decennial form as well as Clark's data provided similar results.

during the period up to the 1770, a shock in ε_{Wt} of one standard deviation leads to an increase of population of about 10 thousand people in the first decade after the shock. The impact of the shock persists for a long period of time. Thus, as expected, before the Industrial Revolution, population responded positively to an increase in real wages. The response of craftsmen's real wages to its own shock leads to a temporary increase of real wages of about 10 percent (the average real wage for the period was about 10 grams of silver), but the effect of the shock also swiftly dies down in less than 10 years. In turn, a ε_{POP} shock has a long and persistent effect on population, which lasts for more than 50 years, although it gradually decreases over time. Real wages initially decrease after a ε_{POP} shock, but return to their equilibrium values in about two decades.

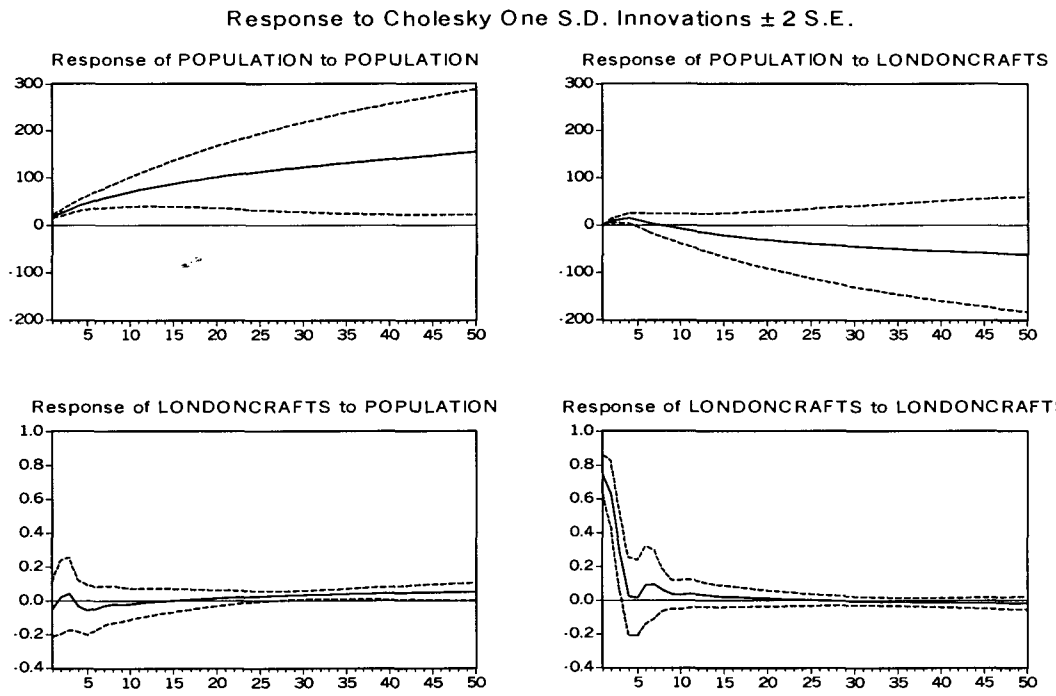
Figure 9a: London Craftsmen 1541-1770



After 1770, the impact of the shocks changes substantially (figure 9b). On the one hand, the effect of idiosyncratic shocks to population gradually increases over time.

Population shocks have a very small and temporary positive effect on real wages. On the other hand, in contrast to period pre-1770, shocks to real wages lead to a substantial decrease of population. Thus, during the Industrial Revolution, increases in real wages were followed by decreases in population, which suggests that parents were indeed making fertility decisions that varied according to their level of income[13]. Since the effects of the shocks to real wages and population were substantially distinct for the period pre- and after 1700, the results suggest that the Industrial Revolution induced a discontinuity in the relationship between wages and population.

Figure 9b: London Craftsmen 1770-1850



[13] Clearly, the changes in population depend on the behavior of both birth and death rates. The results of impulse response functions estimated from bivariate VARs relating birth rates and real wages suggest that birth rates fall after a shock to real wages, which is consistent with the estimation above. The interactions between these birth and death rates are further discussed in the sections below.

For Holland, a VAR and its respective impulse response functions were estimated for three broad periods: 1500-1650 (the Dutch Golden Age), 1650-1800 (the stagnation period), and 1800-1900 (the recovery and industrialization period). During the Dutch Golden Age, the results from the estimation of impulse response functions suggest that the effect of the idiosyncratic shocks increase over time, and that a shock to population has a small but not statistically significant positive effect on real wages. Furthermore, it is noticeable that during the Dutch Golden Age, and in contrast to what happened during the Industrial Revolution, population does not respond negatively to shocks to craftsmen real wages. During the period 1650-1800, the same tendency is observed. In contrast, during the period between 1800 and 1900, ε_{Wt} shocks lead to decreases in population (although the confidence interval widens considerably with time), suggesting that parents responded to shocks in real wages by having a lower number of children.

Figure 9c: Amsterdam Craftsmen 1500-1660

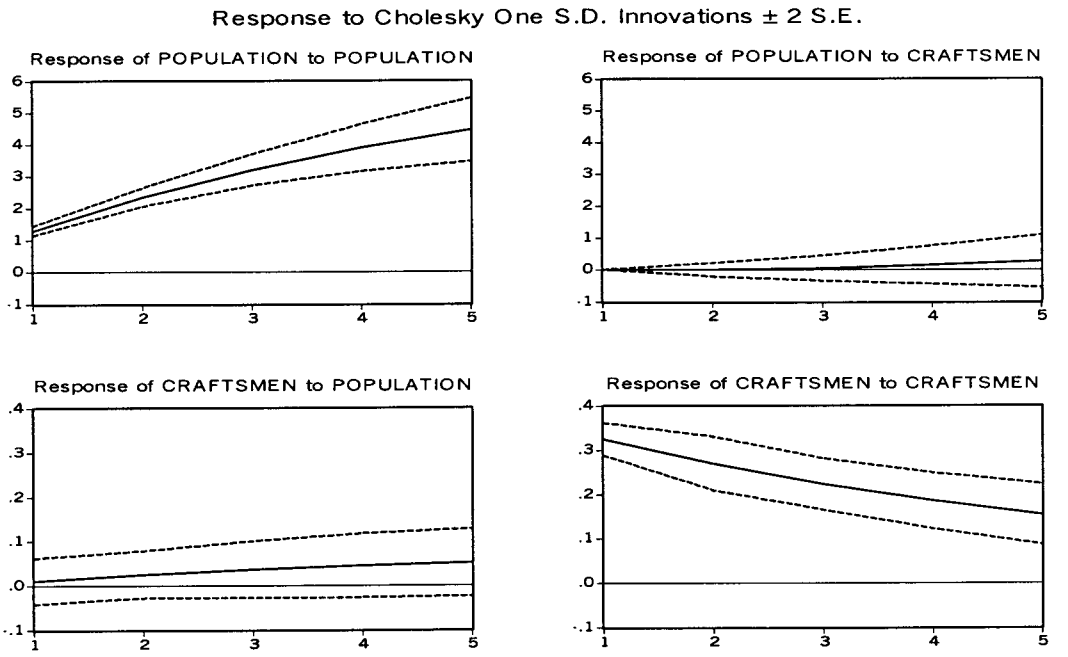


Figure 9d: Amsterdam Craftsmen 1650-1800

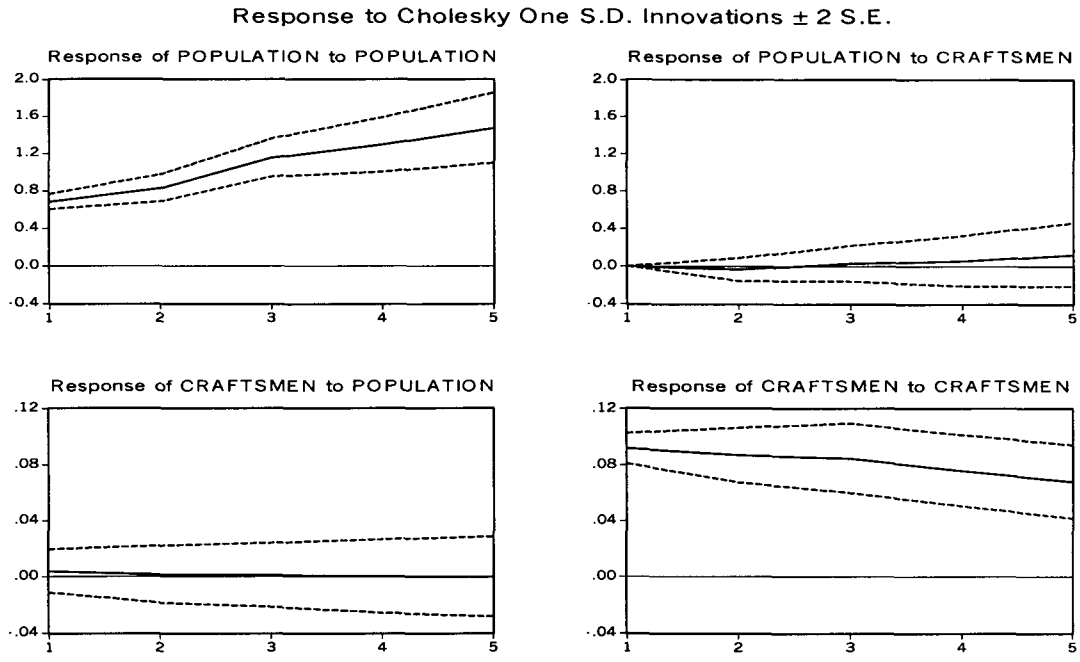
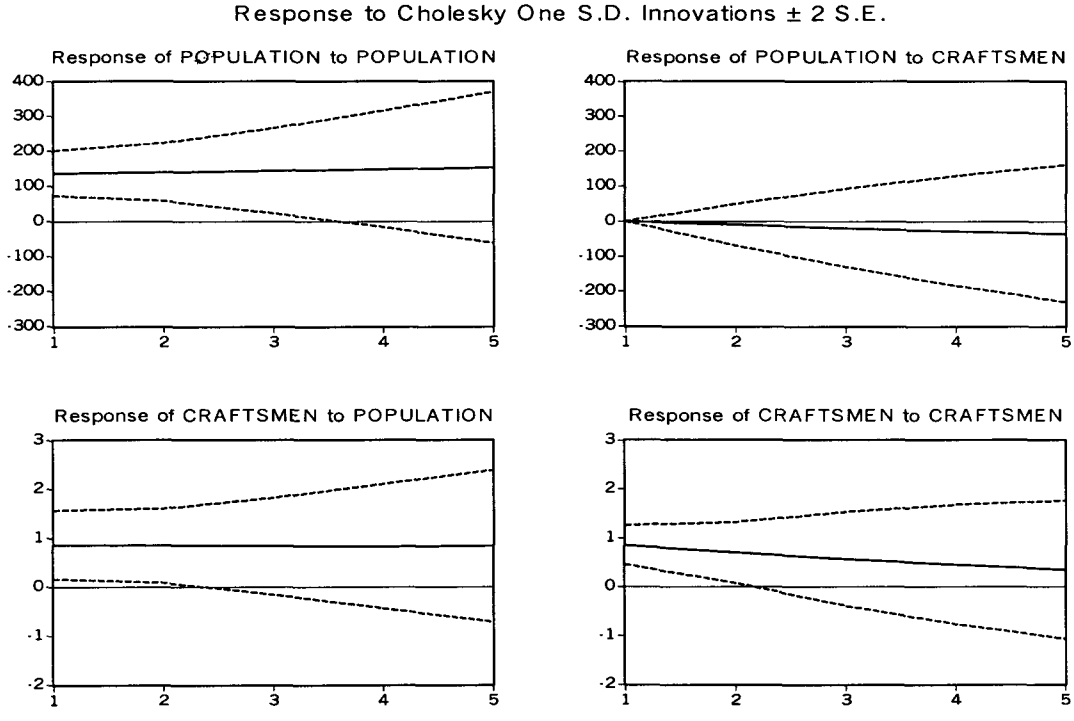


Figure 9e: Amsterdam Craftsmen 1800-1900



Comparing the two early European developers we can conclude that: 1) the English impulse responses relating wages and population change considerably after the mid-18th century, 2) population starts responding negatively to real wages shocks after the Industrial Revolution, and 3) the Dutch impulse responses indicate that during the Dutch Golden Age, wage shocks did not have a considerable effect on population. All in all, the empirical results in this section seem to indicate once again that the Industrial Revolution involved a discontinuity in the driving forces of the growth process. Thus, although the aggregate output indices suggest a certain continuity of the British process, the symptoms of modern economic growth seem to have started with the Industrial Revolution, and not at an earlier period.

Child Quantity versus Child Quality

This section argues that in the 19th century there was another discontinuity in the driving forces of the demographic transition (i.e. fertility decisions), which in turn interacted with the emergence of modern economic growth. In the Malthus to Solow literature, parents' fertility decisions change during the Industrial Revolution due to the acceleration of technical change, which increases the returns to human capital and induces parents to substitute child quality for child quantity. Consequently, the demographic transition ensues. Thus, in this literature, the emergence of modern economic growth is closely interrelated with the demographic transition, and human capital plays a crucial role in both phenomena.

In stark contrast, the prevailing view in the historical literature on the Industrial Revolution dismisses a prominent role for human capital, not only because Britain did not have any special kind of advantage in terms of formal education (Mitch 1999, Crafts

1995), but also because male literacy stagnated during the first three decades of the Industrial Revolution (Cressy 1980). Therefore, the historical literature seems to be at odds with the one of the central tenets of the "Malthus to Solow" models. However, if we take a long run view, the picture that emerges is less contradictory. By 1800, in the most advanced countries in Western Europe the number of brides and grooms that could sign their names was at least four times higher than in 1500[14]. This suggests that human capital improved during and after the Renaissance and the Enlightment[15]. The Chinese and, especially, the Japanese literacy rates also improved during this period. This worldwide increase in literacy rates seems to support Cipolla's (1969) assertion that there was a strong correlation between education levels and the levels of economic development. The rest of this section presents empirical evidence on the improvement of human capital in the 19th century and its impact on the child quantity-quality trade-off.

As mentioned above, in the "Malthus to Solow" literature there is an important relationship between literacy and fertility: if children are normal goods, then fertility decisions can be seen as an additional component of the consumption plans of households. Children generate benefits but also costs, such as education, food, as well as an opportunity cost in terms of income foregone (Becker 1960). Time devoted to child

[14] For the European countries, literacy rates are often proxied by the percentage of brides and grooms that could sign their names. See Schofield (1973), one of the authorities in pre-industrial human capital, for a survey on why this is the most adequate proxy for human capital in pre-19th century Europe. Schofield advocates the use of signatures as a proxy for literacy because of the following reasons: objectivity, easiness to express quantitatively and their homogeneity across space and time.

[15] From the 16th century onwards, there is substantial evidence indicating that the quality of European human capital was also substantially enriched by the development of the scientific method and culture (Jacob 1997, Bekar and Lipsey 2001), by the diffusion of the printing press, and by the Protestant Reformation.

rearing decreases income earnings. Suppose we have a world with N households and two goods, "children" (n) and "other goods" (x). Households' total time endowment T can be spent either working, l, or on child rearing, z. The budget constraint faced by households can be written as:

$$c = w(T - z) + y \tag{6}$$

where c is consumption of "other goods", w is wage income, and y is non-labour income. Assume also that households' preferences are "well-behaved", and hence indifference curves are convex to the origin. In this setting, increases in income will have distinct impacts on fertility rates depending on the source of income. On the one hand, non-wage income increases lead to a parallel shift of the budget constraint, which unambiguously raises fertility rates. On the other hand, if income rises due to an increase in wages, then the budget line will rotate, originating both a substitution effect and an income effect[16]. The income effect increases the number of children, since parents/households will be able to better afford them. However, an increase in wage income also gives rise to a substitution effect by raising the opportunity cost of child rearing, which reduces fertility rates. The net effect is ambiguous, depending on which effect dominates[17]. Based on the previous discussion, we should expect the income effect to dominate in Malthusian economies (implying that increases in income are translated into higher fertility), whereas the substitution effect should dominate in modern economies (and hence fertility declines

[16] Note that increases in wage income have a stronger impact on the decline of fertility rates than non-labor income increases (Ray 1998).

[17] This argument implies that workers during Industrial Revolution increase their hours, as Voth (2001) has shown recently.

after an income increase). There is thus a simple relationship between wages and fertility rates that we can observe empirically.

The available micro data restricts our analysis to some 19th century early European developers. Nevertheless, the findings suggest by these data are consistent with the literature on economic development. For England, data on fertility and mortality were obtained from Wrigley and Schofield (1981) and from Mitchell (1988). The other European fertility and mortality data are also from Mitchell (1988). As before, the wage data are from Allen (2001).

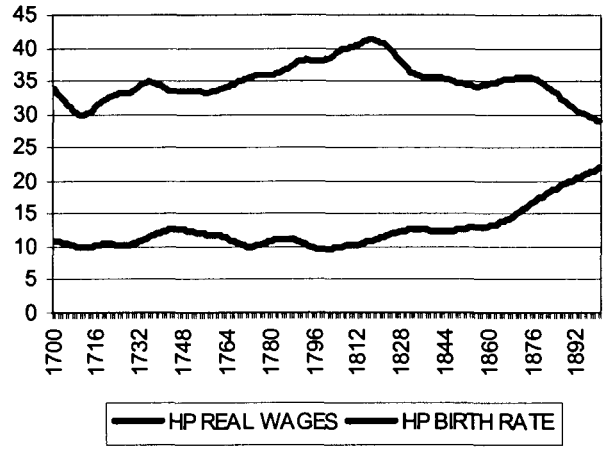
In terms of the English data, a simple scattered plot reveals that there is no clearly discernable pattern of the relationship between real wages and birth rates in the 18th century[18] (figures 10a and 10b). As we can see in figure 10b, birth rates were fairly constant until about the last quarter of the 18th century. Real wages also do not show any particular trend throughout the period.

Figure 10a_ Real Wages and Birth rates in England,

1700-1800 **1800-1900**

[18] In figure 10b, both series were smoothed by the Hodrick-Prescott filter in order to reduce yearly fluctuations.

Figure 10b_ Real Wages and Birth rates in England 1700-1900

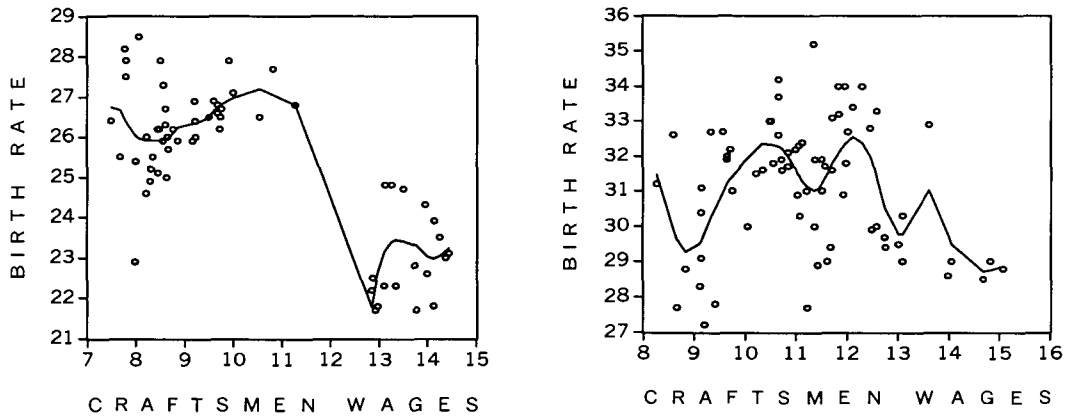


From the last quarter of the 18th century onwards until around 1820, birth rates increased, declining substantially afterwards. Since real wages are rising after the second decade of the 19th century, it seems plausible to argue that the substitution effect started to dominate the income effect, and fertility declined. Similar patterns can be found for both France and Belgium, although in these countries the change in fertility decisions described in the Malthus to Solow literature occurs later in the 19th century[19] (figure 11). All in all, the data from these early European developers suggests that the increase in income associated with the advent of 19th century industrialization led to a temporary rise in birth rates due to the income effect. However, the rise in real wages increased the opportunity cost of child rearing, enhancing the substitution effect, and hence birth rates declined.

[19] However, at the start of our period of analysis, French birth rates were lower than those in Britain.

Figure 11_ Real Wages and Birth rate, 1800-1900

France[20] **Belgium**



In addition, in the Malthus to Solow literature, the change in parents' fertility decisions is highly correlated with an increase in literacy. The relationship between these two variables can also be observed for these early developers. For England, data on literacy were obtained from Cressy (1980), Schofield (1973) and Cipolla (1969). Crude birth rates are from Wrigley and Schofield (1981). As Figure 12 shows, from 1750 to about 1815, birth rates increased although literacy rates also rose. Since throughout the period increases in literacy are highly correlated with real wages, this fact suggests that the income effects still dominated, and hence fertility increased. From the second decade of the 19th century onwards, the continuing rise in literacy combined with the small but gradual increase in real wages seems to have had an effect on parents' fertility decisions, since birth rates in England steadily decline. This fact is consistent with the Malthus to Solow literature.

[20] Contrary to most of the data in this chapter, the Paris wage data are discontinuous from 1790 to 1840. However, the trend can still be observed in Figure 11, since the Epanechnikov Kernel fit allows us to interpolate for missing values.

Figure 12 _ Birth rate vs. Female literacy England, 1750-1900

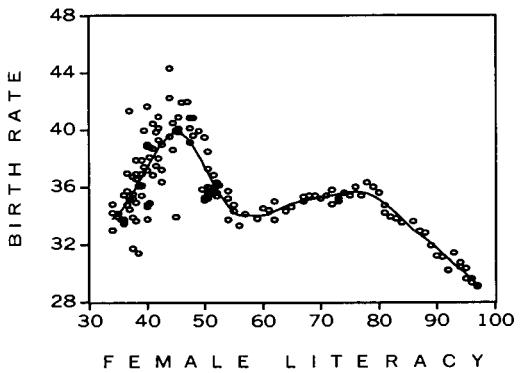
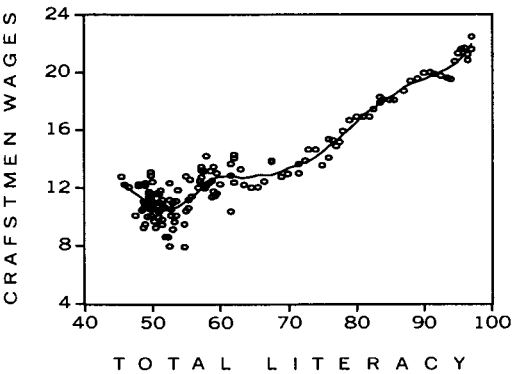


Figure 13 _ Literacy rates vs. real wages England, 1750-1900

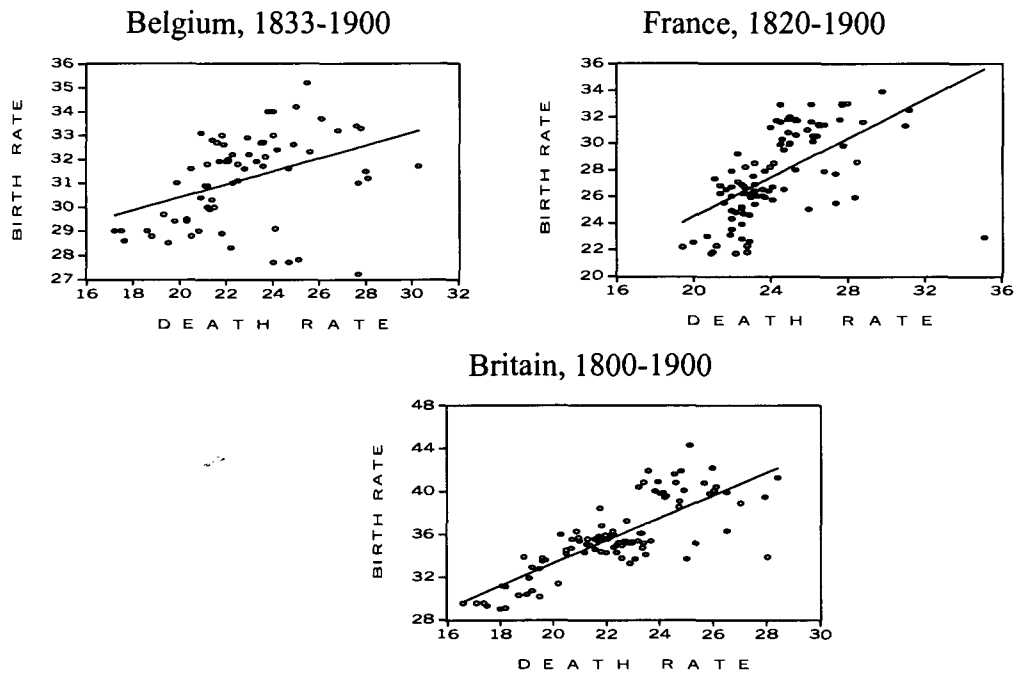


Nevertheless, the Malthus to Solow models are somewhat at odds with the historical records, which suggest that the change in fertility decisions was not the immediate cause of the demographic transition initiated in the 19th century. Throughout most Western Europe, the fall in mortality rates was the main cause of the rise in population from the late 18th century onwards (Easterlin 1996). Until the 18th century, mortality rates were high and very volatile due to frequent epidemics and famines. From the late 18th century onwards, there was a slow but steady improvement in the mortality figures throughout Western Europe. The wide fluctuations of mortality rates were also reduced. Death rates fell due to the gradual improvements in sanitary and hygienic conditions made possible by a higher investment in the health sector as well by an increase in the general public perception of the links between unsanitary conditions and disease (Mokyr 1993).

The decrease in European mortality rates preceding the decline in birth rates in the 19th century has some similarities with the demographic transition of the developing countries during the 20th century. As several microeconomic studies on fertility and mortality have shown for developing countries (McKeown 1977, Mensch, Lentzner and

Preston 1985, Shultz 1981, Schultz 1993), fertility decisions are not independent of mortality rates. Schultz (1981) argues that in general parents respond to a decrease in child mortality by choosing to reduce the number of births[21]. The high correlation between mortality rates and birth rates can also be observed historically for the Belgian, French, and British data[22] (figure 14).

Figure 14 _ Birth rates vs. death rates, 1800-1900



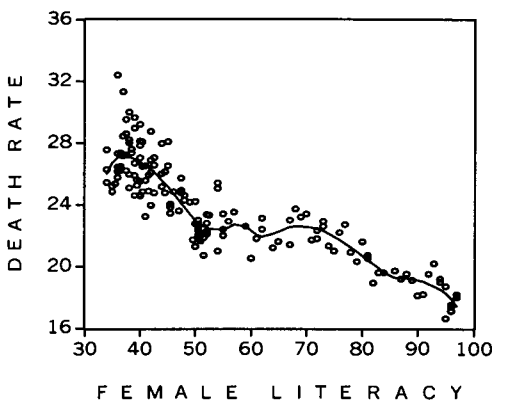
As mentioned above, the fall in mortality from mid-18th century onwards was caused by an improvement in health technology (Easterlin 1996, Mokyr 1993) as well as

[21] This proposition holds as long as there is price-inelasticity of parent demand for surviving children and the cost per surviving child declines in proportion to the rise in the survival rate.

[22] However, there are exceptions to this pattern. Namely, a scattered plot of German birth and death rates for the period 1830-1900 does not indicate any noticeable correlation. The lack of German wage data for the 19th century does not allow us to pursue this issue here, being the subject of future research. In addition, by the end of the 18th century, France had already lower birth rates than most other European countries. France was also one of the most literate countries in Europe.

by an increase in the knowledge of sanitary and hygienic conditions. The rise in literacy (especially female literacy) played an important role in the diffusion of this knowledge to most sections of society. It is thus not surprising that death rates fell with the rise in literacy (figure 15). This is also consistent with the macro data presented in the next section. Although the change in fertility decisions played an important role in the demographic transition (as the Malthus to Solow literature suggests), the behaviour of fertility was also a function of mortality rates. In turn, the rise in literacy was crucial for both the decline in fertility and the improvement in health-related knowledge.

Figure 15 _ Death rate and Female literacy
England, 1750-1900



The same general conclusions are suggested by undertaking a regression analysis for individual countries. Due to data restrictions, the analysis was only performed for English data for the period between 1760 and 1900. In spite of this limitation, we should note that England is the typical example used in both the Malthus to Solow models and the historical literature on the emergence of modern economic growth.

In England, birth rates increased during the 18th century, chiefly due to the fall in marriage age (Wrigley and Schofield 1981). From the end of the 18th century onwards, mortality rates steadily declined, and their volatility also decreased. Birth rates started

falling after the first decade of the 19th century. All in all, the reduction in mortality and the decline in the average marriage age were the main causes of the unprecedented population increase in Britain after the 18th century. Fertility decisions regarding the quantity of children become important in a second phase of the demographic transition, when urbanization accelerated and income per capita increased during the 19th century.

For the regression analysis, birth and death rates are from Mitchell (1988), craftsmen real wages are from Allen (2001), and the literacy figures are from Cipolla (1969), Schofield (1973), and Cressy (1980). Table 1 presents the matrix of correlations between these variables. As we can see, there are high correlations between all the variables, and all the correlations have the expected sign. As expected, birth rates are positive correlated with death rates, and negatively correlated with craftsmen real wages as well as with the different literacy figures. Death rates are negatively correlated with real wages and literacy. Male and female are also highly correlated.

Table 1 _ Correlation matrix

	BIRTH RATE	REAL WAGES	DEATH RATE	MALE LITERACY	FEMALE LITERACY	TOTAL LITERACY
BIRTH RATE	1	-0.6939	0.5073	-0.7306	-0.6727	-0.6967
REAL WAGES	-0.6939	1	-0.8049	0.9502	0.9410	0.9473
DEATH RATE	0.5073	-0.8049	1	-0.8094	-0.8568	-0.8412
MALE LITERACY	-0.7305	0.9502	-0.8094	1	0.9878	0.9953
FEMALE LITERACY	-0.6727	0.9410	-0.8568	0.9878	1	0.9982
TOTAL LITERACY	-0.6967	0.9473	-0.841	0.9953	0.9982	1

Following the discussion above, birth rates are regressed on literacy (female and total), on death rates, on real wages, on a time trend (TIME) that can proxy for improvements in health technology, and on a couple of dummy variables that take into

account a possible structural break in the first decades of the 19th century (D1815 = 1 if $t \geq 1815$, zero otherwise and DT1815 = $t - T_{1815}$ if $t > T_B$, zero otherwise). The results are presented in table 2.

Table 2 _ OLS regression coefficients _ birth and death rates, Britain 1760-1900

Dependent Variable	*Birth rate*	*Birth rate*	*Birth rate*	*Death rate*	*Death rate*	*Death rate*
WAGES	-0.189	-0.139	0.034	-0.347	-0.325	-0.342
	(0.252)	(0.414)	(0.839)	(0.0002)	(0.004)	(0.003)
FEMALE LITERACY	-0.191	-0.223			-0.014	
	(0.0001)	(0.000)			(0.732)	
TOTAL LITERACY			-0.317			-0.004
			(0.000)			(0.939)
BIRTH RATE				0.142	0.144	0.142
				(0.063)	(0.060)	(0.064)
DEATH RATE	0.0426	0.0298	0.064			
	(0.740)	(0.817)	(0.608)			
TIME	0.059	0.078	0.0842	-0.083	-0.081	-0.0826
	(0.0002)	(0.0006)	(0.000)	(0.000)	(0.000)	(0.000)
D1815		-0.951	-1.398	-0.529	-0.618	-0.550
		(0.237)	(0.074)	(0.251)	(0.244)	(0.310)
DT1815				0.0714	0.0763	0.0728
				(0.007)	(0.0115)	(0.023)
CONSTANT	40.344	39.900	43.749	32.468	32.517	32.570
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Prob(F-statistic)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
R^2	0.551	0.555	0.587	0.833	0.833	0.833

(p-values in parentheses)

The empirical results suggest that literacy is an important explanatory variable of birth rates, which is consistent with the analysis above as well as with the literature on economic development. Namely, the results suggest that a one-percent increase in female literacy rates is associated with a 0.2 per cent decline in birth rates. In turn, an 1 percent increase in total literacy is associated with a decline in birth rates of 0.3 percent. Additionally, the coefficients on real wages and on death rates have the expected signs, but they are not statistically significant. In contrast, the coefficient on TIME (the proxy for improvements in health technology) is positive and significant.

The results for the death rate regressions are also consistent with the descriptive analysis above as well as with the historical literature. Birth rates are positively correlated with death rates. On average, a decrease of 1 percentage points in the birth rate is associated with a decline of 0.14 percent in death rates. Real wages are negatively correlated with death rates, suggesting that increases in income were associated with a decrease in the mortality statistics, probably due to improvements in hygienic and sanitary conditions. The coefficient on TIME is negative and statistically significant, which also suggests that death rates decline over time due to the improvements in health technology, as argued by Easterlin (1996) and Mokyr (1993).

The determinants of literacy were then observed by estimating a series of regressions on the same set of variables (table 3). Once again, birth rates and literacy rates are negatively correlated, suggesting that the increase in literacy was an important factor for the decline in fertility during and after the Industrial Revolution. This is especially true with respect to female literacy, as suggested by Schultz (1981) and by Rosenzweig and Evenson (1977). Wages are also an important explanatory variable of literacy, being positively correlated with both female and total literacy. Therefore, wage increases are associated with a rise in literacy, especially after the second decade of the 19th century. In turn, the coefficient on TIME is positive and strongly significant. Since this variable can also be a proxy for technical change, the coefficient on TIME suggests that technical change and human capital were positively correlated, which is consistent with the Malthus to Solow models.

Table 3 _ OLS regression coefficients _ Literacy, Britain 1760-1900

Dependent Variable	*Female literacy*	*Female Literacy*	*Total Literacy*	*Total literacy*
WAGES	2.433	2.235	2.136	1.974
	(0.000)	(0.000)	(0.000)	(0.000)
BIRTH RATE	-0.595	-0.520	-0.631	-0.563
	(0.0001)	(0.000)	(0.000)	(0.000)
DEATH RATE		0.190		0.239
		(0.333)		(0.149)
TIME	0.229	0.332	0.161	0.255
	(0.000)	(0.000)	(0.000)	(0.000)
D1815		-7.163		-6.300
		(0.000)		(0.000)
CONSTANT	15.153	1.457	36.527	22.038
	(0.019)	(0.866)	(0.000)	(0.003)
Prob(F-statistic)	0.0000	0.0000	0.0000	0.0000
R^2	0.963	0.973	0.958	0.970

In short, the empirical results for the British economy in the period between 1760 and 1900 are consistent with the descriptive and graphical analysis presented in this section. The micro data for the early European developers suggests that the change in fertility decisions emphasized by "Malthus to Solow" literature was indeed occurring during the early 19th century. The empirical evidence does suggest that a rise in real wages increased the opportunity cost of child rearing, and parents responded by decreasing fertility. Nevertheless, the fall in birth rates is also highly correlated with the decline in mortality rates, which were decreasing due to improvements in health technology. The micro data for the three early European countries analyzed in this section thus suggests that our modeling of the transition to modern economic growth should take into account not only the change in fertility decisions but also the high correlation between birth and death rates. The next section presents some additional macro cross-country evidence for the period between 1500 and 1870.

Economic Growth and Literacy, 1500-1870

The findings of the sections above suggest that: (1) intensive growth replaced extensive growth during the transition to modern economic growth, (2) literacy was highly correlated with economic development (the Cipolla hypothesis), and (3) fertility declines during the transition to modern economic growth (the Malthus to Solow hypothesis). The historical literature also suggests that there is: (4) a strong correlation between urbanization and literacy (Cressy 1980), and (5) a positive correlation between Protestantism and investment in human capital, since Protestant countries had on average better human capital. Finally, (6) the findings of North and Thomas (1973) suggest that countries with more secure property rights should grow faster. This section undertakes a regression analysis in order to provide some empirical evidence on the hypotheses above. Data were collected from a variety of sources. As before, GDP and GDP per capita for 23 countries and territories were obtained from Maddison (2001). Literacy rates from several European countries are from Cipolla (1969), Cressy (1980), and Stone (1954). China's literacy figures are from Rawski (1979), and Japan's are from Dore (1965) and from Roden (1985). The percentage of the American literate population was extrapolated from Lockridge (1965). India's figures were taken from Parulekar (1957), whereas Africa's were extrapolated from Maddison (2001). Data on fertility per woman were obtained from Livi-Bacci (1989), and Grausman (1976). European urbanization rates were obtained from de Vries (1984), whereas Asian urbanization rates are from Rozman

(1973), Grauman (1976), and Maddison (1998). Birth, mortality and infant mortality rates were obtained from Mitchell[23] (1988).

The following growth regressions were estimated for the periods 1500-1820 and 1820-1870:

$$GRGDP_{15001820} = \beta_0 + \beta_1 X_t + e_t \quad (7)$$

$$GRGDP_{18201870} = \alpha_0 + \alpha_1 X_t + \varepsilon_t \quad (8)$$

where $GRGDP_{15001820}$ and $GRGDP_{18201870}$ denote, respectively, the GDP growth rate for the periods 1500-1820 and 1820-1870, and X_t represents a set of explanatory variables such as the level of GDP per capita in 1500 (GDPCAP1500) and in 1820 (GDPCAP1820), the rate of population growth between 1500 and 1820 (GRPOP15001820), the rate of population growth between 1820 and 1870 (GRPOP18201870), the rate of literacy in 1500 (LITERACY1500) and in 1800 (LITERACY1800), the urbanization rate in 1500 (URBAN1500) and in 1800 (URBAN1800), the average number of children in 1820 (TRF 1820), a dummy variable for Protestant countries (equal to one if the majority of the population of the country is Protestant, zero otherwise), and an index from Banks (1971) reflecting the legislative efficiency in a country (LAW 1830), which varies by a degree from 0 (no efficiency) to 3 (representing maximum efficiency). I also obtained data on primary school enrolment (PRIMARY1830) for 13 countries in the sample from Easterlin (1996). For most regressions I used LITERACY1800 instead of PRIMARY1830 in order to save degrees of freedom, since both measures of human capital provided similar results. The estimation

[23] Since much of the data in this section are based on guess estimates (such as most the Maddison data), the findings should be seen as an indication of general trends and as a catalyst for further research.

results of equations (7) and (8) are presented in tables 4 and 5 in Appendix A. Since heteroskedasticity could be considerable across countries, the standard errors for the coefficients are based on White's (1980) heteroskedasticity-consistent estimators.

For the period between 1500 and 1820, the level of GDP per capita in 1500 does not seem to be an important explanatory variable of growth performance in the period 1500-1820. This finding is not totally surprising, since some of richest countries around 1500, such as Italy in Europe and China in Asia, had disappointing growth performances during the period from 1500 and 1820. In addition, the growth of population between 1500 and 1820 (GRPOP15001820) is not significant in most specifications, suggesting that GDP per capita growth and population growth are still mostly uncorrelated. In turn, literacy in 1500 is negatively correlated with per capita growth, although the literacy coefficient is not significant. The results thus suggest that, during the period between 1500 and 1820, literacy was not an important explanatory variable of economic growth. Hence, for the period 1500-1800, the results are not consistent with the Cipolla hypothesis. Additionally, urbanization in 1500 is negatively correlated with per capita growth during the period 1500-1820. Although the urbanization coefficient is fairly small, the results are not consistent with hypothesis (4). Finally, a variable that is positively and significantly correlated with GDP per capita growth is PROTESTANT, which is consistent with hypothesis (5). On average, from 1500 and 1820, per capita growth rates in Protestant countries were about 0.155 percent per year, which is considerably higher than the average growth in the remaining countries (around 0.11 percent per annum).

The results for the period between 1820 and 1870 are markedly different. In most specifications there is a positive relationship between population growth and GDP per capita growth. Thus, during the 19th century, extensive growth was already being

translated into intensive growth, which is consistent with hypothesis (1). On average, a rise of one percentage points in population is associated with an increase of GDP per capita growth of about 0.3 percentage points per year. Contrary to the period 1500-1800, initial literacy (LITERACY 1800) is also an important variable in explaining GDP per capita growth during the 1820-1870 period. In general, one percent increase in literacy rates is associated with about 0.01 percent increase in the per capita GDP growth rate. Regarding hypothesis (5), and in contrast to the period 1500-1820, and, the PROTESTANT dummy is not significant in most specifications. Thus, Protestantism does not seem to have had a direct influence in the process of development during the period between 1820 and 1870. The link between Protestantism and economic development seems to have occurred through literacy, since PROTESTANT and LITERACY1800 are highly correlated. In addition, the coefficients on both URBAN1800 and TRF1800 are not significant. In turn, LAW1830 is highly significant and positive, suggesting that legislative efficiency is an important explanation of per capita growth during the period, which is consistent with the North and Thomas hypothesis. Regression (11) uses PRIMARY1830 instead of LITERACY1800, but the results are similar to those of the specifications that use literacy in 1800 as the human capital variable. The introduction of GDPCAP1820 does not alter the results of the specification containing the growth rate of population, although it somewhat affected the significance of the other explanatory variables. There is also a negative relationship between infant (INFMORT1800) and adult mortality and per capita GDP growth. However, this relationship is not significant. Nonlinearities in the data were also accounted for by introducing in equations (7) and (8) a quadratic term on literacy in each period. The quadratic term is not significant for the

period 1500-1820. However, the coefficient on the quadratic term is negative and significant in the period 1820-1870, as we can see in regression (12)[24].

Since Cipolla (1969) and the literature on Malthus to Solow argue that human capital played an important role in economic development after the late 18th century, the determinants of literacy were estimated by equations (9) and (10). The results are presented in tables 6 and 7 in Appendix A.

$$LITERACY_{1500} = \delta_0 + \delta_1 X_t + u_t \quad (9)$$

$$LITERACY_{1800} = \lambda_0 + \lambda_1 X_t + v_t \quad (10)$$

In terms of literacy in 1500, one of the most noticeable results is that the dummy for PROTESTANT is almost always a highly significant explanatory variable of literacy (table 6). On average, by 1500, literacy was almost 30 percent higher in soon-to-be Protestant countries than in the remaining countries. Since Luther's 95 theses date from 1517, the results show that even before the Protestant movement started, literacy was already higher in the future Protestant countries. Thus, there is some evidence to suggest that there was already a certain predisposition in these countries to promote literacy even before the Protestant Reformation took place. Second, urbanization is positively

[24] Since literacy seems to matter in the period 1820-1870, but not in the period 1500-1820, I also tested for parameter inconstancy. The data pertaining to both periods were pooled together and the following equation was estimated: $Y_i = \lambda_0 + \lambda_2 D_i + \phi_1 LIT_i + \phi_2 (D_i LIT_i) + \varepsilon_i$
where Y_i represents the growth rate of per capita GDP, LIT denotes literacy, and $D_i = 1$ for observations in the period 1500-1820 and equals 0 for observations in the period 1820-1870. However, both the slope and intercept coefficients on the dummy variable are not statistically significant. There is thus insufficient evidence to conclude that the regressions for both periods are different. Therefore, a change in the coefficients does not seem to explain the different results on the importance of literacy for economic growth during the periods 1500-1820 and 1820-1870.

correlated with literacy, although the coefficient on URBAN1500 is not always significant. This result is consistent with the view that there were higher returns to education in urban centers than in the countryside. Third, the level of GDP per capita in 1500 is positively correlated with literacy in 1500. On average, by 1500, some of the richest countries had also the highest literacy rates. Similarly, the growth rate of GDP per capita during the period 1000-1500 is positively correlated with literacy in 1500. Finally, population growth between 1000 and 1500 is not an important explanatory variable for literacy in 1500.

The results concerning literacy in 1800 are presented in table 7 in Appendix A. In most specifications literacy is strongly correlated with PROTESTANT. On average, Protestant countries had literacy rates almost 15 percent higher than non-Protestant countries. Therefore, more than a subjective work ethic *a la* Weber, it seems that Protestant countries had better human capital, which was then translated into higher rates of GDP per capita growth in the 19th century[25]. Moreover, in all specifications urbanization is positively correlated with literacy in 1800. In general, one percent increase in urbanization rates is associated with an increase of one-percentage point in literacy rates. As expected, the average number of children (TFR1800) is negatively correlated

[25] In these countries, human capital was not only better for the average worker, but also their entrepreneurs and industrialists were much more likely to adopt and invent new technologies and organizational methods (Jacob 1997). Sweden provides a good example of the link between Protestantism and high literacy. Although it remained a poor country until the end of the 19th century, by 1850 Sweden had already the highest literacy rates in Europe. High literacy was made possible by both cultural and religious factors (Sandeberg 1979). Namely, Pietistic Lutheranism as the dominant religion in Sweden played a crucial role in fostering literacy, since it advocated that every good Christian had the duty to read the Bible every day. By the mid-19th century, Sweden had one of the highest life expectancies in Europe, as well as relatively low birth and death rates.

with literacy rates. Namely, each additional child is associated with a decrease of about 5 percentage points in literacy rates. This result seems to indicate that, indeed, during the 19th century there were increasing returns to human capital. Thus, countries in which parents were substituting child quality for child quantity had higher literacy rates, and, consequently, higher rates of GDP per capita growth. Literacy is also positively correlated with legislative efficiency (LAW1830). On average, one point increase in the index (say, from 0 or no legislative efficiency, to 1, or low legislative efficiency) leads to an increase in the literacy rates of about 6 percent. The growth rate of per capita GDP in the period 1500-1820 (GRCAP15001820) is included in some specifications, but the coefficient is not always significant. Similarly, the coefficient on the growth rate of population in the period 1500-1820 is not significant. Finally, infant mortality is negatively correlated with literacy in 1800, which is consistent with the micro studies on fertility and mortality.

Therefore, the regression results based on cross-country macro data are consistent with the findings of the micro data for some early European developers, providing additional evidence on the emergence of modern economic growth.

3. Concluding Remarks

This paper presented empirical evidence on the transition "from Malthus to Solow". The empirical results indicate that temporary intensive growth spurts occurred in several pre-industrial economies. Nevertheless, this paper argues Britain was the first country to experience modern economic growth during the Industrial Revolution, since this is the period when the "symptoms of modernity" became permanent.

The results of a vector autoregression are also consistent with the view that the Industrial Revolution was a period of discontinuities in the process of world economic development. In addition, the paper presented some cross-country evidence for two main periods: 1500-1820 and 1820-1870. Cross-country regressions show that: 1) literacy was highly correlated with the level of economic development and the rates of per capita growth, 2) the average number of children per woman was negatively correlated with per capita GDP growth as well as literacy rates, and 3) urbanization was positively correlated with literacy. There is also evidence that parents started substituting child quality for child quantity during the 19th century, although fertility decisions were highly correlated with the ongoing decline in infant mortality. Micro data relating fertility and mortality rates with real wages for some early European developers not only indicate this change in fertility decisions in the 19th century, but also the close interaction between death and birth rates.

All in all, the empirical results in this chapter suggest that future research should incorporate some of the features that are present in the data. On the one hand, as de Vries (2001) emphasized, our models of the transition to modern economic growth should be more historical. As argued above, pre-industrial economies were much more dynamic than some of our current modeling implies, and certainly were not always trapped in a low equilibrium level of income. Since extensive and intensive growth spurts seem to have been a common feature in pre-industrial economies (Cameron 1997, Jones 1988, Goldstone 2002), the next generations of "Malthus to Solow" models should take into account the existence of these growth spurts in Malthusian economies. Since these growth spurts were always temporary, future research should aim to solve two great puzzles in the transition to modern economic growth: 1) why these growth spurts were not

materialized into sustained growth?, and, 2) what caused sustained growth to emerge during the Industrial Revolution?

On the other hand, the empirical results on human capital indicate a high correlation between literacy and economic development. In this context, more cross-country comparative micro studies on the role of education are clearly needed, in order to further understand the importance of human capital in the transition to modern economic growth.

APPENDIX A

TABLE 4_ GDP PER CAPITA GROWTH 1500-1820

Dependent Variable: Growth in GDP per capita 1500-1820					
Variable	(1)	(2)	(3)	(4)	(5)
Literacy 1500	-0.0079 (-1.974)	-0.008 (-1.156)	-0.0043 (-1.005)	-0.008 (-1.244)	
GRPOP15001820	0.0830 (0.697)		0.0536 (0.4731)		0.0469 (0.422)
GDPCAP1500		3.9E-06 (0.026)		0.0001 (0.788)	
PROTESTANT	0.1455 (3.813)	0.1571 (4.136)	0.158 (4.314)	0.178 (4.905)	0.1326 (4.009)
URBAN 1500			-0.0052 (-1.778)	-0.0063 (-2.047)	-0.0064 (-2.534)
CONSTANT	0.1015 (2.899)	0.1182 (1.545)	0.114 (3.376)	0.070 (0.946)	0.1079 (3.324)
R-squared	0.557	0.545	0.630	0.639	0.568
Adjusted R^2	0.479	0.464	0.538	0.549	0.4996
F-statistic	7.131	6.775	7.523	7.0835	8.322
Prob(F-statistic)	0.0026	0.0032	0.0021	0.0017	0.0009

TABLE 5_ GDP PER CAPITA GROWTH 1820-1870

Dependent Variable: Growth in GDP per capita 1820-1870							
Variable	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Literacy 1800	0.0093 (1.714)	0.0066 (1.624)	0.016 (1.977)	0.0065 (0.762)	0.0055 (0.104)		0.0318 (3.065)
PRIMARY1830						0.0717 (1.796)	
GRPOP820870	0.280 (2.453)	0.577 (2.110)	0.213 (1.661)	0.1411 (1.417)		0.165 (1.119)	0.288 (1.876)
GDPCAP1820					0.0007 (2.914)		
PROTESTANT	0.0985 (0.366)				0.274 (1.246)	0.178 (0.420)	0.0058 (0.024)
URBAN 1800		0.0142 (0.999)					
TRF 1820			-0.101 (-0.998)				
LAW1830				0.2470 (2.059)			
LITSQUARE							-0.00029 (-2.406)
CONSTANT	0.0615 (0.419)	-0.109 (-0.563)	0.554 (0.879)	0.0136 (12.22)	-0.239 (-1.149)	0.0138 (0.091)	-0.160 (-0.932)
R-squared	0.531	0.514	0.747	0.724	0.603	0.702	0.645
Adjusted R^2	0.457	0.428	0.672	0.664	0.541	0.621	0.566
F-statistic	7.170	5.991	9.867	12.219	9.625	8.654	8.180
Prob(F-statistic)	0.002	0.0056	0.0024	0.0003	0.0004	0.003	0.0006

TABLE 6_ LITERACY AND ECONOMIC DEVELOPMENT, 1500

Dependent Variable: LITERACY in 1500					
	(13)	(14)	(15)	(16)	(17)
PROTESTANT	3.186 (1.936)	3.286 (2.939)	1.892 (0.850)	3.185 (1.885)	3.289 (2.872)
URBAN 1500	0.316 (1.936)	0.0038 (0.033)	0.638 (1.211)	0.2959 (1.831)	0.0207 (0.166)
GDGCAP1500		0.0177 (4.691)			0.018 (4.583)
GRCAP10001500			54.628 (2.237)		
GRPOP10001500				3.938 (0.271)	-4.456 (-0.444)
CONSTANT	2.387 (2.285)	-7.252 (-3.336)	-1.400 (-0.963)	1.967 (1.042)	-6.949 (-2.984)
R-squared	0.458170	0.764	0.8046	0.460	0.767
Adjusted R^2	0.397966	0.722	0.707	0.365	0.7084
F-statistic	7.610369	18.328	8.239	4.837	13.147

TABLE 7_ LITERACY AND ECONOMIC DEVELOPMENT, 1800

Dependent Variable: LITERACY in 1800						
	(18)	(19)	(20)	(21)	(22)	(23)
PROTESTANT	11.5042 (3.5459)	18.8166 (5.4585)	22.6383 (3.7384)	11.345 (3.5873)	10.7746 (2.8607)	11.938 (2.030)
URBAN 1800	0.9888 (4.8984)	0.9832 (4.4978)	1.1143 (2.9142)	0.9729 (4.6875)	1.4414 (3.4891)	1.059 (2.749)
TRF 1820	-3.4345 (-1.8929)	-5.3571 (-2.2674)	-6.6381 (-2.7116)	-3.3432 (-1.7275)	-5.5026 (-3.5324)	
INFMORT1800						-0.073 (-1.437)
GDGCAP1820					-0.0180 (-1.2633)	
LAW1830	6.3752 (3.3407)			6.0753 (2.2988)	9.5364 (2.4281)	
GRCAP15001820		37.516 (1.8161)		8.1615 (0.2815)		
GRPOP15001820			-13.6344 (-0.2788)			-38.328 (-2.341)
CONSTANT	22.294 (1.9318)	32.7961 (2.1871)	45.0621 (2.6406)	21.373 (1.741)	43.5622 (2.9588)	31.459 (1.906)
R-squared	0.9689	0.9436	0.9387	0.9693	0.9750	0.976
Adjusted R^2	0.9534	0.9153	0.9081	0.9473	0.9572	0.946
F-statistic	62.382	33.427	30.6317	44.186	54.697	32.384

Chapter 2

Structural Breaks and Two Views of the Industrial Revolution[26]

Abstract

This chapter uses an endogenous structural breaks procedure that allows us to confront two alternative views of the Industrial Revolution. The tests are carried out for two periods: 1700-1800 and 1800-1850. The empirical results show that structural breaks occurred in most industries throughout the period, suggesting that growth was pervasive during the period and not localized in the iron and cotton industries. The econometric results also indicate that, for the period 1700-1800 the population variables underwent structural breaks earlier than the industrial variables. A vector autoregression (VAR), impulse response functions and causality tests are used in order to further understand the relationship between industrial output and population.

JEL classification: N13, O14

Keywords: Industrial Revolution; structural breaks, generalized growth

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1. Introduction

Although its long-term consequences are indisputable, there is still widespread debate on whether or not the Industrial Revolution represented a major discontinuity in the process of British economic development. The pioneering work by Deane and Cole (1969) suggests that the Industrial Revolution was a period in which there was a sharp acceleration in both industrial output and GDP growth rates. In contrast, the studies of Crafts and Harley (Harley 1982, Crafts 1985, Crafts and Harley 1992) indicate that GDP and GDP per capita growth were very slow during the early Industrial Revolution. The Crafts and Harley estimates also show that total factor productivity (TFP) grew very gradually, at an average of 0.1 percent per year before 1800 and around 0.3 percent from 1800 to 1830. Consequently, Crafts and Harley (1992), Clark (2001) and Goldstone (2002) contend that modern economic growth only started after 1830 and not during the Industrial Revolution[27].

In addition, Crafts and Harley argue that growth and innovation were uneven during this period. The Crafts and Harley estimates suggest that output and productivity growth accelerated only in a couple of "dynamic" industries (cotton and iron), implying that innovation and growth were localized in these industries. According to them, outside these two sectors, the British economy was still dominated by small-scale industries that were characterized by low productivity and lack of innovation.

[27] Deane and Cole (1969) estimated that output and industrial growth rates accelerated from less than 1 percent per year to a staggering 3.4 percent in the 1780s. In contrast, Crafts and Harley (1992) estimated that GDP growth increased from 0.6 per cent per year before the Industrial Revolution to 1.4 percent from 1780-1800 and to 1.9 percent between 1800 and 1830. Recently, Clark (2001) downgraded even further these estimates. After Kuznets (1966), modern economic growth is generally characterized by high and sustained rates of growth as well as low volatility.

In stark contrast, opponents of the gradualist view claimed that the macro estimates suffer from a series of flaws that undermine their effectiveness[28] (Berg 1994, Berg and Hudson 1992, Cuenca Esteban 1994). According to the critics, these problems imply Crafts and Harley significantly underestimate output and productivity growth, and entail an unnecessary homogenization of a diverse and dynamic economy. In spite of these criticisms, during the last two decades the pendulum of research on the Industrial Revolution seems to have swung increasingly in the favor of the gradualists. The Industrial Revolution appears to be losing its revolutionary character, being now pictured as just a non-exceptional growth spurt originating in "localized" growth of the textile and iron industries (Clark 2001, Goldstone 2002).

In the last few years, these two views of the Industrial Revolution have been assessed in a variety of ways. Temin (1997) analyzes the trade flows between Britain and the rest of the world during the Industrial Revolution, and argues that if the localized growth hypothesis were true, then the data should confirm that Britain had a comparative advantage in the production of cotton textiles and iron goods. In contrast, Temin shows that Britain not only exported the products of its most dynamic sectors, but also of other "traditional" sectors, such as paper, soap, and woolen goods. Consequently, according to Temin, innovation was pervasive during the Industrial Revolution and not localized in the cotton and iron industries.

In turn, Harley and Crafts (2000) use a CGE model, which shows that the exports of the traditional industries increase even in the absence of TFP growth. According to

[28] These flaws include data unreliability, the difficulty in assigning accurate weights to the several sectors of the British economy in the 18th and early 19th centuries, wide regional disparities, the reliance on adult male data, and the difficulty of estimating non-factory production.

Harley and Crafts, the rise in the volume of exports of the most traditional sectors can be explained by the need to finance increasing food imports (fueled by rapid population growth). In addition, the maintenance of a vigorous export sector related to the traditional industries was also motivated by the quality of the British goods and a poor substitutability of other countries' goods.

Although the Temin and the Harley-Crafts models provide some important insights, neither completely settles the debate on the two views of the Industrial Revolution, especially due to the lack of micro productivity data. Greasley and Oxley (2000) pursue an alternative approach by exploiting the time-series properties of disaggregated industrial output data in a sample of 26 industries from 1815 and 1860 obtained from Hoffmann (1955). They conclude that early industrialization was defined by a small number of stochastic common trends. Granger-type causality tests also suggest that cotton textiles and iron products were the leading sectors in British industrial growth. Greasley and Oxley thus propose an intermediate position between the localized growth view (defended by Crafts and Harley) and the generalized growth/innovation (advocated by their critics), in which several technological waves spread across the British economy with different impact on individual industries.

This chapter also exploits the properties of disaggregated time series in order to compare the two views of the Industrial Revolution. Although the lack of micro productivity data for the period does not allow us to observe innovation directly, we can still observe the behavior of the disaggregated output data in order to search for structural transformations of the time series during the Industrial Revolution. In this context, this chapter uses an econometric technique recently developed by Vogelsang (1997) that endogenously searches for structural breaks of disaggregated time series. The Vogelsang

structural breaks tests provide another tool that allows us to confront the localized growth hypothesis with the view that changes were pervasive to the British economy during the Industrial Revolution. By using the Vogelsang procedure, we can see whether or not structural breaks were restricted to the cotton and iron industries. If the breaks were restricted to these sectors, then we can conclude that growth and structural transformations were localized in these two industries during the Industrial Revolution. If, on the other hand, structural breaks occurred across the British industrial sectors, then growth should not be characterized as being localized. In addition, by analyzing the pre- and post-break trend growth rates in the different industries, we will able to observe whether or not growth accelerated after the breaks occurred.

The paper proceeds as follows. Section 2 describes the Vogelsang structural breaks tests and presents results for two periods, 1700-1800 and 1800-1850. Section 3 debates some of the implications of the tests concerning the relationship between industrial output and population, and presents Granger-causality tests relating these variables. The last section concludes.

2. Structural Breaks and Two Views of the Industrial Revolution

The estimates of Crafts and Harley (1992) suggest that, after the mid-18th century, the growth process was not smooth: aggregate growth increased in the last decades of the 18th century, and then it accelerated further in the 19th century. These estimates based on aggregated data seem to indicate that there were (at least) two possible structural breaks during the Industrial Revolution. Based on the Crafts and Harley estimates, and in order to simplify the analysis, I divide the period of analysis into two broad sub-periods: 1700-

1800 and 1800-1850[29]. This subdivision of the time series is necessary because the Vogelsang tests described below are only able to detect a single break. Hence, if there were multiple breaks, the Vogelsang test would pick up the most likely break, but not other less significant ones. This search for two breaks is also consistent with the work by Crafts and Mills (1994), who found that an aggregate index of industrial output followed a segmented quadratic trend and had breaks occurring in 1776 and in 1831.

The hypothesis to be tested is the following: if the "localized" growth hypothesis is correct, then: 1) in the period before 1800, we should be able to detect structural breaks only in the most dynamic sectors (cotton and iron) of the British economy, and 2) most industrial series should exhibit a structural break after 1830 (i.e. the period when, according to the gradualists, modern growth emerges). On the other hand, if the "generalized growth/innovation" view is correct, then most series should exhibit breaks in their trends in *both* periods, which implies that most industries were subject to structural transformations *throughout* the Industrial Revolution.

Data were obtained from a variety of sources. Most industrial output data are from Hoffmann (1955). Many series in the Hoffmann data start in 1700, and the Hoffmann indices contain not only disaggregated data for several industries, but also other important variables, such as the number of bankruptcies, an index of consumer goods, and an index of producer goods. Some other variables (e.g. beer, steel, shipbuilding, etc.) start only at the end of the 18th century. The Hoffmann data were chosen because they still provide the best source of disaggregated data of the British Industrial Revolution (Greasley and Oxley

[29] Tests were performed for other sub-periods but did not significantly change the results obtained.

2000)[30]. In addition to the Hoffmann data, I use Feinstein's (1998) pig iron output data starting in 1750, Wrigley and Schofield's (1981) population data (the number of births, deaths, marriages, and total population), the number of patents collected by Dutton (1984) and MacLeod (1988), total exports and imports as reported in Mitchell (1988), and the Crafts-Harley (1992) total industrial output index.

The Vogelsang SupWald Tests

In order to test for structural changes in each individual series, I use the SupWald (or $SupF_t$) Vogelsang (1997) test, which provides endogenous estimates of the structural break date without specifying *a priori* the break years[31]. The Vogelsang procedure was chosen due to its advantages in comparison to other tests for structural breaks. In previous tests for structural breaks, some restrictions (e.g. non-trending regressors, stationarity, and no serial correlation) were relaxed, but not all simultaneously. In contrast, the Vogelsang SupWald procedure is a test for a structural break in the trend function of a univariate time series, which allows for serial correlation and is robust in the presence of a unit root. The features of this test are important for this paper, since most series analyzed have trends, exhibit serial correlation, and have unit roots. According to the methodology developed by Vogelsang (1997) and Perron (1989), the tests are divided into two stages. In the first stage, unit root tests are performed. This is an important stage of the

[30] One of the major criticisms of the Hoffmann aggregate indexes made by Harley and Crafts was the weighting of the different sectors of the British economy. According to Crafts and Harley, Hoffmann gave too much weight to the most dynamic sectors, which implied a sharp acceleration of economic growth in the 1770s. In this paper, most tests are carried out on disaggregated data. Hence, this paper avoids the controversy related to the weighting of each series.

[31] These tests were also carried out by Ben-David and Papell (1995, 1997) for GDP and export and import ratios, and by Andresen and Pereira (2001) for series of inward and outward foreign direct investment.

Vogelsang tests, because the critical values depend on whether the series is stationary or contains a unit root. The results of the Augmented Dickey-Fuller (ADF) and the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests are summarized in table 1. For the period 1700-1800, the ADF tests fail to reject the null hypothesis of nonstationarity in 21 cases out of the 24 series in the sample. The KPSS tests provide similar results with respect to the stationarity of the data. In turn, for the period 1800-1850, the unit root hypothesis cannot be rejected in 24 out of the 41 series analyzed. In the second stage of the Vogelsang procedure, the following equations are estimated:

$$y_t = \mu + \beta t + \delta t^2 + \theta DU_t + \gamma_1 DT_t + \gamma_2 DT2_t + \sum_{j=1}^{k} c_j y_{t-j} + \varepsilon_t \qquad (1)$$

$$y_t = \mu + \beta t + \theta DU_t + \gamma DT_t + \sum_{j=1}^{k} c_j y_{t-j} + \varepsilon_t \qquad (2)$$

$$y_t = \mu + \theta DU_t + \sum_{j=1}^{k} c_j y_{t-j} + \varepsilon_t \qquad (3)$$

where y_t represents the series to be tested, T_B denotes the time of the break or the period at which the change in the parameters of the trend function occurs, *t* represents a linear trend, and t^2 denotes the square of this linear trend. Following Perron (1989) and Ng and Perron (1995), I use the general-to-specific data dependent method for selecting the lag length *k*: start with k*=8 and if the t-statistic on γ_j was greater than 1.6 in absolute value k was set to 8, if not, the last lag was removed and the test repeated. In addition, the break dummy variables have the following values: $DU_t = 1$ if $t > T_B$, zero otherwise; $DT_t = t - T_B$ if $t > T_B$, zero otherwise; and $DT2_t = (t - T_B)^2$ if $t > T_B$, zero otherwise.

Table 1 _ Unit Root Tests (Augmented Dickey-Fuller and KPSS)

	1700-1850		1800-1850	
	ADF	LM statistic	ADF	LM statistic
Industries				
Beer	n.a.	n.a.	-2.616	0.1133*
Breads and cakes	n.a.	n.a.	-4.412*	0.0987*
Building	n.a.	n.a.	-1.585	0.1474***
Coal	-1.484	0.2167	3.477***	0.2439
Copper	-1.550	0.2017***	-2.265	0.1227**
Cotton yarn	-2.325	0.2544	-0.767	0.2417
Cotton goods	n.a.	n.a.	-0.6885	0.2438
Flour	n.a.	n.a.	-3.923**	0.1696***
Hemp products	n.a.	n.a.	-5.068*	0.2150***
Iron (Feinstein)	6.103	0.2193	1.536	0.2257
Iron (Hoffmann)	n.a.	n.a.	0.402	0.2348
Pig Iron (Hoffmann)	n.a.	n.a.	1.623	0.2356
Iron and Steel products	n.a.	n.a.	1.349	0.2367
Leather	n.a.	n.a.	-3.895**	0.1403**
Leather goods	n.a.	n.a.	-3.724**	0.1390**
Linens	n.a.	n.a.	-5.884*	0.0689*
Linen yarn	-3.312***	0.1803***	-5.131*	0.2436
Malt	-7.383	0.1623***	-4.479*	0.0985*
Paper	-2.772	0.2942	-0.986	0.2403
Shipbuilding	n.a.	n.a.	-3.685**	0.1121**
Ocean shipping	n.a.	n.a.	-0.478	0.2388
Silk products	-3.330	0.1796***	-2.189	0.1041*
Silk thread	n.a.	n.a.	-2.141	0.1067*
Spirits	n.a.	n.a.	-2.701	0.0968*
Steel	n.a.	n.a.	1.631	0.2367
Sugar	-6.026*	0.0962*	-3.110	0.1278**
Tin	-3.420***	0.1122*	-2.849	0.0812*
Tobacco	n.a.	n.a.	-2.725	0.2241
Woolen goods	-3.396***	0.1676***	-5.762*	0.1592***
Woolen yarn	n.a.	n.a.	-4.776*	0.1959***
Aggregate indexes				
Consumer goods	0.0398	0.2453	-3.119	0.2344
Producer goods	1.883	0.2581	-0.892	0.2387
Total Industry (Hoffmann)	3.536	0.2530	3.686**	0.2493
Total Industry (Crafts+Harley)	-3.193	0.1993***	-1.929	0.2468
Miscellaneous Variables				
Bankruptcies	-5.334	0.1805***	-4.629*	0.1284**
Patents (Hoffmann)	-0.071	0.3052	-2.381	0.1975***
Patents (MacLeod)	0.018	0.3012	-2.444	0.2145***
Exports	1.910	0.1543***	-0.879	0.2128***
Imports	5.548	0.2198	-3.907**	0.2271
Population Variables				
Births	-2.224	0.2735	-3.348***	0.1557***
Deaths	-4.452	0.1462***	-4.589*	0.1526***
Marriages	-4.585	0.1747***	-4.392*	0.1306**
Population	1.721	0.2981	-5.894*	0.2085***

For the ADF tests, the asymptotic critical values for the 1%, 5% and 10% levels are, respectively -3.571, -2.922 and -2.599 For the KPSS tests, the asymptotic critical values for the 1%, 5% and 10% levels are, respectively, 0.216, 0.146 and 0.119.

Each model is then estimated sequentially for *each* possible *break year* with 1 percent trimming, i.e., for $0.01T < T_B < 0.99T$, where T is the number of observations. In Model (1), *SupWald* is the maximum, over all possible trend breaks, of three times the standard F-statistic for testing $\theta = \gamma_1 = \gamma_2 = 0$. In Model (2), *SupWald* is the maximum, over all possible trend breaks, of two times the standard F-statistic for testing $\theta = \gamma = 0$. Finally, in Model (3), *SupWald* is the maximum, over all possible trend breaks, of the standard F-statistic for testing $\theta = 0$. In each model, the null hypothesis of no structural change is rejected if *SupWald* is greater than the critical value[32]. Intuitively and in the context of the Industrial Revolution, the existence of structural breaks in the time series *y* would indicate that the Industrial Revolution led to significant changes in *y*, originating a break in the trend of that series. For instance, if the Vogelsang tests are able to reject the null of no structural change for, say, industrial output, then we can be confident that, within the relevant significance interval, the trend of industrial output has undergone a structural transformation after the break occurred. Comparing the pre- and post-break trend growth rates allow us to measure the magnitude of the change in the trend.

Results

Tables 2 and 3 summarize the results of the Vogelsang tests. Table 2 shows that, between 1700 and 1800, the hypothesis of no structural break can be rejected for all series but copper. Model I is the preferred specification for 21 out of the 23 series. The great majority of structural breaks occurs in the last quarter of the 18th century, with the exception of the population variables (births, deaths, marriages, and total population), which had their breaks in the first half of the 18th century.

[32] Following Ben-David and Papell (1995, 1997), the Vogelsang are performed in raw or untreated data.

Table 2_ SupWald values and break years (1700-1800)[33]

	Break Year	*Model*	*SupWald*	*Signif.*	*Pre-break trend growth*	*Post-break trend growth*
Industries						
Coal	1763	I	39.18	1%	0.8	1.1
Copper[34]	No break	I	18.36	-	-	-
Cotton	1792	I	165.77	1%	5.7	8.5
Linen/Artificial Silk	1772	II	39.36	1%	2.9	2.3
Iron	1790	I	55.66	1%	1.7	8.1
Malt	1797	I	20.29	1%*	0.0045	-0.03
Paper	1782	I	28.7	10%	0.2	1
Sugar	1797	I	72.4	1%	2	8.4
Tin	1749	I	69.04	1%	0.06	0.4
Wool	1765	I	40.81	1%	0.05	1.1
Aggregate indexes						
Consumer goods	1784	I	38.84	1%	0.9	2.4
Producer goods	1770	I	49.77	1%	1	1.9
Total Industry (Hoffmann)	1777	I	347.15	1%	0.8	3.4
Total Industry (Crafts)	1781	II	148.57	1%	0.8	1.7
Miscellaneous Variables						
Bankruptcies	1792	I	82.44	1%	2.2	-4.9
Patents (Hoffmann)	1791	I	32.88	5%	3.5	5.5
Patents (MacLeod)	1791	I	28.11	10%	3.5	5.5
Exports	1765	I	49.86	1%	1.6	2.5
Imports	1783	I	44.3	1%	1.2	5.8
Population Variables						
Births	1730	I	69.76	1%	0.3	0.9
Deaths	1729	I	36.7	5%	0.9	0.5
Marriages	1734	I	37.93	5%	0.9	0.7
Population	1735	I	292.42	1%	0.16	0.7

In terms of the industrial data, the most significant result of the Vogelsang tests is that, for most series, the post-break trend growth is higher than the pre-break trend growth. As expected, the highest rates of post-break trend growth in the sample occurred in the most dynamic sectors, the cotton (8.5%) and iron industries (8.1%), but also in the

[33] For Model 1, the critical values for the 1, 5, and 10 percent significance are 38.35, 31.29, and 27.99 in the unit root case, respectively. For Model 2, the critical values for the 1, 5, and 10 percent significance are respectively, 30.36, 25.1, and 22.29.

[34] The highest SupWald value for copper corresponds to 1768. The trend growth rate for copper in the period 1700-1800 was 3.2 per cent. * Corresponds to stationary critical values. For cotton the pre-break trend growth rate corresponds to the period 1750-1800.

sugar industry (8.4%). However, for most other series, there is an acceleration in trend growth rates after the structural breaks occurred[35]. Trend growth increases from 0.8% to 1.1% in the coal industry; from 0.2% to 1% in the paper industry; from 2% to 8.4% in the sugar industry, from 0.06% to 0.4% in the tin industry, and from 0.05% to 1.1% in the woolen industry. The exceptions to this general tendency of trend growth acceleration occurred in the linen industry (where trend growth rates decreased from 2.9% to 2.3%), and the malt industry (where growth becomes slightly negative after the break occurred).

All in all, the results of table 2 show that during the Industrial Revolution growth accelerated in most industries following the structural breaks, which suggests an increasing dynamism of the British economy during the early Industrial Revolution. More importantly, the structural breaks were not confined to iron and cotton, which is not consistent with the Crafts-Harley hypothesis that growth was localized in these two sectors. In contrast, the empirical results indicate that growth was generalized and accelerating across the British industrial sectors.

Table 2 also shows that patents accelerated substantially in the second of the 18th century. Richard Sullivan (1989) previously found that there was a structural break in the number of patents in 1754. The tests for both the Hoffmann and the Dutton-MacLeod series confirm that there was another prominent break during the early Industrial Revolution, which occurred in 1791. The trend growth rate in patents increased after the break from 3.5% to 5.5%. These breaks in patents cannot be explained by any change in the patent laws, because the British patent system was not substantially reformed until 1852 (although there was a minor reform in 1835). Hence, the breaks in patents are

[35] It is noticeable that the breaks of cotton and iron occur in the last decade of the 18th century. This fact is probably associated with the acceleration of the rate of imitation of the factory system, as chapter 3 argues.

consistent with the signs of 'emerging capitalism' (MacLeod 1988) or by a rise in the rewards offered to inventors. During the Industrial Revolution more people started using the "formal" system of invention, and the patent system became an institutionalized mechanism of protecting property rights[36]. Since the two "dynamic" sectors (cotton and iron) only provided 11 percent of the total number of patents (MacLeod 1988), these findings suggest that either pervasive innovation or the signs of emerging capitalism were also taking place in the "traditional" sectors of the British economy.

The aggregate indexes also show that a trend acceleration occurred during the early Industrial Revolution. Trend growth rates of consumer goods increased from 0.9% to 2.4% after 1784, whereas trend growth of producer goods increased from 1% to 1.9%. The distinct results of the two aggregate industrial output indexes reflect the different weighting procedures of Hoffmann (1955) and Crafts and Harley (1992). In both series there is an acceleration of trend growth rates, although this increase is much more pronounced in the Hoffmann series (from 0.8% to 3.4%) than in the Crafts-Harley series (from 0.8% to 1.7%).

In addition, the number of bankruptcies peaked in the last decade of the 18th century, but then steadily declines after 1792. Since there was no significant change in the British bankruptcy laws until the 19th century, this structural break in the number of bankruptcies likely reveals that many "startups" of the emerging factory system were not successful. This evidence is consistent with the findings of Atkeson and Kehoe (1997), who show that major technological breakthroughs are often associated with large-scale

[36] Much innovation was also happening outside the formal patent system (Dutton 1984, MacLeod 1988). Some inventors favored secrecy, others did not find worthwhile protecting their innovations, and there were still others who found that "collective invention" was preferable to patent protection (Allen 1983). Reliable figures on this "informal" patent system would likely increase the trend growth acceleration in patents.

experimentation by start-up firms leading to high bankruptcy rates. In terms of foreign trade, total imports underwent a structural break in 1783, after which trend growth accelerated from 1.2% to 5.8%, whereas total exports had a structural break in 1765 and trend growth increased from 1.6% to 2.5%. Finally, all population indicators underwent structural breaks in the first half of the 18th century. After the breaks, there is a slight decline in trend growth in the number of deaths (from 0.9% to 0.5%) and in the number of marriages (from 0.9% to 0.7%). In contrast, trend growth accelerates in number births (from 0.3% to 0.9%) as well as in total population (from 0.16% to 0.7%). These results are thus consistent with the view that population accelerated even before the Industrial Revolution took place.

All in all, most series analyzed exhibited significant structural breaks during the 18th century. The population variables were the first to undergo structural breaks during the 1730s, whereas the breaks in most industry series cluster around the early stages of the Industrial Revolution (1770-1800). Although the highest trend growth rates occurred in the cotton, iron, and sugar industries, there was also a trend growth acceleration for the great majority of the other industries. Thus, the findings of the Vogelsang tests show that structural breaks were pervasive in the British industry, and hence growth was not "localized" in cotton and iron.

1800-1850

The results for the period 1800-1850 are summarized in Table 3, and suggest several conclusions. First, for most series, model I is the preferred specification. Model II is the preferred specification for 9 series (malt, paper, sugar, producer goods, total industry Crafts-Harley and imports), whereas model III is the preferred specification for 3

series (malt, wool, and marriages). Second, the structural breaks occur throughout the whole period, although they cluster slightly after the 1830s. Similarly, most industry series underwent structural changes in the 1830s and 1840s, the exceptions being wool and tin. Third, contrary to the period 1700-1800, there is no clear picture regarding trend growth rates, since post-break growth accelerates in only 16 out of the 29 industries. In the remaining industries (except malt, leather good and shipbuilding), post-growth trend growth was still positive but lower than pre-break rates. An interesting result pertains to the cotton industry. The latter had a structural break in 1846 after which trend growth decelerates from 5.8% to 2.7%. This fact is consistent with the findings of Crafts and Mills (1994), which suggest that by mid-19th century there was a deceleration in some of the "leading-sector" industries of the Industrial Revolution. In contrast, both iron and steel had structural breaks in the late 1840s, after which there was a substantial acceleration in trend growth (iron from 4.8% to 7.4% and steel from 1% to 4%), attesting the increasing dynamism of these industries as well as the influence of the railways.

Additionally, all aggregate indexes show an acceleration in trend growth during the period. Consumer goods had a break in 1846, which induced an acceleration of trend growth from 3% to 4.5%. The break in producer goods took place in 1807, and trend growth accelerated from 2.5% to 4%. Both aggregate industrial output indexes undergo structural breaks in the first decades of the 19th century, after which trend growth accelerates to around 3%. The similar magnitude of the structural breaks in trend growth for both indices is not surprising, since the differences in the weighting of the individual series in the aggregate index are less perceptible than in the 1700-1800 period.

Table 3: SupWald values and Break years (1800-1850)

	Break Year	*Model*	*SupWald*	*Signific.*	*Pre-break trend growth*	*Post-break trend growth*
Industries						
Beer	1830	I	66.58	1%	0.4	0.2
Breads and cakes	1820	I	25.61	1%*	2	2.3
Building	1804	I	686.8	1%	3.2	1.8
Coal	1836	I	31.33	5%	2.2	4
Copper	1831	I	50.46	1%	2.7	0.4
Cotton yarn	1846	I	86.85	1%	5.8	2.7
Cotton goods	1844	I	41.49	1%	5	1.4
Flour	1820	I	35.97	1%	2	7.4
Iron (Feinstein)	1844	I	42.36	1%	4.8	7.4
Iron and steel products	1833	II	120.23	1%	4	5.5
Pig Iron (Hoffmann)	1847	I	31.92	5%	5	3.3
Hemp products	1821	I	23.13	1%*	-1.4	2.3
Leather	1840	I	28.53	10%	1.9	0.9
Leather goods	1840	I	31.22	10%	1.9	- 0.2
Linen yarn	1845	I	25.11	1%*	1.6	2.2
Linens	1847	III	14.38	1%	1.9	9
Malt	1830	III	35.49	5%	0.9	-0.04
Paper	1830	II	75.1	1%	2.5	3.7
Shipbuilding	1836	I	30.17	10%	1.7	-2.3
Ocean shipping	1823	I	41.68	1%	-1.5	4.5
Silk goods	1823	II	23.6	10%	1.5	3.3
Silk thread	1836	I	41.98	1%	5.7	2.1
Spirits	1823	I	32.43	5%	0.6	0.63
Steel	1847	I	29.35	10%	1	4
Sugar	1844	II	29.63	5%	4.6	3.3
Tin	1822	I	28.43	10%	1.4	1.8
Tobacco	1813	I	30.81	10%	0.8	1.5
Woolen cloth	1806	III	50.66	1%	2	1.5
Woolen yarn	1821	II	34.18	1%	0.95	1.65
Aggregate indexes						
Consumer goods	1846	I	38.59	1%	3	4.5
Producer goods	1841	II	38.19	1%	2.5	4
Total Industry (Hoffmann)	1813	I	188.44	1%	2.3	3.2
Total Industry(Crafts)	1822	II	303.61	1%	2	3.4
Miscellaneous Variables						
Bankruptcies	1825	I	25.91	1%**	1.6	-0.05
Patents (Hoffmann)	1841	II	36.77	1%	2	3.2
Patents (MacLeod)	1837	I	30.31	5%	2.5	3.1
Exports	1818	I	31.4	5%	0.8	2.1
Imports	1834	II	36.8	1%	-0.02	2
Population Variables						
Births	1828	I	43.8	1%	1.6	1.1
Deaths	1844	I	28.69	10%	0.9	1.3
Marriages	1803	III	51.14	1%	13	1.3
Population	1813	I	274.56	1%	1.34	1.3

* refers to stationary critical values

In turn, a small structural break in bankruptcies occurred in 1825, which probably can be explained by the financial crisis as well as by the minor changes in the British bankruptcy laws that occurred in that year[37]. Bankruptcies trend growth rates become slightly negative throughout the rest of the period. Patents underwent a structural break in 1837, after which trend growth rates slightly declined from 2.5% to 1.9%. This structural break might have been a consequence of the minor reform in patent law that took place in 1835 (MacLeod 1988). The trade variables also show an acceleration in trend growth rates. Total exports had a structural break at the end of the Napoleonic Wars and trend growth accelerated from 0.8% to 2.1%. Total imports underwent a structural break in 1834, after which trend growth rates increased to 2%. Finally, contrary to the period 1700-1800, the breaks of the population variables do not cluster around any particular period. For most of these series, trend growth rates decelerate after the structural break occurred.

Taking stock

The results from the Vogelsang tests indicate that the Industrial Revolution was a period in which there were pervasive structural changes to both the industry and the population variables. These findings support the view that the Industrial Revolution can be characterized as a discontinuity in the process of British economic development, even though GDP growth during the period was sluggish by today's standards. In addition, the

[37] Since the Bubble Act of 1720 until 1861, most businesses in Britain operated under the principle of unlimited liability, which implied that "the failure of a company could be the ruin of its shareholders" (Weiss 1986: 33). Although seen as one of the cornerstones of British industrial success, the principle of unlimited liability complicated the raising of investment capital. Several changes in the bankruptcy laws (in 1810, 1825, 1861, and 1869) gradually removed the unlimited liability principle.

results of the Vogelsang tests show that during the early Industrial Revolution the highest post-break trend growth rates occurred in the iron and cotton industries as well as in the sugar industry. However, the breaks were not confined to the most dynamic sectors, and hence growth was not localized, which is consistent with the findings of Temin (1997) and of Gresley and Oxley (2000). The tests also show that, for the period between 1700 and 1800, the breaks of the population variables preceded in several decades the breaks of the industrial variables. These results suggest that the shifts in the trend of the industrial variables could have occurred due to the influence of population (after taking into account any lags involved), and not merely due to a positive supply shock originated by technological change. Based on these results, the next section investigates whether or not the Industrial Revolution was at least partly a population-led revolution.

3. A Population-Led Revolution?

The view the Industrial Revolution was at least partly population-led (as well as demand-led) has been espoused by many (McKendrick 1982, North 1990, de Vries 1994), but most prominently by John Hicks, who argued: "One cannot repress the thought that perhaps the whole Industrial Revolution of the last two hundred years has been nothing else but a vast secular boom largely induced by the unparallel rise in population" (Hicks 1939: 302). Figure 1a shows that, indeed, there is a close relationship between the level of population (POP) and industrial output (ACTUALGDP) during the Industrial Revolution. However, since both variables clearly trend upwards, it is possible that this close relationship might be chiefly caused by the existence of a common trend. In order to discard this possibility, both variables were detrended. I first regressed each of the variables on a time trend, and obtained the residuals (POPRESIDUALS and

INDGDPRESIDUALS). POPRESIDUALS were then regressed on INDGDPRESIDUALS. The slope coefficient of this regression should thus reflect the true association between industrial output and population. Figure 1b presents a scattered diagram of POPRESIDUALS and INDGDPRESIDUALS, showing that, even after removing the influence of the trend, there is a close and positive relationship between population and industrial output.

Figure 1a_ Population Vs Industrial Output, 1700-1850

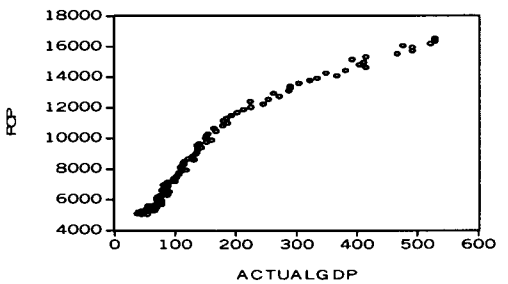
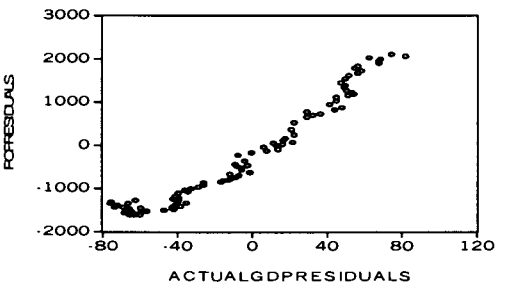


Figure 1b_ Population Vs Industrial Output, 1700-1850



Although the diagrams above suggest a strong and positive relationship between industrial output and population, it is plausible to assume that the two variables interact with each other, making it difficult to ascertain which variable is exogenous. Both population and industrial output were then treated symmetrically or endogenously, by estimating a vector autoregression (VAR). The VAR approach provides additional insights on the dynamic relationship between these two variables, since each variable is affected by current and past realizations of both variables. A VAR of order q relating industrial output and population can be written as:

$$IND_t = \beta_{10} + \phi_{1j} \sum_{j=1}^{q} IND_{t-q} + \phi_{1j} \sum_{j=1}^{q} POP_{t-q} + e_{INDt} \qquad (4)$$

$$POP_t = \beta_{20} + \phi_{2j} \sum_{j=1}^{q} IND_{t-q} + \phi_{2j} \sum_{j=1}^{q} POP_{t-q} + e_{POPt} \qquad (5)$$

where IND and POP denote, respectively, industrial output and population. It is assumed that ε_{INDt} and ε_{POPt} are white-noise disturbances with standard deviations of σ_{IND} and σ_{POP}, and that $\{\varepsilon_{INDt}\}$ and $\{\varepsilon_{POPt}\}$ are uncorrelated. In order to determine the appropriate lag length in the VAR of order q, I began with the longest feasible length given the degrees of freedom and used the Akaike information criterion[38]. The results of the VAR are reported in Appendix A. Since the coefficients of the estimated VARs are difficult to interpret (especially because often the coefficients alternate in sign), I followed the usual procedure of estimating impulse response functions. The latter provide the response of the dependent variable to the shock in the error terms (also known as innovations or impulses), ε_{INDt} and ε_{POPt}. For instance, suppose that ε_{INDt} in equation (4) increases by a value of one standard deviation. This increase in ε_{INDt} will not only change industrial output in the current period, but also in the future periods. Similarly, since IND also appears in (5), ε_{INDt} will also affect POP. Shocks in ε_{POPt} will have similar impacts. In formal terms, the impulse responses can be found from the vector-moving average representation of (4) and (5). For illustrative purposes, suppose we have the following first-order VAR relating industrial output and population:

$$\begin{bmatrix} IND_t \\ POP_t \end{bmatrix} = \begin{bmatrix} a_{10} \\ a_{20} \end{bmatrix} + \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} IND_{t-1} \\ POP_{t-1} \end{bmatrix} + \begin{bmatrix} e_{1t} \\ e_{2t} \end{bmatrix} \tag{6}$$

The vector-moving average representation of (6) is:

$$\begin{bmatrix} IND_t \\ POP_t \end{bmatrix} = \begin{bmatrix} \overline{IND} \\ \overline{POP} \end{bmatrix} + \sum_{j=0}^{\infty} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}^j \begin{bmatrix} e_{1t-j} \\ e_{2t-j} \end{bmatrix} \tag{7}$$

[38] In general, other lag-selection criteria agreed on the lag selection.

Define a 2 x 2 matrix[39] ϕ_i with elements $\phi_{jk}(i)$ (Enders 19995: 305), such that $\phi_I=[1/1-b_{12}b_{21}]\begin{bmatrix} 1 & -b_{12} \\ -b_{21} & 1 \end{bmatrix}$. Then, we can write (7) as:

$$\begin{bmatrix} IND_t \\ POP_t \end{bmatrix} = \begin{bmatrix} \overline{IND} \\ \overline{POP} \end{bmatrix} + \sum_{j=0}^{\infty} \begin{bmatrix} \phi_{11}^{(i)} & \phi_{12}^{(i)} \\ \phi_{21}^{(i)} & \phi_{22}^{(i)} \end{bmatrix} \begin{bmatrix} \varepsilon_{INDt-j} \\ \varepsilon_{POPt-j} \end{bmatrix} \tag{8}$$

where $\phi_{11}^{(i)}$ is the expected one-period response of a one-unit change in ε_{INDt-1} on IND, and $\phi_{12}^{(i)}$ is the expected one-period response of a one-unit change in ε_{INDt} on POP. $\phi_{21}^{(i)}$ and $\phi_{22}^{(i)}$ denote the responses to ε_{POPt} shocks. These coefficients are known as the impulse response functions.

Since in (8) the error terms ε_{INDt-j} and ε_{POPt-j} are correlated, it is likely that if ε_{INDt-j} changes then ε_{POPt-j} will be affected, which implies that POP_t will also be altered. Hence, we need to undertake orthogonalization, in which $e_{1t} = \varepsilon_{INDt} - b_{12}\varepsilon_{POPt}$, and $e_{2t} = \varepsilon_{POPt}$. This orthogonalization is known as the Choleski decomposition, and constrains the system such that there are no contemporaneous effects of IND_t on POP_t (Charemza and Deadman 1997, p. 163).

In the estimation of impulse response functions, there is still some debate on whether or not both variables should be jointly stationary. On the one hand, Enders (1995) argues that all variables in a VAR should be stationary. In this case, and since the

---

[39] From (7), the error terms e_{1t} and e_{2t} were re-written in terms of ε_{INDt} and ε_{POPt} such that:

$$\begin{bmatrix} e_{1t} \\ e_{2t} \end{bmatrix} = [1/1-b_{12}b_{21}] \begin{bmatrix} 1 & -b_{12} \\ -b_{21} & 1 \end{bmatrix} \begin{bmatrix} \varepsilon_{IND_t} \\ \varepsilon_{POP_t} \end{bmatrix},$$

where ε_{INDt} and ε_{POPt} are white-noise disturbances of the following structural vector autoregression:

$$IND_t = b_{10} - b_{12}\, POP_t + \gamma_{11}\, IND_{t-1} + \gamma_{12}\, POP_{t-1} + \varepsilon_{INDt}$$

$$POP_t = b_{20} - b_{21}\, IND_t + \gamma_{21}\, IND_{t-1} + \gamma_{22}\, POP_{t-1} + \varepsilon_{POPt}$$

unit root tests show that IND is I(1), whereas POP is I(0), a possibility for estimating the VAR is to use either the residuals obtained by linear detrending both variables, or to use first differences. On the other hand, Sims (1980) contends that the results of transformed data are often unsatisfactory, arguing that it is preferable to work with the levels, as long as it is recognized the effects of unit roots on the distribution of the estimators. Since there are no compelling reasons regarding the preferences for either methodology, impulse response functions were estimated in terms of levels (i.e. the raw data on industrial output, ACTUALGDP, and population, POP), the residuals resulting from linear detrending (ACTUALGDPRESIDUALS and POPRESIDUALS) and growth rates (GROWTHGDP and GROWTHPOP). The impulse response functions of the Choleski decomposition for the period between 1700 and 1800 are reported in Figures 2-4.

Figure 2 shows the impulse response functions for the level variables. On the horizontal axis we have the number of periods after the shock in the error terms (ε_{INDt} or ε_{POPt}), whereas the vertical axis gives us the magnitude of these shocks on a particular variable. The impulse response functions of the level variables show that the response of industrial output to an ε_{INDt} shock dampens over time, although it does not return to the original equilibrium levels. Similarly, an ε_{POPt} shock has an increasing effect on population over time. Thus, innovations to industrial output have a permanent effect in industrial output, and innovations to population have a positive permanent effect in population. The response of industrial output to population is initially negative in the first three periods after the shock, but then it becomes gradually positive. During the period between 1700 and 1800, population responded positively to shocks to industrial output.

Figure 2 _ Impulse Response Function: levels, 1700-1850

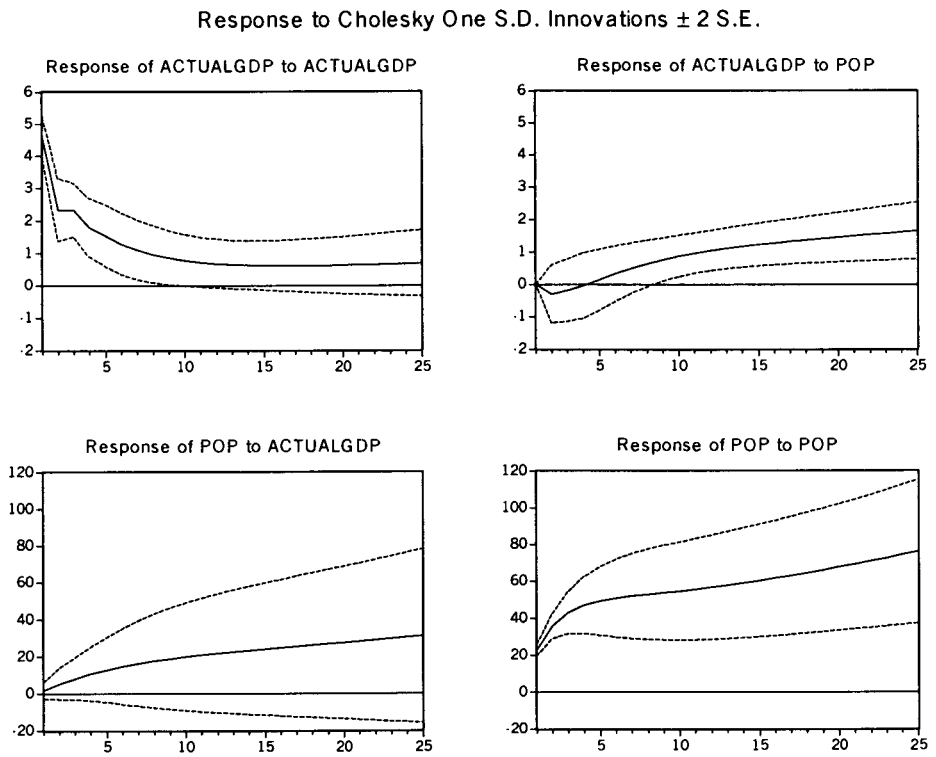


Figure 3 shows the impulse response functions of the detrended variables (POPRESIDUALS and ACTUALGDPRESIDUALS). Most impulse responses are similar to those of the trended variables. The exception is the response of detrended population to an ε_{INDt} shock: a shock of one standard deviation to industrial output leads to a very mild positive response of population in the first five periods, becoming progressively (but only slightly) negative with time.

In addition, figure 4 shows that the effect of a shock of one standard deviation of both industrial output growth (GROWTHGDP) and population growth (GROWTHPOP) dampens swiftly in less than 10 periods. A shock to industrial output has initially a positive impact on the rate of population growth of about 0.1 percent in the first period, gradually decreasing in the following periods until it returns to equilibrium levels. In turn,

a shock to population growth leads to a very small positive response of industrial output in the first two periods, becoming slightly negative in the following two periods, and returns to equilibrium levels in the fifth period after the shock occurred. The responses of both population growth and industrial output growth to its own shocks are initially positive, but also dissipate after the first 5 periods. All in all, in contrast to what happened with the levels and the detrended variables, shocks to the growth rates of both population and industrial output do not have lasting effects, fading away after five periods. The impulse response functions of the one-year differences gave similar results to those of the growth rates.

Figure 3 _ Impulse Response Function: detrended variables, 1700-1850

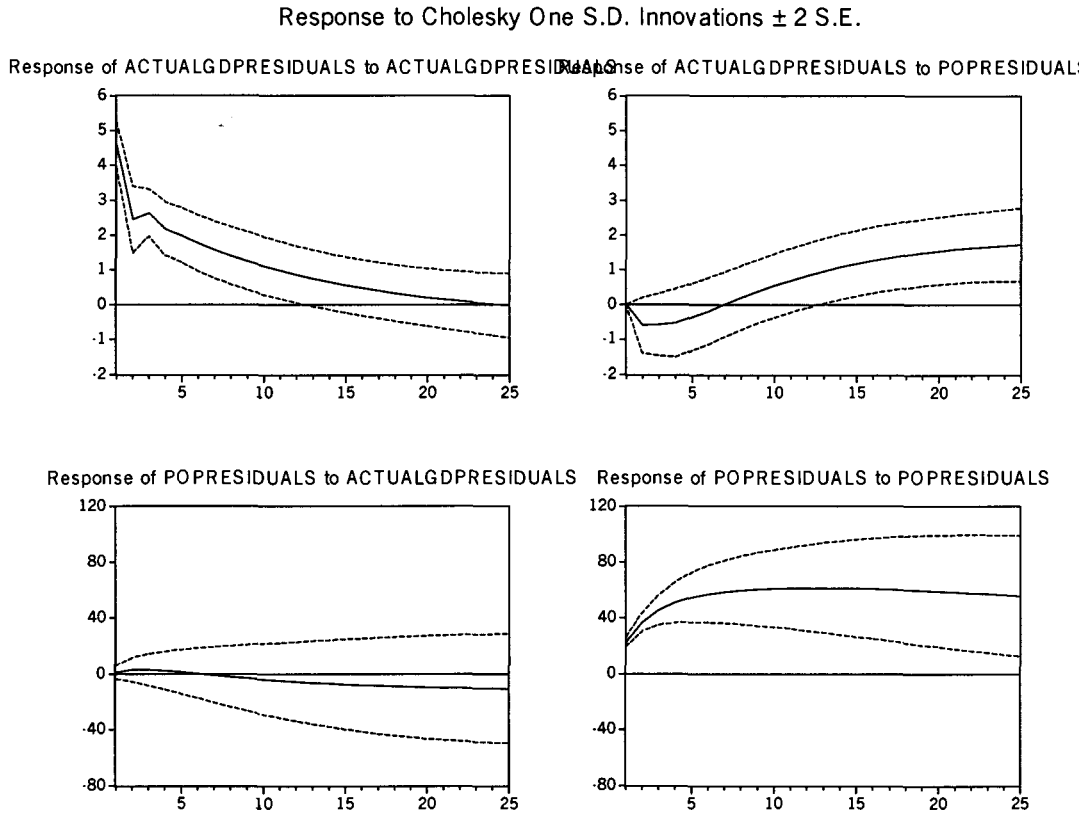
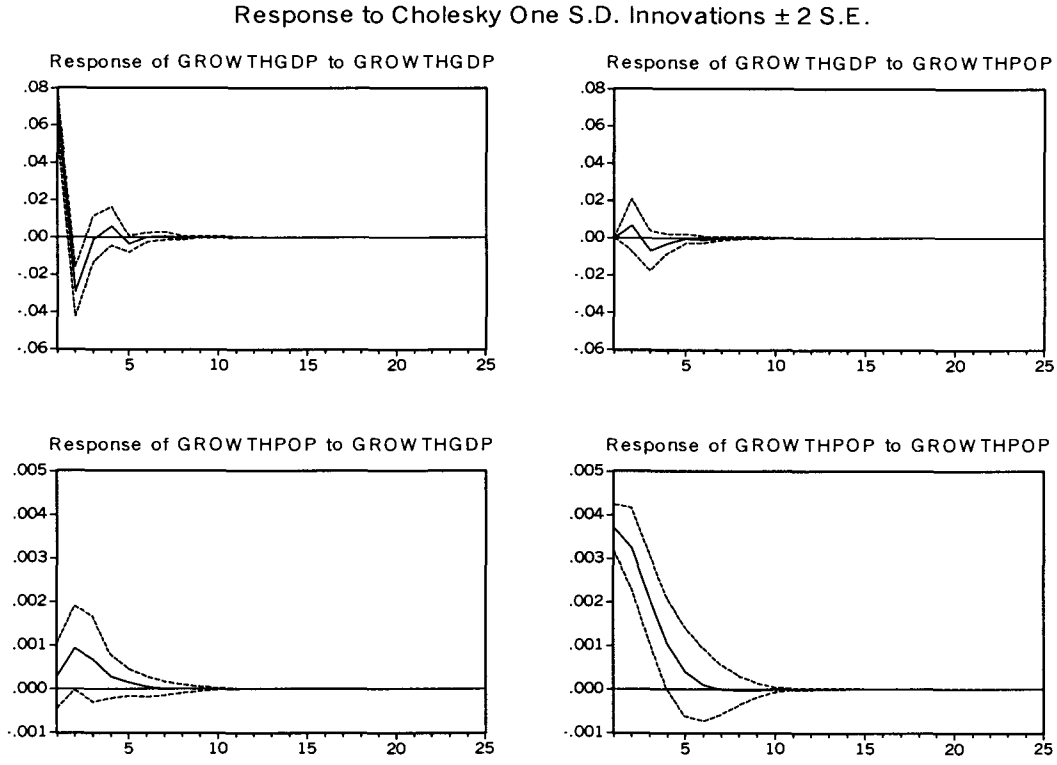


Figure 4 _ Impulse Response Function, growth rates, 1700-1850



In sum, the impulse responses suggest that shocks to population led to permanent and positive effects to industrial output, indicating that some population-led growth occurred during the period between 1700 and 1850. In addition, there is some contradictory evidence on the impact that output shocks had on population. On the one hand, the raw data on population and industrial output show that shocks to the latter have a positive and permanent effect on the former. On the other hand, residualized data indicates that ε_{INDt} might have a small negative impact on population. Finally, shocks to the growth rates seem to have only temporary effects.

Causality: Population and Industrial Output

A question that remains is the causality between the industrial and population variables. Did industrial output increase as a response to the increase in population or did population rise because output (and income) increased? In econometric terms, although we cannot establish causality, we can observe whether one variable can help forecast another variable by using the concept of Granger causality. Formally, y does not Granger-cause x if, for all $s>0$:

$$MSE[\hat{E}(x_{t+s}|x_t, x_{t-1}, ...)] = MSE[\hat{E}(x_{t+s}|x_t, x_{t-1}, ..., y_t, y_{t-1,...})] \qquad (9)$$

That is, y does not Granger cause x if the mean squared error of a forecast of x_{t+s} that uses (x_t, x_{t-1}, ...) is the same as the mean squared error of a forecast of x_{t+s} that uses both (x_t, x_{t-1}, ...) and (y_t, y_{t-1}, ...).

In the context of our analysis, the following equation was estimated by OLS:

$$IND_t = \beta_0 + \beta_1 POP_{t-1} + \beta_2 POP_{t-2} + ... + + \beta_p POP_{t-p} +$$

$$+ \gamma_1 IND_{t-1} + \gamma_2 IND_{t-2} ++ ... + \gamma_p IND_{t-p} + \varepsilon_t \qquad (10)$$

where p denotes the lag length. An F test is conducted so that $\gamma_1 = \gamma_2 = ... = \gamma_p = 0$. Following Hamilton (1994), the sum of squared residuals (RRS_1) from (10) was then calculated and was compared with the sum of squared residuals (RRS_2) of a univariate autoregression for IND_t estimated by OLS. Finally, the following ratio was calculated:

$$S = \frac{(RRS_1 - RRS_2)/p}{RRS_2/(T-2p-1)} \qquad (11)$$

If ratio (11) is greater than the 5% critical value, the null hypothesis that POP does not Granger-cause IND is rejected. Following the results of the VAR approach presented in the Appendix, the lag length p was set equal to 2. In addition, since these Granger

causality tests are only appropriate with stationary data, the tests were performed for one-period differenced data, growth rates and detrended data. The results are shown below:

Table 4: Granger Causality Results

Null Hypothesis:	Obs	F-Statistic	Probability
POPRESIDUALS does not Granger Cause ACTUALGDPRESIDUALS	99	4.15564	0.01865
ACTUALGDPRESIDUALS does not Granger Cause POPRESIDUALS		0.81359	0.44636

Null Hypothesis:	Obs	F-Statistic	Probability
GROWTHPOP does not Granger Cause GROWTHGDP	98	0.94826	0.39113
GROWTHGDP does not Granger Cause GROWTHPOP		1.85018	0.16295

Null Hypothesis:	Obs	F-Statistic	Probability
POPDIFFERENCES does not Granger Cause ACTUALGDPDIFFERENCES	100	0.7045	0.40334
ACTUALGDPDIFFERENCES does not Granger Cause POPDIFFERENCES		1.01785	0.31554

In terms of detrended data, we can reject the null hypothesis that POPRESIDUALS does not Granger Cause ACTUALGDPRESIDUALS at the 5% significance level, indicating that, indeed, population does Granger-cause industrial output. Thus, the results indicate that population can help forecast industrial output during the period between 1700 and 1800. In contrast, we cannot reject the null that ACTUALGDPRESIDUALS does not Granger Cause POPRESIDUALS. In turn, the null hypothesis cannot be rejected for both the growth rates and the one-year differences.

Even though the tests above do not necessarily suggest that the Industrial Revolution was a population-led phenomenon, it is still plausible to argue that output growth in many industrial sectors may have been driven by the use of more inputs in response to rising demand. Therefore, bivariate causality tests were performed between the industries in our sample and the level of population for the period corresponding to the Industrial Revolution. Since many of the series in the sample have unit roots, I used

the Toda and Yanamoto (1995) Granger-causality tests, which remain valid even if the data are nonstationary. The Toda and Yanamoto (1995) causality tests involves estimating a VAR in the levels of the variables of equations (4) and (5). As before, the lag length is selected according to the Akaike Information Criteria. However, if a variable has a unit root, the VAR will be estimated with an extra lag. If the series is I(0), no extra lag is added. The final step of the Toda and Yanamoto (1995) procedure is a Wald test of the significance of the lagged POP (or IND_t) variables. If the coefficients of POP are jointly zero, then POP does not cause IND, and vice-versa. The results are presented in table 5.

Based on the Toda and Yanamoto causality tests, we can see that population does Granger-cause many of the series in the sample. For the industrial data, population Granger-causes 21 out of the 29 industries, including beer, breads and cakes, building, coal, cotton goods, cotton yarn, flour, iron (the Feinstein figures), linens, linen yarn, malt, paper, shipbuilding, ocean shipping, silk products and silk thread, sugar, tobacco, woollen cloth and woollen yarn. These industries include most of the food-related sectors, but also some of the most dynamic industries of the period, such as cotton, iron and sugar. On the other hand, most of the industries for which we cannot reject the null of noncausality include steel, copper ore, hemp products, pig iron (Hoffmann series), iron and steel products, steel, and the leather industries. In some of these industries, such as steel and iron products, we have evidence of pervasive technical change (Mokyr 1990), and hence it is not surprising that population did not play a major role in their development.

Table 5: Granger Causality Results, 1760-1850

Industries	p-value Population does not cause Y	p-value Y does not cause Population
Beer	0.0004*	0.0635**
Breads and cakes	0.0233*	0.0041*
Building	0.0022*	0.8409
Coal	0.0535**	0.4737
Copper	0.6666	0.0930**
Cotton goods	0.0000*	0.0003*
Cotton yarn	0.0001*	0.1579
Flour	0.0097*	0.0537**
Hemp products	0.1479	0.0743**
Iron (Feinstein)	0.0000*	0.5945
Pig Iron (Hoffmann)	0.2193	0.5512
Iron and steel products	0.3465	0.5255
Leather	0.2384	0.0014*
Leather products	0.2062	0.0021*
Linens	0.0230*	0.0064*
Linen yarn	0.0004*	0.4118
Malt	0.0062*	0.0535**
Paper	0.0045*	0.5935
Shipbuilding	0.0697**	0.0162*
Ocean Shipping	0.0189*	0.1111
Silk products	0.0285*	0.0677**
Silk thread	0.0402*	0.0007*
Spirits	0.2348	0.0776**
Sugar	0.0319*	0.0042*
Steel	0.2768	0.5131
Tin	0.0413*	0.0711
Tobacco	0.0070*	0.0179*
Woolen cloth	0.0099*	0.0001*
Woolen yarn	0.0026*	0.0000*
Aggregate indexes		
Consumer goods	0.0002*	0.0005*
Producer goods	0.0424*	0.3213
Total Industry (Hoffmann)	0.0000*	0.7238
Total Industry (Crafts+Harley)	0.0000*	0.0003*
Miscellaneous Variables		
Bankruptcies	0.0004*	0.0635**
Patents (Hoffmann)	0.1210	0.0254*
Patents (MacLeod)	0.0947**	0.0080*
Exports	0.1162	0.3525
Imports	0.0876**	0.1993
Population Variables		
Births	0.0000*	0.0023*
Deaths	0.0001*	0.0002*
Marriages	0.0092*	0.0000*

* denotes rejection the null of noncausality in favor of causality at the 5% level, ** denotes 10% level

In terms of the aggregate indexes, the results of the Toda and Yanamoto (1995) causality tests provide somewhat a different picture to that of the results presented in table 4, but are consistent with the results of the impulse response functions. That is, we can reject the null of noncausality between population and total industrial output. The same is true for the indexes of producer and consumer goods.

Patents, bankruptcies, and imports are all Granger-caused by population. Not surprisingly, the null of noncausality cannot be rejected for exports, showing the latter were dependent on foreign demand and not on the level of domestic population. Finally, as expected, there is bidirectional causality between the population variables, such as births, deaths and marriages.

Summing up

All in all, the results from both the impulse response function and the Granger-causality tests seem to suggest that population interacted substantially with British industrial output during the 18th century. As the impulse responses of the level variables indicate, not only did shocks to population have long-lasting effects on industrial output, but also shocks to the latter had long-term effects on population. In terms of the results of the Granger-causality tests, we can conclude that population helps to better predict industrial output in many of the individual series. Thus, population did play a role during the Industrial Revolution, although it is somewhat difficult to quantify how important was this population-led boom *a la* Hicks. However, a caveat is warranted, since the nature of these tests does not imply much about causality inference.

Therefore, from the both VAR analysis and the causality tests, although we can infer that population and industrial output interacted considerably during the 18th century,

we cannot conclude that the Industrial Revolution was a population-led phenomenon[40]. Although the population increase and its demand-side effects were certainly important for some industries, there is no overwhelming evidence to suggest that it was the primary cause of the Industrial Revolution. The Industrial Revolution should still be seen as primarily a supply-side phenomenon caused, first and foremost, by technological change (Mokyr 1999). The most revealing piece of evidence that shows the power of technical change during the Industrial Revolution is that the unprecedented rise in population after the mid-18th century was sustained with constant or even slightly rising standards of living. Hence, what is surprising during the Industrial Revolution is not that standards of living do not rise significantly until the 1820s as shown by Feinstein (1998), but that they did not fall in the presence of an unprecedented dramatic increase in population.

4. Concluding Remarks

This chapter used an endogenous structural break procedure that shows that growth was not localized during the early Industrial Revolution. For the period between 1700 and 1800, the tests suggest two main results. First, the population variables (births, deaths, marriages, and total population) were the first to undergo structural breaks, around the 1730s. Second, although the highest post-break trend growth rates occurred in the most dynamic sectors (cotton and iron), most industrial series were subject to structural changes during this period after which there was some trend growth acceleration.

[40] Causality between industrial growth and population is difficult to establish due to the lack of micro data, which could be used to provide firmer foundations for a more complete and accurate causality analysis. "In order to establish causality inference between population and industrial output additional regression analysis based on micro and archival data would have to be undertaken. This is a topic for future research.

Furthermore, most breaks in industrial output cluster in the period after the 1760s. All in all, the Vogelsang tests indicate that, during the early Industrial Revolution, structural changes were pervasive and the British economy became increasingly more dynamic, as suggested by Greasley and Oxley (2000). Impulse response functions and causality tests indicate that population partly fuelled the growth of some individual industries, although there is not enough evidence suggesting that the first Industrial Revolution was mostly a population-induced phenomenon.

Although the results of Vogelsang tests suggest that growth was not localized in the cotton and iron industries, it is true that, by today's standards, aggregate output and productivity did not grow significantly until the 1830s. Yet, sluggish growth should neither be synonymous with the absence of changes nor with localized growth. In fact, it is often common for growth and productivity to increase gradually whenever there are major technical and organizational changes occurring in the economy (Lipsey and Bekar 1995, Lipsey 2002). The Industrial Revolution was not an exception to this. During early stages of the Industrial Revolution not only there were massive structural changes motivated by the emergence of the new machines, but also the transition to the factory system involved a lengthy process of social learning that was fundamental for the development of the microinventions associated with the new machines. Chapter 3 discusses the long diffusion of the new organizational innovation, the factory system, and its impact on slow economic growth.

Appendix A: VAR Results

Table 6

Standard errors in ( ) & t-statistics in [ ]					
	ACTUALGDP	POP		ACTGDPRESIDUALS	POPRESIDUAL
ACTUALGDP(-1)	0.513155	0.57225	ACTGDPRESIDUALS(-1)	0.539402	0.335929
	-0.09829	-0.49353		-0.09539	-0.47571
	[5.22082]	[1.15951]		[5.65448]	[0.70616]
ACTUALGDP(-2)	0.254772	-0.138	ACTGDPRESIDUALS(-2)	0.298038	-0.52691
	-0.1001	-0.5026		-0.09141	-0.45584
	[2.54523]	[-0.27457]		[3.26051]	[-1.15592]
POP(-1)	-0.01311	1.566084	POPRESIDUALS(-1)	-0.02602	1.620522
	-0.01953	-0.09805		-0.01716	-0.0856
	[-0.67120]	[15.9730]		[-1.51571]	[18.9321]
POP(-2)	0.019282	-0.56471	POPRESIDUALS(-2)	0.031075	-0.6203
	-0.01985	-0.09968		-0.01777	-0.08859
	[0.97133]	[-5.66547]		[1.74920]	[-7.00166]
CONSTANT	-18.9698	-25.1117	C	-2.85825	-14.2947
	-5.61583	-28.1977		-0.80437	-4.01126
	[-3.37792]	[-0.89056]		[-3.55341]	[-3.56365]
R-squared	0.954833	0.999476	R-squared	0.990204	0.99963
Adj. R-squared	0.952911	0.999454	Adj. R-squared	0.989787	0.999614
Sum sq. resids	1964.581	49530.29	Sum sq. resids	1981.702	49282.24
S.E. equation	4.571629	22.95469	S.E. equation	4.591506	22.89714
F-statistic	496.7915	44817.16	F-statistic	2375.415	63498.41
Log likelihood	-288.377	-448.128	Log likelihood	-288.806	-447.88
Akaike AIC	5.926801	9.154107	Akaike AIC	5.935478	9.149086
Schwarz SC	6.057868	9.285174	Schwarz SC	6.066545	9.280153
Mean dependent	74.51617	6150.657	Mean dependent	-10.8973	-358.448
S.D. dependent	21.06742	982.0294	S.D. dependent	45.43386	1165.897
Determinant Residual Covariance		10948.07	Determinant Residual Covariance		11030.3
Log Likelihood (d.f. adjusted)		-741.345	Log Likelihood (d.f. adjusted)		-741.716
Akaike Information Criteria		15.17869	Akaike Information Criteria		15.18618
Schwarz Criteria		15.44083	Schwarz Criteria		15.44831

Chapter 3

The Industrial Revolution as an Organizational Revolution[41]

Abstract

The fundamental feature of the first Industrial Revolution was a reorganization of the British economy originated by the development of an organizational general purpose technology, the factory system. During the Industrial Revolution there was both slow per capita GDP growth and pervasive innovation because it took time for the investment in organizational capital to be fully realized and a process of social learning to be completed. In spite of low rates of growth, the organizational revolution was crucial for the emergence of modern economic growth.

JEL codes: N13, O14

Keywords: organizational revolution, general purpose technologies, social learning

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1. Introduction

Recent research (Crafts 1985, Harley 1982, Crafts and Harley 1992, Clark 2001) has probably inflicted a lethal blow to the long-prevailing view that the first Industrial Revolution was a period of a sudden and sharp acceleration of economic growth. It is now almost consensual that growth during that period was, at best, slow. According to Crafts and Harley (1992), British GDP per capita growth averaged 0.17 percent per year between 1760 and 1800 and 0.52 percent between 1800 and 1830. Similarly, Clark (2001) estimated that, between 1760 and 1830, output per person in Britain increased merely at an yearly average of 0.26 percent.

In spite of slow growth, there is also strong evidence that structural change occurred in many sectors of the British economy during the Industrial Revolution. Mokyr (1990) argues that technical change was pervasive to industries as diverse as soap making or chlorine bleaching. Berg and Hudson (1992), Berg (1994), Mantoux (1927) and Fong (1928) show that there were wide-ranging organizational changes in most sectors of the British economy. Temin (1997) demonstrates that the British exported products from both the "traditional" and the "dynamic" sectors, supporting the view of pervasive change. The findings of chapter 2 also suggest that structural breaks were widespread to most industrial sectors of the British economy and were not localized in the cotton and iron industries. All in all, the claim that there were pervasive structural transformations in the British economy during the Industrial Revolution also seems to be well established. The question that remains is thus how to reconcile slow growth in per capita GDP with the pervasive transformations that occurred during the British Industrial Revolution.

This chapter contends that the emergence of modern growth during the Industrial Revolution is compatible with the existence of slow aggregate growth. In spite of sluggish growth, during the Industrial Revolution the British economy went through a series of structural transformations that forever changed its structure. In this context, the Industrial Revolution should be seen as an organizational revolution, originated by the development of an organizational general purpose technology (GPT): the factory system[42]. The co-existence of slow aggregate growth and pervasive technical change in the context of General Purpose Technologies (GPTs) has been previously analyzed by Lipsey and Bekar (1995), Bekar (1999), Lipsey, Bekar and Carlaw (1998) and by Lipsey (2002). These authors argue that the organizational changes in the Industrial Revolution were the culmination of centuries of incremental change in process technology. Based on this premise, the main contribution of this chapter is to analyze the diffusion of a specific organizational GPT in the context of the Industrial Revolution as well as survey the reasons for the slow transition to the factory system.

The chapter proceeds as follows. Section 2 reviews some of the common explanations for slow aggregate growth during the Industrial Revolution. This section also suggests that the introduction of the factory system contributed to more than 30 percent of per capita GDP growth between 1760 and 1860. However, the diffusion of the factory system was long and protracted. Section 3 argues that the slow diffusion of the factory system was not atypical. In general, the diffusion of technologies takes a considerable amount of time. The same can be argued for the diffusion of new organizational innovations, such as the factory. The section introduces a simple model of

[42] The term organizational GPT was introduced by Lipsey, Bekar and Carlaw (1998).

organizational diffusion, which shows that, within reasonable parameters, the slow diffusion of the factory system is more consistent with a multifaceted explanation rather than a sole overwhelming advantage of the factory (such as transaction costs) over the putting-out system. In addition, this section presents some descriptive estimates of the diffusion parameters for seven industries. Section 4 analyzes several reasons for the slow diffusion of the factory system, such as: a long process of social learning which eliminated organizational and technical uncertainties, a late "critical mass" effect, the behavior of interest groups, and the competitiveness of the putting-out system. The last section characterizes the Industrial Revolution as an organizational revolution and relates it to the emergence of modern economic growth.

2. GPTs and Slow Aggregate Growth

There are several common explanations for the existence of slow growth during the Industrial Revolution. In a classic article, Williamson (1984) argues that slow growth resulted from the crowding out of capital accumulation due to the French Wars. Nevertheless, although the French Wars certainly reduced the speed of capital accumulation, most evidence suggests that the ultimate reasons for the existence of slow growth are more related with the transition to a modern economy than with the war itself (Mokyr 1999, Harley 1999). Alternatively, Crafts and Harley (1992) and Mokyr (1999) argue that slow growth was the result of the dual nature of the British economy. During the Industrial Revolution a large "traditional" (low-productivity) sector coexisted with a small "dynamic" (high-productivity) sector. Since at the outset of the Industrial Revolution the cotton and iron industries had a small share in national output, their fast

productivity growth did not initially have a substantial impact on the rest of the economy, and hence growth was slow. In this view, growth accelerated only after the iron and cotton sectors attained a bigger share in the overall economy, which occurred only in the 19th century.

Another recent approach emphasizes the role of General Purpose Technologies (GPTs). The latter can be defined as drastic innovations that have "the potential for pervasive use in a wide range of sectors in ways that drastically change their modes of operation" (Helpman 1998, p. 3), which have several characteristics, such as: 1) scope for improvement, 2) wide variety and range of uses, and 3) strong complementarities with other technologies (Lipsey, Bekar and Carlaw 1998). Bekar (1999) claims that slow growth in the Industrial Revolution could be explained by a shift between GPTs, from water- to steam-based technologies. In spite of being radical innovations, the impact of new GPTs may not be felt immediately due to a variety of factors, such as slow diffusion due to technological inertia (David 1990), the development of new intermediate goods that require the diversion of resources from productive to research activities (Helpman and Trajtenberg 1998), large learning costs (Greenwood and Yorukoglu 1996), large-scale experimentation by start-up firms leading to high bankruptcy rates (Atkeson and Kehoe 1993), an acceleration of obsolescence rates of human and physical capital (Howitt 1998), and the existence of technological spillovers or social learning between firms (Aghion and Howitt 1998). Therefore, although GPTs may have a substantial impact on economic growth in the long run, the effect of a new GPT on output could be modest or even negative in the short run. In the context of the Industrial Revolution, Bekar (1999) argues that the introduction of the new GPTs led to substantial structural transformations (e.g. the factory layout), which needed time to materialize. All these transformations

required radical structural changes of the British economy, and hence growth was sluggish.

In spite of its theoretical appeal, Crafts (2001) has recently dismissed the importance of GPTs in the context of the Industrial Revolution. Based on a growth-accounting exercise, Crafts concluded that: 1) the Information and Communication Technology GPT has been substantially more important to growth than steam and electricity, and 2) the steam GPT had a very modest impact on GDP per capita growth until the arrival of the railways in the 1830s[43]. Although Crafts admits that more reliable measures of technological (or organizational) spillovers could potentially change the results on steam and electricity, this early assessment downplays the GPT interpretation as an explanation for slow aggregate growth in the Industrial Revolution.

Notwithstanding these findings, the GPT story remains pertinent in the context of the Industrial Revolution, since steam was not the only emerging GPT during that period. In fact, if we also take into account organizational GPTs such as the factory system, it is still plausible to argue that GPTs had a substantial impact. Indeed, one of the greatest novelties of the Industrial Revolution was the introduction of a new organizational GPT, the factory system[44]. The structural changes brought by the factory system became one of the defining features of the birth of modern economic growth. When growth accelerated after the 1830s, the factory system had already become a predominant organizational

[43] The ICT contribution to growth is estimated to be between 30.4 and 56.3 percent of GDP per person growth during the period 1974-2000. In comparison, the contribution of electricity to GDP per person growth was between 28 and 47 percent during the period 1899 and 1929. Steam contributed to about 3 percent of per person GDP growth during the period 1760-1830, and 23.6 percent from 1830 to 1860.

[44] Arguing that the factory system is a crucial GPT does not mean that steam and water were unimportant. These GPTs were all complementary to each other (Geharty 2003).

system. The rest of this section calculates the contribution of the factory system to growth in per capita GDP.

The Contribution of the Factory System

We can use Crafts's (2001) approach in order to estimate the contribution of the factory system to economic growth during the Industrial Revolution. Assuming constant returns to scale and perfect competition, we can use the shares in total output as a proxy for the shares in factory payments. Following Crafts (2001), Oliner and Sichel (2000), and Schreyer (2000), assume that growth in output (Y) is attributed to the contributions from factory capital (K_{FACT}), non-factory capital (K_0), labor hours (L), and total factor productivity (TFP):

$$\hat{Y} = \phi_L \hat{L} + \phi_{FACT} \hat{K}_{FACT} + \phi_0 \hat{K}_0 + \hat{A} \qquad (1)$$

where $\hat{Y} = \Delta Y/Y$, $\hat{L} = \Delta L/L$, $\hat{K} = \Delta K/K$, and $\hat{A} = \Delta A/A$. In addition, ϕ_L, ϕ_{FACT} and ϕ_0 are, respectively, the shares of the labor, the factory and the non-factory capital goods sector in national income. In per capita terms:

$$\hat{Y} - \hat{L} = \phi_{FACT}(\hat{K}_{FACT} - \hat{L}) + \phi_0(\hat{K}_0 - \hat{L}) + \hat{A} \qquad (2)$$

In addition, if there are any spillovers or positive externalities from the factory system, we have:

$$\hat{Y} = \phi_L \hat{L} + \phi_{FACT}(1+\rho)\hat{K}_{FACT} + \phi_0 \hat{K}_0 + \hat{A} \qquad (3)$$

where ρ denotes the impact of knowledge spillovers on output. In this formulation, the contribution of the new organizational GPT occurs due to growth in TFP[45], the production of new capital goods in the factories as well as possible knowledge spillovers from the factory system. Following Oliner and Sichel (2000), TFP can be further decomposed into an expression relating aggregate TFP growth to sectoral TFP growth. Let λ and π denote the gross output shares of the factory and non-factory sectors in total output. We can thus write aggregate TFP growth as a weighted average of TFP growth in the factory and non-factory sectors:

$$\hat{A} = \lambda \hat{A}_{FACT} + \pi \hat{A}_0 \qquad (4)$$

In the context of the Industrial Revolution, we can use (2) and (4) to estimate the contribution of the new organizational GPT to growth in GDP per capita. With that purpose, I collected data from several existing studies on the Industrial Revolution. Manufacturing capital stock growth is from Feinstein[46] (1988, p. 448). The income share is calculated from Feinstein (1988) and then multiplied by 0.35, which is the standard capital share in national income for the period (Crafts and Harley 1992, Harley 1999). Factory capital contribution is obtained by multiplying factory capital stock growth and the income share. In addition, manufacturing TFP growth is from Crafts (1985, p. 84).

[45] As Carlaw and Lipsey (2002) argue, total factor productivity is not a good measure of technical change. With this caveat in mind, I use these measures of TFP growth in order to reproduce Crafts's (2001) paper on GPTs, and hence to provide comparable figures for the factory system.

[46] I also used an alternative estimate of manufacturing capital stock growth from Crafts (1985, ch. 2). Crafts assumes that the capital-output ratio is constant during the period and that capital grew at the same rate as a Divisia industrial-output growth index. The rates of capital stock growth are then equal to the rates of the Crafts industrial output index. Using these lower estimates of manufacturing capital growth does not substantially reduce the estimated contribution of the factory in per capita GDP growth, which is then equal to 33% in 1760-1800, 24% in 1800-1830, and 34% in 1830-1860.

The share of factory output in total output is obtained by multiplying the share of industrial output in total output and the share of factory output in total industrial output. Industrial output shares are from Mitchell (1988) and from Deane and Cole (1962, p. 291). Based on Usher (1920) and Fong (1928), reasonable guess estimates for the share of the factory in total industrial output are 40% from 1760 to 1800, 65% from 1800 to 1830, and 80% from 1830 to 1860. Factory TFP contribution is obtained by multiplying factory TFP growth and the factory output share. Finally, the growth in GDP per capita is from Crafts and Harley (1992). Table 1 presents the results of the contribution of the factory system to per capita GDP growth.

Table 1 _ Total Factory Contribution to British per capita GDP growth, 1760-1830

	1760-1800	**1800-1830**	**1830-1860**
Factory capital stock growth	1.65	4.3	2.8
Income share (per cent)	2.4	3.25	4.9
Factory Capital Contribution	***0.0396***	***0.14***	***0.137***
Factory TFP growth	0.2	0.3	0.8
Output share	10	19.5	28
Factory TFP contribution	*0.02*	*0.0585*	*0.224*
Total Factory Contribution (as % GDP/Person growth)	**0.0596 (35%)**	**0.198 (38%)**	**0.361 (33%)**

As table 1 shows, between 1760 and 1800, the factory system contributed to 35 percent of per capita GDP growth. Between 1800 and 1830, the contribution of the new organizational GPT rose to around 38 percent of per capita GDP growth, declining slightly to 33 percent during the period between 1830 and 1860. These figures could be higher if there were spillovers associated with the diffusion of the factory system. In Crafts's (2001) paper, TFP growth spillovers account for 36% (in the period 1899-1929) and 71% (from 1919 to 1929) of the total electricity contribution to per capita GDP growth. I argue below that spillovers might have been important during the Industrial Revolution, especially concerning the social learning involved in the diffusion of the new

technological and organizational innovations. Accounting for these spillovers would certainly further increase the contribution of the new organizational GPT to British per capita growth. Nevertheless, since the existing studies have not yet found spillovers associated with the factory system, I do not take them into account in the calculations. Even without taking into account any spillovers, the contribution of the factory system is certainly comparable to that obtained by Crafts (2001) for the steam and electricity GPTs, such as electricity and the information and communication technologies. Therefore, although steam might have not contributed much to British growth before the introduction of the railways, another GPT (the factory system) was an important engine of growth during the Industrial Revolution, as argued by Mantoux (1927) and Fong (1928). Consequently, in order to understand why GDP growth was slow during the period, we need to analyze the causes of the long diffusion of the factory system.

3. Organizational Diffusion in the Industrial Revolution

The gradual acceleration of productivity growth was intimately related to the slow diffusion of the factory system. Until late in the industrialization process, much of production was still done in the traditional organizational system, the cottage industry. This is true even in the "modern" sectors. In 1841, more than 30 percent of all workers employed in the cotton industry were outside the factory system. By 1871, this number had fallen to 12 percent. In the metal trades, by 1841, 65 percent of the workers were not employed in factories. In contrast, in 1871, only 25 percent of the workforce in the metal trades was outside the factory system. Some other industries and professions, such as cloth producers, tailors, and shoemakers, had made little progress until 1871 (Usher 1920, p. 362). By 1901, the British Census of Population reveals that in the textiles sector only

2 percent of the workforce was outside the factory system, whereas in the remaining industrial sectors less than 10 percent of their labor force was outside the factory system. In short, the diffusion of the factory system was a long-drawn-out process, since even in the "modern" sectors it took more than 100 years for the factory to become the predominant organizational system. However, the diffusion pattern of the new technologies associated with the Industrial Revolution factory is not at all atypical. In general, the diffusion of new technologies takes a considerable period of time[47]. Organizational innovations (such as the factory system) are also subject to the same protracted process of diffusion. This section presents a model of organizational diffusion of the same variety of models of technological diffusion as described by Mansfield (1968, 1989) and by Karshenas and Stoneman (1995). The model summarizes some of the reasons for the long-drawn-out diffusion of the factory system.

Assume that at time t there are J firms deciding where to produce, which can be done either at "Home" (the cottage industry) or in a centralized place called "Factory". Suppose that initially (at t_0) all J firms produce under the putting out system, and that new machinery is developed, which augments the payoffs of factories. At time t, suppose that $k < J$ firms decide to invest in factories. Assume that the proportion of firms that decide to remain producing in the cottage industry (and hence do not adapt the new organizational innovation) depends on the proportion of firms that have already invested in factories, the relative profitability of factories, the fixed cost required to build a new factory, and the extent of "technological conservatism" in the economy. That is:

[47] As Karshenas and Stoneman (1995, p. 265) emphasize: "Whether it be a new consumer technology spreading across households or a new producer (process) technology spreading across firms it would not be unusual for the time period between first use of a technology and say 90 per cent usage of that technology to take several decades rather than several years."

$$\lambda_{jt}(t) = f_j(m_t/J, \Pi_{jF}/\Pi_{jH}, K_j, G) \quad (5)$$

where λ_{jt} (t) is the proportion of firms that adopt the new organizational innovation (the factory) between time t and t+1; m_t/J is the proportion of potential adopters that have invested in new factories at time t; Π_{jF} and Π_{jH} represent, respectively, the profitability of factories and home production, so that Π_{jF}/Π_{jH} is the relative profitability of factories (which depends on several variables such as relative productivity); K_j is the investment required to build a new factory; and G is a parameter that reflects the power of vested interests. Taking a Taylor's series expansion of (5), and dropping the third and higher order terms for relative profitability (Π_F/Π_H), K_i, and G, and second and higher order terms for (m_t/j)[48], (5) can be re-written as a differential equation:

$$dm_t = \beta\,(m_t/j)\,(j - m_t)\,dt \quad (6)$$

Solving (6) yields a logistic curve:

$$\frac{m_t}{j} = \frac{1}{1+e^{-(\theta+\beta t)}} \quad (7)$$

where θ is the constant of integration. Assume further that the rate of diffusion (or imitation) of the factory depends positively on the relative profitability term, negatively on the amount of investment required, and negatively on the relative force of vested interests. That is:

$$\beta = \alpha_1 + \alpha_2\,(\Pi_{jF}/\Pi_{jH}) + \alpha_3\,K_i + \alpha_4\,G + \varepsilon_t \quad (8)$$

where ε_t is a random error term with zero mean, $0 < \Pi_{iF}/\Pi_{iH} < 1$, $0 < K_j < 1$, $0 < G < 1$, $\partial\beta/\partial(\Pi_F/\Pi_H) > 0$, $\partial\beta/\partial K_i < 0$, and $\partial\beta/\partial G < 0$. From (7) and (8), we can see that, just like a

[48] The literature on technological diffusion shows that the coefficient $(m_t/j)^2$ is close to zero (Mansfield 1968).

typical GPT, the diffusion of the factory system follows a logistic curve. The exact shape and slope of this logistic curve depends on the individual parameters. Ideally, we would like to obtain data on each of the variables of equation (8), and then estimate the α_i coefficients. However, since we do not have data for these variables for the period associated with the Industrial Revolution, some simulations and numerical solutions are needed in order to model the diffusion of the factory system. Figures 1 and 2 summarize the results of the numerical solutions for different constants of integration. As these figures show, the higher the constant of integration the faster is the transition to the factory system. In figure 1, if $\theta = 7$ and $\beta = 1$, the rate of imitation is high early in the diffusion process, and the transition is completed in less than 50 years. In contrast, if $\theta = 1$ the transition is slower, and the values of β determine the timing of the acceleration of the imitation rate. In this context, suppose, for instance, that factories had an overwhelming advantage vis-à-vis the putting-out system, such as Williamson's (1980) transaction costs hypothesis suggests. That is, assume that factories are intrinsically more efficient than the putting out for a given technology. Then, the productivity parameter will be rather large and β will be fairly high. Suppose that the parameters are such that β is equal to unity or higher. As we can see in Figures 1 and 2, if factories were overwhelmingly more efficient, then the transition from the cottage industry to factories would have been very swift. For instance, when $\beta = 1$, after one entrepreneur chooses to invest in a factory, the rate of imitation increases very rapidly, and in less than a decade the vast majority of firms is producing in a factory. If the constant of integration is bigger or if $\beta > 1$, then the transition is even swifter. Thus, on its own, a sole overwhelming advantage such as low transaction costs cannot in this model explain adequately the slow

diffusion of the factory system, which is consistent with the findings of Jones (1982), Mokyr (2002), and Szostak (1989).

Figure 1 _ Diffusion of Factory System, θ = 1

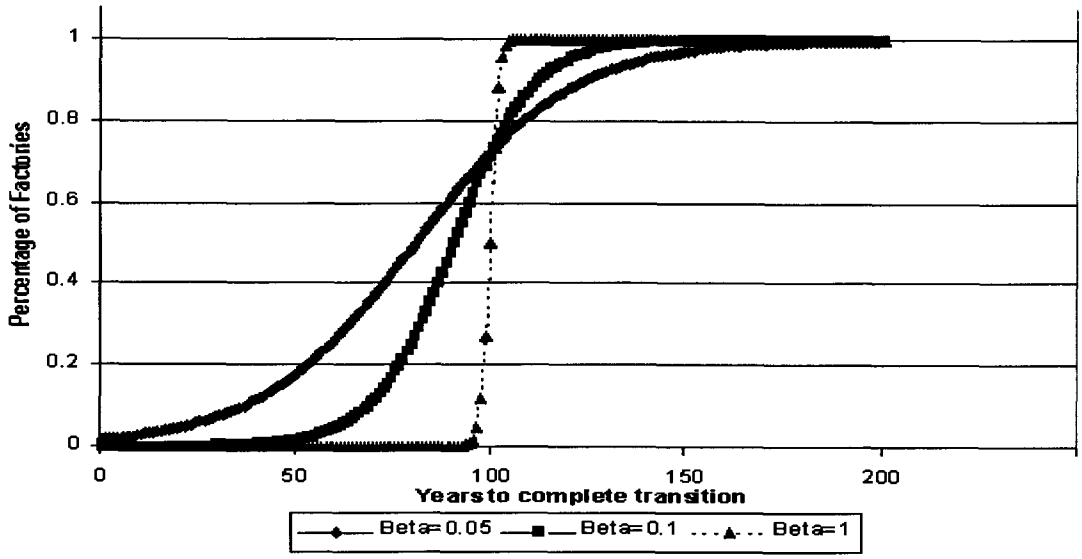
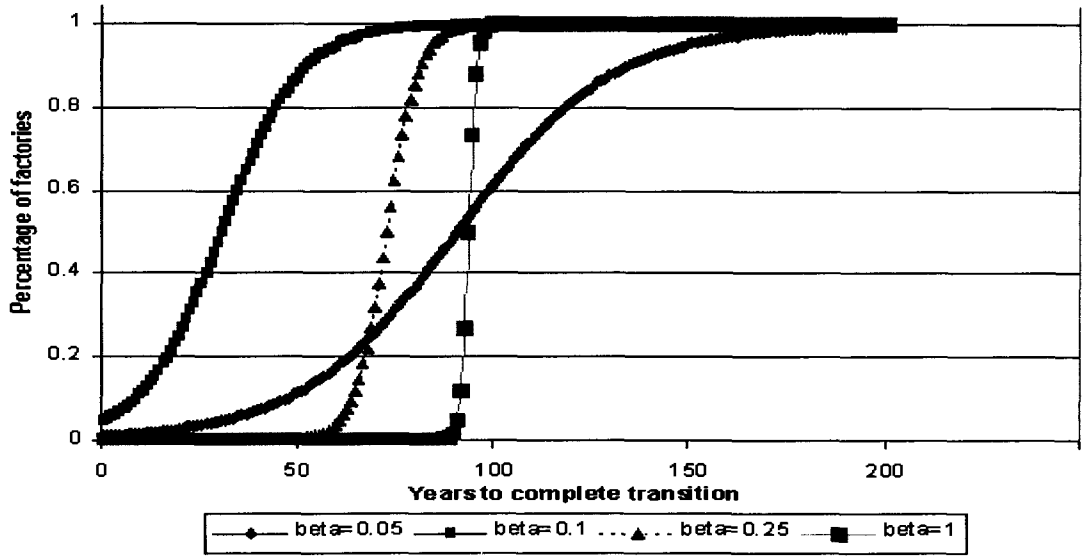


Figure 2 _ Diffusion of Factory System, θ = 7



On the other hand, if factories have very high overhead costs (as Fong (1928) argues), then β will be smaller. Consequently, the rate of imitation will be lower, and hence transition will be much slower. The same result occurs if antagonistic interest groups are powerful, diminishing the value of β. For example, if $\beta = 0.05$, the transition will be smooth, but it will take more than 150 years to be completed.

The simulation results for different constants of integration and distinct values of β thus suggest that the slow transition to the factory system is better explained by a combination of factors, and not by a single outstanding organizational advantage. First, it is likely that the productivity parameter was rising over time. In the early Industrial Revolution, for the average entrepreneur, the relative profitability of the factories was low due both to the competitiveness of the putting out and to the technical problems associated with some of the new technologies (Berg 1994). Gradually the technical problems were solved and efficiency increased, and hence the relative profitability of factories rose with time. Second, the transition to the factory system was somewhat delayed by the existence of vested interest in several sectors. However, as section 4 argues, these interest groups only achieved temporary victories and their impact was not substantial. Consequently, the parameter on the relative importance of interest groups should not very high, and was likely decreasing over time. Finally, for entrepreneurs, overhead costs were an important consideration on whether or not to invest in a factory, especially due to the scarcity of funds in the early Industrial Revolution (Crouzet 1985, Mokyr 1999). The development of the formal credit markets in the 19th century reduced this financial bottleneck, and industrial financing became more readily available. On the

other hand, social learning and the increasing rate of imitation decreased the importance of the overhead costs for investment in factories.

Based on the evidence on the long transition to the factory system, it is probable that the diffusion of the new organizational GPT is better captured by values of β that are in the interval [0.01, 0.4]. For these values of β, the transition to the factory system is relatively smooth but prolonged, extending for a period between 110 and 150 years, which confirms the long trajectory of mechanization that intensified in the Industrial Revolution. The lack of high-frequency data and the small number of industries available make difficult the estimation of equations (7) and (8). Ideally, in order to estimate (8), we would have to have a set of characteristics, such as firm size, the relative profitability of factories, the investment required to build a new factory, and the power of vested interests. Unfortunately, we do not have these data for the period associated with the Industrial Revolution, and hence it is not possible to estimate the structural parameters of equation (8). Nevertheless, it is possible to estimate equation (7). Usher (1920) and Fong (1928) provide some low-frequency data for several industries, such as clothing, cotton, metal trades, silk, leather, and wool, although for most industries we only have very few observations (six for the majority of series). For these series, we have 30-year averages on the relative importance of the factory system in total industry output from 1750 to 1901. For these industries, the results below should be seen mainly as a descriptive exercise, and not as an estimation of the structural parameters. We have better data for mechanical weaving reported by Mitchell (1988). From the Mitchell data we can calculate the annual percentage of factories in industry output from 1806 to 1863 (the year when the total

weaving production was 100 percent factory-made). From 1791[49] to 1806, I extrapolated the increase in factory production from the trend. The results of the estimation did not change significantly by restricting the sample from 1806 to 1863. Table 2 reports the results of the estimation of equation (7) in these six industries[50].

Table 2 _ Diffusion of factory system in selected industries

	θ	β
Mechanical Weaving	-2.370** (0.1183)	0.0643
Mechanical Weaving (1806-1863)	-2.568** (0.158)	0.068
Clothing	-8.756** (1.799)	0.0524
Cotton	-3.605** (0.799)	0.045
Metal	-5.977** (0.525)	0.0458
Silk	-6.201** (1.125)	0.0479
Wool	-7.074** (0.812)	0.0576

As we can see from table 2, the β coefficients are in the [0.01, 0.4] interval, which is consistent with the simulation results as well as with the view factories did not have an overwhelming organizational advantage over the domestic industry. For these parameters, the diffusion of the factory system is long and protracted. In addition, the lowest θ belong to the industries (clothing and wool) in which there was a longer transition to the factory system.

[49] 1791 was the year of the introduction of the second Cartwright power weaving factory. The first 1785 factory was burned down by weavers.

[50] Since all series except mechanical weaving are 30-year averages, whereas the simulation results are based on annual observations, the third column of table 2 reports β adjusted by the number of years.

All in all, this descriptive exercise suggests that, for reasonable parameters estimates, the results of the model are not consistent with the view that the rise of the factory system was caused by a single overwhelming advantage, such as lower transaction costs. Rather, the diffusion of the factory depended on the interaction of several factors, which impeded a swifter transition of the factory system. The next section discusses the main factors that retarded the diffusion of the new organizational GPT.

4. The Slow Diffusion of the Factory System

This section surveys the main causes of the lengthy transition to the factory system, which include: 1) the competitiveness of the putting-out system, 2) the low margin of efficiency of the new factories over the cottage industry, 3) the behavior of interest groups, 4) social learning and organizational spillovers, and 5) a late "critical mass" effect. All these factors interacted with each other, and contributed for a protracted diffusion of the factory system.

Competitiveness of the Cottage Industry

The cottage industry thrived in the centuries that preceded the Industrial Revolution. Between the 15th and the 18th centuries, the putting-out system was the main engine of the textile industry, especially in the woolen and worsted sectors (Milward 1981, p. 22). The putting out then developed into other branches of textiles and other industries such as leather goods and small metal wares, and by the mid-18th century it was an important component of most industries. Due to their sophistication and complexity, on the eve of

the Industrial Revolution the organization of many putting-out networks closely resembled the structure of modern firms (Milward 1981, p. 37), enabling the mass production of several products (Mokyr 1990, p. 77). By the end of the 18th century, several factors made the cottage industry an extraordinary competitor for the early factories. First, low wages in the cottage industry temporarily compensated for the higher efficiency of the new machines in the factories. In order to remain competitive, the early textile factories also opted for a policy of low wages, especially by hiring women and children, since their wages were substantially lower than those offered to adult males[51]. Second, the new putting-out networks were highly adaptable to new circumstances and competitive environments (Jones 1982). The 19th century putting-out networks not only were much more capitalistic and competitive than their 18th century counterparts, but also achieved some productivity improvements due to their sophisticated division of labor (Berg 1994, Huberman 1996). The putting-out networks were also preferred due to their low overhead costs (Fong 1928). This was an important factor because self-finance and an informal capital market were the main sources of funds during the early Industrial Revolution (Crouzet 1985, Mokyr 1999).

In spite of these advantages, the cottage industry was plagued by a variety of factors, such as high transport costs, chronic problems of product flows, and embezzlement (Williamson 1980, Jones 1982). More importantly, the structure of the putting out did not allow the standardization of products (Szostak 1989) or the existence

[51] Hiring women had several advantages for the early textile factories. This was especially true in spinning, because traditionally it was an occupation for women. For surveys on the role of women see, for example, Horrel and Humphries (1995), Berg (1994) or Pinchbeck's (1930) classic book.

of significant economies of scale. In the long run, all these factors hampered the competitiveness of the cottage industry.

Since the centralization of operations in many sectors preceded the innovations and mechanization of the late 18th century, Oliver Williamson (1980) argued that factories were increasingly favored due to their lower transaction costs relative to the cottage industry. According to Williamson, for a given technology, the factory system was innately superior to the putting out. However, as critics emphasized (Jones 1982, Mokyr 2002, Szostak 1989), by itself a simple transaction costs approach cannot explain the longevity and competitiveness of the putting-out system. In contrast, Landes (1969) and Mokyr (2002) argue that the new technologies of the Industrial Revolution could be better exploited in a factory than in the putting out, allowing for an increase in the minimum scale of operations, bigger economies of scale and faster productivity growth. In the longer term, these advantages became crucial in reaping the benefits of an increasingly integrated internal market enabled by institutional advancements and by vastly improved transportation networks (Szostak 1991). Factories also permitted the supervision of workers, improving the quality and uniformity of products, and enabling a higher discipline of the workforce[52] (Landes 1986).

Finally, factories might have emerged in the late 18th century also as a response to a widening of the knowledge base of the techniques during the Industrial Revolution, which no longer could be dealt with efficiently by the household (Mokyr 2002). Consequently, specialization became inevitable. In contrast to the household, the factory allowed for

[52] Marglin (1974) contends that factory discipline coerced more effort from workers, whereas Clark (1994) argued that factory discipline was important, because workers lacked self-control. In this view, workers hired capitalists in order to accomplish higher earnings. These arguments have been largely refuted by Landes (1986) and Mokyr (2002).

distinct individuals with different information sets to be gathered into the same economic unit, reducing access costs to the increasing knowledge pool. Furthermore, the factory facilitated spatial and temporal exchange of information between workers and a variety of experts, from engineers to mechanics. Thus, the huge increase in the epistemic base of technology during the Industrial Revolution made factories increasingly more attractive, and gradually entrepreneurs opted to centralize their operations rather than spreading production over to extensive networks of households (Mokyr 2002).

All in all, it is likely that technological and organizational innovations were two sides of the same coin. In a recent paper, Tom Geharty (2003) argued that the adoption of the new machines, the establishment of centralized organization, and measures to improve quality control were all mutually complementary activities. In this sense, engaging in the centralization of operations increased the marginal returns of introducing new machinery, and vice-versa. That is, not only factories encouraged technological innovation, but also new large-scale powered machinery in turn fomented (and often required) the increasing use of factories. In this sense, as argued in section 5, the mutual reinforcement between factory and technology one of the crucial elements of the emergence of modern economic growth.

Technical glitches and the slow adoption of new energy sources

Most new technologies of the Industrial Revolution were very crude at the time of their inception, and it took some time for them to become fully operational and productive. Furthermore, there were many technical difficulties associated with the development of some technologies, which prevented their earlier diffusion in many industries. The initial low efficiency of the new technologies was slowly improved during

a period highly intensive in learning by doing and learning by using. After inventors, technicians and factory workers solved these initial technical and efficiency problems, the productivity of the sectors associated with the new technologies rapidly increased[53].

These technical difficulties had to be solved before mechanization could be introduced and the advantages associated with the factory could be fully exploited. Therefore, in many instances, the diffusion of machinery (and the factory) depended on how well and how swiftly inventors and technicians unraveled these problems in particular sectors. For example, many of the new machines were initially much more suitable to cotton than to other fibers. Cotton was easier to manipulate, its fiber was more flexible and more resistant than linen, worsted or wool. Therefore, the introduction of mechanized spinning was technically easier in cotton than in other industries (Berg 1994). Power weaving was also plagued by several technical problems for many decades, delaying the hegemony of the factory system in the weaving sector. Initially, power looms were expensive to run, notoriously prone to break down, and their output was of poor quality. Consequently, the handloom weavers remained competitive by lowering their real wages and by pursuing a policy of product diversification and differentiation. They maintained a market niche in the fine muslin trade, and rivaled the new machines in the markets for plain and coarse goods (Berg 1994, p. 245). Nevertheless, from the second decade of the 19th century onwards, the technical problems of the power loom were gradually solved, the quality of their output increased, and productivity accelerated relentlessly: between 1819 and 1842, the power loom enabled the number of picks per

[53] The diffusion of the new technologies and the new organizational method (the factory) is thus similar to the logistic-shaped efficiency curve typical of most GPTs described in a forthcoming book by Bekar, Carlaw and Lipsey.

minute to increase 133 percent. Sparked by the competition, the handloom weavers fought back, and by 1840 their productivity increased between 25 and 30 percent (Berg 1994). However, the unabated competition of the factories and the ever-increasing productivity of the power loom implied that this productivity increase of the handloom weavers was not translated into wage increases. In stark contrast, in order to remain competitive, weavers saw their wages fall rapidly and many abandoned their handlooms.

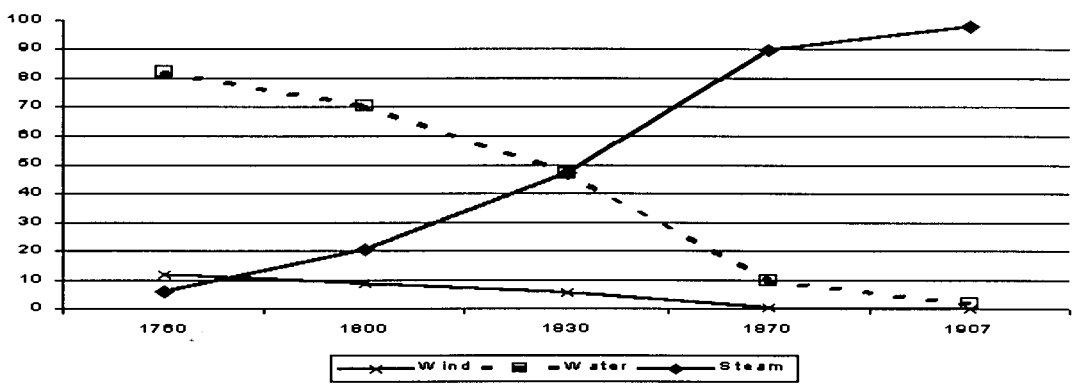
In addition, some technologies were more suited than others to the emerging organizational structures. Many technologies were not originally designed to be operated in the factories. For instance, the spinning jenny was initially intended to work in small-scale environments typically associated with the cottage industry. The introduction of the spinning jenny did not lead to a major redesign of work practices or the layout of the buildings where it was operated (Mantoux 1927), and hence it was found in both the putting-out system and the factory. In contrast, both Crompton's mule and Arkwright's water frame enabled a substantial increase in the scale of operations, enhancing the advantages of factories[54].

Furthermore, the transition to the new energy sources was slow. Human, animal and wind power were the principal sources of energy in the proto-factories, early factories and in the cottage industry. The water frame and the mule gradually changed this state of affairs. In a later stage, steam power released the early factories from the location shackles intrinsic to waterpower, and further increased the minimum scale of operations. However, the transition to water- and steam-powered economy was gradual.

[54] The water frame was originally designed by Arkwright to be also used in the cottage industry, but soon it was mostly used in factories.

As figure 3 shows, the diffusion of steam followed a logistic curve typical of the diffusion of new technologies. At the end of the 18th century, waterpower was the hegemonic source of inanimate power in the British economy, with steam in a distance second place. Gradually, steam power gained importance during the first decades of the 19th century, and by 1830 water and steam both accounted for about 47 percent of all power utilized in Britain (Kanefsky 1979).

Figure 3 _ Motive Power 1760-1907



Source: Kanefsky (1979) cited in Hills (1989)

The slow application of steam to the factory floor can also be explained by numerous technical problems as well as by the cost advantages of the waterwheels: wheels were cheap, lasted a long time, and saved on labor and on coal. In the longer term, steam power would eventually become the dominant source of energy in the factory system due to larger economies of scale and less location constraints. Nevertheless, until the economies of scale associated with steam were fully realized and the capital invested in water-powered factories had worn out, waterpower remained a strong competitor. Furthermore, waterpower inaugurated large-scale factory organization (von Tuzelman

1978). Even if steam had not been introduced, both the factory system and the factory layout would have been developed, since the main organizational changes and the design of the new factories occurred chiefly during the emergence of the water-powered technologies. As Mantoux (1927, p. 251) has put it:

> It was during this decisive period [when the water frame was introduced] that the main lines of the factory system were laid down. By the time when... steam came into general use the factory system was fully grown, and it was altered by this new invention very much less than we might be led to suppose.

Nevertheless, without steam (or water) power, not only the transition to the factory system would have been longer, but also output and productivity growth would have been slower in the first half of the 19th century.

All in all, the modest productivity increases achieved by the cottage industry, conjugated with the decline in real wages of the putting-out workers, provided an extra breath of fresh air to the putting-out system, which led some entrepreneurs to retard their investment in factories. Nevertheless, after the technical difficulties with the new technologies were solved, the rise of the factory system proceeded unabated.

Interest groups

It is a well-known fact that, in the short run, technological progress has winners and losers. Whenever the losers from technical change belong to well-organized interest groups, they can react against competing innovations, retarding or even stifling their diffusion (Mokyr 1992, 2002). During the Industrial Revolution, three types of interest groups played a role in slowing down the diffusion of the new machinery and organizations: 1) the 'old economy' sectors, such as the woolen industry, 2) people that

appropriated rents from previous technological advances, such as the handloom weavers, and 3) workers affected or concerned with technological unemployment.

The reaction of the 'old' economy: the woolen industry

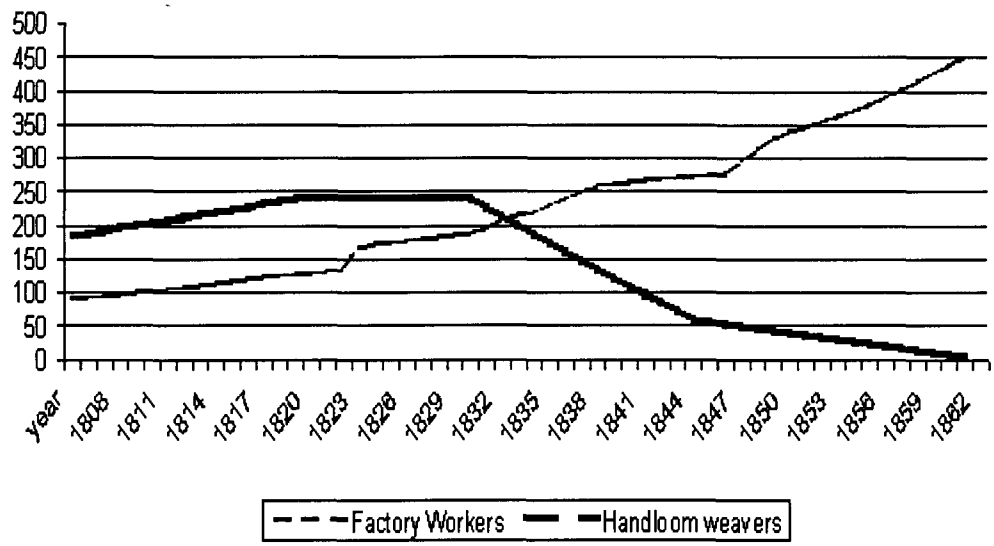
By the late 17th century, cotton-printed cloth imported from India (known as calicoes) became so demanded that it began to be regarded as a serious competitor by the woolen industry. The latter was Britain's oldest and most influential industry, but was also dominated by conservative forces that fought fiercely against any competitor that would disrupt the *status quo* of the industry (Mantoux 1927, p. 86). After several petitions to the Parliament, publications of pamphlets, and many demonstrations of discontentment, the vested interests of the woolen industry obtained a temporary victory against the importation of Indian calicoes, which was strictly forbidden by two Acts of Prohibition in 1712 and 1721. However, loopholes in the Acts exempted the printing of fustians (a mixture of cotton and linen) and allowed the printing of calicoes to be exported (Chapman 1967, pp. 12-13). Organized mainly around the cottage industry, the British fustian industry flourished in the following decades, and later formed the basis upon which the success of the cotton industry was erected. Thus, the interest groups that had lobbied against the competition from the infant cotton industry unintentionally sheltered the latter against foreign competitors and helped it survive and grow.

Technological Bottlenecks: The rise and fall of the handloom weavers

During the Industrial Revolution, technological bottlenecks and vested interest were often related. In this context, the rise and fall of the handloom weavers provides a prime example of the linkages between technological bottlenecks and the creation of interests

groups. Figure 4 illustrates the market for handloom weavers during the period between 1750 and 1830. Suppose that, in 1750, there were L_{1750} handloom weavers that earned a real wage of $(W/P)_{1750}$. By most accounts this real wage was quite low, since at the time there was a surplus of weavers relatively to the amount of thread available. By the 1770s, the huge increase in the supply of yarn enabled by the introduction of Arkwright's water frame and Crompton's mule changed this picture noticeably. Since the weavers could not respond to the tremendous increase in yarn, mechanical spinning created a bottleneck in weaving, which raised the demand for handloom weavers to L^d_{1780}. The wages of the handloom weavers rose so dramatically that "they gave themselves great airs, and could be seen parading about the streets, swinging their canes and with £5 notes ostentatiously stuck in their hatbands." (Mantoux 1927, pp. 238-239).

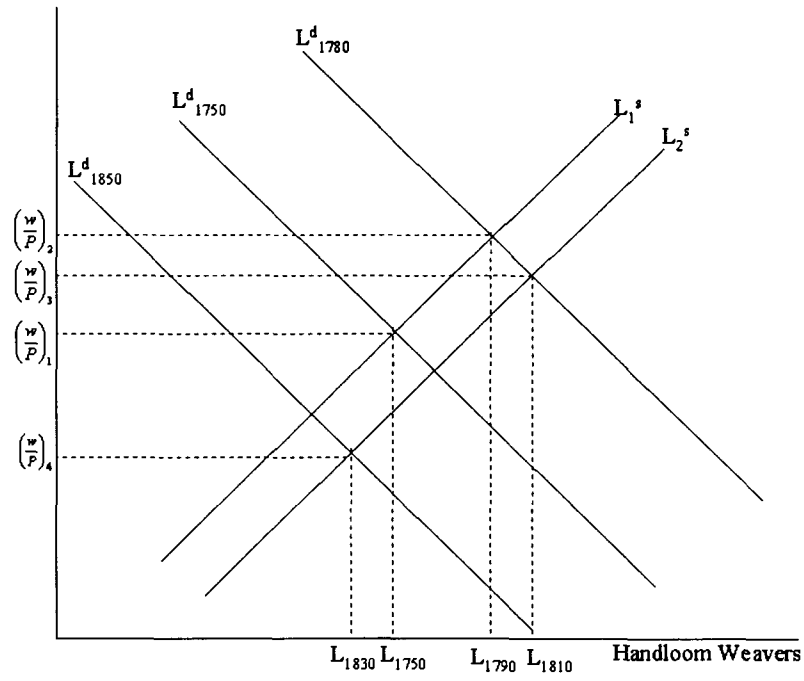
Figure 4_ Weaving Factory Workers and Handloom Weavers (1800-1865)



Source: Mitchell 1988

The infant cotton industry responded to the high wages of the weavers and the huge demand for cotton products by expanding to the countryside, attracting many small farmers, agricultural laborers and immigrants. For some time, the supply of handloom weavers expanded: by 1799 there were about 108 thousand handloom weavers, by 1806 there were 184 thousand, whereas by 1824 there were already 240 thousand handloom weavers (Figure 5). However, the happy times did not last. Their change of fortunes occurred after the invention of the power loom in 1785 by Edwin Carwright. Fearing the competition from the new machines, the handloom weavers tried to prevent the diffusion of the power loom by burning down Cartwright's power weaving factories in 1787 and in 1791. Other riots and demonstrations broke out in the following years. Although Cartwright went bankrupt and the weavers' opposition did not abate, the movement towards power weaving was already inexorable. In the following decades, several weaving factories were set up throughout Britain. The number of power looms increased steadily from 2,400 in 1803, to around 14,650 in 1820, 55,500 in 1829, and more than 100,000 in 1833 (Hill 1989, p. 117). The gradual adoption of mechanical weaving led to a decrease in the labor demand for handloom weavers. Consequently, the real wages of the handloom weavers fell sharply in the following decades to a level lower than that in 1750, i.e. $(W/P)_{1830} < (W/P)_{1750}$. From the 1830s onwards, the number of weavers steadily declined, as factories became more efficient and the putting out lost competitiveness. By 1840, the times of £5 notes in hatbands were only a distant memory for the handloom weavers and most of them lived in poverty.

Figure 5_ Market for Handloom Weavers



In sum, after benefiting from the technological gains of mechanical spinning, the handloom weavers became the victims of another technological innovation that substituted for their work. Although the weavers achieved sporadic successes against the diffusion of the power loom, the movement towards the factory system was already relentless.

Technological unemployment

Fear of technological unemployment was a major cause of the resistance against the new machines and the diffusion of the factory system. In her study of the British patent system, Christine Macleod (1988) shows that the prevailing view during the 17th century was unfavorable to technical change, because it was feared that labor-saving innovations encouraged unemployment and exacerbated the existing social tensions. By the 18th

century, the increasingly popular scientific mentality and culture led many moral philosophers to defend industrial development and technical change. Still, the general public "outside the Royal Society's idealist orbit" was still mostly overtly against the introduction of new machinery (MacLeod 1988, p. 202). Industrialists were certainly aware of this generalized sentiment against technical change, since the great majority of patentees in the 18th century refer the saving of labor as an advantage of the new invention[55] (MacLeod 1998). For an entrepreneur, the threat of riots and other disturbances against his factories was always very much present, as attested by the Luddite movement and by the hundreds of workers' revolts in the early 19th century. However, the threat of technological unemployment was not an overwhelming obstacle to the diffusion of the factory system. At best, these vested interests achieved some sporadic success against individual entrepreneurs. However, their victory was merely temporary. Whenever riots broke out, machines were destroyed or factories burned down, the same entrepreneur or other would-be industrialists would usually build another factory somewhere else. At the end of the day, in an era of mounting technological dynamism, the forces of technological inertia were not strong enough to prevent the diffusion of the factory system.

Social Learning

The Industrial Revolution was not only a period of sweeping technological and organizational changes, but also an epoch of great experimentation. New sectors were

[55] The fear of reprisals from workers was probably the main reason for inventors to emphasize the capital-saving and the creation-of-employment nature of their inventions, rather than a genuine belief that their inventions were not labor-saving.

created (e.g. chlorine bleaching, gas lighting), others profoundly transformed (e.g. cotton), and others reformed (e.g. woolen and worsteds). The extraordinary structural change of this organizational revolution meant that many economic agents had to learn their new or changed roles in a markedly different economic environment.

Of all those involved, workers were probably the most affected by the arrival of factories. There are several accounts of the difficulty of workers in adapting to the discipline of the factory (Berg 1994, Clark 1994, Fong 1928, Mantoux 1927). In the pre-industrial world, work was known to be notoriously irregular. Working hours were very uneven during the week, and work was often seasonal according to the harvest periods. In stark contrast, the factory and the diffusion of the clock profoundly altered these work practices. Factory work involved regular (and long) work shifts, imposing strict time restrictions that workers were not accustomed to in the cottage industry. Hence, during the early decades of the factory system, many workers demonstrated against the tyranny of factory time (Fong 1928). Slowly, workers had to learn to adjust to the new impositions of factory life by changing long-established daily routines and work habits. Furthermore, workers had to get used to being supervised. In the artisan system, work was typically organized on a family basis, whereas in the cottage industry workers and managers did not share the workplace. Therefore, it was not feasible for the merchant-capitalist to closely supervise his (sometimes, hundreds of) outworkers. In contrast, factory workers were subject to close scrutiny of their work, which caused many conflicts between managers and workers (Fong 1928, Landes 1986). Problems of adverse selection and moral hazard had to be slowly solved by the social interactions of workers and managers in the new workplaces. This was achieved by a process of trial and error that persisted for several decades.

Social learning was also important for the development of industrial entrepreneurship, since the early industrial entrepreneurs had to create and learn many of the tasks that came to characterize industrial capitalism. Before the late 18th century, manufacturing was "industry without industrialists" (Crouzet 1985, p. 4). Industrial management and entrepreneurship had to be developed and refined, slowly diffusing with the factory system. In this context, technological and organizational spillovers as well as "collective invention" *a la* Allen (1983) were neither confined to the iron industry nor to technical advancements. Indeed, collective invention was very important for the development of industrial management and entrepreneurship. Most industrialists had a thriving correspondence with many of their colleagues, as well as with several engineers and technical experts (Mantoux 1927). The knowledge on the new technology as well as many engineering skills were also often shared and diffused in the numerous public lectures and workshops organized throughout Britain by institutions such as the Royal Society of London (Jacob 1997). This dissemination of knowledge among potential industrialists was crucial for the diffusion not only of the new machines but also of the factory system. Entrepreneurs learned with one another how to make their factories more efficient and/or how to design the optimal minimum scale of operations for their firms. All this collective invention led to many organizational spillovers in the diffusion of the factory system. In turn, these organizational (and technological) spillovers enabled substantial social savings that are not captured by the official statistics[56]. Social learning is crucial whenever there are technological advances because: "The way that a firm typically learns to use a new technology is not to discover everything on its own but to

[56] These spillovers could entail a further increase of the contribution of the factory to GDP growth.

learn from the experience of other firms in a similar situation, namely other firms for whom the problems that must be solved before the new technology can successfully be implemented bear enough resemblance to the problems that must be solved in this firm" (Aghion and Howitt 1998, p.129). The same process of knowledge propagation and organizational imitation occurred during the Industrial Revolution, and was one of the crucial developments of the organizational revolution.

In addition, social learning was also an important component in the development of other features of industrial management. New accounting methods and procedures had to be developed and implemented. Industrialists and the new figure of the manager had to learn how to find the minimum scale of operations of their firms, how to increase profits, cut costs, and how to organize production in the most efficient way (Pollard 1965). For pioneers such as Lombe, Arkwright or Cartwright, trivial questions (e.g. how many machines to employ in the new factory? How big should the factory building be?) were often the most critical ones. Misjudging or miscalculating the optimal scale of the new factory would be an almost certain route to failure and bankruptcy, no matter how important their particular innovation was (as attested by the failing endeavors of inventors such as John Kay, Wyatt and Cartwright).

All in all, a grand process of social learning accompanied the deep structural changes brought by the technological and organizational developments of the Industrial Revolution. Social learning and knowledge sharing allowed for a substantial increase in the relative profitability of factories over the putting out. However, social learning is a necessary but highly time-consuming activity. Hence, both the technological and organizational transformations needed time to become fully operational, prolonging the transition to the factory system and retarding the acceleration of productivity.

Critical Mass and the rate of imitation

Early examples of proto-factories were not totally uncommon before the Industrial Revolution in sectors as diverse as iron smelting, mining, silk throwing, and the pottery industry (Mendels 1972). Still, these were punctuated examples of centralization amidst the predominant mode of production, the putting-out system. Indeed, industrial success was a phenomenon that started mostly after the Industrial Revolution, since most proto-factories (especially the large ones) did not survive for considerable periods of time (Crouzet 1985), and most of them did not employ mechanical machines (Landes 1986). Nevertheless, the existence of proto-industrialization shows that there was a long trajectory of mechanization stretching back to earlier decades and, in some case, centuries (Mendels 1972, Bekar and Lipsey 2001). The difference between the period of proto-industrialization and the Industrial Revolution was that the new technologies accelerated the transition to the factory by enhancing the advantages of the factory with respect to home production and the artisan system. After the early industrialists such as Arkwright and Watt obtained spectacular profits with the new factories, an increase in the imitation rate ensued and factories of all sizes sprung everywhere[57]. However, this increase in the rate of imitation was only achieved after many technological and organizational uncertainties were solved. As Rosenberg (1996) argues, pervasive uncertainties are often the norm in the development of new technologies. As we saw above, during the Industrial Revolution several technical problems complicated an entrepreneur's decision of whether or not to invest in the new technologies. However, these problems were compounded by

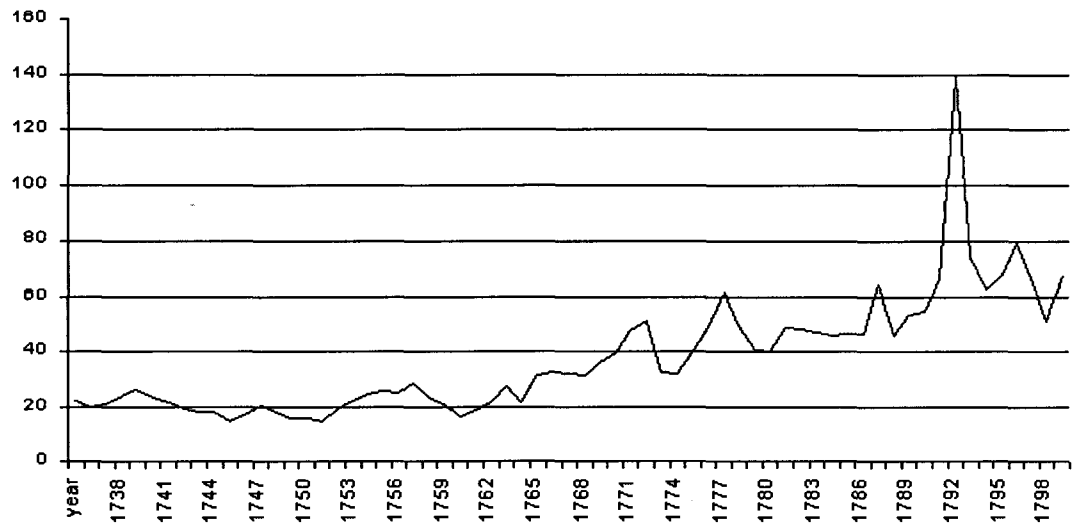
[57] In the short run, the "gold fever" in the cotton industry also benefited many putting-out networks, which increased in size and in complexity (Huberman 1996).

the widespread uncertainties intrinsic to the diffusion of the new organizational methods. Investing in a new factory was an expensive and risky business in which there was a wide probability distribution of outcomes. Pervasive organizational uncertainties implied that this probability distribution was likely skewed towards the lower end of the distribution of outcomes, as attested by the relatively high number of bankruptcies during the early Industrial Revolution as well as during the process of proto-industrialization. Hence, many potential investors preferred to invest elsewhere (especially in commerce and landowning) or to delay their investments (Crouzet 1985, Pollard 1965), rather than to engage in a risky and highly uncertain industrial endeavor. Eventually, these problems were solved not only by social learning, but also by the share of knowledge between businessmen and investors, as well by the achievement of a critical mass in the number of entrepreneurs willing to invest in the factories. Often, when an entrepreneur was successful and after his patent expired (if there was one), many others would try to emulate his achievement by investing in the new factories. If profits in an industry were high, the rate of imitation was also high, which dramatically increased the number of competitors in the sector. Additional competition meant that there was a lower survival rate for the less adaptable firms to the new competitive environment, increasing the number of bankruptcies. During the 'bandwagon effect' that occurred following the large profits obtained by the early cotton textile factories, many resources were diverted to the sectors of the 'new economy'[58], and many people sold most of their possessions in order to buy the new machines. Others made joint ventures with private financiers or tried to

[58] "The old loom-shops being insufficient, every lumber-room, even old barns, cart-houses and outbuildings of any description, were repaired, windows broke through the old blank walls, and all fitted up for loom-shops. This source of making room being at length exhausted, new weavers' cottages with loom-shops rose up in every direction; all immediately filled." W. Radcliffe (quoted in Mantoux 1927, p. 246)

obtain financial backup in other ways. Consequently, there was a remarkable increase in the number of firms and the number of workers in the industrial sector, both in the factory system and the cottage industry. The culmination of this bandwagon effect took place in the last decade of the 18th century, when bankruptcies peaked sharply (figure 6), probably due to a plethora of factors such as overinvestment, mismanagement of resources, or the weeding out of the ablest competitors. This sharp rise in the number of bankruptcies is consistent with the findings of Atkeson and Kehoe (1997) that large-scale experimentation by startup firms leads to high bankruptcy rates.

Figure 6 _ Bankruptcies, 1736-1800



Source: Hoffmann 1955

All in all, the final push in the long trajectory of the factory system occurred after a critical mass in the number of entrepreneurs willing to invest in factories was achieved. After the relative profitability of factories increased and the productivity of the new machines was enhanced, the factory system gave the final blow against a cottage industry that increasingly could not compete solely with low wages and modest productivity gains.

Nevertheless, if this critical mass had been achieved earlier, the transition to the factory system would have been swifter.

Taking Stock

In sum, the slow transition to the factory system can be explained by several factors. First, there were many technical problems associated with the development of new technologies, which delayed a full implementation of the new inventions in the factory floor. Second, antagonistic interest groups were able to retard the introduction of the new inventions and the new organizational methods in some industries. However, the forces of technological inertia were not strong enough. The victories against technical change were only temporary, affecting mostly individual entrepreneurs and not entire sectors. Finally, the slow transition to the factory system occurred because a process of social learning accompanied the diffusion of the new organizational GPT. New organizational methods had to be learned and refined, and organizational uncertainties had to be removed before the factory system could become the hegemonic organizational system. All these factors contributed for the slow diffusion of the factory system. As the results of section 2 suggest, the new organizational GPT contributed to about a third of all growth during the period. The slow transition to the factory system was thus instrumental for the slow (by today's standards) rates of growth registered during the period. Even so, as argued in the next section, the new organizational GPT was an important contributor for the emergence of modern economic growth.

5. The Organizational Revolution and Modern Economic Growth

In spite of slow growth, the Industrial Revolution was an epoch of remarkable technological and organizational changes. In this context, the Industrial Revolution should be seen as an Organizational Revolution, which contributed for the emergence of modern economic growth. Therefore, the Industrial Revolution was not a mere "growth spurt" like many others before in History. Economic growth certainly did not start with the Industrial Revolution. In the pre-industrial world, economic growth was often a prominent feature during certain expansionary periods or golden ages (Jones 1988, Goldstone 2002, Snooks 1994). However, before the Industrial Revolution, economic growth was sporadic and often unspectacular. In pre-industrial societies, periodic epochs of growth and technological creativity punctuated periods of relative stasis, in which stagnation and decline were often the most prominent features (Mokyr 1990). Hence, systematic and sustainable economic growth only started with the Industrial Revolution.

Two factors helped initiate modern economic growth during the Industrial Revolution. Firstly, by then, the knowledge base had achieved a critical mass, after which increasing returns in the accumulation of human capital ensued (Mokyr 2002). The attainment of this knowledge critical mass was made possible by the widespread diffusion of scientific and engineering skills in Western Europe (Bekar and Lipsey 2001) as well as by the unprecedented increase in human capital. Secondly, the Organizational Revolution provided the necessary structural changes upon which modern growth could be sustained. In previous growth spurts, the structure of the economy was not fundamentally changed, since the modes of production continued to be essentially the same, and most population

remained tied to the primary sector[59]. In stark contrast, the introduction of the new organizational system during the Industrial Revolution profoundly altered the structure of the economy. After the diffusion of the factory system was in full swing, the engine of modern growth was ready to roar. Economic growth accelerated after the 1830s because the preconditions for modern growth were already established during the Industrial Revolution.

6. Conclusion

This paper argued that the Industrial Revolution was an organizational revolution, during which there was a substantial reorganization of the British economy originated by the development of an organizational general purpose technology, the factory system. Although aggregate GDP growth was slow, there were pervasive structural changes in the British economy that enabled the emergence of modern economic growth. A faster transition to the factory system would have allowed for a swifter acceleration of productivity and GDP growth. During the Industrial Revolution there was both slow per capita GDP growth and pervasive innovation because it took time for the investment in organizational capital to be fully realized and a process of social learning to be completed. In spite of low rates of growth, the organizational revolution was instrumental for the emergence of modern economic growth.

[59] A possible exception is the Dutch Golden Age, which took place from around 1550 to 1650, when about 35 percent of the Dutch population became urbanized. Nevertheless, after the Dutch growth spurt ended, urbanization receded somewhat (de Vries and Woulde 1997).

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