From Growth Spurts to Sustained Growth[1]

The Nature of Growth and Unified Growth Theory

GONÇALO MONTEIRO
Department of Economics
University of York
York, YO10 5DD
United Kingdom
gm501@york.ac.uk

ALVARO S. PEREIRA
Department of Economics
University of York
York, YO10 5DD
United Kingdom
asp500@york.ac.uk

Abstract

This paper presents new evidence on the existence of pre-industrial growth spurts and the nature of economic growth during the transition from Malthus to Solow. In this research, growth spurts are an intrinsic feature of the economy, but throughout history their effect on standards of living is mostly temporary. Sustained rises in living standards only become sustained when there are complementarities between the triple engines of growth of technological development, human capital and the organization of the workplace. In Malthusian economies, most technologies were basic and only required straightforward knowledge or human capital, and thus the skill-technology complementarity did not play a role in their development. As a consequence, most technological developments in Malthusian economies generated growth spurts that did not become sustained, although there was a temporary increase in standards of living. However, the increasing complexity of the epistemic knowledge base reported by the historical literature meant that investments in applied technology were progressively more significant, enhancing the role of human capital. After a certain threshold of the knowledge base was surpassed, more and more complex applied technologies were developed, and growth spurts became permanent features of the economy.

Keywords: growth spurts, unified growth theory, sustained economic growth

JEL classification: O10, O33, O40

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1. Introduction

Is economic growth a relatively recent phenomenon that started with industrialization about 200 years ago or was there growth before? If so, was pre-industrial growth different from today's? In pre-industrial economies were the gains from technological advances only translated into more population without a rise in living standards? What repercussions did the so-called "golden ages" (of empires, of city-states, and of nations) have on national and global economic development? These are some questions that generations of researchers have addressed, and which have been recently re-examined by new research in both macroeconomics and global economic history.

Following the developments of endogenous growth theory in the 1990s, the macroeconomics literature has recently focused on the transition from "Malthus to Solow" (Galor 2005, Galor and Weil 2000, Galor and Moav 2002, Hansen and Prescott 1999, Doepke 2004, Lagerlöf 2006), as well on the Industrial Revolution (Lucas 2002, Jones 2001). This literature, also known as unified growth theory (Galor 2005), 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. Although some attention had been previously devoted by macroeconomists to the transition to sustained growth[2], the new developments in unified growth theory not only enabled the integration of economic growth theory with the demographic transition, but also improved our understanding of the transition from Malthusian economies to modern economic growth. Even so, unified growth theory has not yet devoted a lot of attention to the nature of pre-industrial growth and its impact in the transition from Malthusian times to sustained growth. Existing research typically assumes that growth was uneventful during the Malthusian epoch, and became only significant in the last 200 years. In

[2] Some classical works in this area include Kuznets (1966), Lewis (1955), Rostow (1960). Recent works include Kremmer (1991), and Goodfriend and McDermott (1995).

contrast, the historical literature has often emphasized the existence of growth spurts or golden ages that lasted for a few decades. Thus, Jones (1988) states that economic growth is the norm and not the exception in human societies, recurring several times in pre-industrial economies. Cameron (1997) argues that rounds or waves of growth occurred throughout history, each wave building upon the preceding one. Clark (2001: 1) claims that "the Industrial Revolution was the last … of [the] growth spurts stretching back to the Middle Ages". Similarly, Goldstone (2002) argues that "efflorescences" or golden ages were prevalent in pre-industrial times, and thus he contends that: "We need to consider more complex dynamics than either a once-and-for-all shift from non-growth to growth, or economic growth as a gradual and universal process that occurs everywhere and always." (Goldstone 2002: 327). Lipsey et al. (2006) contend that the main source of pre-industrial growth is related to the development of General Purpose Technologies that enabled the rejuvenation of growth. Qualitative and descriptive historical evidence also seems to suggest that there were several pre-industrial growth spurts both in Europe and in Asia. The existence of these growth spurts implies that growth did not emerge solely in the modern period, although the nature of growth seems to have changed after industrialization (Mokyr 1999).

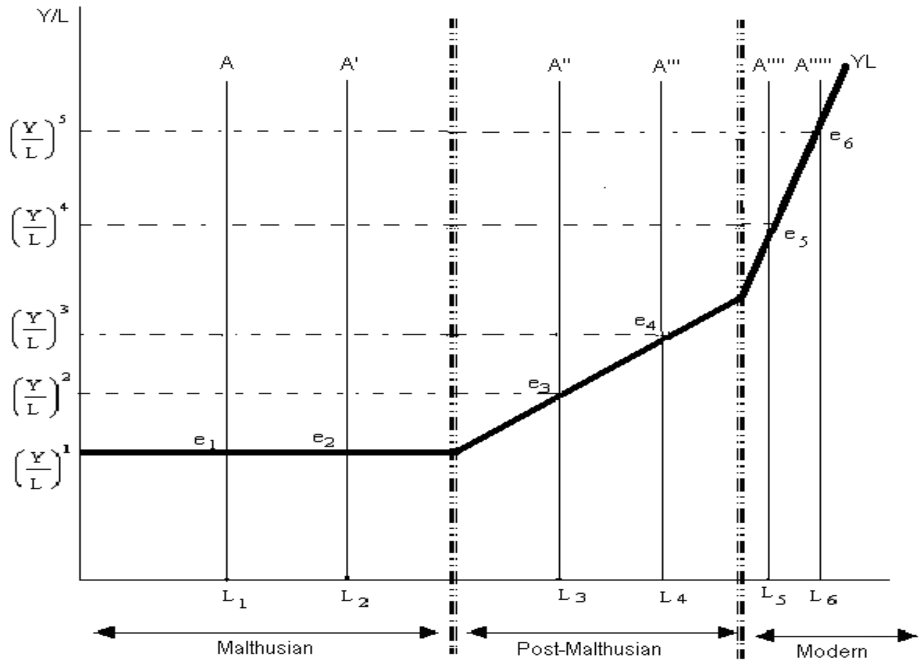
This paper tries to bridge the gap between the two literatures by presenting new empirical and historical evidence on the existence of pre-industrial growth spurts. This research also provides new foundations concerning the nature of economic growth during transition to sustained growth. In addition, the paper sheds new light on the existence of historical poverty traps, which entail the existence of multiple equilibria in pre-industrial economies. The paper proceeds as follows. Section 2 reviews some of the most significant "golden ages" in pre-industrial economies and presents empirical evidence on these growth episodes by looking at the relationship between real wages and population for a plethora of countries. Section 3 surveys the main characteristics of pre-industrial growth spurts. Section 4 introduces a model in which growth spurts are an intrinsic feature of pre-industrial economies, but their impact on living standards is temporary. The rise in living standards only becomes sustained when the complementarity of the triple engines of growth (consisted of human capital, technology and organizational change) emerges[3]. Section 5 concludes.

2. Growth Spurts in Pre-Industrial Economies

Galor and Weil's (2000) canonical work on unified growth theory portrays the transition from to sustained growth as a three phase-framework through which economies evolve: Malthusian, post-Malthusian and modern. The main features of these economies are summarized in Figure 1. Income per capita is represented on the vertical axis, and population on the horizontal axis. The curve YL provides the different stages of development, whereas the vertical line A denotes the level of technology. The vertical dotted lines describe the different types of economies. To simplify, each level of technology is assumed to be independent of the standards of living and to depend solely on population. Suppose we start at point e_1, which corresponds to a Malthusian economy. The level of technology is A_1, income per capita is $(Y/L)'$ and the level of population is L_1. Assume that there is an exogenous technological change (e.g. the development of the printing press) that increases the level of technology to A_2. At the new equilibrium point e_2 there is now a higher population (L_2), but there is no change in the standards of living, which remain constant at $(Y/L)'$. Thus, in a Malthusian economy, changes in income (or technology) are only translated into higher populations and not into higher standards of living.

[3] In Malthusian economies, technologies were basic and the skill-technology complementarity is not important. Hence, technological developments in Malthusian economies generate growth spurts that did not become sustained. However, the increasing complexity of the epistemic knowledge base increased the returns to investments in applied technology and enhanced the role of human capital. After a threshold of the knowledge base was surpassed, more and more complex applied technologies were developed, and growth spurts became permanent features of the economy.

Figure 1: From Malthus to Solow: Galor-Weil Model



In turn, in a Post-Malthusian, increases in income are translated into both higher population and higher standards of living, albeit the former effect was still dominant. Thus, an increase of the level of technology from, say, until A'' to A''' takes the economy from e_3 to e_4, which originates an increase both in the level of population from L_3 to L_4 and in the living standards from $(Y/L)^2$ to $(Y/L)^3$. In addition, during the Post-Malthusian stage, we have $\Delta L > \Delta(Y/L)$, since the *population effect* is stronger than the *standards-of-living* effect. Finally, in a modern economy the line *YL* becomes very steep, and increases in the level of technology are chiefly translated into higher standards of living. In a modern economy, a high level of technology increases the returns to human capital, and parents substitute child quality for quantity. Thus, an increase of level of technology increases the standards of living from $(Y/L)^4$ to $(Y/L)^5$, whereas population increases only from L_5 to L_6. Moreover, in a modern economy, the steepness of the *YL* curve implies that $\Delta(Y/L) > \Delta L$, and hence the standards-of-living effects dominate the population effects. In short, in this framework, Malthusian economies are virtually static, and hence the transition to sustained growth is seen as the transition from stagnation to growth. In this setting, growth becomes sustained due to skill-technology complementarity (Galor and Weil 2000), structural change (Hansen and Prescott 2002) or due to the role of demand (Voigtlaender and Voth 2005).

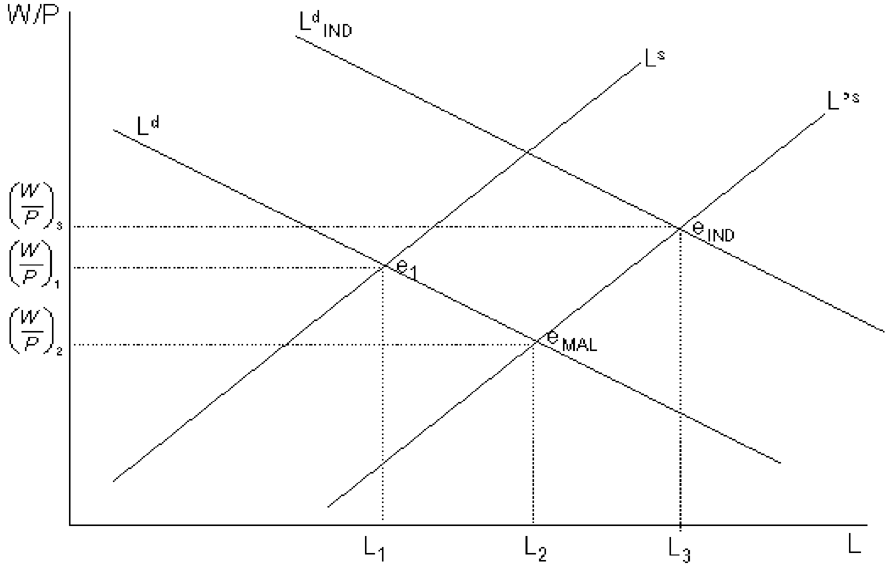
In turn, the historical literature has a long tradition of analysis of the transition to sustained growth[4]. While economic historians have often disagreed on the nature of pre-industrial growth, most agree that the so-called Malthusian economies were much more dynamic than most models suggest. Although historical data on the very long run are often unavailable or unreliable, fortunately we have reasonably good data on wages and population, offering us some clues about the existence of growth spurts. In terms of the transition to modern economic growth, economic historians have often emphasized an important negative relationship between wages and population in pre-industrial economies (see, for instance, Braudel 1979, Wrigley 1988). Figure 2 summarizes the main features of this relationship.

In Malthusian economies, income gains are translated into more population and a larger labor supply. Suppose we start at e_1, with real wage $(W/P)_1$, corresponding to the level of labor L_1. After an income gain occurs, population grows and the labor supply shifts to L'^s. As a consequence, the level of labor rises to L_2, whereas real wages fall to $(W/P)_2$. On the other hand, a contraction of the labor supply leads to an increase in real wages[5]. In contrast, in modern economies, sustained productivity gains shift the labor demand upwards, causing real wages to rise and offsetting the depressing effect on wages from higher population.

4 See, for instance, Kuznets (1969), Ashton (1961), Mantoux (1927), Deane and Cole (1969), and, more recently, Jones (1988, 2003), Easterlin (1982) and Pomeranz (2000).

5 This is exactly what happened after the Black Death, when population fell by almost a quarter in many European regions, and living standards rose to levels that were not seen until the 1800s (Allen 2001).

Figure 2 _ Wages Vs. Population in Malthus to Solow



The wage-population relationship can be observed for several European and Asian economies, for which there are good wage and population data. 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), de Vries (2000), and Maddison[6] (1998, 2001). The only notable exception is England, for which we have average real wage data from Clark (2001, 2006). In terms of wage data, for most countries there are not economy-wide real wage data. The wage data are for some representative professions (such as, laborers and craftsmen) that can proxy for the behavior of overall real wages. Most data on real wages are from Allen (2001). The Allen data are presented in grams of silver, a uniform measure that facilitates cross-country comparisons[7]. Additionally, wage data from Istambul were obtained from Pamuk (2000), Japan wage data from Bassino and Ma (2005), and China wage data from Allen et al. (2005). Chinese population data are from Maddison (2002). In countries for which

[6] The Turkish population data were also corrected by a personal communication with Sveket Pamuk.

[7] The Allen data used are: Belgium (Antwerp: 1400-1900), England (London 1400-1900), Holland (Amsterdam: 1400-1900), Italy (Florence 1340-1900, Milan 1600-1900), Spain (Madrid: 1550-1900, Valencia: 1410-1790). The Istanbul data: 1560-1913 period, Japan: 1750-1900, and China: 1800-1910. China's and Japan's figures are silver wages.

there are sufficient data, the wage-population relationship is observed with the help of a non-parametric kernel-based method. By using local polynomial kernel regressions of real wages on population we can uncover structural features in the data that cannot be captured by a regular parametric framework. In this approach, observations are weighted taking into account a kernel function. Local polynomial kernel regressions fit WP (real wages), at each value of L (population), by choosing the parameters β to minimize the weighted sum of squared errors:

$$\text{m(L)} = \sum_{i=1}^{N} WP - \beta_0 - \beta_1(L - L_t) - \beta_2(L - L_t)^2 - \ldots - \beta_k(L - L_t)^k)^2 K\left(\frac{L - L_t}{h}\right) \qquad \text{(i)}$$

Where *N* is the number of observations, $K(\cdot)$ is a kernel function that integrates to 1, and *h* is the bandwidth or smoothing parameter. When $K\left(\frac{L - L_t}{h}\right)$ is a constant, equation (1) is reduced to a linear estimation function. The Epanechnikov kernel minimizes the asymptotic mean integrated squared errors, and hence it is optimal when compared to other kernels (Wand and Jones 1995). The Epanechnikov kernel[8] is equal to:

$$K\left(\frac{L - L_t}{h}\right) = \frac{3}{4}\left(1 - \left(\frac{L - L_t}{h}\right)^2\right) I\left(\left|\frac{L - L_t}{h}\right| \leq 1\right) \qquad \text{(ii)}$$

Where *I* is an indicator function that is equal to one when the argument is equal or less than one and zero otherwise. Figures 3-12 present the empirical evidence on the wage-popualtion relationship for all the countries in our sample.

[8] 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: 1) versatility of exploring a relationship between two variables, 2) prediction of observations without having to use a fixed parametric model, 3) tool for finding spurious observations, 4) method for interpolating for missing values.

Fig. 3 _ Florence Craftsmen 1350-1700

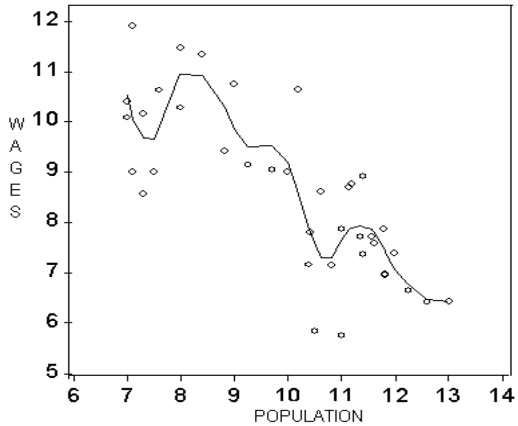


Fig. 4a _ Madrid Craftsmen 1550-1900

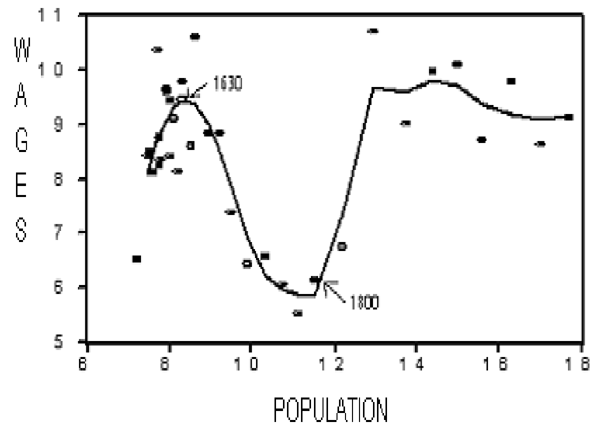


Fig. 4b _ Valencia Craftsmen

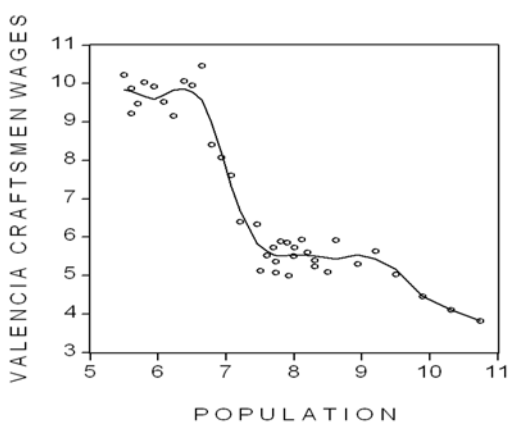


Fig. 4c _ Valencia Craftsmen (XY pairs)

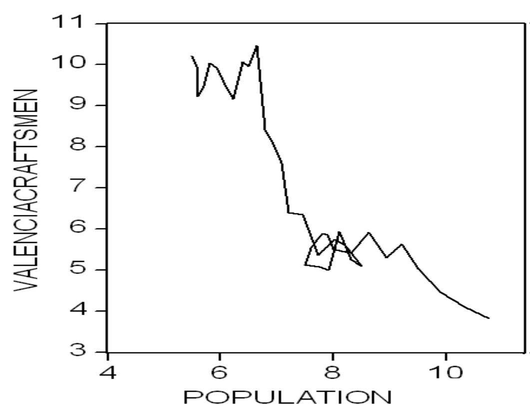


Fig. 5a _
Dutch GDP per capita 1550-1900

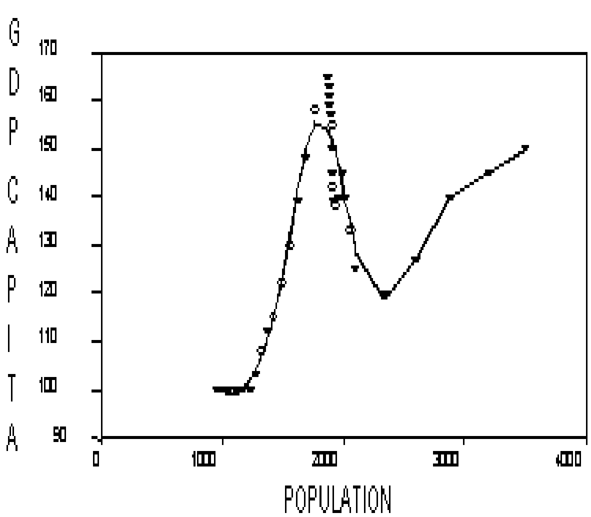


Fig. 5b _ Amsterdam Craftsmen 1400-1900

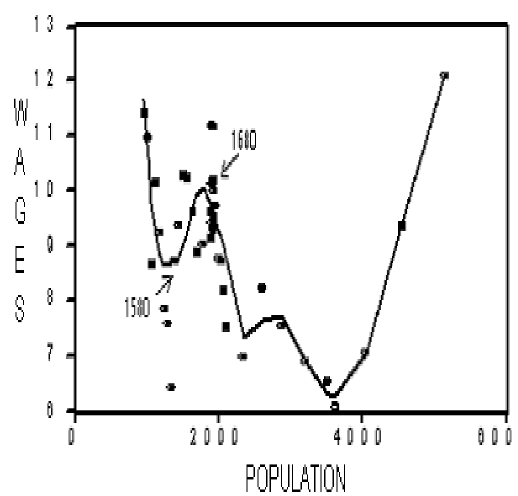


Fig 6a _ London Craftsmen 1400-1900

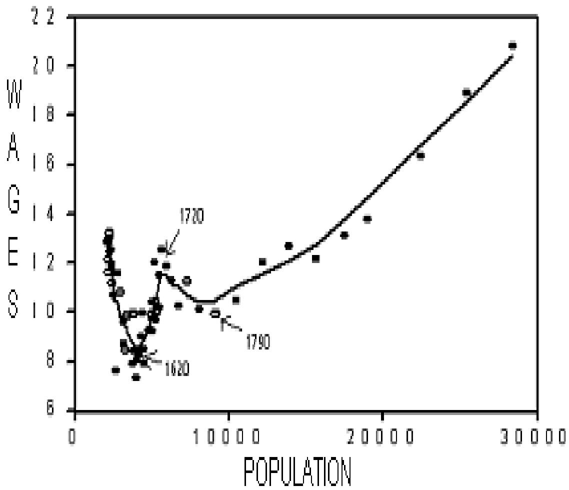


Fig 6b _ Oxford Craftsmen 1400-1900

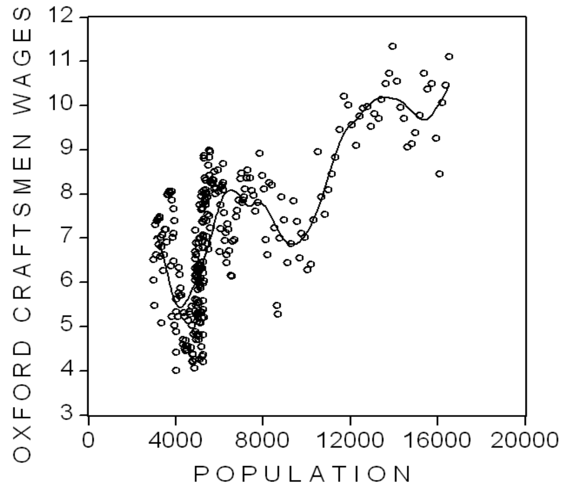


Fig. 6c _ Farm Real wage (Clark data)

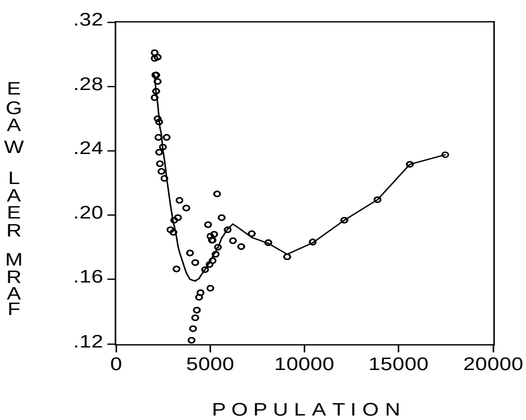


Fig 6d. _ Real GDP (Clark data)

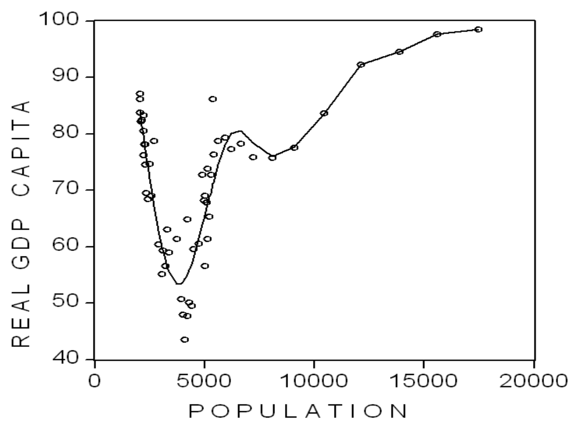


Figure 9a _ Augsburg Laborer Wages

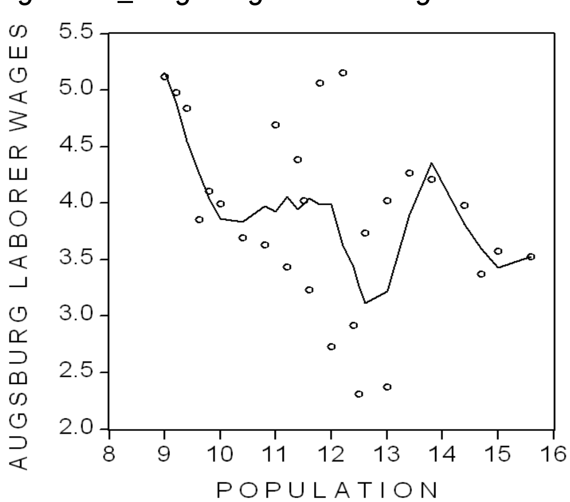


Fig. 9b_ Munich Craftsmen Wages

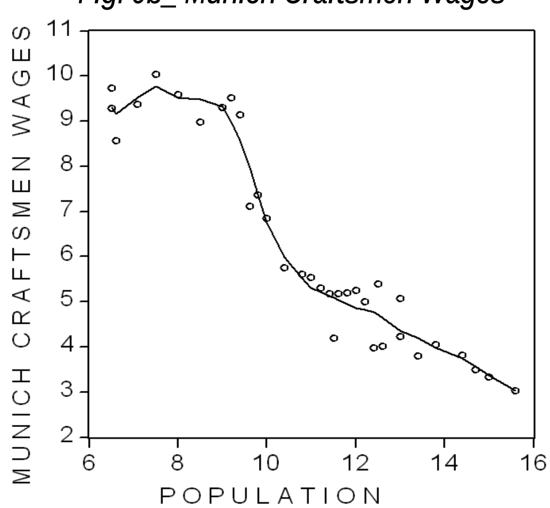


Fig. 7a _ Vienna Crafstmen 1490-1800

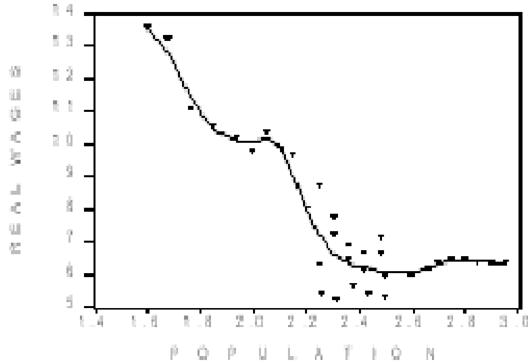


Fig. 7b _ Vienna Laborer 1490-1800

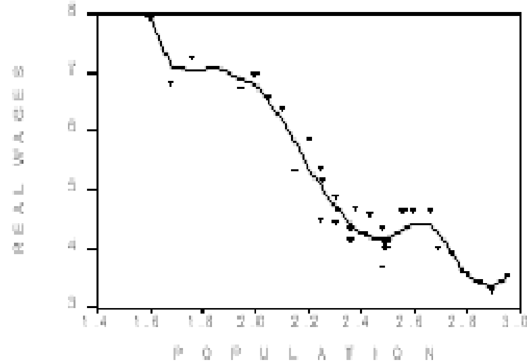


Fig. 7a _ Antwerp Crafstmen 1400-1900

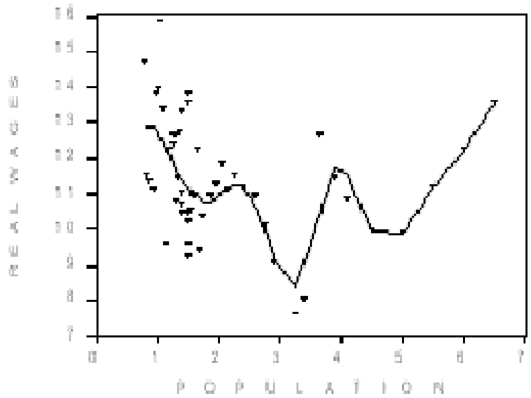


Fig. 7b _ Antwerp Laborer 1400-1900

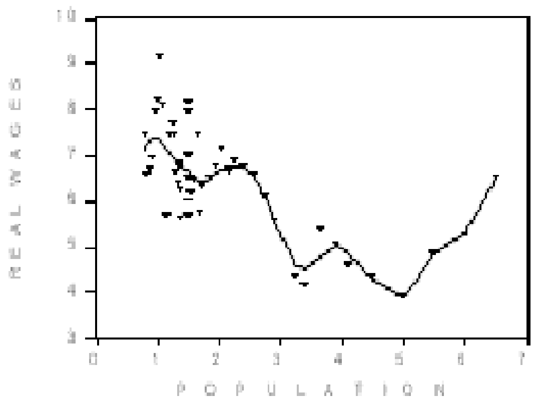


Figure 8a _ Paris Laborer 1430-1790

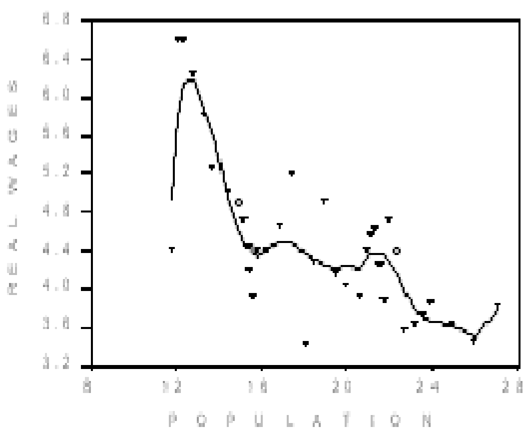


Fig 8b _Strasbourg Laborer 1390-1860

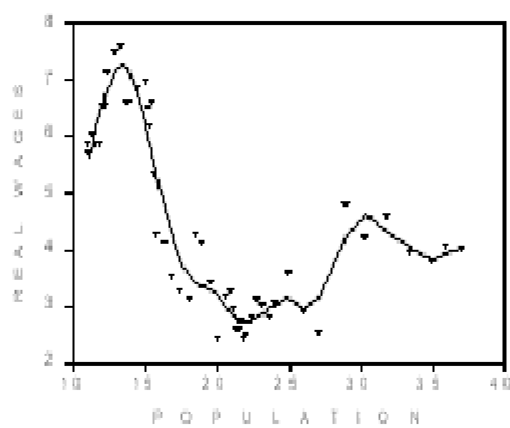


Fig 9a _ Krakow craftsmen 1410-1900

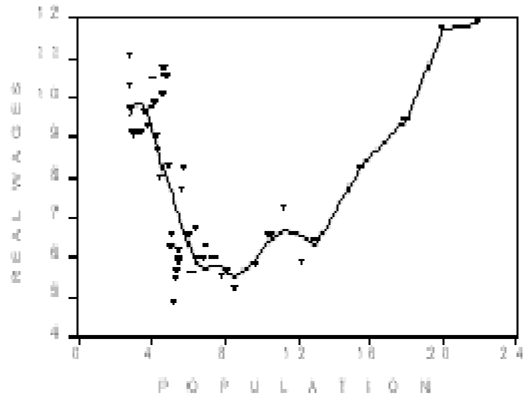


Fig 9b _ Krakow laborer 1410-1900

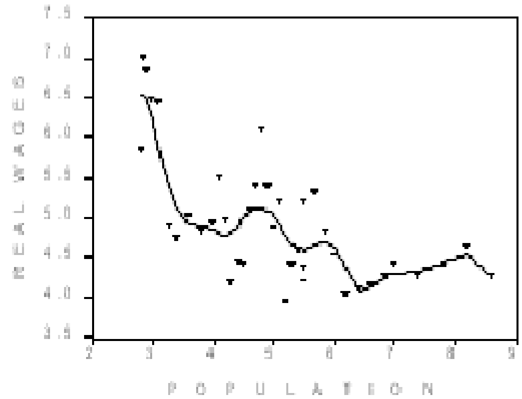


Fig. 10 _ Japanese silver wages 1750-1910

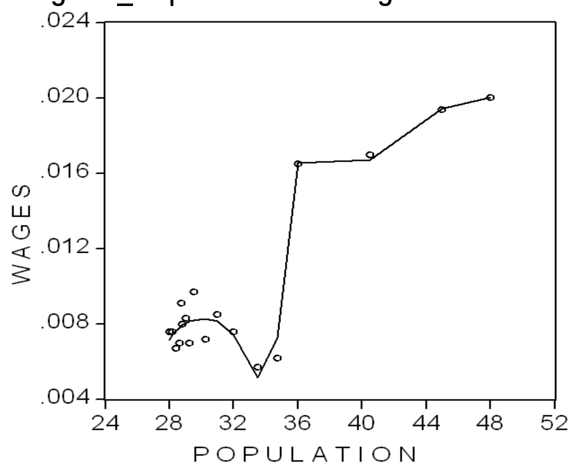


Fig 11 _ China 1820-1910[9]

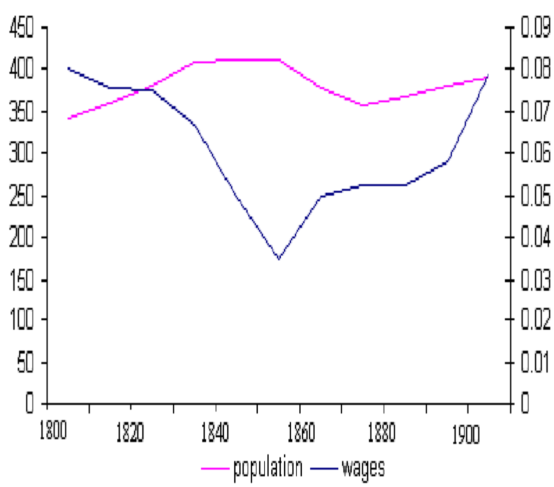
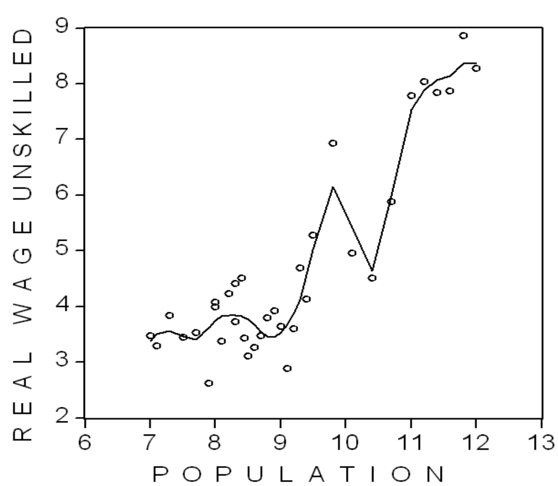


Fig. 12 _ Istanbul unskilled 1560-1915



[9] Alas, we don't have enough decennial observations to use a non-parametric technique for the Chinese data.

Figures 3-11 show that, for most countries, there is a strong inverse relationship between real wages and population until the 19th century. However, as can be seen from the figures, pre-industrial economies were by no means static. Several European economies underwent temporary growth spurts throughout the period, which lasted a few decades before growth petered out. During these growth spurts, real wages increased simultaneously with population, showing that such occurrence is not exclusive to modern economies. The main difference between the pre- and post-industrial period is that growth spurts seem to have become permanent since the industrialization movement took place in the 19th century. Before industrialization, all growth spurts would, sooner or later, die out and growth would come to a grinding halt. Since growth spurts seem fairly common in the pre-industrial period, it is important that we understand the causes behind their start and their end. With that in mind, the next section analyzes some of the most significant growth spurts in pre-industrial economies.

3. Growth Spurts in History

This section reviews the main characteristics of some of the most important pre-industrial growth spurts. The examples below do not exhaust the known growth spurts, which likely include the great empires of the Asian and European Classical antiquity. In contrast, the growth spurts below were chosen because there are more qualitative and quantitative data concerning them and because they offer important lessons regarding the nature of pre-industrial growth. Most of the growth spurts surveyed in this section also pertain to figures 3-11. We believe that the examples provide a good sample of the main features of growth spurts in the pre-industrial period[10].

[10] We could, of course, simplify our approach and say that, according the Maddison (2001) data, in the 1,000 years before the Industrial Revolution economic growth consisted of cyclical Malthusian variations around an average growth rate of about 0.1 percent per year. As Grantham (1999: 10) puts it: "[Pre-industrial economies] advanced through alternating phases of expansion and contraction along a long-run productivity trend that probably did not exceed 0.1

The European Frontier Movement

Late medieval Europe provides the classical example of Malthusian cycles in pre-industrial economies, and it is thus the ideal starting point of our discussion. Between the 10th and the 14th centuries, Europe experienced a significant period of economic expansion and population growth. The period ended abruptly in the mid of the 14th century with the arrival of a major pestilence (the infamous Black Death), as well as endemic wars and famines. In this period, growth was due to both gains from trade and technical change. Trade expanded considerably under substantial population growth and urbanization. There were also several new inventions and the adoption of more efficient systems of agricultural production (such as the three-field system). This was an epoch in which Europe imported and adapted several technologies from others, such as Islam, Asia and the classical Antiquity. The most important technologies of this period include windmills, more efficient waterwheels, dams, the nailed horseshoe, the stirrup, the modern horse collar, better boats (e.g. the *cog*), soap, butter, strong distilled liquors, skis, wheelbarrows, paper, the lateen, and improved window glass (Mokyr 1990). Population growth fueled by land intensification and the adoption of more efficient modes of production enabled the start of a virtuous circle of development and growth, which fomented the growth of cities and the expansion of trade. At the start of the period, there were very few cities, and population was mainly scattered in small villages. Population growth fueled urbanization and commerce. By the 13th century, most towns were still small, although there were also some bigger cities[11]. National and international trade also grew tremendously, and fairs and markets sprouted throughout Europe. By the 13th century, the economic and population expansion started to reach its limits, causing rents and prices to rise

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percent per year.". We could then pretty much ignore what happened in terms of growth during this period. However, we believe that by modeling and analyzing pre-industrial growth spurts, and by understanding why they failed to generate sustained growth, helps us explain why the spurt of the Industrial Revolution became permanent and enabled us to achieve modern growth.

[11] Milan and Venice had around 200,000 inhabitants, Paris 100,000, Ghent and Bruges 50,000, and London 30,000.

significantly. The downturn of the Malthusian cycle occurred in the mid 14th century with the arrival of several wars, famines and pestilences. Population fell by more than 25 percent in many regions, and, consequently, real wages rose dramatically in the following decades until population started to recover. All in all, the growth spurt in medieval Europe was made possible by increasing trade as well as improvements in the agricultural sector, and ended when the European economies reached some sort of Malthusian constraints in terms of population and limited land productivity.

Italian Renaissance

In the late Middle Ages, the Italian cities of Venice and Genoa specialized in long-distance trade in the Mediterranean sea, and became transit ports of Asia and Arab goods destined to Western Europe. During this period, Florence also became a leading manufacturing center and the biggest financial center in Western Europe. These and other Italian cities flourished under a combination of factors that include international trade and institutional developments that fueled productivity improvements in the commercial sector. The Italians developed several important commercial innovations that decreased transaction costs and greatly stimulated trade (North and Thomas 1973). The most important innovations included the founding of trading companies or partnerships, the development of insurance in long-distance trade, double-entry bookkeeping, the bill of exchange, the *commenda*, and banking (Crouzet 2001: 41-43), leading to a so-called commercial revolution (Cipolla 1970). Several of these innovations were designed to improve the establishment of property rights, improving efficiency and enhancing productivity. As a consequence, trade flourished, population expanded, and urbanization accelerated. Several technological and organizational innovations in the textile sector allowed the manufacturing sector also to expand substantially. Figure 3 shows that for most of the 15th century the wage-population inverse relationship was temporarily disrupted, as wages increased at the same time as population.

The Italian growth spurt came to an end due to increasing competition from commercial rivals, and from the damages inflicted by several conflicts. The first blow to their quasi monopoly occurred after the wars with the Ottoman Empire in the late 15th century, which ended the commercial supremacy of the Italians in the Levant. Italian-based trade suffered another major setback with the discovery of the competing sea route to India by the Portuguese in the early 1500s, which led to a substantial decrease in the commerce of spices in the ports of the Levant. Finally, the occupation of the Spice Islands by the Dutch in 1605 *de facto* ended Venice's and Genoa's spice trades.

In sum, international trade, institutional developments in commercial-related activities and some manufacturing were the main causes for the Italian golden age. This growth spurt ended because the gains from trade were gradually exhausted by increasing competition from foreign rivals, as well as due to losses related to wars and the decline of the growth-promoting sectors, such as banking (in Florence) and manufacturing. The amounting losses in long-distance trading stimulated a redirection of trade-related profits and, by the end of the growth spurt, Italian traders increasingly invested in landed estates instead of new commercial adventures (Pounds 1974: 470). After the growth spurt was over, the Italian cities entered a long period of general stagnation. According to Cipolla (1970), the Italian case is a good example of the ambivalence of international trade: while from the 11th to the 16th centuries, it was a growth engine of the economy, from the 16th century onwards international trade became an "engine of decline" (because of foreign competition and the rising demand for Italian agricultural products), leading to a complete inversion of relative economic position of Italy and contributing to its relative decline.

The Iberian Spurt

In the 15th and 16th centuries, fueled by their famous global geographical endeavors, the Iberian economies had their own golden ages. The Portuguese expansion can be traced to the trade-related gains from the exploitation of coastal Africa, the discovery of the sea route to India, the establishment of trading posts in Asia, and the exploitation of Brazil. By becoming the first global empire (Russell-Wood 1992), the Portuguese were able to diversify the portfolio of exported goods and resources as well as to dramatically increase the size of markets. During this period, there were several trade- and navigation-related technical inventions, including the *caravel* (a cargo ship that sailed faster than its previous counterparts in Western Europe), the utilization of the astrolabe and important improvements in map-making (Godinho 1981). The profits from the large inflows of gold from East Africa, slaves, the spice trade and several Brazilian agricultural goods gave an unprecedented affluence to this small European country. Although there are no reliable and consistent data for the period, there are several reports that suggest a substantial increase in living standards (especially in Lisbon) and a considerable population increase (Braudel 1982, Russell-Wood 1992).

Similarly, 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 4). The discovery and exploitation of the Americas led to substantial trade-related gains, especially in terms of natural resources and South American bullion. Spain built the biggest global empire the world had ever seen, and the commercial sector benefited accordingly. Wage data for Valencia craftsmen and laborers also show that the Spanish growth spurt was experienced in other regions outside Madrid (Figure 4b and 4c). Nevertheless, after 1630, the relationship between real wages and population became once again negative until early in the 19th century. A long period of stagnation and decline followed. Indeed, similarly to Portugal, the growth spurt didn't do much to improve the long-term performance of the Spanish economy[12]. The latter remained

[12] As Cipolla (1970: 8) has put it: "The Spanish empire grew up on the unexpected and accidental returns of the conquest. The influx of bullion and the induced expansion of global demand had certain positive effects in stimulating

underdeveloped and hence even during the golden 16th century several Spanish authors pointed out that their kingdom had to import most manufactured goods. In fact, the enormous amounts of bullion from the Americas might have made Spain richer but also likely had a detrimental effect on the long-term performance of the Spanish economy, not only due to high inflation, but also because of the diversion of resources from productive activities (Drelichman 2005). Thus, the Spanish growth spurt was unsustainable, and soon petered out. After the growth spurt ended, real wages and population reverted to their previous inverse relationship.

The Dutch Golden Age

Between around 1550 and 1650, the Netherlands had its own golden age, during which GDP per capita, real wages and population all increased. Thus, de Vries and Woude (1997) assert that the Dutch economy started to exhibit some signs of "modernity" during this period, since the Malthusian negative relationship between living standards and population was no longer present. In large part, this important growth spurt was trade-related. By using and improving many of the commercial-related innovations of the Italians, the Dutch were able to build a large empire that spanned throughout most continents. However, besides this commercial expansion, during this period Holland also developed an advanced manufacturing sector, and there were important developments in agriculture, in hydraulic engineering and in shipping. Building upon and improving the existing techniques associated with the Italians, the Dutch achieved a relatively high degree of technological sophistication in many of these sectors (Mokyr 2000, de Vries and Woude 1997). 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

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the growth of some activities in the course of the sixteenth century. But fundamentally the country failed to change. Spain remained essentially a country of peasants, shepherds and landlords."

negatively sloped (figure 5a), and only after the 19th century did population and GDP per capita increase simultaneously once again. The wage data also confirm these findings (figure 5b). After the 17th century, the Dutch economy entered an extended period of stagnation.

Although this Golden Age took the Dutch economy to a higher equilibrium level than its European counterparts, characterized by unprecedented urbanization rates and considerable structural change, the knowledge base of techniques remained somewhat limited and traditional. As Mokyr (2000: 12) emphasizes: "[The] advanced technology that helped propel the Dutch economy into unprecedented … riches in the 17th and 18th centuries was still mostly the traditional, pragmatic knowledge at the level of artisans or applied engineers: mechanically clever, well-designed techniques, but without much of an epistemic base in the deeper natural phenomena that made them work. As a consequence, technological progress ran into diminishing returns." Technological conservatism also seems to have played a role in the stagnation period that followed the Dutch growth spurt. Jacob (1997) argues that gradually the Dutch elites lost interest in technological development and, consequently, investment in techniques and engineering declined. Wars as well as political-economy factors also contributed to Dutch economic decline.

Growth Spurts in China[13]

Growth spurts were not confined to Europe. Although traditionally portrayed as a dormant giant, for many centuries the Chinese economy was not only one of the most dynamic in the world, but also the source of many of the most important inventions, such as paper, gunpowder, or the clock. Consequently, it is not surprising that the Chinese economy underwent several pre-industrial growth spurts, the most important of which occurred in the Sung (960-1279 AD) and the Qing (especially between 1680 and 1780) periods. During the Sung period, agriculture was boosted by a

[13] The final version of this paper will also include a subsection on the Ottoman empire.

series of factors that increased productivity. There was an elimination of the conscription of labor, an innovative tax reform allowed farmers to use money rather than grain to pay their duties, and several agricultural innovations were introduced. As a result, per capita incomes seem to have increased although population expanded rapidly (Jones 1988). In turn, population growth promoted urban growth, creating the biggest cities in the world. Human capital accumulation was enhanced by the introduction of a national school system, which aimed to attract the brightest minds to the service of the emperor and the state. In addition, an important innovation of the Sung period was the introduction of money and the development of credit, which stimulated trade, both nationally and internationally. Technical innovation was also carried out in many areas of the economy[14]. Nevertheless, the Sung golden age petered out for internal and external reasons. Hartwell (1966) argues that the end of the Sung was caused chiefly because of the Jurchen and Mongol invasions. In contrast, more recent historiography points out the exhaustion of trade opportunities and the agrarization of Chinese society as the main causes of the decrease in creativity and dynamism of the economy.

A later growth spurt took place during the Qing period. The Qing settled in new territories (in Mongolia and central Asia), colonized new lands, introduced New World crops, and restored free peasantry. Trade and markets expanded considerably and education was promoted[15]. As a result of all these changes, population increased at a dramatic rate, more than doubling in the 18th century. However, and although there are no good data for the period, according to some reports, the rise in population was initially also accompanied by a small increase in living standards. Namely, it seems that the introduction of new crops and some agricultural innovations let to a rise

[14] For centuries, China was the main source of many of the world's greatest inventions, including irrigation and fertilizing techniques, seed drills, the deep-tooth harrow, the iron plow, the use of blast furnaces, the spinning wheel, sophisticated water clocks, the compass, paper, paper money, porcelain, explosives, gunpowder, copper sulphates, pharmaceuticals, the wheelbarrow, the horsecollar, the umbrella, the toothbrush (Mokyr 1990).

[15] Rawski (1979) argues that non-elite literacy was fundamental for the many administrative regulations of the Qing.

in per capita consumption of foodstuff, as well as cotton and silk products (Pomeranz 2000). Still, by mid-18th century, the Qing expansion started to run into several constraints and began to "[sink] into ecological, administrative, and economic growth downspins due to its inability to cope with ongoing massive population growth" (Goldstone 2002: 353). Under the heavy administrative building of the Qing, corruption became pervasive and the tensions and conflicts with the Western powers put even more strain into the empire. By early 20th century, the pressures became insurmountable and the Chinese imperial system crumbled down under the revolution of 1911.

Tokugawa and Meiji Japan

Although Japan has been often portrayed as a backward country until the opening up to the West in 1867, recent historiography has shown that the two centuries that preceded the Meiji Restoration were instrumental for the modernization of Japan. Thus, today the consensus among the leading researchers is that it is not possible to envisage the Japanese economic miracle without looking at the Tokugawa period. The latter was a highly hierarchical feudal regime, which had the ruling samurai at the top, followed by farmers, artisans, and traders. In spite of being feudal in nature, the Tokugawa period included a system of incentives that in the long run were beneficial to economic growth and enabled an improvement in living standards. During this period, the central government or Shogunate presided over the matters of national security and foreign relations, but the feudal lords (around 200 in total) had virtually complete autonomy in their administration duties (Smith 1948). The lords were obliged to take residence in Edo, the capital of the country, for half of the year, but also had an incentive to promote economic development in their own domains in order to raise revenues, which would increase their political clout in the capital. Tokugawa Japan's peculiar political arrangement stimulated economic competition between the different regional domains, and fomented technological development and the expansion of markets (Morris-Suzuki

1994: 14). From the late 17th century onwards, the lords fomented education (firstly of the samurai and later of commoners), which became an important pacifying and unifying element of the country (Dore 1965). Many lords also promoted Western (Dutch) studies, the translation of scientific and technical books, the acquisition of Western and Chinese technologies[16], as well as agricultural and commercial development. Since the ruling class samurai were not entitled to engage in warfare and it was compusory for them to be educated, Tokugawa Japan soon had a large class of educated but underemployed samurai, many of whom pursued scientific and technological interests. By 1867, at least 40 percent of the males and 15 percent of the females were literate (Dore 1965, Passin 1965). In addition, during this period, most industries expanded substantially (Ushida 27-36), and the domestic industry (or putting-out system) became fairly sophisticated (Landes 1998). The wage-population relationship confirms the existence of a growth spurt during the late Tokugawa period, during which wages and population increased simultaneously (figure 10), albeit not very dramatically. The significant break that we see in the figure corresponds to the Meiji period, and can be justified by the increase in silver wages (together with population) in the early Restoration epoch, when full-fledged industrialization began. Real wages increased, albeit not as dramatically (Bassino and Ma 2005).

Growth Spurts in Britain and the Industrial Revolution

Throughout most of the 17th century until around 1720, the English economy experienced a growth spurt, enabling population and real wages to both trend upwards. However, this growth

[16] In spite of the *sakoku*, the national isolation policy implemented in 1639, the Japanese maintained regular trade with the Chinese and allowed Dutch ships into Nagasaki, a Dutch entrepot. Notwithstanding the *sakoku*, 17th century Japan witnessed the “enthusiastic borrowing of Chinese ideas and culture” (Morris-Suzuki 1994: 17). During the Tokugawa era, the earliest Western industries introduced were related to the military sector, such as iron, armaments, and shipbuilding. Cotton spinning and other consumer industries based on Western technology were introduced only during the Meiji period or at end of the Tokugawa period. (Smith 1948: 136). In the Tokugawa era, important *hans* such as Saga, Satsuma, and Mito also promoted Dutch studies and industrial development of the iron and shipbuilding industries, by building Western-style reverberatory furnaces, used to smelt iron for Western-type guns

spurt did not become self-sustaining, since after the 1720s real wages declined whereas population continued to increase. This trend persisted until the start of the Industrial Revolution. A similar story can be told with Clark's (2001) farm real wage and GDP data. Trade, institutional advances and industrial development were the likely sources of this growth spurt. North and Weingast (1989) attribute much of the significant income gains during this period to the institutional and constitutional developments associated with the Glorious Revolution. According to them, the 17th century marks a substantial break in the growth process of Britain. In this view, the temporary return to a negative relationship between wages and population can be seen as a small deviation from a positive trend that started in the 17th century and was reinforced by the industrialization process. In contrast, Sussman and Yafeh (2006) argue that Britain's rise to technological and economic supremacy was the culmination of a long process of development of the legal system, science as well as the formation of an efficient fiscal state. Similarly, there is substantial evidence suggesting that manufacturing development was an important factor for the growth spurt in the 17th century. 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 (Milward 1981), diffusing to other industries such as leather goods and small metal wares, and enabled the mass production of several products (Mokyr 1990: 77).

In turn, the wage-population evidence confirms the well-established fact that the Industrial Revolution marks a departure from pre-industrial times, since after industrialization the relationship between real wages and population became permanently positive, heralding the arrival of modern economic growth. The most important innovations of the early industrial period were the puddling and rolling technique, the use of coke, the water frame, the spinning jenny, Crompton's mule, the power loom, the cotton gin, the carding machine, chlorine bleaching, the emergence of a small machine-tool making industry, the steam engine, improvements in waterpower efficiency, gas lighting, food canning, and hot-air ballooning (Mokyr 1990). Many of these new technologies increased the rewards for entrepreneurs to invest in more centralized modes of production, such as the factory system. After this period, there was a fundamental complementarity between these two engines of growth that fueled industrial development and made the growth spurt permanent.

The relationship between wages and population can also be observed for other countries. Figures 7-12 present the empirical evidence for these countries. The reasons for these growth spurts are similar to those presented above, namely, commercial expansion, institutional change and technology-related.

Taking Stock: The Causes and Consequences of Growth Spurts

The historical evidence shows that, as Jones (2003: 40) emphasizes: “Instead of thinking of growth as an aberration, [we should] try thinking it as the norm”. Many of these growth spurts were trade-related, although technological and institutional improvements, resource abundance or the expansion of markets also contributed. Similarly, Grantham (1999: 200) argues that the growth spurts were caused by "endogenous fluctuations in the degree of market integration". Even so, it is worthwhile reiterating that all pre-industrial growths were temporary and failed to generate sustained economic growth[17], either due to political economy factors (wars, vested interests, etc.), the diminishing returns associated with trade or with particular technological avenues, a low level of the knowledge base (and the skill-technology complementarity) or a small organizational base (before the factory system).

[17] As Goldstone (2002: 341) puts it: “What all [pre-industrial growth spurts] failed to do, however, was to sustain a sharply rising level of per capita income past two or three generations of population growth. Thereafter, innovation ceases or provides diminishing returns as vested interested and conservative states or churches halt the pace of change in knowledge and technology”

It is also noticeable that most of these growth spurts not only led to a temporary rise of living standards, but also often were periods of technological improvement. New technologies as well as institutional innovations were introduced during many of these growth episodes (de Vries 2001, Goldstone 2002). Still, after these growth spurts were over, technological and institutional innovations were not lost and, sooner or later, were diffused to other regions, which would then use and perfect these innovations during their own growth spurts[18]. For instance, in the Italian growth spurt there was both explicit technological borrowing from China (e.g. cotton weaving), as well as endogenous technological innovations (e.g. Zonca's silk-throwing machine powered by water) and many institutional advances (such as the *commenda*). In turn, during their Golden Age, the Dutch used extensively many institutional and technological advances of the Italians.

We should also point out that the timing of many of these growth spurts correlated well with changes in technological leadership. Thus, for instance, many of the European growth spurts correspond to the technological leaders of the period in question. In fact, as Epstein (2005: 1) emphasizes:

> "The geographical location of technological leadership in premodern Europe moved over time. Between the eleventh and the nineteenth centuries, Europe's technological frontier shifted increasingly north-west: from the east-central Mediterranean to northern Italy during the thirteenth and fourteenth centuries, to southern Germany and Bohemia in the late fifteenth, to the southern Low Countries in the sixteenth, to the Dutch Republic and finally to Britain during the seventeenth and eighteenth... *Each new regional leader added the innovations of its predecessors to its local technical stock and recombined them for further technological advances*." (our emphasis)

In addition, the empirical evidence on growth spurts also corroborates Mokyr's (1999) argument that the main difference between the growth episodes before and after the Industrial Revolution is the "irreversibility of events". Growth is not unique to the modern era, but substantial

[18] There are some examples of technological reversion after a growth spurt, but not many, the most touted of which is probably the Chinese "forgetting" the invention of the clock during the Sung dynasty and rediscovering it when Europeans arrived at their shores centuries later.

compound growth is. And thus the inevitable question arises: why did the nature of growth change with industrialization? On the one hand, institutional development seems to have been part of the story, especially to keep growth going in the 19th century (Mokyr 2005). Acemoglu, Johnson and Robinson (2005) also argue that institutional development was crucial for the industrialization process. On the other hand, institutions can only be part of the answer, since Epstein (2005) presents evidence suggesting that the institutions associated with the technological advances of the Industrial Revolution were not fundamentally different from those a century earlier. In this sense, two additional factors seem to be responsible to translate the Industrial Revolution growth spurt into modern economic growth. First, by the late 18th century, the knowledge base seems to have achieved a critical mass, after which some sort of 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 (Lipsey, Carlaw and Bekar 2006) as well as by the unprecedented increase in human capital that took place in the centuries preceding industrialization, with literacy rates of many countries increasing more than fourfold from 1500 to 1800[19] (Table 1). Second, by introducing the factory system, the industrialization process led to an organizational revolution, which 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. The arrival of the factory system changed all this and the industrialization growth spurt became permanent.

[19] While literacy rates did not improve substantially during the British Industrial Revolution (Mitch 1999), when we take a long-run view of human capital accumulation it is undeniable that there was dramatic improvement of this variable.

Table 1 _ Literacy in selected countries and regions, 1500-1800

Country	Literacy in 1500	Literacy In 1800	Country	Literacy in 1500	Literacy in 1800
Austria	6	21	Eastern Europe	1	4
Belgium	10	49	Russia	1	4
France	7	37	USA	-	50
Germany	6	35	UK	10	52
Italy	12	22	China	7	18
Netherlands	10	68	India	2	3
Sweden	10	85	Japan	7	27
Portugal	1	10	Other Asia	3	3
Spain	1	20	Africa	-	2

Source: European data are from Cipolla (1969), Cressy (1980), and Stone (1954). China's figures are from Rawski (1979), Japan's from Dore (1965) and Passin (1965), USA's were extrapolated from Lockridge (1965), India's from Parulekar (1957), and Africa's were extrapolated from Maddison (2001)

Similarly, the recent unified growth theory emphasizes that a major distinction between Malthusian and modern economies is the skill-technology complementarity (Galor and Weil 2000). In the context of development economics, Lloyd-Ellis and Roberts (2002) also assert that human capital and technological change are twin engines of growth. According to them, skills and technology are static complements in production and dynamic complements in the growth process. Lloyd-Ellis and Roberts show that human capital and technology are equal partners in economic development, and that sustainable economic growth cannot be generated without one of them. The importance of the skill-technology complementarity also seems to be corroborated by the existing historical evidence, especially when we take into account the organizational changes brought by the factory (Pereira 2004). The next section presents a model of growth spurts, which entails the existence of multiple equilibria and historical poverty traps in pre-industrial economies.

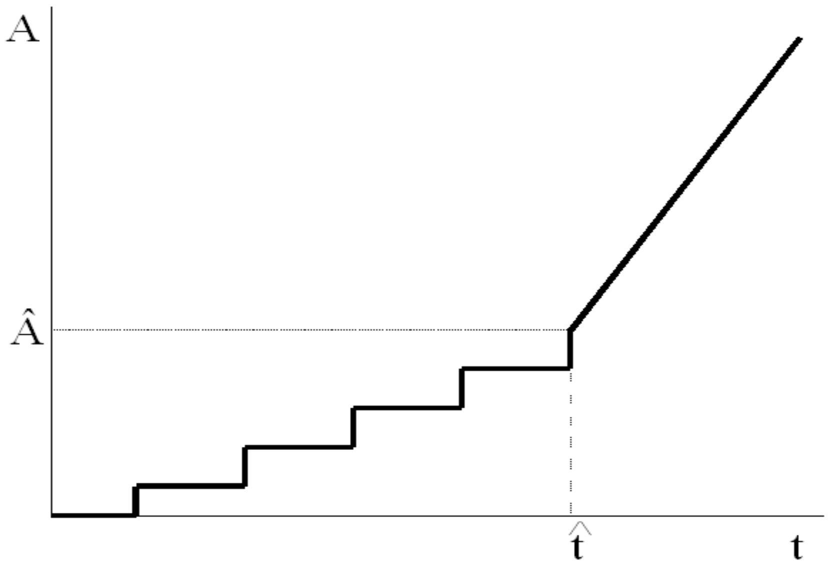
4. Modeling Growth Spurts

Modeling growth spurts in the context of unified growth theory is not completely novel. In a recent paper, Voigyländer and Voth (2005) develop a model in which exogenous positive agricultural shocks have the potential to bring about an Industrial Revolution. Similarly, Lagerlöf (2005) provides reasonable numerical parameters to the Galor-Weil (2000) model and finds that the time paths for population and the remaining variables display oscillatory behavior, that is, they generate endogenous cycles. As mentioned above, the historical literature has also emphasized the importance of growth spurts in any explanation of pre-industrial growth.

In our research, growth spurts are an intrinsic feature of the economy, although throughout history their effect on standards of living is mostly temporary. The rise in living standards only becomes sustained when the complementarity of the triple engines of growth (human capital, technology and organization) emerges. In Malthusian economies, most technologies are basic and only require straightforward knowledge or human capital, and thus the skill-technology complementarity does not play a role in their development. As a consequence, most technological developments in Malthusian economies generate growth spurts that do not become sustained, although there is a temporary increase in standards of living. In these growth spurts, there is capital accumulation and temporarily higher living standards, but no sustained productivity improvements. In opposition to the Malthusian era, the increasing complexity of the epistemic knowledge base (Mokyr 2002) implies that investments in applied technology become progressively more significant, enhancing the role of human capital. After a certain threshold of the knowledge base is surpassed, more and more complex applied technologies are developed, and growth spurts became permanent features of the economy.

In graphical terms, pre-industrial growth spurts can be thought as stepwise increases in the level of technology, A. Thus, when $t < t\^{}$ then $A < \hat{A}$, implying that the knowledge base is too small to generate sustained increases in A, and growth spurts are only temporary. When the knowledge base achieves a critical mass (when $A > \hat{A}$) increases in technology become sustained. As a consequence, growth spurts taking place after t^ will become permanent, and compound economic growth follows.

Figure 13 _ Growth Spurts and Technological Change

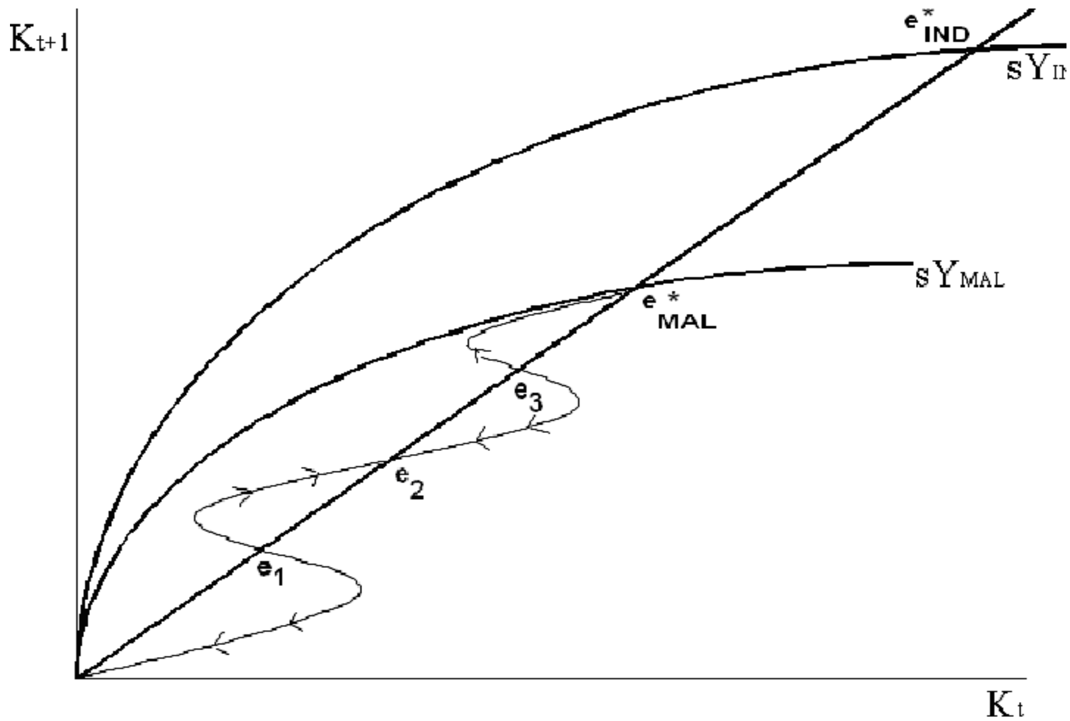


Another feature of modeling pre-industrial economies is captured well by the literature on poverty traps, which has been one of the most dynamic in development economics and macroeconomics in the last few years[20]. A poverty trap can be defined as "any self-reinforcing mechanism which causes poverty to persist" (Azariadis and Stachurski 2005), and can be produced by a plethora of mechanisms, including "scale economies in production, incomplete financial markets, economic and political institutions that privilege the well-to-do or simply work poorly, and social norms" (Bowles, Durlauf and Hoff 2006: 11). Poverty traps lead to self-reinforcing mechanisms and to non-ergodic growth processes (Mookherjee and Ray 2001). Consequently, poverty traps entail the existence of multiple equilibria and possibly critical thresholds that are necessary to surpass in order for an economy to go from a low-level equilibrium

[20] For a recent survey on poverty traps see Azariadis and Stachurski (2005). Research on poverty traps also includes Azariadis and Drazen (1990), Azariadis (1996), Bowles, Durlauf and Hoff (2006), Galor and Tsiddon (1991), Mookherjee and Ray (2001), Ray (2000). Classical works on the topic include Nelson (1956) and Rosenstein-Rodan (1943).

to a higher steady state. Not surprisingly, the concept of poverty traps is particularly suited to analyze the transition from Malthus to Solow. In fact, Malthusian traps can be seen as the ultimate historical “poverty” traps, in which economies remained for centuries in a low-level equilibrium. In this sense, and paraphrasing Azariadis and Stachurski (2005), a historical poverty trap can be defined as any self-reinforcing mechanism that causes a Malthusian trap to persist. However, as the empirical evidence suggested, Malthusian economies were not completely static, since these long periods of low-level equilibrium were punctuated by income increases that took the economy above subsistence. As we argued above, the historical evidence suggests that economies were evolving through time, not only because of the gradual increase in the knowledge base *lato sensu*, but also because there were growth spurts that often (although not always) took economies to a higher equilibrium level of income (at least temporarily). These growth spurts or golden ages were periods of technological and institutional advances. Thus, the empirical evidence suggests that “Malthusian” economies had several (low-level) equilibria, and that growth spurts had the potential to take an economy to a higher equilibrium. The latter would be characterized by higher population, higher income and better technology. These ideas are synthesized in Figure 14, which combines historical poverty traps with the notion of shifting equilibrium that was found in pre-industrial economies. Suppose that there are types of economies: Malthusian (MAL) and modern or industrialized (IND). Due to the existence of poverty traps, it is possible for an economy to remain trapped in a low-level equilibrium. In this diagram, there are several Malthusian equilibria, two unstable (when $K_t = 0$, e_1 and e_3) and two stable (e_2 and a high-level Malthusian equilibrium, e^*_{MAL}). As in a typical poverty trap model, nothing guarantees that economies necessarily get to the high steady-state equilibrium e^*_{IND}. However, as argued in the previous section, Malthusian economies can go through different growth trajectories, and an economy at e^*_{MAL} is substantially better off than at e_2, being richer and more capital abundant

Figure 14 _ Poverty Traps in Mathus to Solow



Furthermore, figure 14 implies that before an economy reaches the high steady-state industrialized equilibrium, it has to get to e^*_{MAL}. For instance, in historical terms, e_2 would represent Western Europe in, say, the 14th century, whereas, at the outset of the Industrial Revolution, Europe would be already at e^*_{MAL}. The highest Malthusian steady state e^*_{MAL} is thus a critical threshold that has to be surpassed in order for economies to able to industrialize (or modernize).

4.I. The Basic Model Setup

Before we present the model, it is convenient to notice that since we want to consider economy-wide variables it is satisfactory to use a continuous-time approach. This approach, however, lacks realism at the family level, because it neglects the integer restriction on the number of children[21]. Therefore, we consider a continuous version of the Barro-Becker model, [Becker and Barro (1988); Barro and Becker (1989)] where the agent's utility is derived from consumption and the number of children.

a. Birth and Deaths

When using a continuous-time approach, we must treat births and deaths as continuous flows, and thus N_t –population at time t– not as the integer number of individuals, but rather the measure of an interval, populated by a continuum number of agents. Letting $n \geq 0$ be a family's birth rate and $d > 0$ the mortality rate, we know that: a) Families decide how many children they want (i.e. n is treated as a choice variable at any point in time); and b) The mortality rate depends on health expenditure by families, sanitation and age. For tractability reasons, we ignore the latter. Under these conditions, population size changes according to:

$$\dot{N} = (n - d)N \tag{1.1}$$

With the initial value of population at time zero given by N_0.

b. Preferences

The representative agent maximizes the discounted utility of her dynasty, born at time zero, and this can be represented in a general form by:

$$\Omega_0 = \int_0^{\infty} N_t \theta_t U\left(c_t, n_t, d_t\right) e^{-\rho t} dt \tag{1.1}$$

where θ_t denotes the weight function of generation t. In other words, if $\theta_t = 1$ the parent attaches a weight equal to unity for his children's utility regardless of the size of the family, i.e. the utility is just the sum of individual's utility levels. This is called the "*complete altruism or egalitarian case".* In

[21] For a more detailed discussion see Barro and Sala-i-Martin (2004) section 9.2.2 page 411, in particular how to modify the discrete time model into a continuous approach

contrast, if $\theta_t = N_t^{\varpi - 1}$ we have the "*incomplete altruism case"* reflecting the fact that individuals in larger generations are systematically less taken care of than individuals in smaller generations. In addition if $\varpi = 0$ we get that only the average utility of each child counts for the parent and the altruistic concern is minimized. Another way to account for this is to rewrite (2) as:

$$U = \int_0^\infty N_t^{1-\psi} U\left(c_t, \bar{c}\right) e^{-\rho t} dt \qquad (1.2')$$

Where the complete altruistic case is given by $\psi = 0$ (also known as a Benthamite social welfare function), whilst the altruistic concern is decreasing with ψ. At the other extreme we have $\psi = 1$ and only the average utility of each child counts for the parents (a Millian social welfare function).

The first "*Malthusian"* component of our model reflects the fact there is a subsistence level of consumption, $\bar{c}$, representing the amount of consumption below which individuals cannot survive. In other words, it represents the minimum level of consumption required to allow for the satisfaction of the minimum basic needs of life[22]. Steger (2000) provides an analysis of the empirical relevance of subsistence consumption, and concludes that whilst it seems to be of minor importance (irrelevant) for middle (high) income economies, it is quite relevant for low-income economies. The requirement of subsistence consumption can be formalized by the use of Stone-Geary preferences, yielding:

$$U\left(c, \bar{c}\right) = \frac{\left[\left(c - \bar{c}\right)\right]^{1-\sigma}}{1-\sigma} \qquad (1.2)$$

Where σ reflect the inverse of the intertemporal elasticity of substitution. The traditional Stone-Geary preferences are consistent with the existence of poverty traps. The explanation is that poor families will not save until they have more income than the necessary to meet their basic needs,

[22] The World Bank uses this notion by defining the cost required to sustain an individual's dietary needs and thus define a poverty line. In 1990, the World Bank used two measures of poverty lines. A lower poverty line of $275, and an upper poverty line, measured in 1985 PPP prices, amounting to $370.

but, once these needs are met, households begin to save and they may even save enough to move them away from the poverty trap they were in. In our model, preferences take the form:

$$\Omega = \int_0^{\infty} N_t^{1-\psi} \frac{\left[\left(c-\overline{c}\right)\right]^{1-\sigma}}{1-\sigma} e^{-\rho t} dt \tag{1.3}$$

Although Stone-Geary preferences by themselves generate multiple equilibria, in our model the presence of multiple equilibria is reinforced by the introduction of a state variable (population) in the objective function[23]. Another important aspect is that the traditional Stone-Geary preferences are ill specified if $c < \overline{c}$, since this implies a negative marginal utility of consumption. In this case, consumption is below subsistence, and the utility loss is infinite. For consistency purposes we assume this also holds. By combining these two assumptions we can eliminate the issue of multiplicity of equilibria, and still retain the poverty trap, by defining the utility function in line with the assumption made by Galor and Weil (1998), to yield:

$$U(c) = \begin{cases} \frac{\left[\left(c-\overline{c}\right)\right]^{1-\sigma}}{1-\sigma} & \text{if } c \geq \overline{c} \\ -\infty & \text{if } c < \overline{c} \end{cases} \tag{1.4}$$

c. Production of final output

We consider that production takes place according to a simple neoclassical production function with constant return to scale technology that requires three inputs. The first input is labour, N, whose supply depends on the endogenous fertility decisions of each family. The second input is land (L) and is in fixed supply. This factor accounts for the second "*Malthusian*" component of the model. Finally we have technology, T, which will allow us to measure the inputs in efficiency units, rather than in physical units. Specifically, let us define efficiency-unit coefficients $T_t = \left(A_t, B_t\right)_{t=0}^{\infty}$ for labor and land specifically. In the absence of technological progress, output will not exceed the

23 See Kurz (1968).

subsistence level, and therefore the economy remains at the subsistence level of consumption. The production function can be represented as

$$Y_t = F\left(A_t N_t, B_t L\right) \tag{1.5}$$

It is worthwhile to make the following remarks. First, and similarly to what happens in Galor and Weil (2000), we assume there are no property rights over land so that the return to land is zero, while workers receive the marginal product of their work, i.e. $w = F_N \equiv w\left(N_t, \overline{L}, A_t, B_t\right)$. Second, we consider that production can be allocated between consumption and the cost of having children, which for simplicity we assume is constant. In other words, we consider the rearing cost of having children to reflect education, parent time, health, food, etc; and for simplicity we assume the marginal cost of having one child, θ, is constant[24]. This yields:

$$Y_t = F\left(A_t N_t, B_t L\right) = N_t c_t + \theta N_t n_t \tag{1.6}$$

d. Technology

We consider the link between population and technological progress by allowing technology to be a function of population size, i.e. our threshold depends on the level of population. This reflects the idea that a larger population size, allows for a faster diffusion of new ideas, and thus generates non-neutral technology progress. We consider a specification that resembles the one used by Azariadis and Drazen (1990), but with some adjustments. First, the threshold at which there is a "technological jump" is in terms of population and not physical capital. Second, we consider that the jump represents a change from neutral to non-neutral technological progress. In other words, we consider that up to a certain population level changes in technology are neutral, i.e. it affects the marginal product of both factors in the same proportion and thus leaves the

[24] In this model, we consider that saving (and thus investment) occurs in the form of children, because people are the sole form of capital. This assumption seems reasonable in a predominantly agrarian, pre-industrial economy, i.e. the type of society we are considering in this paper.

production shares unchanged. Once the economy, passes that technological threshold, technological progress favors one factor over the other, and the input shares in production is modified accordingly. This approach yields,

$$T\left(N_t\right)\begin{cases}\text{neutral technological progress} & \text{if } T<\tau \\ \text{non-neutral technological progress} & \text{if } T>\tau\end{cases} \tag{1.7}$$

The intuition for this specification is that the first technological discoveries represent basic and general-purpose discoveries, like a shovel or a plough, and they affect the marginal product of both sectors proportionally. This kind of transfer is reflected in an increase in the steady state level of population, while steady state consumption remains unchanged. The equilibrium in this case is back at the Malthusian equilibrium, i.e. same population and subsistence consumption. At a later stage, when the economy has accumulated enough technology and/or when new discoveries begin to have a larger impact in substituting labor by machines or in the reorganization of labor, the steady-state equilibria are affected and the economy moves away from the Malthusian trap.

As the coefficients $\left(A_t, B_t\right)$ change over time, and we are still under a neutral technological progress, technical progress is:

_ Harrod-neutral if $A_t = A_0$ and $B_t > B_{t-1}$ for all t

_ Hicks-neutral if $A_t > A_{t-1}$ and $B_t > B_{t-1}$ for all t

_ Solow-neutral if $A_t > A_{t-1}$ and $B_t = B_0$ for all t

For instance, if one uses a CES production function, this becomes:

$$Y_t = \left[a\left(Le^{\delta t}\right)^{-\rho} + b\left(Ne^{\lambda t}\right)^{-\rho}\right]^{-1/\rho} \tag{1.8}$$

Where $A_t = e^{\lambda t}$ and $B_t = e^{\delta t}$. If $\delta = \lambda$, technological progress is Hicks-neutral, whilst if $\lambda = 0$ technological progress is Harrod-neutral[25]. We draw on Hung and Makdissi (2004) result that as long as the technological progress is neutral it does not matter if technological progress is endogenous or exogenously determined. The final result of neutral technological progress is an increase in population while consumption remains at the subsistence level. This effect is altered when we introduce non-neutral technological progress. Given the same end result, we do not consider the case where the increase in technology requires the agent to devote some time to research. Finally, combining expression (1.1) with(1.7) yields:

$$\dot{N}_t = \frac{F\left(A_t N_t, B_t L\right)}{\theta} - \frac{c_t N_t}{\theta} - dN_t \tag{1.9}$$

The agent's problem is to maximize (1.4) subject to (1.10) while keeping in mind equation (1.8) and the conditions that $c - \overline{c} \geq 0$ and $n_t > 0$. (1.10)

II. Macroeconomic Equilibrium

The Hamiltonian to this problem is given by

$$H\left(c, N, \lambda_1, \lambda_2\right) = N^{1-\varepsilon} \frac{\left(c_t - \overline{c}\right)^{1-\sigma}}{1-\sigma} + \lambda_1 \left(\frac{F\left(A_t N_t, B_t L\right)}{\theta} - \frac{c_t N_t}{\theta} - dN_t \right) + \lambda_2 \left(c_t - \overline{c}\right) \tag{1.11}$$

Where λ_1 represents the shadow value of one extra child, and λ_2 is associated with condition (1.5) necessary to ensure an interior solution, i.e. $c - \overline{c} > 0 \Rightarrow \lambda_2 = 0$. The maximum principle yields:

$$N_t^{1-\varepsilon} \left(c - \overline{c}\right)^{-\sigma} + \lambda_2 - \lambda_1 \frac{N_t}{\theta} = 0 \tag{1.12}$$

[25] A possible approach to solving the model is to use the CES production function and then differentiate the neutral from the non-neutral case by making assumptions about the parameters

$$\dot{N}_t = \frac{F\left(A_t N_t, B_t L\right)}{\theta} - \frac{c_t N_t}{\theta} - dN_t \quad (1.13)$$

$$\dot{\lambda}_1 - \rho\lambda_1 = -\frac{1-\varepsilon}{1-\sigma} N_t^{-\varepsilon}\left(c_t - \overline{c}\right)^{1-\sigma} - \lambda_1\left[\frac{A_t F_N\left(A_t N_t, B_t L\right)}{\theta} - \frac{1}{\theta}c_t - d\right] \quad (1.14)$$

$$\lambda_2\left[c_t - \overline{c}\right] = 0; \lambda_1 \geq 0; \left[c_t - \overline{c}\right] \geq 0 \quad (1.15)$$

$$\lim_{t\to\infty} e^{-\rho t} N_t \lambda_1 = 0; \lim_{t\to\infty} e^{-\rho t} \lambda_1 \geq 0; \quad (1.16)$$

Where $F_x = \partial F/\partial x$, and to simplify the notation we write F_N instead of $F_N\left(A_t N_t, B_t T\right)$. The interpretation of the conditions (2.2)-(2.4) is standard. Expression (2.2) is the traditional arbitrage condition between the marginal utility of consumption and the current marginal cost of one extra child. Equation (2.4) reflects the equality between the rate of return of investing in children to the rate of time preference[26]. Finally, recalling the interior solution as expressed by (1.5) leads to expression (2.5). Differentiating (2.2) with respect to time and using (2.3) and (2.4) yields the equation describing the adjustment of consumption,

$$\dot{c}_t = \frac{\left(c_t - \overline{c}\right)}{\sigma}\left[\frac{A_t F_N\left(A_t N_t, B_t L\right)}{\theta} - \frac{\varepsilon F\left(A_t N_t, B_t L\right)}{\theta N_t} - \left(\rho + \left(1-\varepsilon\right)d\right) - \frac{1-\varepsilon}{\left(1-\sigma\right)\theta}\left(\overline{c} - \sigma c_t\right)\right] \quad (2.7)$$

Imposing the steady state conditions, $\dot{N}_t = \dot{c}_t = 0$, yield two equations that can be solved simultaneously, in order to obtain the steady-state values of consumption and population. Setting $\dot{N}_t = 0$ yields:

$$c_t = \frac{F\left(A_t N_t, B_t L\right)}{N_t} - \theta d \quad (1.17)$$

Whilst setting $\dot{c}_t = 0$ gives:

[26] Remember that we considered that the effect of N on ideas is not internalized by the firm when making its decisions.

$$\begin{cases} c_t - \overline{c} = 0 & \text{when } \lambda_2 > 0 \\ c_t - \dfrac{\overline{c}}{\sigma} + \dfrac{(1-\sigma)}{(1-\varepsilon)\sigma}\left[A_t F_N(.) - \dfrac{\varepsilon F(.)}{N_t} - \theta\left[\rho + (1-\varepsilon) d\right]\right] = 0 & \text{when} \lambda_2 = 0 \end{cases} \tag{1.18}$$

Solving both expressions simultaneously we get the steady state solution to the model:

$$\hat{c} = \frac{1}{\sigma - \varepsilon}\left[(1-\varepsilon)\overline{c} + (1-\sigma)\theta(\rho + d) - (1-\sigma)A_t F_N\right] \tag{1.19}$$

$$\frac{F\left(A_t \hat{N}_t, B_t L\right)}{\hat{N}} = \hat{c} + \theta d \tag{1.20}$$

If we denote the steady state by *, the information can be summarized as:

$$c^* = \begin{cases} \overline{c} & \text{if } \overline{c} > \hat{c} \\ \hat{c} & \text{if } \overline{c} \le \hat{c} \end{cases} \tag{1.21}$$

$$\frac{F\left(A_t N_t^*, B_t L\right)}{N_t^*} = \begin{cases} \left(\overline{c} + \theta d\right) & \text{if } \overline{c} > \hat{c} \\ \left(\hat{c} + \theta d\right) & \text{if } \overline{c} \le \hat{c} \end{cases} \tag{1.22}$$

Along the optimal path, the steady state must be larger than the subsistence level. Using (2.10), it implies that $\left((1-\sigma)/\sigma - \varepsilon\right)\left[\overline{c} + \theta(\rho + d) - A_t F_N\right] > 0$. Notice we cannot make any judgment about the parameters unless we make further assumptions.

III. Transitional Dynamics.

The aim of this section is to show that our model can replicate the empirical evidence presented in the previous sections. In general, we show that as long as technological progress is neutral, and the economy has not reached a certain population level, the economy will experience growth spurts that die out. Therefore, under this condition the long-run implication of technological progress is an increase in population, but consumption remains at the subsistence level. Once the economy has achieved a certain level of technology, technological progress becomes non-neutral, i.e. affects the productivity of one factor relative to the other, and this gives the growth spurts a permanent character. The first step is to analyze the type of equilibrium given by $\left(\hat{N},\hat{c}\right)$. In order to do this we linearize the system around the steady state and characterize the equilibrium by looking at the determinant. We then proceed to do the phase diagram analysis.

The linearized system of expression (2.3) and (2.7) is:

$$\begin{bmatrix} \dot{N}_t \\ \dot{c}_t \end{bmatrix} = \begin{bmatrix} \frac{A_t F_N}{\theta} - \frac{c_t}{\theta} - d & -\frac{N_t}{\theta} \\ Z_1 a_{21} & Z_1\left(\frac{(1-\varepsilon)\sigma}{(1-\sigma)\theta}\right) \end{bmatrix} \tag{2.1}$$

Where $Z_1 = \frac{c - \overline{c}}{\sigma}$ (2.2)

$$a_{21} = \frac{A_t^2 F_{NN}\left(A_t N_t, B_t L\right)}{\theta} - \frac{\varepsilon A_t F_N\left(A_t N_t, B_t L\right)}{N\theta} + \frac{\varepsilon F\left(A_t N_t, B_t L\right)}{\theta^2 N^2} \tag{2.3}$$

The determinant is:

$$\Delta = \frac{Z_1}{\theta^2}\left[A_t^2 F_{NN} N_t + \frac{(\varepsilon-\sigma)}{1-\sigma}\left(\frac{F\left(A_t N_t, B_t L\right)}{N} - AF_N\right)\right] \tag{2.4}$$

A few comments are needed about the determinant. First, Hung and Makdissi (2004) show that if $0 < \varepsilon < \sigma$ the solution path satisfying conditions (2.2)-(2.6) is optimal. Hence, we use that same condition in our model. Second, and as usual by the properties of the production function, $F_{NN} < 0$. Therefore, the sign of the determinant depends on $\left(\frac{F\left(A_t N_t, B_t L\right)}{N} - AF_N\right)$. This term is equal to the difference between the average and the marginal product of labour, which is positive under a Cobb-Douglas specification[27]. Thus, we consider this term to be positive, and hence the determinant is negative. This implies we have one positive and one negative root, and the equilibrium is saddle-path stable. The other possible equilibrium is the subsistence consumption, and this represents the poverty trap. If we have neutral technological progress, the economy will spend most of the time in the latter equilibrium. The equilibrium where the economy settles depends also on the parameters of the model and the starting point for this economy, N_0.

The phase diagram is straightforward with the only "complication" arising with the $\dot{c} = 0$ line, not only because we need to consider the two conditions defined by (2.12), but also because the slope is indeterminate and depends on the relation between the marginal product, the average product of labour and the second derivative of the production function. Starting with $\dot{N} = 0$, and using expression (2.8), the slope is given by:

$$\frac{dc_t}{dN_t} = \frac{A_t F_N}{N} - \frac{F(.)}{N_t^2} < 0 \tag{2.5}$$

and the arrows of motion are given by

$$\frac{\partial \dot{N}}{\partial c_t} = -\frac{N}{\theta} < 0 \tag{2.6}$$

Looking at $\dot{c} = 0$, expression (2.9), we see the slope is undetermined:

$$\frac{dc_t}{dN_t} = -\left[\frac{1-\sigma}{(1-\varepsilon)\sigma}\right]\left[A_t^2 F_{NN} - \frac{\varepsilon}{N}\left(A_t F_N - \frac{F(.)}{N_t}\right)\right] \tag{2.7}$$

And we have:

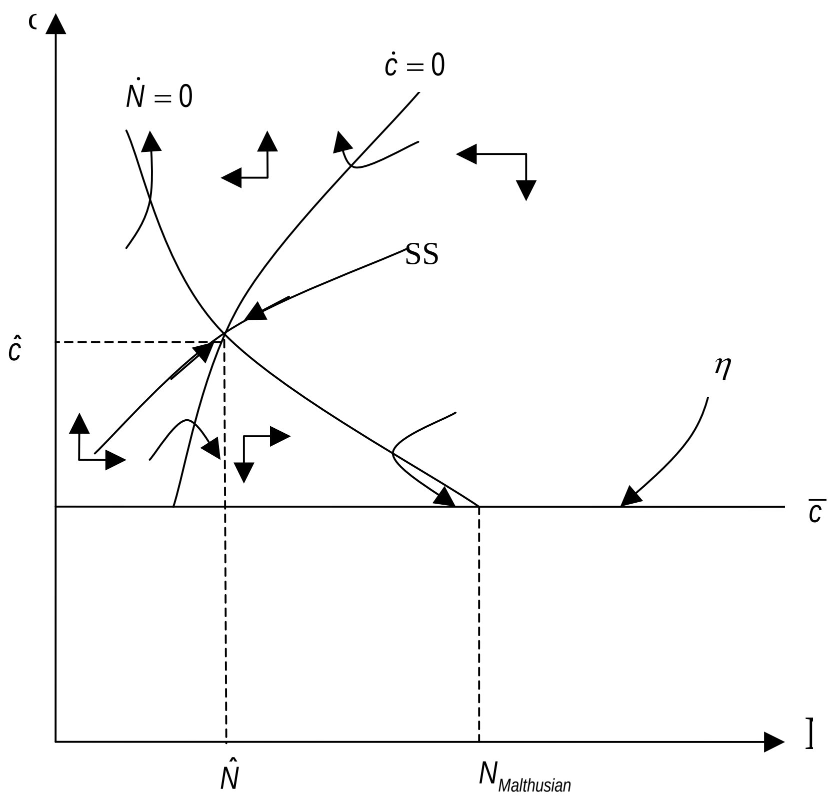
27 In addition, if one considers the stages of production, we know that firms should produce in stage two. At this stage, APL>MPL and the employment of additional variable inputs increase the efficiency of fixed inputs but decrease the efficiency of variable inputs. Maximum production efficiency must fall somewhere in this stage

$$i)\left[A_t^2F_{NN}-\frac{\varepsilon}{N}\left(A_tF_N-\frac{F(.)}{N_t}\right)\right]<0\rightarrow\frac{dc_t}{dN_t}>0$$

$$ii)\left[A_t^2F_{NN}-\frac{\varepsilon}{N}\left(A_tF_N-\frac{F(.)}{N_t}\right)\right]>0\rightarrow\frac{dc_t}{dN_t}<0$$

Fortunately, the behavior is similar for both cases, and thus we present the positive slope situation, i.e. i). This, in turn, implies that $\frac{\partial\dot{c}}{\partial N_t}<0$. Graphically, we have:

Figure 15 _ Phase Diagram



Before we proceed to analyze a technological shock, it is worthwhile to note the following:

a) The $\dot{c}=0$ and the $\dot{N}=0$ loci do not go below the subsistence consumption, because the utility is ill specified if consumption is below subsistence. We eliminate any equilibrium below subsistence consumption, with the assumption represented in expression (1.5).

b) The $\dot{c}=0$ line contains an upward section that determines the steady-state equilibrium by its intersection with the downward sloping line $\dot{N}=0$, and a horizontal section, where consumption equals subsistence consumption.

c) If $N_0>\hat{N}$ the economy adjusts to the Malthusian equilibrium, $\left(N_M,\overline{c}\right)$, along the η path. In fact the economy will follow this path until it reaches the consumption constraint, and then adjust along the subsistence consumption line

d) If $N_0<\hat{N}$ the convergence path sticks to the subsistence consumption, unless the economy starts at consumption level that puts the economy in the SS path, which insures the convergence to the optimal steady state.

e) Subsistence consumption serves as an attractor, when the economy is moving away from $\hat{c}$ due to some neutral technological shock.

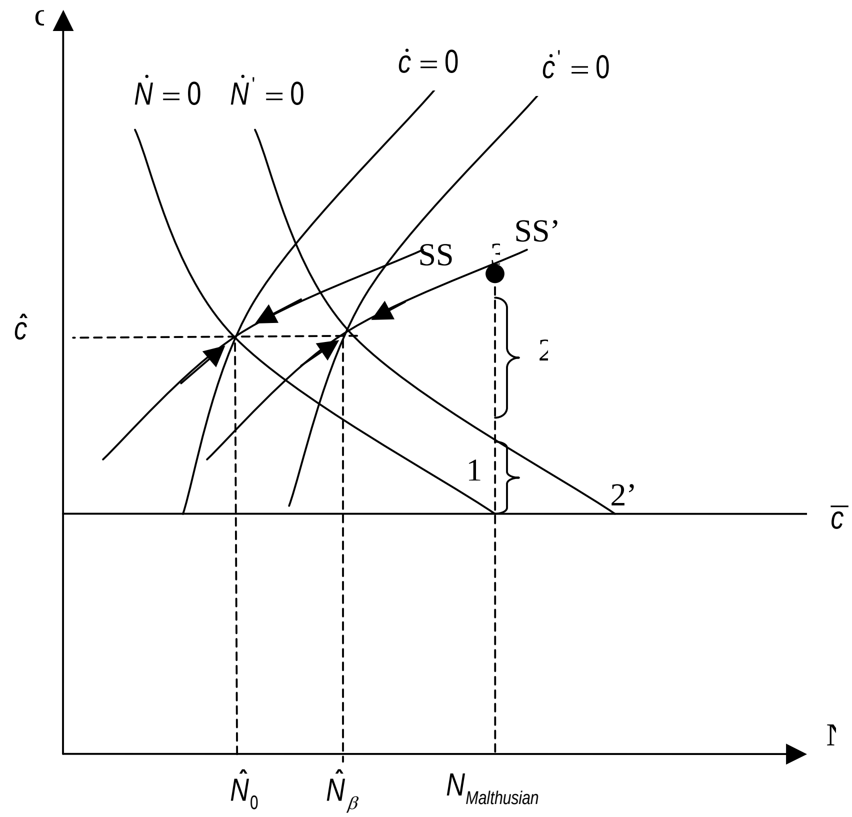
Point e) can be seen with the aid of graphical analysis. If technological progress is neutral, production shares are left unchanged, and thus marginal productivity of both factors changes in the same proportion. This type of technological progress can be represented simply by assuming that A=B in our specification. Therefore, in light of the constant returns to scale assumption, we can write the production function as $F\left(A_tN_t,B_tL\right)=A_tF\left(N_t,L\right)$. Assuming that our equilibrium was initially derived with a certain level of technology A, and we allow it to be increased by a factor β, the production function is represented as $\beta AF\left(N_t,L\right)$.

This type of technological progress results in a horizontal shift of both curves, because the production function appears in both steady state conditions. Graphically, we get that the steady state consumption is left unaffected, whereas the steady state level of population increases (Figure 16). In the short-run, population remains at the Malthusian level, while consumption jumps up. At first sight, the final equilibrium can occur at three possible places, depending on the jump in consumption. The jump in consumption defines where the economy equilibrium will be. If consumption at time zero jumps to region 1, the final equilibrium is the old Malthusian equilibrium. If the economy jumps to region 2, the new equilibrium is at point 2', with consumption at the subsistence level, but higher population. Finally, if the economy jumps to point 3 (the new stable path) the economy moves away from the Malthusian trap into new steady state equilibrium with the same consumption as before the technological shock, and higher population. Looking at (2.13), we see that the economy must jump to region 1, and thus remain at the same Malthusian equilibrium as before the shock.

If we consider the existence of a certain technology threshold at which technological progress stops being neutral and becomes non-neutral, then the story takes a different turn. Although technological progress is neutral, and the economy returns to the Malthusian poverty trap, the fact remains that the economy's knowledge base increases with increases in technology. It gets to a point that the economy has accumulated enough technology that induces a change in productivity of one input relative to the other. When that happens the economy moves away from the trap to the new equilibrium. In this discussion we will consider a shift in technological progress that brings about an increase in the marginal productivity of land relative to labor[28]. In our specification, it means that the increase in B is larger than the increase in A, but if we were to use the CES production function specification [expression (1.9)], this would imply that $\delta > \lambda$.

[28] We could look at input returns instead.

Figure 16 _ Neutral Technological Progress

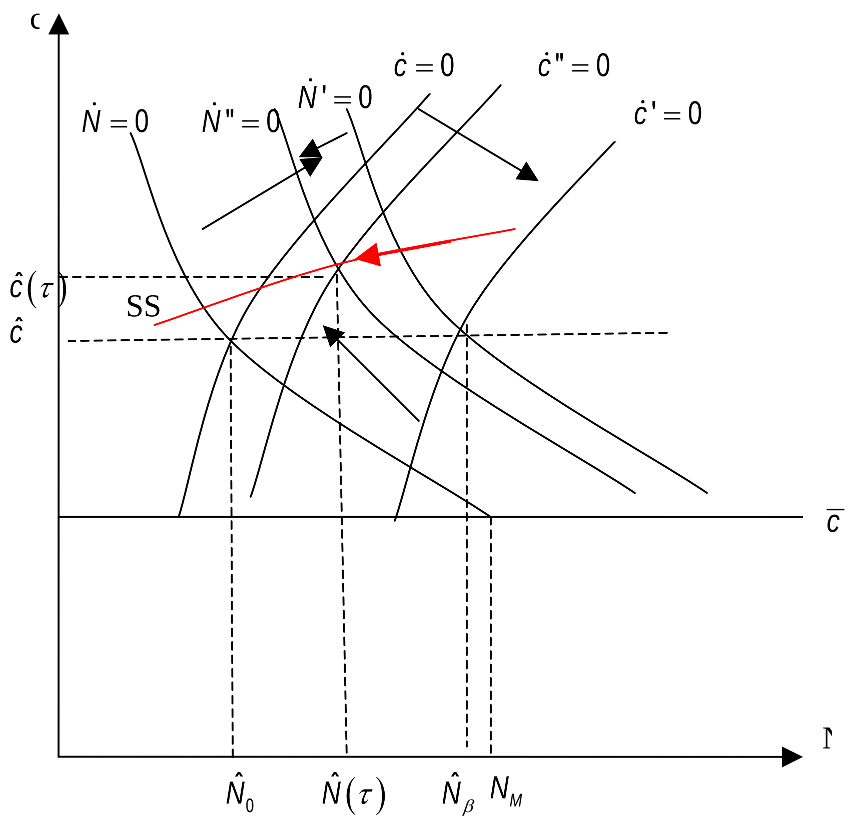


Graphically, this would imply that, we would first have a couple of shifts like the one pictured in Figure 16. However, when the threshold is achieved the technological process becomes non-neutral and the effect of technological progress is reversed, leading the curves to shift to the left. This is easier to understand if we assume like Hung and Makdissi (2004) that the production function is Cobb Douglas and that the technical shift parameter affects the exponent directly, i.e. $F(L,N,\tau) = L^{1-\gamma(\tau)}N^{\gamma(\tau)}$. If the marginal productivity of land increases, we must have $\gamma'(\tau) < 0$.

For simplicity, we leave the stable path out of the graphic and present only the stable path for the last equilibrium. Imagine that the economy has observed consecutive technological progress.

This technological progress, however, is neutral because the economy has not achieved the technology threshold. Therefore, the economy moves from curve $\dot{c}=0 \rightarrow \dot{c}'=0$ and $\dot{N}=0 \rightarrow \dot{N}'=0$. These shifts would continue until the economy reaches the technology threshold. (To make the graphic less complicated we present only one shift). In terms of equilibrium we see that the steady state consumption is not affected but population grows. As explained before, the economy remains at the Malthusian equilibrium.

Figure 17 _ Combination of both technologies



Once the economy reaches the technology threshold, technology progress becomes non-neutral and the adjustment is different and both curves shift left, i.e. $\dot{c}'=0 \rightarrow \dot{c}''=0$ and $\dot{N}'=0 \rightarrow \dot{N}''=0$. The economy adjusts along the SS path and escapes the poverty trap. This new equilibrium has a higher consumption and population level than the original equilibrium before the technological shocks. Compared to the intermediate steady state (the one with neutral technological progress), this represents an improvement in terms of consumption, but a decrease in terms of population. This effect on population is a consequence of the type f technology bias we have analyzed. However, please note that during the neutral technological shocks the economy remains at the Malthusian trap, because of the magnitude in the jump in consumption.

5. Conclusions

This paper presents empirical evidence that suggests that pre-industrial economies were much more dynamic than many of our growth models assume. Growth spurts (and not generalized stagnation) were an intrinsic feature of the pre-industrial world, during which often there were several technological and institutional advances, even if trade was the initial cause of the growth spurt.

All in all, our model replicates important features of pre-industrial growth spurts and the start of sustained growth. The paper adds to the existing unified growth literature by providing empirical evidence on pre-industrial growth spurts and by explicitly modeling the changes on the nature of growth during the transition from Malthus to Solow

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APPENDIX: *Labor Shocks and the Nature of Growth: a VAR approach*

Did the nature of shocks change with industrialization? Were labor supply shocks more important than labor demand shocks in pre-industrial economies? These questions are important to understand whether or not the nature of growth has changed with industrialization. In order to observe the nature of these shocks, we can look at the dynamic relationship between real wages and population 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):

$$x_t = \mu + \sum_{j=0}^{\infty} \phi_i \varepsilon_{t-j} \qquad (4)^{29}$$

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

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

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[30]. 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)[31]. As we can see in Figure 9a, 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,

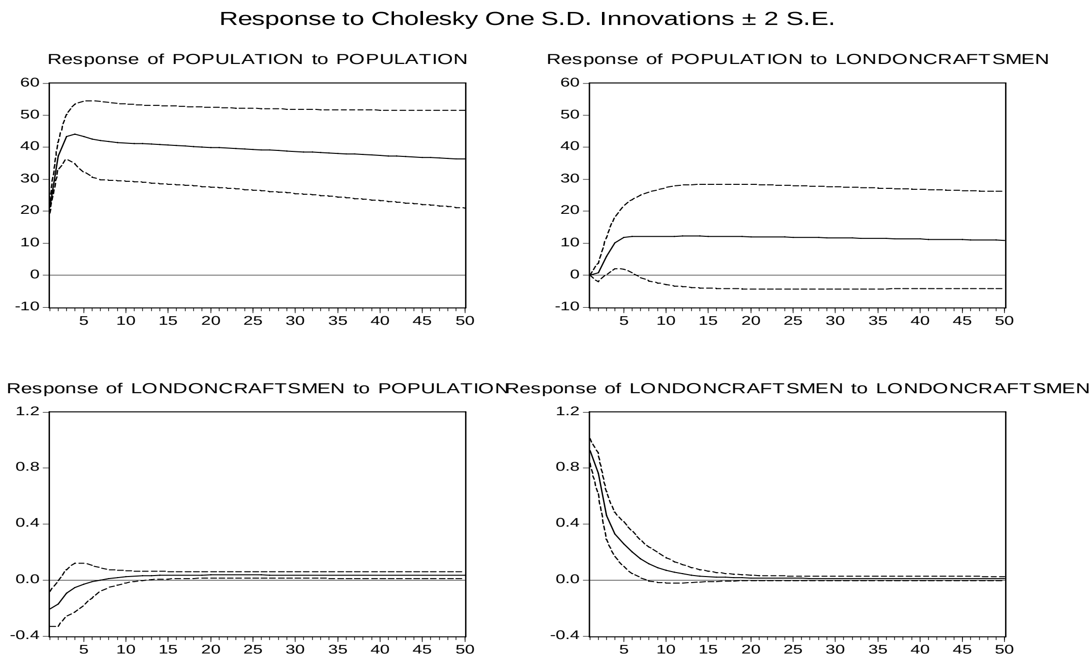
[29] e_i are the white-noise disturbances for a VAR in standard form, whereas ε_I are the errors terms for a structural VAR. Chapter 2 presents the formal relationship between them for a VAR of order 1.

[30] 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

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

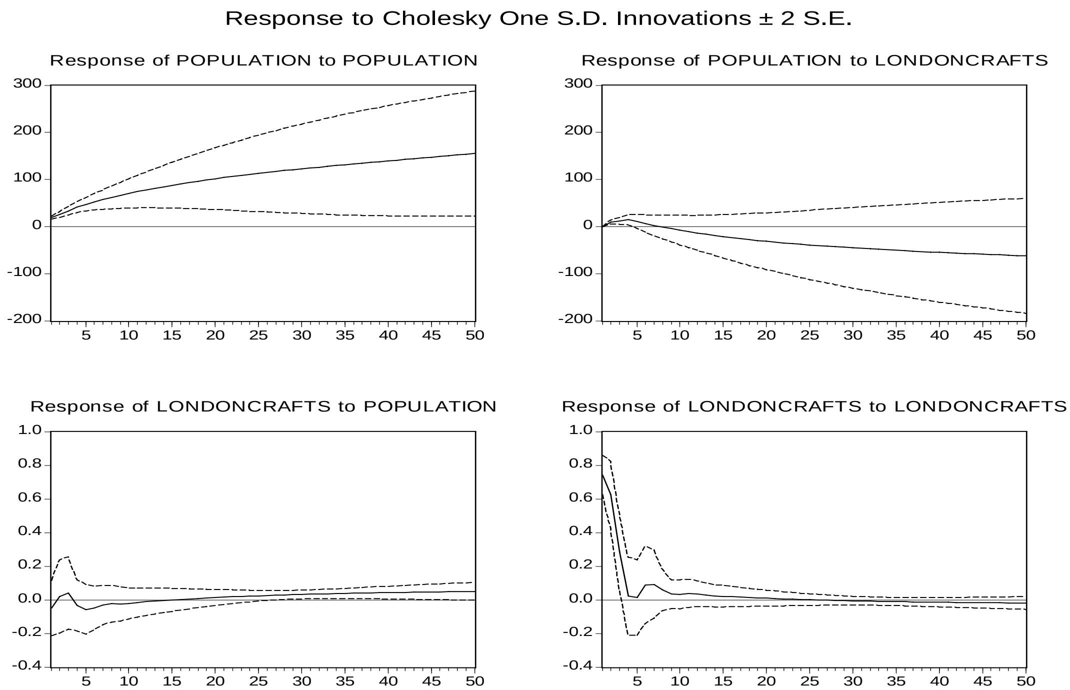
before the Industrial Revolution, population responded positively to an increase in real wages. The response of craftsmen's real wages to its own shock leads to a temporary increase of real wages of about 10 percent (the average real wage for the period was about 10 grams of silver), but the effect of 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[32]. 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



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}

[32] 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.

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

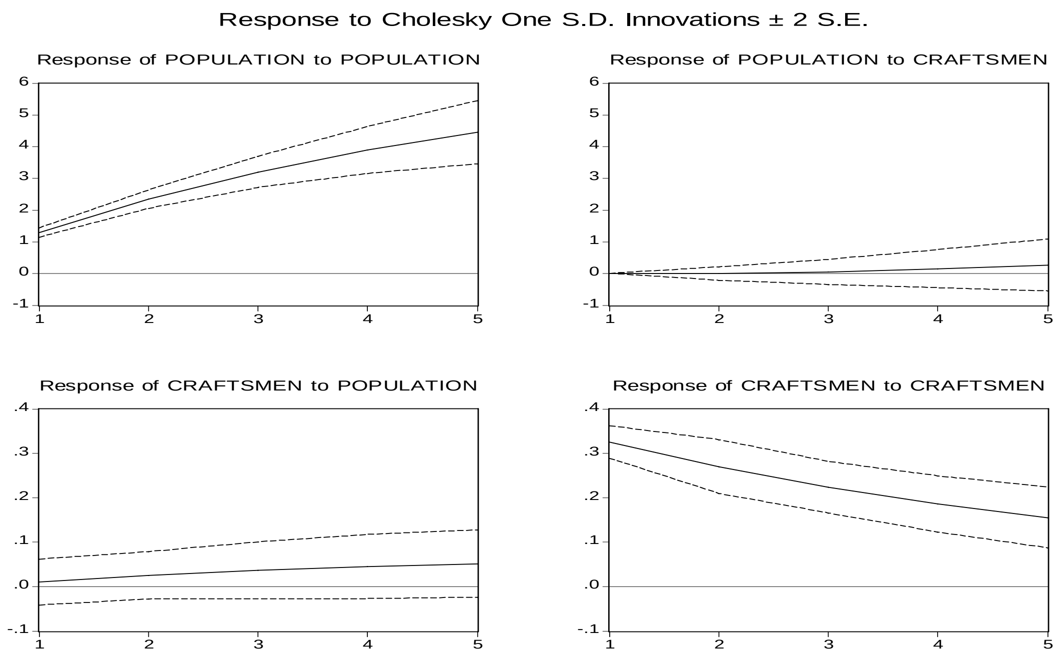


Figure 9d: Amsterdam Craftsmen 1650-1800

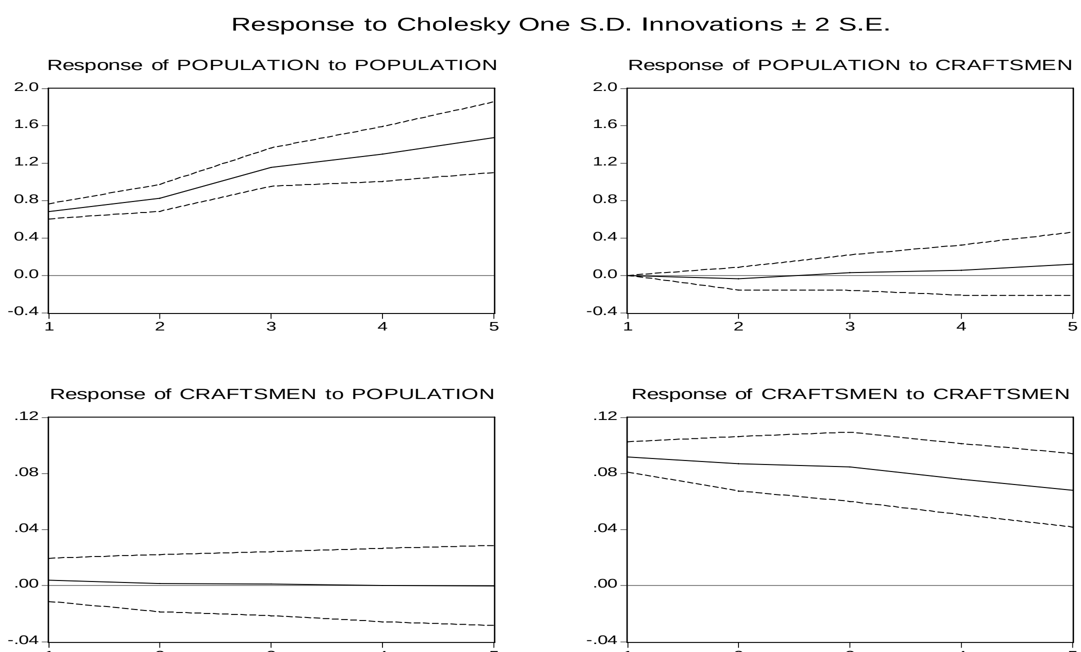
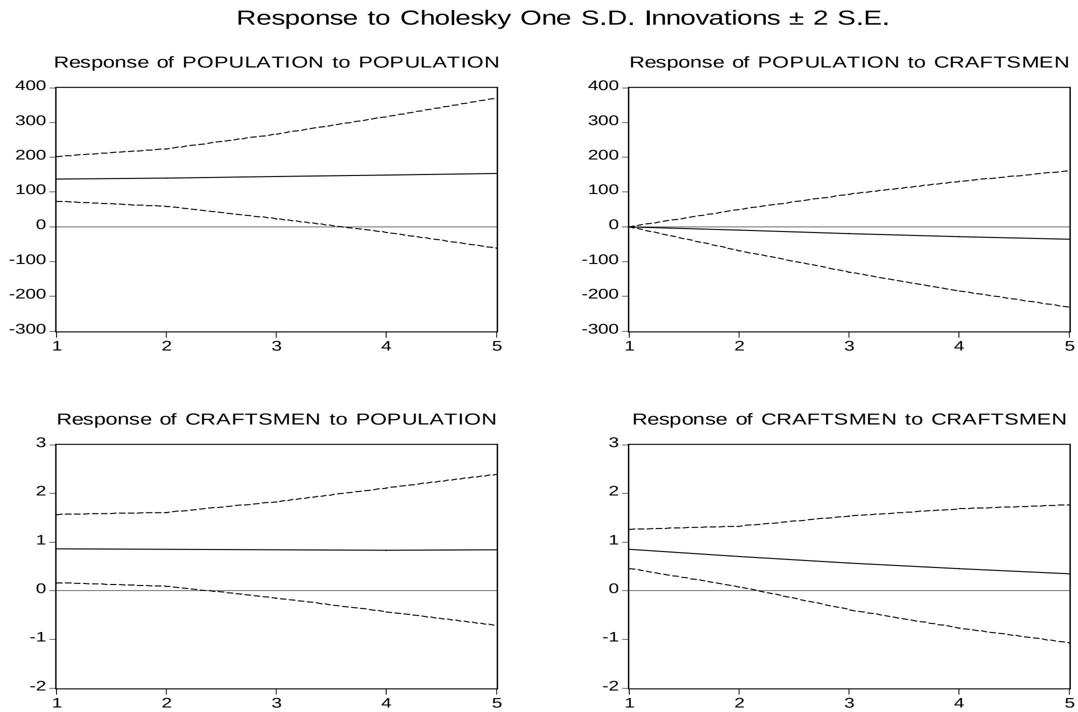


Figure 9e: Amsterdam Craftsmen 1800-1900



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 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.