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The evolution of markets and the revolution of industry: a unified theory of growth

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Abstract This paper puts forth a theory of the *Industrial Revolution* whereby an economy transitions from Malthusian stagnation to modern economic growth as firms implement cost-reducing production technologies. This take-off of industry occurs once the market reaches a critical size. The mechanism by which market size affects process innovation relies on two overlooked facts pre-dating England's *Industrial Revolution*: the expansion in the variety of consumer goods and the increase in firm size. We demonstrate this mechanism in a dynamic general equilibrium model calibrated to England's long-run development, and explore how various factors affected the timing of its industrialization.

Keywords Unified growth theory · Industrial Revolution · Innovation · Competition · Consumer Revolution

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1 Introduction

Unified growth theory, in modeling the process by which economies transition from Malthusian stagnation to modern economic growth, has shown to be of great value in elucidating

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one of history's great mysteries, the *Industrial Revolution*.[1] In an attempt to match the process of industrialization in the world as whole, the modeling of this transition has abstracted from a number of salient features of England's transition from a stagnant, predominantly rural economy to a vibrant, industrial one.[2] In particular, it has abstracted from both the large increase in the variety of consumer goods that preceded the *Industrial Revolution*, the so-called *Consumer Revolution* documented by Styles (2000) and Berg (2002), and the organizational shift in the workplace from the cottage industry and putting-out system to the centralized factory, documented by Szostak (1989) and Berg (1994). Additionally, this literature has abstracted from a major source of growth during the *Industrial Revolution* documented by Mokyr (1990) and Randall (1991), namely, the deliberate introduction of cost-reducing technologies by firms.[3]

This paper seeks to enhance our understanding of the causes of the *Industrial Revolution* by putting forth a unified growth theory where both an increase in consumer varieties and an increase in firm size are essential for the introduction of cost-saving technologies and an economy's take-off. In this theory, a growing market allows an economy to sustain a greater variety of consumer goods, making them more substitutable and raising their price elasticity of demand. This causes a drop in mark-ups and an intensification of competition, the consequence of which is that firms need to sell more goods in order to break even. This facilitates process innovation as larger firms can spread the fixed cost of raising productivity over a greater quantity of output. Therefore, firms start to innovate and living standards start to rise when the market reaches a critical size and competition becomes sufficiently intense. The *evolution* of markets is thus a precondition for the *revolution* of industry.

To generate the elasticity effect whereby larger markets lead to lower mark-ups, we embed Lancaster (1979) preferences into a monopolistically competitive model of product and process innovation. The Lancaster construct, based on Hotelling (1929) spatial model of horizontal differentiation, assumes that each household has an ideal variety of an industrial good, identified by its location on a circle. As goods 'fill up this circle', neighboring varieties become closer substitutes, implying a higher price elasticity of demand and a lower mark-up (Helpman and Krugman 1985; Hummels and Lugovskyy 2009). As shown by Desmet and Parente (2010) in a static one-sector model, these preferences imply a positive effect of market size on process innovation.

Apart from the preference structure, the model is fairly standard and on some dimensions simpler than alternative unified growth models. As in many unified growth theories, it introduces a subsistence constraint associated with consumption of an agricultural good produced according to a constant returns production technology that uses a fixed factor of production. Additionally, whereas households in the model derive utility from children, it assumes no explicit tradeoff between quality and quantity of children. Instead, it assumes a time cost of rearing children that eventually increases in the economy's income and population as a simple way of capturing the secular rise in resources devoted to raising children to adulthood.[4] With these features, the model not only generates a rapid transition from Malthusian

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[1] Some of the important papers in this literature are Galor and Weil (2000), Hansen and Prescott (2002), Lucas (2002), Galor and Moav (2002), and Voigtländer and Voth (2006).

[2] See the 2008 Klein Lecture by Galor (2010) for an excellent overview of the achievements of unified growth theory.

[3] For example, in Voigtländer and Voth (2006) increasing returns in the variety of intermediate goods drives an economy's take-off. In Galor and Weil (2000), Lucas (2002) and Galor and Moav (2002) the take-off is due to an increase in the returns to human capital accumulation.

[4] See, e.g., Becker et al. (1990), Galor and Weil (2000), and Lucas (2002) for theories that emphasize the quality-quantity trade-off. In as far as the increase in human capital requirements is reflected in a rising time cost

stagnation to modern growth, but also a structural transformation with a declining agricultural share, and a demographic transition with population growth initially rising with the advent of industrialization and subsequently falling.

The model works as follows. On account of low initial agricultural productivity, the subsistence constraint binds and the economy starts off with most of its population employed in agriculture. Given that so few people work in the industrial sector and given the fixed operating cost of industrial firms, only a small number of consumer varieties are produced, implying low substitution between goods, high mark-ups, weak competition, and importantly, small firm size. As a result, firms do not find it profitable to incur the fixed costs of innovation. However, exogenous increases in agricultural TFP during this Malthusian-like phase allow for increases in the population and a larger industrial base, which result in more consumer varieties, tougher competition, and larger firms. Eventually, the industrial market reaches a critical size so that firms become sufficiently large to find process innovation profitable. At this point, firms endogenously lower their marginal costs, and an industrial revolution ensues.

Process innovation in the industrial sector then sets off a structural transformation and an increase in population growth, followed by a demographic transition. As incomes rise, the nonhomotheticity of preferences that follows from the subsistence constraint implies that households both move out of agriculture and have more children. This leads to accelerating population growth. As child rearing costs start to increase with output and population, however, the income effect on fertility no longer dominates so that the population growth rate eventually declines: the demographic transition. In the limit, as living standards continue to rise, the subsistence constraint disappears, and the economy converges to constant agricultural and industrial shares of economic activity. The rise in the time rearing cost ensures that the population growth rate converges to zero, and the price elasticity of demand approaches a constant. Firms stop increasing in size and the rate of innovation becomes constant. Thus, the economy converges to a modern growth era with a constant positive growth rate of per capita GDP.

To assess the plausibility of our theory, we calibrate the model to the historical experience of England from 1400 to 2000. In particular, we restrict the model parameters to match pre-1700 and post-1950 English observations, and then compare the model's predictions to the available data over the 1700–1950 period. We find the model's predictions are in line with the main features of England's experience over this period, including its growth rate of per capita GDP, its structural transformation, and its relative prices. Given this finding, we proceed to examine within the calibrated model how a number of different factors may have affected the timing of England's take-off. We examine three factors, each of which has been emphasized by other researchers as being important for England's *Industrial Revolution*: agricultural productivity (Schultz 1968; Diamond 1997), institutions (North and Thomas 1973; North and Weingast 1989), and trade and transport (Szostak 1991; Findlay and O'Rourke 2007). Our counterfactuals suggest that each of these factors was important for England's development, possibly hastening the start of the *Industrial Revolution* by a century or more.

There are a number of strands of literature to which our paper relates. With respect to more recent work, we contribute to a subset of the unified growth literature that uses model calibration to gain intuition for the causes of the *Industrial Revolution*. Important papers in this literature include Harley and Crafts (2000), Stokey (2001), Lagerlöf (2003), Lagerlöf (2006),

Footnote 4 continued
of rearing children, our assumption can be viewed as capturing the increase in child quality in a reduced-form way.

Voigtländer and Voth (2006), Boucekkine et al. (2007), and Bar and Leukhina (2010).[5] As these calibrated models emphasize different mechanisms, they tend to examine the effect of a different set of factors on the timing of England's take-off. With respect to older work, our theory echoes back to three branches. The first is the *Industrial Organization School*, which views the emergence of large firms with supervised production as the key to the *Industrial Revolution*. Important contributions to this literature are Mantoux (1928), Pollard (1965) and Berg (1994). The second is the *Social Change School*, which equates the *Industrial Revolution* to the development of competitive markets. This view is present in the work of Toynbee (1884), Polanyi (1944) and Thompson (1963). The final branch of this older literature emphasizes demand side factors, in particular, the growth of the home market and the development of consumer demand. Here some of the important papers are Gilboy (1932) and McKendrick (1982).

The rest of the paper is organized as follows. Section 2 serves to motivate our theory by summarizing the empirical evidence related to our theoretical mechanism. Section 3 describes the model and characterizes the optimal decisions of agents. Section 4 defines the equilibrium and shows algebraically that the economy converges to a balanced growth path. Section 5 calibrates the model to the historical experience of England, and considers how agricultural productivity, institutions, and transport affect the date of the economy's take-off. Section 6 concludes the paper.

2 Empirical motivation

As motivation, we present historical evidence from England regarding the key features of our theory. Recall that in our theory an expanding market brings about an increase in the number of consumer varieties leading to tougher competition and lower mark-ups, so that firms must become larger to break even. The increase in firm size, then, strengthens the incentives of firms to lower their marginal costs. Given this mechanism, one would ideally like to have historical data for England on mark-ups and the price elasticity of demand as a first step in convincing the reader that our theory is empirically plausible. Unfortunately, no such historical data exist. [6] However, there is a good deal of indirect evidence available on the large increase in consumer goods that preceded the *Industrial Revolution* and on the secular rise in firm size. We now present some of this evidence.[7]

2.1 Consumer Revolution

Product innovation in the form of new consumer varieties is an essential element of our model. A growing body of literature that goes under the heading of the *Consumer Revolution* argues that product innovation was every bit as common as process innovation. Berg (2002), for example, in analyzing the nature of British patents for the period 1627–1825 in a subset of

[5] Similar to our mechanism, Boucekkine et al. (2007) rely on a circle construct. However, whereas we employ a circle construct for consumption varieties to generate a take-off in process innovation, they employ a circle construct for the spatial location of educational facilities to generate a take-off in schooling capital.

[6] Nonetheless, the lone long-run study on mark-ups does support our theory: Ellis (2006) finds a 67 % decline in the United Kingdom between 1870 and 2003. Moreover, empirical studies based on more recent data provide ample support for those elements for which no hard historical evidence exists (see Desmet and Parente 2010, and references therein).

[7] We do not use this section to document the pervasive changes in technologies (i.e. production processes) undertaken by firms in a wide range of industries in England during the *Industrial Revolution*, since they are well-documented in, for example, (Mokyr, 1990, chaps. 5 and 6)

industries that includes metal wares, glass, ceramics, furniture and watches, found that over one-quarter of the 1610 patents specified new product designs or variations of existing ones. In a narrower study, Griffiths et al. (1992) documents that roughly half of the 166 patented and non-patented improvements in the textile industry between 1715 and 1800 concerned product innovation. Similarly, De Vries (1993), using records from probate inventories, documents increasing variety in household durables through the 18th century, despite relatively stagnant wages.

The increase in new consumer goods and varieties is not a post-18th century phenomenon. For example, Weatherill (1988) places the peak of the *Consumer Revolution* somewhere between 1680 and 1720. Referring to the 1500–1700 period, Styles (2000) lists a number of consumer products that were either entirely English inventions or drastically remodeled goods from other societies. For example, from continental Europe, Delftware plates, Venetian glass, and upholstered chairs and from Asia and the New World, porcelain, tea, tobacco, sugar, lacquered cabinets, and painted calicos all became available to English consumers in this period. This is consistent with our theory, in which the expansion in varieties starts before the *Industrial Revolution.*

2.2 Firm size and market size

Another implication of our mechanism is that firm size increases with market size. A large, extensive literature documents increasing establishment size with the advent of the *Industrial Revolution*. For example, Lloyd-Jones and Le Roux (1980) find that the median number of workers in cotton firms in Manchester more than tripled between 1815 and 1841, and Feinstein and Pollard (1988) report that in pig iron production per furnace increased in England from 400 tons in 1750 to 550 in 1790.

Of course, our theory relies on increases in firm size well before the start of an economy's take-off. Although hard statistics are more difficult to find going back further in England's history, there are well-documented examples of rudimentary factories with centralized production often employing large workforces, the so called proto-factories in the period leading up to the *Industrial Revolution*. For example, workshops employing over forty parish apprentices existed in Nottingham as early as the 1720s. Indeed, by the time Hargreaves and Arkwright went to Nottingham with their inventions, the concentration of labor in factories was a fairly familiar idea (Berg 1994). These proto-factories differed from their followers in that they tended to be limited to specific parts of the production process. For example, in the cotton industry, spinning became centralized, whereas weaving was still left to the cottage industries. Similarly, in the woolen industry, although the artisan system was retained, clothiers used cooperative mills that centralized part of the production process.

Prior to this, the evidence is a bit more suggestive and open to interpretation. A burgeoning literature on *proto-industrialization*, however, suggests that firm size did increase before the 18th century. Proto-industrialization, which refers to the 1500–1700 period in which non-agricultural goods were produced in the countryside for large regional, and even international, markets, corresponds to the *putting-out* system whereby merchant capitalists sold inputs to rural households and bought finished goods in return. Under this system merchants controlled and centralized a number of activities, such as marketing and finance, but left production decentralized and in control of rural households. If one interprets the putting-out network as an organization, then the size of organizations was clearly increasing before the *Industrial Revolution*. This is the view of Mokyr (2002), who argues that what distinguishes a firm from a household is the extent to which consumption is separated from production. With this distinction, all households that were paid to produce cloth for the same merchant-entrepreneur were employees of the same firm, leading Mokyr (2002) to conclude that "large firms were quite widespread before the Industrial Revolution" (page 121). The only difference, compared to the factory system, is that not all tasks were performed under the same roof.[8]

That firm size was related to market size in the preindustrial period can also be seen by comparing establishment sizes of firms operating in different markets. Mathias (1959), for example, in analyzing the brewing industry, finds that over the 1700–1800 period the average number of barrels produced by common brewers in London was more than double their counterparts in the rest of England, suggesting a positive relation between market size and firm size. Moreover, he finds that the average size of common brewers in London increased from 9822 barrels per producer in 1700 to 14019 barrels per producer in 1800, whereas in the rest of England it hardly increased. This constrast in production growth of breweries mimics the contrast in population growth between London and the rest of England during the 18^{th} century.[9]

3 The model

In this section we describe the structure of the model economy, and the relevant optimization problems of agents. The economy is closed and time is discrete and infinite.[10] There are three sectors: a farm sector, an industrial sector, and a household sector. The farm sector is perfectly competitive and produces a single non-storable consumption good using labor and land inputs according to a constant returns to scale technology which is subject to exogenous technological change. The industrial sector is monopolistically competitive and produces a finite set of differentiated goods, each of which has a unique address on a circle. There is both product and process innovation in the industrial sector. The household sector consists of one-period lived agents, each of whom derives utility from consumption of the agricultural good, consumption of the differentiated industrial goods, and children. For each household, there is a unique variety of the differentiated good that it prefers above all others, identified by the household's location on the circle. Households earn income by either working in the farm sector or the industrial sector. In addition to working, households use their time to rear children, who constitute the household sector in the next period.

3.1 Farm sector

Being perfectly competitive, the farm sector is straightforward to describe. Farms produce a single, non-storable consumption good, that serves as the economy's numéraire. The farm technology is constant returns to scale using labor and land. To avoid the issue of inheritance, we assume the supply of land, which is normalized to 1, is owned equally by farms.

[8] Many researchers, particularly Mendels (1972), argue that the rise of the cottage industry was a critical step in the eventual industrialization of the British economy. Indeed, Mendels claims that the proto-industrialization period was an essential transition phase from the feudal world of the Middle Ages to the capitalist world of the modern era. Our work complements this area of research. In our theory increases in firm size not only predate the start of the *Industrial Revolution*, they are necessary for it to occur.

[9] In the case of United States, Sokoloff (1988) documents the same pattern between firm size and market size in the period leading up to the United States' industrial revolution. Similarly, Stabel (2004) documents this pattern for 16th century Flanders.

[10] A richer version would allow for multiple countries and transportation (or trade) costs. Although this would allow us to analyze the importance of the international trade for England's take off, it would come at the cost of increased analytical complexity.

3.1.1 Production

Let Q_{at} denote the quantity of agricultural output of the stand-in farm, and L_{at} the corresponding agricultural labor input. Given the normalization of the land supply in the economy to 1, agricultural output is

$$Q_{at} = A_{at} L_{at}^{\theta}, \quad 1 > \theta > 0 \tag{1}$$

with A_{at} denoting agricultural TFP.

Agricultural TFP grows at a rate $g_{at} > 0$ during period t, so that

$$A_{at+1} = A_{at}(1 + g_{at}), \tag{2}$$

where

$$g_{at} = \max\{\gamma_a, g_{xt}\}, \tag{3}$$

with $\gamma_a > 0$ being a constant, exogenously determined growth rate, and g_{xt} being the endogenously determined growth rate of industrial TFP in period t. The motivation for this specification is that, consistent with the historical record, it allows for some population growth during the preindustrial era. Absent this rise in the population, demand for industrial goods never reaches the critical level needed for the economy to take off.[11] Additionally, the specification allows agricultural TFP growth to accelerate once the industrial sector starts innovating. In this way, we are able to capture in a very simple way the dramatic secular rise in the growth rate of agricultural TFP since the *Industrial Revolution*, as documented by Federico (2006) and Bar and Leukhina (2010).[12]

3.1.2 Profit maximization

The profit maximization problem of farms is simple, as they are price takers. The profit of the stand-in farm is

$$\Pi_{at} = A_{at} L_{at}{}^{\theta} - w_{at} L_{at} \tag{4}$$

where w_{at} is the agricultural wage rate. Farms choose L_{at} to maximize equation (4). This yields the standard first order condition

$$w_{at} = \theta A_{at} (L_{at})^{\theta - 1}. \tag{5}$$

Total profits (or land rents) are thus

$$\Pi_{at} = (1 - \theta) A_{at} (L_{at})^{\theta} \tag{6}$$

and profits per unit of time worked, $\pi_{at} = \Pi_{at}/L_{at}$, are

$$\pi_{at} = (1 - \theta) A_{at} (L_{at})^{\theta - 1}. \tag{7}$$

[11] However, if there were no decreasing returns to land, i.e., if $\theta = 1$, then the economy would be able to sustain positive population growth, leading to the escape from the Malthusian trap. Nevertheless, without agricultural TFP growth, we would not be able to generate the observed decreasing agricultural employment share.

[12] Alternatively, though at the cost of substantial complexity, the same qualitative results could be obtained by having farms use industrial goods as intermediate inputs, rather than assuming that agricultural TFP growth depends on technological progress in the industrial sector. As technological improvement in industry lowers the relative price of industrial goods, farms would use more industrial intermediate inputs, thereby increasing farm labor productivity. Results for this setup are available from the authors upon request.

Without loss of generality, we assume that all land rents are paid out to farm workers based on the time they work.

3.2 Household sector

At the beginning of period t there is a measure N_t of one-period lived households uniformly distributed on a circle with circumference χ.

3.2.1 Endowments

Each household is endowed with one unit of time, which it uses to rear children and to work in either the farm or the industrial sector. Denote by N_t^f and N_t^x the measure of households employed in agriculture and industry. Thus,

$$N_t = N_t^f + N_t^x. \tag{8}$$

3.2.2 Preferences

A household derives utility from the number of children it raises, n_t, consumption of the agricultural good, c_{at}, and consumption of the differentiated industrial goods, $\{c_{vt}\}_{v \in V_t}$, where V_t denotes the set of differentiated goods produced at time t. Following the literature on the structural transformation and the demographic transition, each household has an agricultural subsistence constraint, represented by $c_{\bar{a}}$ in the utility function. Departing from the literature on the demographic transition, we assume that household utility does not depend on the quality of children. With respect to the differentiated goods, a household's utility depends on how far a given good is from its ideal variety, which is identified by the household's location on the circle. For this reason, the utility function of each household is indexed by that household's ideal variety. In particular, the utility of a household located at point $\tilde{v}$ on the χ-circumference circle is:

$$U_{\tilde{v}}(c_{at}, n_t, \{c_{vt}\}_{v \in V_t}) = [(c_{at} - c_{\bar{a}})^{1-\alpha}[g(c_{vt}|v \in V_t)]^{\alpha}]^{\mu}(n_t)^{1-\mu}, \tag{9}$$

where

$$g(c_{vt}|v \in V_t) = \max_{v \in V_t}\left[\frac{c_{vt}}{1 + d_{v\tilde{v}}^{\beta}}\right]. \tag{10}$$

The subutility $g(c_{vt}|v \in V_t)$ is based on Lancaster (1979) and captures the idea that the further away an industrial variety v lies from a household's ideal variety $\tilde{v}$, the lower the utility it derives from consuming a unit of variety v. In particular, the quantity of variety v that gives the household the same utility as one unit of its ideal variety $\tilde{v}$ is $1 + d_{v\tilde{v}}^{\beta}$, where $d_{v\tilde{v}}$ denotes the shortest arc distance between v and $\tilde{v}$, and $\beta > 0$ is a parameter that determines how fast a household's utility diminishes with the distance from its ideal variety.

To develop further intuition for the Lancaster construct, note that since households are uniformly distributed around the circle, and only a finite number of varieties will be produced in equilibrium, a household will typically not have the option of buying its ideal variety. This setup also implies that if all varieties were to sell at the same price, then each household would buy the produced variety located nearest to its ideal on the circle.

Whereas the Lancaster preference structure is an essential element of our model, it is not the only construct that generates a positive link between effective market size and process innovation through the elasticity of demand. For example, Ottaviano et al. (2002) use a quasilinear utility function with quadratic subutility to generate this effect, and Yang and Heijdra (1993) accomplish this with Spence–Dixit–Stiglitz preferences assuming that individual firms internalize the effect of their pricing decisions on the aggregate price level. The reasons we adopted Lancaster preferences is that its effect does not depend on whether firms take into account how their price choice affects the aggregate price level, and it implies that demand increases with income. Moreover, the elasticity effect arises in a very intuitive way in the Lancaster setting; the bounded product space implies that as varieties 'fill up the circle', neighboring varieties become closer substitutes, implying a higher price elasticity of demand. [13]

3.2.3 Utility maximization

As all households start out identical and can choose in which sector to work, they earn the same income in equilibrium, so that there is no need to differentiate household choices by their sector of employment. Let y_t denote the income payment per unit of time. For a farm worker, y_t is the sum of the agricultural wage rate and profit rate, whereas for an industrial worker, it is just the industrial wage rate. Then, as the total amount of time worked by the household is its time endowment less the time rearing cost of children, a household's budget constraint is:

$$y_t(1-\tau_t n_t) \geq c_{at} + \sum_{v\in V} p_{vt}c_{vt} \tag{11}$$

Provided assumptions on the technology parameters ensure that the subsistence constraint is always satisfied, i.e., $y_t(1-\tau_t n_t) > c_{\bar{a}}$ for all $t \geq 0$, maximizing (9) subject to (11) yields the following first order necessary conditions:

$$c_{at} = \mu(1-\alpha)(y_t - c_{\bar{a}}) + c_{\bar{a}} \tag{12}$$

$$\sum_{v\in V_t} p_{vt}c_{vt} = \mu\alpha(y_t - c_{\bar{a}}) \tag{13}$$

$$\tau_t n_t = (1-\mu)\left(1-\frac{c_{\bar{a}}}{y_t}\right). \tag{14}$$

To further characterize the optimal consumption of the differentiated goods, note that the subutility function (10) is linear with respect to the set of differentiated goods. Thus, there is no reason for any household to consume more than one industrial variety. In particular, an agent buys the variety $v' \in V_t$ that minimizes the cost of an equivalent unit of its ideal variety, $p_{vt}(1+d^{\beta}_{v\tilde{v}})$. Namely,

$$v' = \text{argmin}[p_{vt}(1+d^{\beta}_{v,\tilde{v}})|v \in V_t]. \tag{15}$$

Using (13), a household with ideal variety $\tilde{v}$ therefore buys the following quantity of variety v':

$$c_{v't} = \frac{\mu\alpha(y_t - c_{\bar{a}})}{p_{v't}}. \tag{16}$$

Its demand for all other varieties $v \in V_t$ is zero.

[13] To our knowledge, Peretto (1998; 1999a; 1999b) is the first to establish the link between market size and take-off, adopting the Yang and Heijdra (1993) construct. Although our mechanisms are similar, there are important differences: market-size is defined by the capital stock in Peretto (1999b); multiple steady states exist; population dynamics are absent; no quantitative analysis is undertaken.

3.2.4 Demographics

Each child requires a share τ_t of parental time. This cost is indexed by time as to allow it to increase with the economy's population. More specifically, the time rearing cost is assumed to be a monotonically increasing function of the population. Technically, we invoke this assumption in order to generate the demographic transition, corresponding to the decline in the population growth rate. Empirically, the assumption captures the secular rise in the cost of rearing children, particularly in the last 150 years, associated with the rise of human capital. For now, we are silent on the exact functional form that τ_t takes.

As households are free to work in either sector, they will earn the same income in equilibrium, and hence will choose the same number of children. Consequently, the law of motion for the population is

$$N_{t+1} = n_t N_t \tag{17}$$

where n_t is the number of children per household. That is, the children of households in period t become the households in period $t + 1$.

3.3 Industrial sector

The industrial sector is monopolistically competitive, and produces a set of differentiated goods, each with a unique address on the χ-circumference circle. As in Lancaster (1979), firms can costlessly relocate on the circle. The technology for producing industrial goods uses labor as its only input. The existence of a fixed cost, which takes the form of labor, gives rise to increasing returns, and the economy's monopolistically competitive industrial structure. Each monopolist chooses its price and technology, taking aggregate variables and the choices of other firms as given. Free entry and exit into the industrial sector ensures that all industrial firms make zero profits, allowing us to determine the number of equilibrium varieties. We first describe the production technology and the process innovation technology and then solve for the optimal choices of a firm producing variety v.

3.3.1 Production and process innovation

Let Q_{vt} be the quantity of variety v produced by a firm; L_{vt} the units of labor it employs; A_{vt} its technology level, or production process; and κ_{vt} its fixed cost in terms of labor. Then the output in period t of the firm producing variety v is

$$Q_{vt} = A_{vt}[L_{vt} - \kappa_{vt}]. \tag{18}$$

Both the fixed labor cost, κ_{vt}, and the technology level, A_{vt} , depend on the firm's rate of process innovation, g_{vt}. In particular, similar to Young (1998), the fixed labor cost is given by

$$\kappa_{vt} = \kappa e^{\phi g_{vt}}, \tag{19}$$

where $\phi > 0$. Thus, there are two components to the fixed cost: an innovation cost, represented by $e^{\phi g_{vt}}$, that is increasing in the size of process innovation, g_{vt}, and an operating cost, κ, that is incurred even if there is no process innovation. The firm's technology level, A_{vt}, is given by

$$A_{vt} = (1 + g_{vt})A_{xt}, \tag{20}$$

where the benchmark technology all firms start off with in period t, A_{xt}, is the average technology used by industrial firms in period $t-1$:

$$A_{xt} = \sum_{v \in V_{t-1}} \frac{1}{m_{t-1}} A_{v,t-1}, \tag{21}$$

where m_{t-1} is the number of varieties produced in period $t-1$, i.e., $m_{t-1} = card(V_{t-1})$. Therefore, if $g_{vt} = 0$, so there is no process innovation, a firm uses the industrial benchmark technology, A_{xt}, whereas if $g_{vt} > 0$, the firm uses a technology that is $(1+g_{vt})$ times greater than the benchmark technology.[14]

The aggregate growth rate of industrial TFP, g_{xt}, is thus

$$g_{xt} = \frac{A_{xt} - A_{xt-1}}{A_{xt-1}}. \tag{22}$$

3.3.2 Profit maximization

The fixed operating cost implies that each variety, regardless of the technology used, will be produced by a single firm. In maximizing its profits, each firm behaves non-cooperatively, taking the choices of other firms as given. Profit maximization determines the price and quantity to be sold, the number of workers to be hired, and the technology to be operated. As is standard in models of monopolistic competition, firms take all aggregate variables in the economy as given.[15]

Using (18), the profits of the firm producing variety v, Π_{vt}, can be written as

$$\Pi_{vt} = p_{vt} C_{vt} - w_{xt} \left[\kappa e^{\phi g_{vt}} + \frac{C_{vt}}{A_{xt}(1+g_{vt})} \right], \tag{23}$$

where w_{xt} is the wage in the industrial sector, and p_{vt} is the price of variety v.

The problem of the firm producing variety v is to choose (p_{vt}, g_{vt}) to maximize (23), subject to the aggregate demand for its product, C_{vt}. As usual, the profit maximizing price is a mark-up over the marginal unit cost $w_{xt}/[A_{xt}(1+g_{vt})]$, so that

$$p_{vt} = \frac{w_{xt}}{A_{xt}(1+g_{vt})} \frac{\varepsilon_{vt}}{\varepsilon_{vt} - 1}, \tag{24}$$

where ε_{vt} is the price elasticity of demand for variety v,

$$\varepsilon_{vt} = -\frac{\partial C_{vt}}{\partial p_{vt}} \frac{p_{vt}}{C_{vt}}.$$

The first order necessary condition associated with the choice of technology, g_{vt}, is

$$-\phi \kappa e^{\phi g_{vt}} + \frac{C_{vt}}{A_{xt}(1+g_{vt})^2} \leq 0, \tag{25}$$

where the strict inequality in the above expression corresponds to a corner solution, i.e., $g_{vt} = 0$.

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[14] Thus, we assume complete intertemporal knowledge spillovers. While the existence of this spillover implies a dynamic inefficiency, it is not important to the points we wish to establish. We make the assumption because it is not possible to solve for an equilibrium with asymmetric firms using Lancaster's construct. Without the assumption of complete intertemporal knowledge spillovers, new varieties would start out at a lower technology, and hence there would not be a symmetric equilibrium.

[15] In principle this requires firms to be of measure zero, a condition that is not satisfied. See Desmet and Parente (2010) for a discussion of how firms could be made of measure zero, without changing any of the results.

4 Equilibrium

As is standard in this literature, we focus exclusively on symmetric Nash equilibria where firms are equally spaced around the unit circle, use the same technology, and charge the same price. This section defines a symmetric Nash equilibrium for our economy, and explores the limiting properties of the equilibrium. To facilitate this, we start by deriving the aggregate demand for each good in the symmetric case.

4.1 Aggregate demand

We first determine the aggregate demand for each industrial good. Since in a symmetric Nash equilibrium all varieties produced are equally spaced around the circle, aggregate demand for a given variety depends only on the locations and the prices of its closest neighbors to its right and its left on the circle. Let d_t denote the distance between two neighboring varieties in period t. This distance is inversely proportional to the number of varieties, m_t, namely,

$$d_t = \frac{\chi}{m_t}. \tag{26}$$

Since the nearest competitors to the right and to the left of the firm producing variety v are each located at the same distance d_t from it, we do not need to differentiate between them, and thus denote each competitor by v_c and their prices by p_{ct}.

To begin, we derive the aggregate demand of all households for variety v. The first step is to identify the location of the household on the circle that is indifferent between buying variety v and variety v_c. Recall that each household will buy that variety for which the unit cost of an equivalent unit of its ideal variety is lowest. Thus, the household that is indifferent between buying varieties v and v_c is the one whose cost of a quantity equivalent to one unit of its ideal variety in terms of v equals the cost of a quantity equivalent to one unit of its ideal variety in terms of v_c. Consequently, the household that is indifferent between v and v_c is the one located at distance d_{vt} from v, where

$$p_{ct}[1 + (d_t - d_{vt})^{\beta}] = p_{vt}[1 + d_{vt}^{\beta}]. \tag{27}$$

Given this indifference condition applies to households both to the right and to the left of v, the uniform distribution of households around the χ-circumference circle implies that a share $2d_{vt}/\chi$ of them consumes variety v. Since each household spends $\mu\alpha(y_t - c_{\bar{a}})$ on the industrial good, the total demand for v by households is

$$C_{vt} = \frac{2d_{vt}N_t c_{vt}}{\chi} = \frac{d_t N_t}{\chi}\frac{\mu\alpha(y_t - c_{\bar{a}})}{p_{vt}}. \tag{28}$$

where the second equality uses the result that all firms are spaced evenly in the symmetric equilibrium, so that $2d_{vt} = d_t$.

With this demand in hand, we can solve for the price elasticity in a symmetric Nash equilibrium. This involves three steps. First, from (28) it is easy to show that

$$-\frac{\partial C_{vt}}{\partial p_{vt}}\frac{p_{vt}}{C_{vt}} = 1 - \frac{\partial d_{vt}}{\partial p_{vt}}\frac{p_{vt}}{d_{vt}}. \tag{29}$$

Next, by taking the total derivative of the indifference equation (27) with respect to p_{vt}, we solve for $\partial d_{vt}/\partial p_{vt}$, and substituting this partial derivative in (29) yields

$$\varepsilon_{vt} = 1 + \frac{[1 + d_{vt}^{\beta}]p_{vt}}{[p_{vt}\beta d_{vt}^{\beta-1} + p_{ct}\beta(d_t - d_{vt})^{\beta-1}]d_{vt}}. \tag{30}$$

Finally, we invoke symmetry, i.e., $p_{vt} = p_{ct}$ and $2d_{vt} = d_t$, so that (30) reduces to

$$\varepsilon_{vt} = 1 + \frac{1}{2\beta}\left(\frac{2}{d_t}\right)^{\beta} + \frac{1}{2\beta}. \tag{31}$$

Thus, as the number of varieties increases, the price elasticity of demand increases.

4.2 Symmetric equilibrium

We next define a symmetric Nash equilibrium for our economy. Because the decisions of households, industrial firms and farms are all static, the dynamic equilibrium for the model economy is essentially a sequence of static equilibria that are linked through the laws of motion for the population, the benchmark technology in the industrial sector, and TFP in the farm sector.

In equilibrium firms in the industrial sector must earn zero profits. This is a consequence of there being free entry. Thus,

$$p_{vt}Q_{vt} - w_{xt}\left[\kappa e^{\phi g_{vt}} + \frac{Q_{vt}}{A_{xt}(1+g_{vt})}\right] = 0 \tag{32}$$

This condition effectively determines the number of varieties and the distance between varieties.

The zero profit condition (32), together with the mark-up equation (24) and the elasticity equation in the symmetric equilibrium (31), provides the key to understanding the positive relation between market size and firm size. From the elasticity expression (31) it is apparent that as the number of varieties increases, and the distance between firms decreases, the price elasticity of demand increases. This result is intuitive: by increasing the number of varieties, the circle becomes more crowded, making neighboring varieties more substitutable. From the price expression (24), it follows that the greater elasticity leads to tougher competition, reducing the mark-up. The zero profit condition (32) then implies that the size of firms, in terms of production, must increase: given the same fixed cost, a firm must sell a greater quantity of units in order to break even. As we will see later, larger firms find it easier to bear the fixed cost of innovation, leading to a positive relation between market size and technological progress.

We now define the dynamic *Symmetric Equilibrium*.

Definition of Symmetric Equilibrium *A Symmetric Equilibrium is a sequence of household variables* $\{c_{vt}, c_{at}, n_t, y_t, N_t\}$, *farm variables* $\{Q_{at}, L_{at}, \pi_{at}\}$, *industrial firm variables* $\{Q_{vt}, L_{vt}, p_{vt}, g_{vt}, \varepsilon_{vt}, A_{vt}\}$, *and aggregate variables* $\{V_t, w_{xt}, m_t, w_{at}, d_t, N_t, A_{xt}, g_{xt}, A_{at}\}$ *that satisfy*

- *(i) utility maximization conditions given by (12), (13) and (14).*
- *(ii) farm profit maximization conditions given by equations (1), (5), and (7)*
- *(iii) industrial profit maximization conditions given by (18), (19), (20), (24), (25), and (31)*
- *(iv) market clearing conditions*
  - *(a) industrial goods market: Eq. (18) = Eq. (28)*
  - *(b) industrial labor market:*

$$m_t L_{vt} = N_t^x(1 - \tau_t n_t) \tag{33}$$

  - *(c) farm goods market: equation*

$$Q_{at} = \mu(1-\alpha)N_t(y_t - c_{\bar{a}}) + N_t c_{\bar{a}}. \tag{34}$$

(d) farm labor market:

$$L_{at} = N_t^f (1 - \tau_t n_t) \tag{35}$$

(v) zero profit condition of industrial firms given by (32)
(vi) indifference condition of households to work in either sector

$$y_t = w_{at} + \pi_{at} = w_{xt} \tag{36}$$

(vii) population feasibility given by (8)
(viii) aggregate laws of motion for A_{xt} given by (21); for N_t given by (17); and for A_{at} given by (2), (3), and (22).

Conditions (i)–(vii) define each period's static equilibrium, whereas condition (viii) states the laws of motion of technology and population that link the sequence of static equilibria, thus defining the dynamic equilibrium.

4.3 Equilibrium properties

For the economy to undergo an industrial revolution, industrial firms must become sufficiently large, which ultimately requires a large enough industrial sector. In the absence of agricultural TFP growth (and assuming that industrial firms are initially too small to find process innovation profitable), the population cannot increase, implying the economy is forever trapped in a Malthusian steady state with a constant living standard. However, with agricultural productivity growth, either income, population or both will increase over time. With these developments, the size of the industrial sector grows, and at some point innovation takes off.

For the economy to converge to a balanced growth path with a constant innovation rate and a positive constant growth rate of per capita GDP, population growth must go to zero. Whereas guaranteeing this result may seem restrictive in terms of the model structure, it is not. In fact, as we show below, a simple way of guaranteeing this result is to assume that the time cost of raising children to adults is eventually increasing in the level of the population, i.e., $\tau_t'(N) > 0$ for all $N \geq N^*$. Given that in equilibrium there will be a positive relation between population size and productivity, this assumption can be reinterpreted as the child rearing cost being increasing in productivity. This would be similar to assuming an increasing role of human capital in the production process, in line with the quantity-quality tradeoff in parents' fertility decisions (Galor and Weil 2000).[16] In the numerical section of the paper we show that the assumption of a positive relation between population and the cost of child rearing is able to capture the observed population dynamics in the data.

Proposition 1 *The economy converges to a balanced growth path with constant technological progress in industry provided TFP grows in agriculture, $g_{at} > 0$, and the cost of rearing children is eventually increasing in the level of the population, $\tau_t'(N) > 0$ for all $N \geq N^*$.*

Proof We start by showing that y_t in the limit goes to infinity. If $g_{at} > 0$ and population does not grow, y_t must increase. Recall that the growth in y_t can be written as:

$$g_{at} - (1-\theta)\frac{\dot{L}_{at}}{L_{at}} > 0. \tag{37}$$

[16] Simon and Tamura (2009) present evidence that suggests that as more people settle in a given piece of land, the cost of having children increases on account of increases in the cost of living space. Our assumption that the time rearing cost is eventually increasing in the population is also a reduced-form way of capturing their finding.

The only way that y_t might go down is if $\dot{L_{at}}/L_{at}$ is large enough. The only way for $\dot{L_{at}}/L_{at}$ to be positive is if the increase in demand for agricultural goods is positive. But, as can be seen from (34), the only way for this to happen, provided the population is constant, is for y_t to increase. By continuity, this argument implies that if population growth is not too large, y_t must increase over time. Of course, if population growth is large enough, $g_{at} > 0$ does not ensure $y_t > 0$. However, since $\tau'(N) > 0$ for $N \geq N^*$, population growth must eventually slow down, so that y_t must eventually increase over time if $g_{at} > 0$. Therefore, as long as $g_{at} > 0$, in the limit y_t will go to infinity.

The fact that y_t goes to infinity in the limit implies that each household will have the following number of children in the limit:

$$n = \frac{1-\mu}{\tau} \tag{38}$$

where $n - 1$ can be interpreted as the population growth rate. Given that τ is strictly increasing with population for $N > N^*$, n must be decreasing with population for $N > N^*$. This implies that the population growth rate must eventually go to zero. If so, in the limit the shares of agricultural and industrial households converge to fixed numbers. To see this, first recall the income equal expenditure conditions in both sectors in the limit when y_t goes to infinity:

$$yN^f(1-\tau n) = \mu(1-\alpha)yN \tag{39}$$

$$yN^x(1-\tau n) = \mu\alpha yN \tag{40}$$

Now divide equation (39) by (40):

$$\frac{N^f}{N^x} = \frac{1-\alpha}{\alpha}. \tag{41}$$

The constant shares, together with the constant population, implies that in the limit the total number of hours worked in industry also converges to a constant.

It is now easy to show that in the limit g_v is a constant. The case where $g_v = 0$ is trivial. Thus, we focus on the case of an interior solution ($g_v > 0$). The zero profit condition, $Q_v = \kappa e^{\phi g_v} A_x(1 + g_v)(\varepsilon - 1)$, together with the first order condition for technological progress, (25), implies that g_v is a positive function of the price elasticity of demand:

$$g_v = \frac{\varepsilon_v - 1}{\phi} - 1. \tag{42}$$

Since the total production of each firm is $\kappa e^{\phi g_v} A_x(1 + g_v)(\varepsilon - 1)$, the number of hours worked in each firm, $Q_v/(A_x(1 + g_v)) + \kappa e^{\phi g_v}$, can be rewritten as $\kappa e^{\phi g_v}\varepsilon$. This, together with the fact that the total number of hours worked in industry is μN^x in the limit, implies that the number of firms is $m = \mu N^x/(\kappa e^{\phi g_v}\varepsilon)$, where $m = \chi/d$. Substituting into (31) gives

$$\varepsilon_v = 1 + \frac{1}{2\beta}\left(\frac{2\mu N^x}{\kappa e^{\phi g_v}\varepsilon_v\chi}\right)^{\beta} + \frac{1}{2\beta}. \tag{43}$$

Now re-write (43) as

$$2\beta\varepsilon_v^{\beta+1} - (2\beta+1)\varepsilon_v^{\beta} - (2\mu N^x/\chi\kappa e^{\phi g_v})^{\beta} = 0 \tag{44}$$

and take the total derivative of this expression with respect to g_v. This yields

$$\frac{\partial\varepsilon_v}{\partial g_v} = -\frac{\beta(2\mu N^x)^{\beta}(\chi\kappa)^{-\beta}\phi e^{-\phi g_v\beta}}{2\beta(\beta+1)\varepsilon_t^{\beta} - (2\beta+1)\beta\varepsilon_v^{\beta-1}}. \tag{45}$$

From (31) we know that $\varepsilon_v > 1$, so that this derivative (45) is strictly negative. Given that (43) implies that ε_v is decreasing in g_v and (42) implies that ε_v is increasing in g_v, and given that N^x is constant in the limit, there is a unique, and constant, g_v, and thus a unique, and constant, ε_v. Therefore, if N^x is constant, g_v is also constant. The economy therefore converges to a balanced growth path with constant growth in the industrial sector. □

Having established that the economy converges to a balanced growth path with constant technological progress in the industrial sector if agricultural TFP growth is positive and the cost of rearing children is increasing in the population, we examine how the limiting rate of technological progress depends on the balanced growth path population, N, and the R&D innovation cost, ϕ.

Proposition 2 *Technological progress in the balanced growth path is an increasing function of population, N, and a decreasing function of the innovation cost parameter, ϕ.*

Proof As argued in the proof of Proposition 1, on the balanced growth path, expressions (42) and (43) determine the rate of technological progress and the price elasticity of demand. Expression (42) does not depend on N^x, whereas expression (43) does. To see this, re-write (43) as (44) and totally differentiate, keeping g_v fixed. This gives

$$\frac{\partial \varepsilon_v}{\partial N^x} = \frac{(2\mu/\chi\kappa e^{\phi g_v})^\beta \beta (N^x)^{\beta-1}}{2\beta(\beta+1)\varepsilon_v^\beta - (2\beta+1)\beta\varepsilon_v^{\beta-1}} \tag{46}$$

Since $\varepsilon_v > 1$, the above partial derivative is strictly positive, so that an increase in N^x leads to a greater elasticity of demand for any given g_v. Recall that expression (42) implies that the elasticity is upward sloping in g_v, whereas expression (43) implies that the elasticity is downward sloping in g_v. This, together with the fact that a greater value of N^x causes an upward shift in expression (43), allows us to conclude that g_v is increasing in N^x. Since N^x is a fixed share of N, g_v is therefore also increasing in the size of the population.

To show that g_v is decreasing in ϕ, we use a similar argument. Re-write (43) as (44) and totally differentiate with respect to ϕ, keeping N^x and g_v constant. This gives

$$\frac{\partial \varepsilon_v}{\partial \phi} = -\frac{\beta(2\mu N^x)^\beta (\chi\kappa)^{-\beta} g_v e^{-\phi g_v \beta}}{2\beta(\beta+1)\varepsilon_v^\beta - (2\beta+1)\beta\varepsilon_v^{\beta-1}} \tag{47}$$

Since $\varepsilon_v > 1$, the above partial derivative is strictly negative, so that an increase in ϕ leads to a smaller elasticity of demand for any given g_v. By analogy with the above argument, this implies that g_v is decreasing in ϕ. □

The intuition for the positive relation between the size of the limiting population and the balanced growth path rate of technological progress is straightforward. A greater population leads to a larger number of households employed in the industrial sector. The greater size of the industrial sector, and the larger number of varieties produced, imply lower mark-ups and tougher competition. To break even, industrial firms must become even larger. These larger firms then endogenously choose to innovate more. This is obvious from the first order condition on technology choice, (25), which exhibits two effects: an increase in innovation raises a firm's fixed cost and lowers its marginal cost. The first (negative) effect is independent of firm size, whereas the second (positive) effect is increasing in firm size. As a result, larger firms innovate more.

Propositions 1 and 2 have important implications. Starting off in a situation with no technological progress in industry, two situations can arise. If population reaches the critical size for take-off before population growth converges to zero, we will get an industrial revolution, and the economy will converge to a balanced growth path with strictly positive technological progress in industry.[17] However, if population growth converges to zero before that critical size is reached, we have an industrialization trap, and the industrial sector never innovates. As Proposition 2 suggests, this industrialization trap becomes increasingly likely, the higher is ϕ. This is easy to see when considering the extreme case of ϕ being infinite. Then obviously there will never be any take-off.[18]

The result that a balanced growth path is reached only when population growth goes to zero reflects the presence of a scale effect. Empirically, the question of whether there are scale effects (in growth rates) in the postwar period is controversial. For example, at the aggregate level, Jones (1995) finds no evidence of scale effects, whereas Alesina et al. (2000) do, once they control for trade openness. Likewise, at the micro level, Laincz and Peretto (2006) conclude there are no scale effects, whereas Backus et al. (1992) report scale effects in the manufacturing sector.

It is not this paper's intent to weigh in on this debate. However, even if scale effects are not supported empirically for the postwar period, the limiting property of the model should not be viewed as a failure of our theory. There are several ways to eliminate the scale effect in the limit while still preserving the mechanism for the economy's take-off. One is to employ the Yang and Heijdra (1993) construct as in Peretto (1999a). Another is to follow Kortum (1997) and assume that the cost of finding each new idea becomes increasingly difficult. Using either of these two approaches would not significantly change the qualitative properties of the model.

5 Numerical experiments

In this section, we calibrate the model to the historical record of England and use the calibrated structure to examine how the timing of the *Industrial Revolution* might have been affected by a number of factors emphasized by other researchers as being important for England's take-off.

Before proceeding, we note that there are two issues that make the calibration challenging. The first is the disagreement among historians over what economic progress England made before 1750. Specifically, the controversy centers on the question of whether England experienced any growth in per capita output and any decline in agriculture's share of economic activity in the 1300–1700 period. Over the last two decades, a revisionist view championed by Crafts and Harley (1992), Maddison (2001), and Broadberry et al. (2010) concludes that England grew over this early period. Clark (2009), however, in constructing national income accounts, finds support for the traditional view of completely stagnant living standards. The picture of agriculture's share of employment over this period is likewise murky; whereas researchers associated with the revisionist view such as Allen (2000) report declines in the employment share from around 73.6 % in 1400 to 68 % in 1600, Clark (2009) reports a

[17] In the numerical section that follows we identify the date of an economy's take-off as the period in which technological progress in industry becomes strictly positive, and the start of an industrial revolution as the period in which technological progress exceeds 0.5 % per year.

[18] We do not call this a development trap because as long as agricultural TFP growth is positive, welfare will be increasing in steady state. It is only when agricultural TFP growth is zero that we may get a true Malthusian development trap. An interesting extension of the model would assume γ_a go to zero in the limit so as to generate situations where development traps would or would not occur.

constant, much lower share of 55 % over this period.[19] Given these very different pictures of early English development, we choose a target in the calibration that is somewhere in between the traditional and revisionist views.

The second issue is the dramatic decline and recovery in England's population associated with the *Black Death* in 1347. This poses a challenge to the calibration on account that population is the only endogenous determinant of market size and firm size in the model.[20] The dilemma, specifically, is what initial date and population dynamics to target in the calibration. One possibility is to start the model in 1300 and calibrate to the subsequent large drop and recovery in England's population (through a one-time increase in the child rearing cost). A second possibility is to ignore this shock completely and calibrate to a constant population between 1300 and 1600. Still another possibility, is to start the model in 1400, thereby dealing only with the rebounding population. As there is no strong reason for favoring one of these over the others, we choose the last option. [21]

5.1 Calibration

The general calibration strategy is to assign parameter values so that the model equilibrium is characterized initially by a Malthusian-like era and in the limit by a modern growth era. Empirically, the key observations of the Malthusian era targeted in the calibration are: (i) the dominant share of agricultural activity in the economy, (ii) the slow rate of increase in England's population over the 1400–1600 period, and (iii) small firm size. Empirically, the key observations of the modern growth era targeted in the calibration are: (i) a constant, positive rate of growth of per capita GDP, and (ii) a dominant share of industrial activity in the economy. Theoretically, for the model to generate a modern era with constant growth, the function for the time rearing cost of children must eventually be increasing in the population size. This is another key restriction in the calibration exercise.

Before assigning parameters, it is necessary to identify the empirical counterpart of a model period. Given that households live for one period during which they raise their offspring, it is reasonable to interpret a period as the time that elapses between generations. In models that employ a two-period generational construct, a period is typically assigned a length of 35 years. However, since our model covers much of the last millennium and life expectancies were far shorter before the 20th century, we choose 25 years instead.

Table 1 lists the parameter values and provides brief comments on how each was assigned. A few additional words are warranted in the case of some of the assignments. First, the target for firm size in 1400, which is set to 2 workers, is not based on any exact estimate or study, but rather on the idea that a typical workplace in 1400 probably consisted of a master craftsman and an apprentice. This target variable is critical for restricting the circumference-size parameter, χ. Second, we normalize the 1400 population to 100 rather than 2.5 million, the actual size of England's population in 1400. As long as the circumference is calibrated to 2 workers in 1400, the choice of initial population size is irrelevant to the quantitative

[19] The shares are defined as the fractions of the population employed in agricultural activities and non-agricultural activities. They are not the fraction of the population living in rural and urban areas.

[20] As we demonstrate in the last part of this section, there are other non-endogenous factors that will affect the market size.

[21] We did undertake a calibration that targeted a constant population between 1300 and 1600 and the decline in agriculture's share of employment over that period as reported by Allen (2000). Although the parameter values are quite different between the two calibrations, the quantitative equilibrium properties are very similar.

Table 1 Parameter values

Parameters	Comments/observations
1. Population	
$N_0 = 100$	Normalization in 1400
2. Industrial technology parameters	
$A_{x0} = 0.75$	English relative price in 1700 as reported by Yang and Zhu (2008)
$\kappa = 0.42$	Average ratio of non-production workers in U.S. manufacturing outside central offices to total workers of 14 % between 1973 and 1987 (Berman et al. 1994)
$\phi = 4.0$	Limiting growth of per capita GDP equal to 2 % per year
$\chi = 4.05$	Firm size of 2 workers in 1400
3. Agricultural technology parameters	
$A_{a0} = 10$	Normalization
$\gamma_a = 0.0095$	No change in agricultural employment share between 1400 and 1600 as argued by Clark (2009)
$\theta = 0.71$	1700 Labor share in agriculture estimate (Clark 2002; Hayami and Ruttan 1971)
4. Preference parameters	
$c_{\bar{a}} = 2.00$	Agricultural share of employment between 1400 and 1600 of 0.70 (Allen 2000; Clark 2009)
$\alpha = 0.98$	2 % Limiting share of agriculture's share of employment (Mitchell 1988)
$\mu = 0.912$	2000 parent time rearing cost as reported in de la Croix and Doepke (2004) adjusted for shortened period length (25 years in our paper versus 30 years in de la Croix and Doepke).
$\beta = 0.50$	Mark-up estimates between 5 and 15 % in the limit (Jaimovich and Floetotto 2008)

equilibrium properties.[22] The unimportance of the initial population size makes it clear that firm-size in our theory is the key determinant of innovation. That is, population size only matters in as far as it affects firm size.

Another assignment that requires some explanation is the labor share parameter in the farm technology. In the data, the share of agricultural output that goes to farm labor has increased steadily over the last four centuries. Labor's share in agriculture was 67 % in 1600 according to Clark (2002) and 86 % in 1950 according to Hayami and Ruttan (1971). As the model does not allow for this secular rise, the labor share parameter, θ, is set to the 1700 trend-value based on a linear interpolation of the 1600 and 1950 estimates.[23]

The calibration also requires us to specify and parameterize the function for the child rearing cost. Rather than estimate the function by using population and time-use data, we back out the function by setting the value of the time rearing cost in period t, τ_t, to match the historical population increase in England in that same period, with the restriction that the time cost is constant before 1800. The motivation for this additional restriction is that although one can easily justify a rising time cost of rearing children starting in the 19th century, particularly

[22] The quantity of land must also be changed in proportion to the population change in order to generate the same equilibrium.

[23] We have redone the calibration to match the post-1950 estimate, and the equilibrium properties are quantitatively the same.

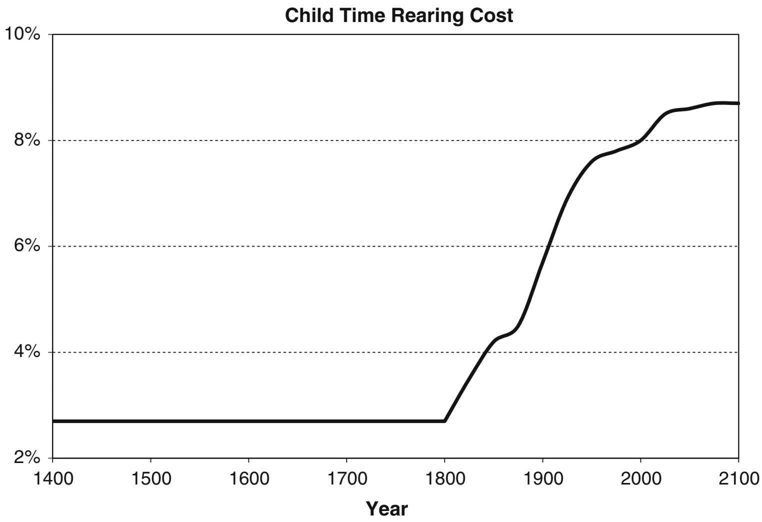

Fig. 1 Child rearing cost

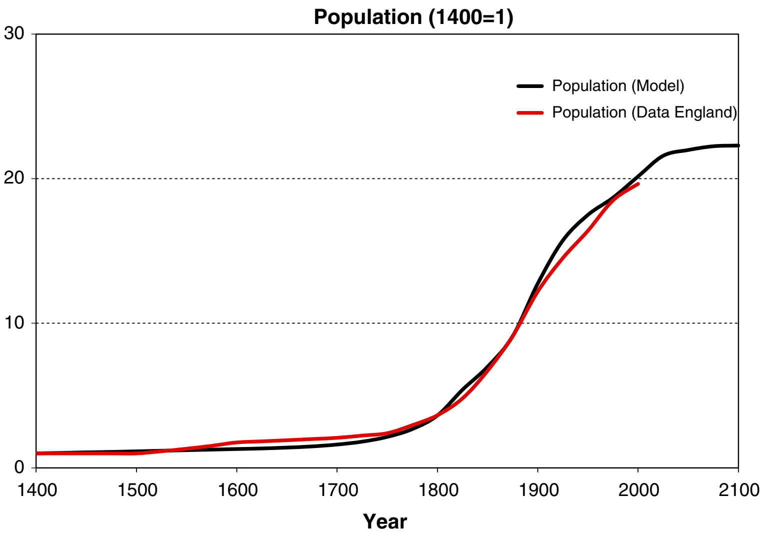

Fig. 2 Population

after England's *Second Industrial Revolution*, it is hard to point to any evidence that suggests it increased substantially prior to this period. The population data are taken from Allen (2000) from 1400 to 1800 and thereafter from the decennial United Kingdom Census.

Figure 1 depicts the time costs of rearing a child in each period as implied by the calibrated function, and Fig. 2 shows the English population (as well as the model population expressed relative to their 1400 levels). The calibrated function implies a three-fold increase in this child rearing cost from 2.7 % of a parent's time in 1750 to 8.7 % in 2000. How plausible are these calibrated time rearing costs? They are certainly in line with cross-country estimates of child rearing costs in the latter half of the 20th century. For example, Ho (1979) finds that

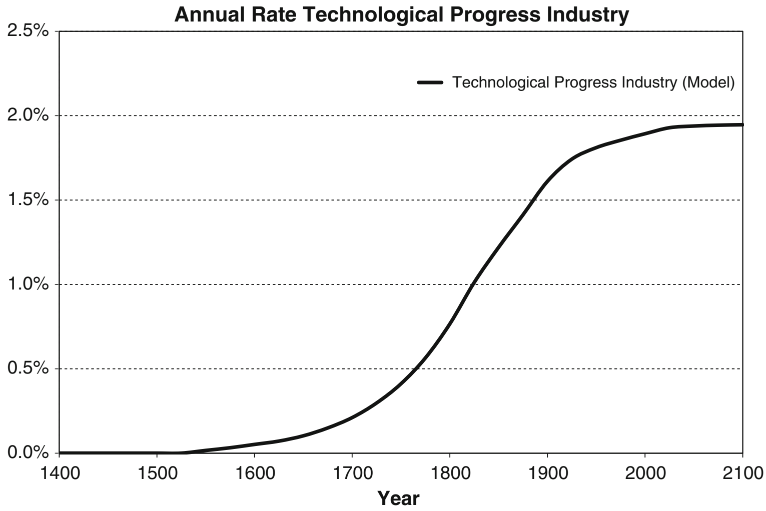

Fig. 3 Technological progress

the per child rearing cost in the rural Philippines in 1975, which then had a per capita GDP roughly equal to England's in 1850, was 4.2 %. In the calibration, the 1850 child rearing cost for England is 4.15 %. For another example, de la Croix and Doepke (2004) report a child rearing cost between 7.5 and 15 % for the United States in 2000. In the calibration, the 2000 time rearing cost is 8.7 %. Thus, the calibration is empirically plausible along this dimension.[24]

Figure 3 shows the size of the innovation in each period whereas Fig. 4 depicts the growth rate of real GDP per capita, each expressed as an average annual growth rate. Real GDP in the model is computed using a chain weighted method. Figure 4 also includes Broadberry et al. (2010) estimates for English growth rates from 1400 to 1900. As Fig. 4 shows, the model does a very good job matching England's growth rate of per capita GDP over this period. As seen in Fig. 3, the first year in which industrial firms innovate is 1550. Most economic historians identify the start of the *Industrial Revolution* sometime in the second half of the 18th century, when annual GDP growth per capita surpassed 0.5 % (Broadberry et al. 2010). Consistent with this view, our model predicts that this threshold was reached in 1775. For this and future purposes, we identify the start of an industrial revolution with a 0.5 % annual growth of per capita GDP in the model.

Figures 5 and 6 report the model's predictions with respect to its agricultural transformation. Figure 5 depicts agriculture's share of employment as predicted by the model, and compares it to the English data based on Allen (2000) for the 1400–1800 period and on Mitchell (1988) thereafter. Figure 6 shows land's share of GDP for the model and for England based on Bar and Leukhina (2010).[25] The model predicts a transition out of agriculture which is somewhat too slow. One factor that clearly contributed to the speed of England's structural

[24] Alternatively, instead of endogenizing the demographics and calibrating the child rearing cost to the historical population increase, we could have treated the demographics as exogenous and fed in the population increase numbers directly. This would not change the main message of the paper as our theory of the take-off and acceleration of growth does not emphasize the effect of income of population.

[25] The model does not do so well in matching agriculture's share of output as measured by Broadberry et al. (2010). Given perfect mobility of labor between sectors and Cobb-Douglas utility, the equalization of income

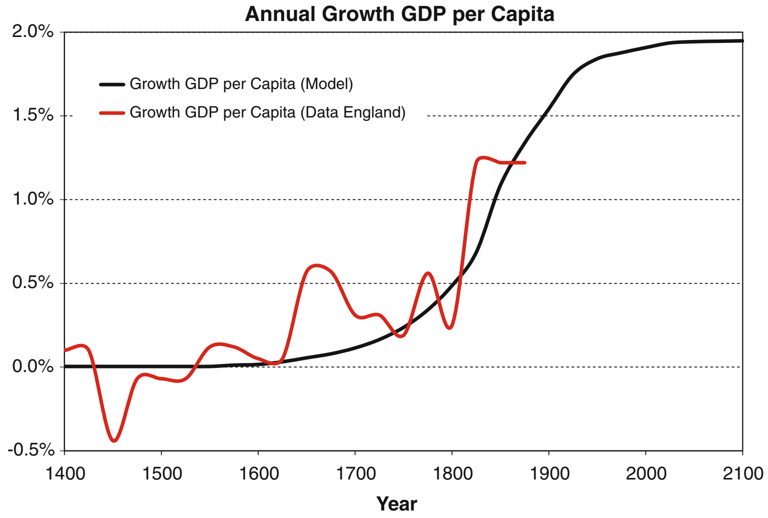

Fig. 4 Growth GDP per capita

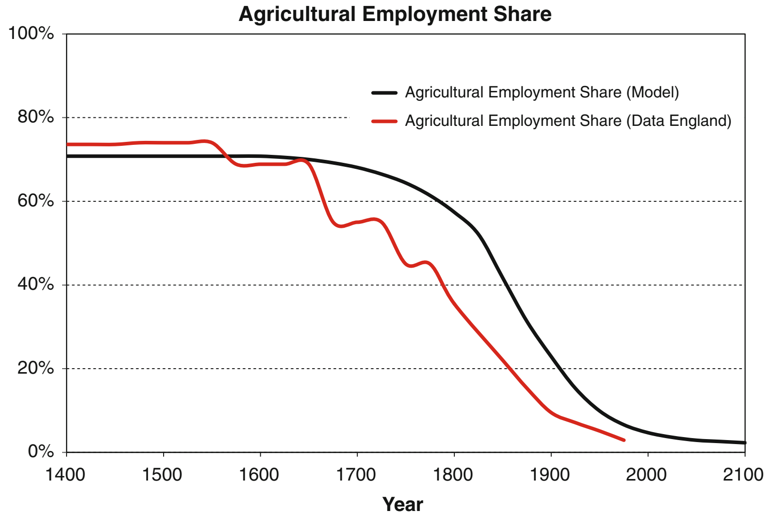

Fig. 5 Agricultural employment share

transformation but not considered in this model is net food imports, which according to Clark (2009) went from −1 % of GDP in 1560 to +10 % by 1800. Given that our model economy is closed, it generates a slower drop in agriculture's share of employment in England. The model's more gradual decline in the land share is also easily understood. In the data the land share decreases because of both the structural transformation and the declining land share in agriculture. However, in our model the land share in agriculture is fixed. By taking an

Footnote 25 continued
implies that agriculture's share of output is exactly equal to its share of employment. Matching the lower output shares would require complicating the model, detracting from its main point.

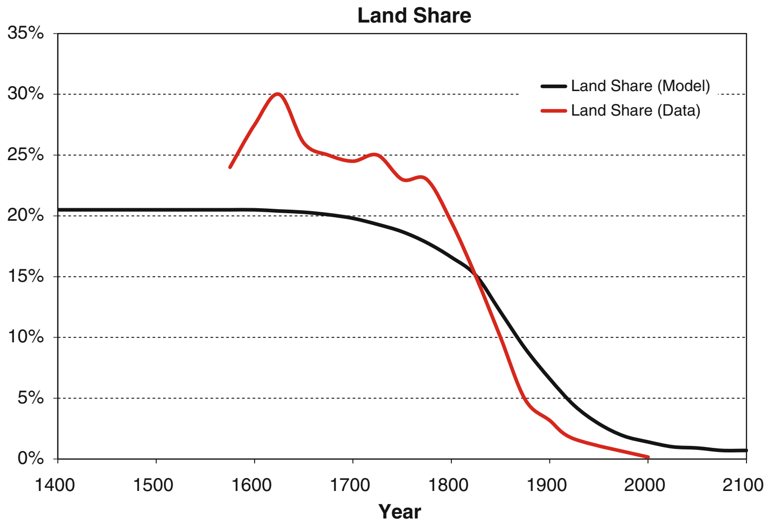

Fig. 6 Land income share

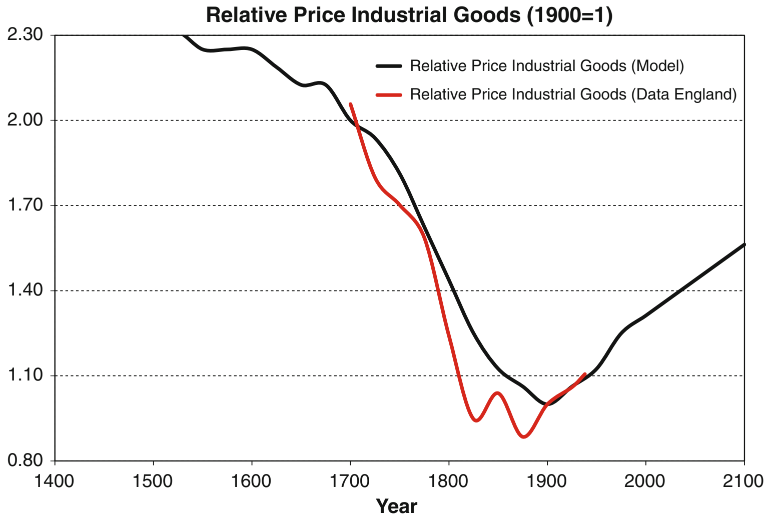

Fig. 7 Relative price industrial goods

average of the land share in 1600 and 1950, the predicted land share in the model is slightly too low in the early period, and slightly too high in the later period.

Figure 7 compares the model's predictions for relative prices with the English data starting in 1700. Data on relative prices are from Yang and Zhu (2008) for the 1700–1909 period, and are then extended through 1938 using the Sauerbeck price series in Mitchell (1988).[26] The evolution of relative prices (Fig. 7) predicted by the model seems reasonable. The relative

[26] We were not able to extend the British data on relative prices beyond 1938. For the United States, however, the relative price of manufactured goods has shown no secular trend in the 20th century. This is consistent with the model's prediction of a constant relative price in the balanced growth path.

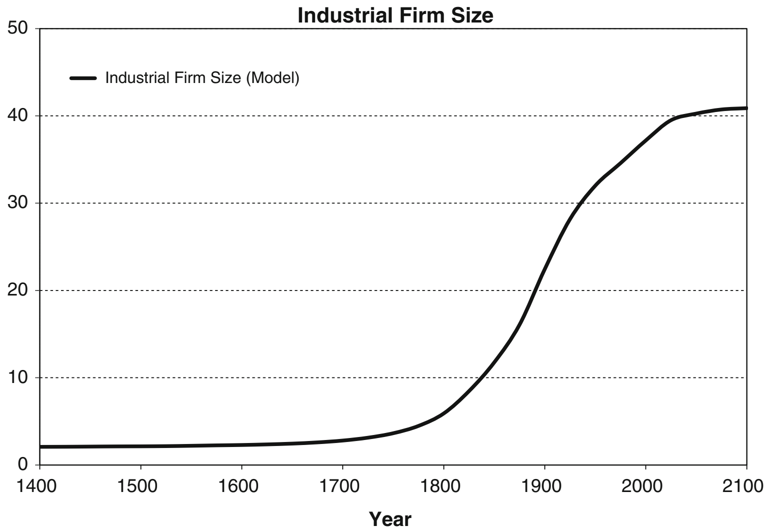

Fig. 8 Industrial firm size

price in the model displays the same size decline between 1700–1900 as in the data. Moreover, the model matches the subsequent price increase post 1900. The non-monotonicity of the relative price reflects the behavior of the ratio of the industrial wage rate to technology, $w_x/[A_x(1+g_v)]$, which affects the price charged by an industrial firm as shown in equation (24). This ratio declines throughout much of the transition period from Malthusian stagnation to modern growth, and then increases slightly before converging to a constant. This pattern arises because the absolute size of the agricultural population initially increases, then decreases, and eventually stabilizes as the economy converges to a constant population. Because land is a fixed factor, this implies that agricultural household income initially grows slower, then faster, and eventually at the same rate as technical progress in industry. Since households must be indifferent between working in both sectors, the evolution of industrial household income is similar: it first grows more, than less, and eventually at the same rate as technological progress. This explains the non-monotonic behavior of this ratio, and the relative price of industrial goods.

In terms of the specific mechanism underlying our theory—the relation between market size, firm size and innovation—the calibrated model implies a fairly small increase in firm size prior to 1700, but a large increase thereafter. In particular, Fig. 8 shows that the number of workers per establishment increases by a factor of less than 1.5 from 1400–1700 and thereafter by a factor of 15. Surprisingly, there is no systematic report of firm size or establishment size for England before the 18th century to which to compare our model. Although not directly comparable, establishment size data for the U.S. manufacturing sector provided by Atack and Bateman (2006) before 1970 and by the U.S. Census of Manufactures thereafter displays a similar increase: between 1850 and 2000 average establishment size grew by a factor of 4.25 in U.S manufacturing manufacturing. In the model, the increase in firm size over this same time period is 4.08.

On other dimensions that are similarly specific to our theoretical mechanism, such as the secular trend in mark-ups or varieties, comparisons with the data are likewise hard to make. To our knowledge, there is only one trend estimate on mark-ups in England, namely, Ellis

Table 2 Timing of the industrial revolution

	Delay in industrial revolution	
	1850	1950
1. Agricultural productivity		
Decrease in agricultural TFP growth γ_a	−22 %	−40 %
2. Institutions		
Increase in fixed operating cost κ	38 %	57 %
Increase in innovation cost ϕ	15 %	16 %

(2006) who reports a 67 % decline in the mark-up in Britain between 1870 and 1985. This is far larger than the 7 % decline predicted by our model over this period. The Ellis estimate, however, is not calculated from price and wage data, but instead estimated within a specific model economy using a state-space approach. We could not find any data which would give some sense of the increase in the number of consumer varieties in England. Recall, however, that in our theoretical model the number of varieties coincides with the number of firms. Therefore, in as far as we match the size of firms and the number of workers in the industrial sector, we are also matching what corresponds to the number of varieties in our model.[27]

In summary, the model does a reasonable job matching the main features of England's *Industrial Revolution*, especially with respect to England's rate of economic growth. Although its predictions with respect to dimensions of the data specific to our mechanism such as firm size and mark-ups are impossible to verify, they do not seem implausible based on the limited data we have. In light of these results, it is informative to investigate how factors that are likely to differ across societies affect the timing of the industrial revolution. This is the subject we analyze next.

5.2 The timing of the industrial revolution

In this section we explore the sensitivity of the model to the parameter values. Rather than document the quantitative implications of each parameter, we focus on those that most closely correspond to different hypothesis put forth by other researchers for why England was the first country to industrialize. We start by focusing on the following two aspects. First, numerous researchers, such as Schultz (1968) and Diamond (1997), have argued that high agricultural productivity is a pre-condition for take-off. We therefore consider how the start of the industrial revolution is affected by the economy's rate of agricultural TFP growth in the pre-industrial period, γ_a. Second, other researchers, such as North and Thomas (1973), North and Weingast (1989), and Ekelund and Tollison (1981), have claimed that institutional change in England was fundamental to its development path. We explore this view by analyzing how the timing of the industrial revolution is related to the parameters most likely to be affected by government policy and institutions, namely, the fixed operating cost parameter, κ, and the fixed innovation cost parameter, ϕ.

Table 2 shows the change in each parameter value needed to delay the start of the industrial revolution until 1850 or 1950. These two alternative dates should be compared to the

[27] The coincidence of number of firms and number of varieties is natural if one re-interprets the Lancaster variety model as a spatial model, in which goods are differentiated by location. That being said, there are of course ways to introduce a distinction between the number of firms and the number of varieties. For example, we could modify the model to allow for the introduction of new goods through the introduction of new variety circles.

actual starting date of 1775 in the benchmark calibration. As before, in all experiments we identify the start of the revolution as the year when the annual growth rate of per capita GDP reached 0.5 %. Note that we look at the changes in one parameter at a time, keeping all other parameters at their benchmark calibration levels. What Table 2 shows is that small changes in parameters lead to large changes in timing. For example, a 40 % lower growth rate of agricultural TFP delays the industrial revolution by 175 years. Though this is a large relative decline, we are starting from a benchmark annual growth in agricultural TFP of 0.95 %, so that this amounts to a mere 0.38 % point absolute decrease. To understand why this is enough to substantially delay the industrial revolution, note that to achieve the same accumulated growth as with the benchmark TFP over a period of 300 years would take nearly two centuries longer when annual TFP growth is 0.38 % points lower. The same picture emerges when considering the impact of the costs of institutions. A 57 % increase in the fixed operating cost, κ, or a 16 % increase in the innovation cost, ϕ, each delay the start by 175 years. Whereas a 57 % increase in the fixed operating cost may seem large, it translates into only a 10 % increase in the ratio of fixed workers to total workers in industry in 1400.

A final hypothesis we consider for England's early industrialization, most closely associated with Szostak (1991), is the large increase in turnpike and canal miles that significantly lowered transportation costs and integrated England's markets.[28] The basic mechanism of our model emphasizes the positive link between market size and competition. In the model tougher competition shows up as a decrease in the distance between neighboring firms on the variety circle. If market size increases because of population growth, as in the benchmark model, the distance between neighboring varieties drops because more firms enter the market. If, however, market size increases because of market integration, as when roads and canals reduce transport times, the distance between neighboring varieties effectively drops even without more firms entering the market. In the model this can be interpreted as a decrease in the size of the circle circumference.

To assess the relevance of market integration caused by infrastructure investment, we ask by how much the circle circumference must be reduced to generate an industrial revolution in 1775, in the absence of any population growth.[29] In other words, we reset the growth rate of agricultural productivity and the child rearing costs, so that neither the population nor income increases in the preindustrial period, keeping all other parameters to their values in Table 1. For this parameterized economy, we allow the circumference of the circle to decrease at a constant rate ρ per period between 1450 and 1900, namely, $\chi_{t+1} = (1 - \rho)\chi_t$, and calibrate ρ so the industrial revolution starts in 1775.[30] The calibrated value we find for ρ is 0.05, implying a 1900 circumference that is roughly 50 % of its 1400 size. In a geography or spatial reinterpretation of the model, this 50 % reduction translates into a 50 % reduction in traveling times or transport costs, which does not seem implausible in light of the historical record.

This experiment, albeit crude, illustrates the important point that our model does not require agricultural TFP growth and population growth for an industrial revolution to happen. Market size is not just about the number of people, but also about how well integrated

28 Szostak's (1991) view for why the increase in market size was important for England's industrialization is along the lines of Adam Smith's increasing returns to specialization

29 A more rigorous examination of the transportation hypothesis would reinterpret the circle in terms of spatial differences rather than variety differences.

30 The starting date of 1450 is completely arbitrary. Starting the decline in the circumference at a later date would just imply a larger value of ρ for the 1750 start of the industrial revolution.

markets are.[31] This is relevant in light of the estimates by Clark (2009) that show how both population and agricultural TFP were stagnant in the preindustrial period.

6 Conclusion

This paper has put forth a unified growth theory that is consistent with the well documented increase in the variety of consumer goods that preceded the *Industrial Revolution* and the gradual shift in the workplace to larger and more centralized production units. It is also uniquely situated in this literature in that it focuses on the introduction of cost-reducing production technologies by firms as the driving force behind industrialization and growth. We have shown that our theory is plausible by calibrating the model to England's long-run development. We have also examined in the calibrated model the role of various factors emphasized by other researchers as being important for the timing of England's industrialization. A virtue of our theory is that this disparate set of factors all affect the date at which the economy industrializes by changing the price elasticity of demand.

Relative to other unified growth theories, this paper's novelty lies in the mechanism by which larger markets bring about an economy's take-off, rather than in the idea that an expansion of markets is critical for industrialization. The importance of market size is, of course, an old idea, prevalent in the writings of Adam Smith (1776), and a cornerstone of a number of recent growth theories such as Goodfriend and McDermott (1995) and Voigtländer and Voth (2006). However, in contrast to our mechanism, most of these alternative theories typically assume some type of production externality. Our theory does not rely on any type of spillover.

Despite its long history, the view that market size was critical for determining the timing of the *Industrial Revolution* is not without controversy. Crafts (1995), for example, has criticized population-based theories on account that larger countries have not grown faster in the postwar period. In our theory the effective size of the industrial market, and not population size per se, is the key determinant of an economy's take-off. Whereas the effective size of the industrial market depends on a country's total population, it is also affected by transport costs, internal and external trade barriers, agricultural productivity, income levels, and institutions.

Compared to other European countries and China, the evidence suggests that on the eve of the *Industrial Revolution* markets in England were more national in scale. For example, using spatial variations in grain prices, Shiue and Keller (2007) show that England was more integrated than the rest of Europe or China. But did the expanding market size in England also imply that the market for *industrial* goods was larger than in other countries? Although there is some evidence that suggests they were, clearly more research is needed in this area. Given that we have shown that our mechanism is quantitatively plausible, we see this as a useful venue for future research.

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[31] In this experiment we focused on transport infrastructure, but international trade is of course another factor that contributed to larger and more integrated markets (see, e.g., Findlay and O'Rourke 2007). A reduction in trade costs in an open economy version of the model would hasten the start of the industrial revolution through the same mechanism. Given the extra notation involved, we do not quantify the effect of greater openness.

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