The Evolution of Markets and the Revolution of Industry: A Unified Theory of Growth *

Klaus Desmet
Universidad Carlos III
and CEPR

Stephen L. Parente
University of Illinois
and CRENoS

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Abstract

This paper puts forth a unified theory of growth. According to this theory, an economy's transition from a Malthusian era with stagnant living standards, to a modern era, with sustained and regular increases in income per capita requires markets to reach a critical size, and competition to reach a critical level of intensity. An *evolution* in markets is thus a precondition for a *revolution* in industry. By allowing an economy to produce a greater variety of goods, a larger market makes goods more substitutable, raises price elasticity of demand, and lowers mark-ups. With lower mark-ups firms become larger in order to break even, which raises the return to innovation as a larger firm is able to ammortize R&D costs over a larger of quantity of goods. We demonstrate our theory in a dynamic general equilibrium model and use it to demonstrate how various factors emphasized in the literature affect the starting date of this transition.
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1 Introduction

Sometime in the 18th century, England escaped a Malthusian trap of stagnant living standards as technological progress accelerated and output growth outpaced population growth. One hundred and fifty years later, England's transformation from a primarily agrarian society was essentially complete as it emerged as a fully industrialized country with a constant and robust growth rate of per capita output. England is not unique in this experience; although different in time and place, other countries have gone through similar revolutions. An important question is why did the world's first *Industrial Revolution* have to wait until the 18th century and occur in England and not some place else?

This paper proposes a novel mechanism to explain an economy's transition from a Malthusian era with stagnant living standards, to a modern growth era, with sustained and regular increases in income per capita, and in doing so provides a novel answer to the question of why England first. The paper's central hypothesis is that markets need to become sufficiently large and competition sufficiently strong before an economy can take off. An *evolution* in markets is thus a precondition for a *revolution* in industry. In particular, a gradual increase in market size during the Malthusian era, associated with population growth and lower transport costs, spurs greater competition, and sets the industrial revolution in motion, allowing the economy to move from low to high growth.

Markets need to be large enough and competition intense enough, or firms will not find it profitable to innovate. The mechanism from market size and competition to innovation works as follows. A larger market allows an economy to sustain a greater variety of goods and services, making them more substitutable. As a result, price elasticities of demand increase, and mark-ups drop. These changes raise the return to innovation. With a drop mark-ups, firms must sell more units of output in order to break even. Hence firms become larger, and larger firms are able to amortize the fixed R&D costs over a greater quantity of goods. Therefore, only after the market reaches a critical size and competition is strong enough, does innovation endogenously take off.

We generate this elasticity effect by embedding Lancaster (1979) preferences into a model of process and product innovation. The Lancaster construct, which is based on Hotelling's (1929) spatial model of horizontal differentiation assumes that each household has an ideal variety identified by its location on the unit circle. As shown by Helpman and Krugman (1985) and Hummels and Lugovskyy (2005), when the population increases, more varieties enter the market. As goods 'fill up the circle', neighboring varieties become closer substitutes, so that the price elasticity of demand increases and mark-ups fall. Desmet and Parente (2007) exploit this feature and show in a one-period model how the higher elasticity of demand, whether due to a larger population or more liberalized trade, raises the return to process innovation, thereby leading to a larger increase in productivity.[1]

Our model not only gives rise to a transition from stagnation to modern growth, but also to a structural transformation and a demographic transition. The structural transformation, the demographic transition and the transition to modern growth are all linked. This is to say that the development path of the economy as it transits to modern growth is affected by the accompanying structural transformation and demographic transition while the population path and sectoral composition path are affected by its transition to modern growth.

To generate the structural transformation, we include a farm sector that produces a subsistence good in the model. This captures the idea that agents need a minimum amount of food to survive. This is a standard way of introducing nonhomotheticicities in preferences, implying that as consumers become richer, they dedicate a decreasing share of their incomes to food consumption (Galor and Weil, 2000; Caselli and Coleman, 2001). With the start of the industrial revolution and rising living standards, the share of labor employed in agriculture falls in favor of industry.

To generate the demographic transition, we include children in the preferences of

[1] This mechanism is by construction absent with Spence-Dixit-Stiglitz preferences, since its constant elasticity feature precludes a link between market size, elasticity and innovation. This key difference is not only theoretically relevant, it is also empirically important. There is ample evidence of a positive relation between market size and demand elasticity. This empirical regularity is present whether markets expand because of population growth (Campbell and Hopenhayn, 2005) or because of trade liberalization (Tybout, 2003; Hummels and Klenow, 2005).

parents and assume a different cost to rearing children between the farm sector and the industrial sector. There is no quality decision, however, and so the demographic transition does not involve any human capital.[2] The increase in the population growth rate corresponding to the first phase of the demographic transition is a consequence of rising TFP growth in agriculture that is brought on by the acceleration of growth in industry. The growth rate of agricultural TFP in the model is assumed to depend on the level of technology in the industrial sector to capture the mechanization of farming that occurred throughout the nineteenth century in England on account of technological innovations in industry. As agricultural TFP and industrial TFP accelerate, living standards in both sectors rise, and households in both sectors have more children. The decrease in the population growth rate corresponding to the second phase of the demographic transition is a consequence of compositional effects arising from the economy's structural transformation. Because the cost of rearing children is higher in the industrial sector, the population growth rate begins to fall as more of the population resides there. [3]

Our paper is part of an emerging literature known as *unified growth theory* that attempts to model the transition from Malthusian stagnation to modern economic growth within a single framework. Important contributions include, amongst others, Kremer (1993), Goodfriend and McDermott (1998), Jones (2001), Galor and Weil (2000), Lucas (2001), Hansen and Prescott (2002), and Voigtlander and Voth (2006). Clearly, the main difference with our work lies in the novelty of the mechanism we emphasize. For example, Hansen and Prescott (2002) is based on exogenous technological progress. Galor and Weil (2000) relies on increasing returns and externalities associated with human capital production to generate the industrial revolution. Our model, instead, focuses on the link between market size, competition and innovation.

In light of the existing empirical evidence, our framework presents a number

[2]For this reason, our theory avoids the criticism of human capital stories of the industrial revolution made. In particular, Mokyr (2006) and Feinstein (1988) provide evidence that suggest that human capital was not an important factor in the early phase of England's *Industrial Revolution*.

[3]In fact, the laws restricting child labor in 19th century England applied only to factory work, and explicitly excluded farm work (Doepke and Zilibotti, 2005).

of advantages over these other theories and models. Mokyr (2006), for example, has criticized those theories that are based on human capital accumulation on the basis that there was no significant increase in the number of educated people in the 18th Century. Voth (2003), for another, has criticized those theories that rely exclusively on a positive link between population size and innovation, as this relation is empirically elusive. He argues that the broader concept of market size is more appropriate, because at the end of the 18th century England was more populous than equally wealthy Holland, and much richer than more populous France.

These criticisms do not apply to our theory. Education, or human capital, is not part of our theory. Additionally, the relevant variable for take-off in the model is the size of the market, and not population per se. While it is certainly true that a country's overall population is a critical determinant of the size of its market and the intensity of competition, other factors matter as well. For example, lower transportation costs and trade barriers, higher per capita income, higher agricultural TFP, and more urbanization all increase market size, and thus imply an earlier take-off date.[4] Needless to say, regulation and institutions also matter, as they affect the fixed cost of innovating. We show via a series of numerical experiments how these different factors affect the timing of an economy's industrial revolution.

Greater population, better institutions, higher agricultural TFP, lower transportation costs, higher income, and greater openness are factors that have been identified by others as being important for understanding why the *Industrial Revolution* first happened in England in the 18th century. The contribution of this paper, therefore, is not in identifying the factors that are important for the start of the industrial revolution. Nor does the paper's contribution rest in the idea that the expansion of markets and firm size is critical for innovation. The idea that larger firms have a greater incentive to innovate on account that they can spread the fixed R&D costs over a larger quantity of goods is an

[4]Simon (1977) and Kremer (1999) have emphasized the importance of population growth for development, whereas Williamson and O'Rourke (2005) and O'Rourke and Findlay (2007) have been at the forefront of the camp that stresses the role of international trade. Schultz (1971), and more recently Diamond (2007), have argued that an agricultural revolution is a precondition for an industrial revolution.

idea that is prevalent in Schumpeter (1942). Instead, the paper's essence is the mechanism whereby market size affects firm size and the incentive to innovate by raising the price elasticity of demand and by lowering the mark-up. Many of the factors identified by others as being important for the start of England's industrial revolution work to increase market size, and so all were important for the same reason in our theory.

As these other factors are consistent with alternative theories of the industrial revolution, empirical evidence in support of greater openness, better institutions and the like are insufficient to test our theory. Instead, what is needed is historical data on price elasticities and mark-ups. While we are unaware of a long historical time series for these two variables, there is a good deal cross-sectional evidence that finds that larger markets are associated with higher price elasticity of demand and lower mark-ups. In terms of historical time series, there is data on the increase in firm size going back to 1800. For example, Atack et al. (2008) documents an increase in the size of manufacturing firms in the 1870-1900 period in the United States and Granovetter (1984) produces similar findings for the United States between 1904 and1977.

The rest of the paper is organized as follows. Section 2 describes the model and characterizes the optimal decisions of agents. Section 3 defines the equilibrium and shows algebraically that the equilibrium is unique and in the limit converges to a balanced growth path provided certain parametric relations hold. Section 4 describes a set of numerical computations intended to fully illustrate the equilibrium properties of the model and its mechanics. Section 5 concludes the paper.

2 The Model

In this section we describe the structure of the model economy. Time is discrete and infinite. 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 via a production function that uses labor and land and 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 the unit circle.

There is both product and process innovation in the industrial sector. The household sector consists of one-period lived agents. For each household, there is a variety of the differentiated good that he prefers above all others. In addition to industrial goods, each household derives utility from consumption of the agricultural good, and by having children. Households either work in the farm sector or the industrial sector. They use their income to buy agricultural and industrial goods. Households also chose the number of children, who then constitute the household sector in the next period. There is a time cost of rearing children that depends on the sector the household works/lives in. In what follows we describe the model structure and the relevant optimization problems encountered by agents in each sector.

2.1 Industrial Sector

The industrial sector is monopolistically competitive, and produces a set of differentiated goods, each with a unique address on the unit circle. The technology for producing these goods uses labor as its only input. The existence of a fixed cost, which takes the form of labor, gives rise to increasing returns. Since the fixed cost is not a sunk cost, there is free entry and exit of firms. Additionally, as in Lancaster (1979), firms can costlessly relocate on the circle.

2.1.1 Production.

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

$$Q_{vt} = A_{vt}[L_{vt} - \kappa_{vt}] \tag{1}$$

The fixed cost is given by

$$\kappa_{vt} = \kappa e^{\phi g_{vt}}, \tag{2}$$

where $\kappa > 0$ and $\phi > 0$ are parameters and g_{vt} is rate of process innovation chosen by the firm at the start of the period over the technology it begins the period with. 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 the innovation and an operating cost represented by κ that is incurred even if there is no innovation (i.e., $g_{vt} = 0$).

The technology a firm begins the period with is referred to as the benchmark technology, and is equal to the average technology used by industrial firms in the preceding period. Formally, let A_{xt} denote the benchmark technology, V_t denote the set of varieties produced, and let m_t denote the number of firms or varieties produced in period t, i.e., $m_t = card\{V_t\}$. Then,

$$A_{xt} = \sum_{v \in V_t} \frac{1}{m_{t-1}} A_{v,t-1} \tag{3}$$

The technology used in period t by the firm producing variety v is thus

$$A_{vt} = (1 + g_{vt}) A_{xt} \tag{4}$$

2.1.2 Profit Maximization

The fixed labor 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. Each firm chooses the price and quantity of its good to be sold, the number of workers to hire, and the technology to be operated. As is standard in models of monopolistic competition, firms take all aggregate variables in the economy including the industrial wage rate in the economy as given.[5]

An industrial firm's profits, $\Pi_{vt} = p_{vt} Q_{vt} - w_{xt} L_{vt}$, where w_{xt} is the wage in the industrial sector, and p_{vt} is the price of variety v. Using (1), profits can be written as

$$\Pi_{vt} = p_{vt} Q_{vt} - w_{xt} [\kappa e^{\phi g_{vt}} + \frac{Q_{vt}}{A_{xt}(1 + g_{vt})}] \tag{5}$$

A firm chooses (p_{vt}, γ_{vt}) to maximize the above equation, subject to aggregate demand. The profit maximizing price is a markup over the marginal unit cost $w_{xt}/[A_{xt}(1+ g_{vt})]$, so that

$$p_{vt} = \frac{w_{xt}}{A_{xt}(1 + g_{vt})} \frac{\varepsilon_{vt}}{\varepsilon_{vt} - 1} \tag{6}$$

[5] In principle this requires firms to be of measure zero, a condition that is not satisfied. See Desmet and Parente (2008) for a discussion of how firms could be made of measure zero, without changing any of the results.

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

$$\varepsilon_{vt} = -\frac{\partial Q_{vt}}{\partial p_{vt}} \frac{p_{vt}}{Q_{vt}}$$

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

$$-\phi \kappa e^{\phi g_{vt}} + \frac{Q_{vt}}{A_{xt}(1+g_{vt})^2} \leq 0 \tag{7}$$

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

2.2 Farm Sector

The farm sector is perfectly competitive. Farms produce a single, non-storeable consumption good via a constant returns to scale technology, with labor and land as its only inputs. Farms own their land, which is fixed in supply in the economy and normalized to 1. The agricultural good serves as the economy's numeraire.

Let Q_{at} denote the quantity of agricultural output of the stand-in farm and let L_{at} denote the corresponding agricultural labor input. Then

$$Q_{at} = A_{at} L_{at}^{\theta} \quad 1 \geq \theta > 0 \tag{8}$$

In the above equation, A_{at} is agricultural TFP, which grows at a rate $\gamma_{at} \geq 0$. Thus,

$$A_{at+1} = A_{at}(1 + \gamma_{at}) \tag{9}$$

As can be seen, the growth rate of agricultural TFP is indexed by time so as to allow it to change over time. We allow for this possibility because the historical record shows a large secular rise in the growth rate of agricultural TFP following the start of the *Industrial Revolution.* [6] As many historians have linked these increases in agricultural productivity with innovations from the industrial sector that mechanized farming, we assume that γ_{at} is a function Γ of the growth rate of the benchmark technology in the industrial sector, namely,

$$\gamma_{at} = \Gamma(A_{xt}/A_{xt-1}) \tag{10}$$

[6] For estimates, see Federico (2006).

The profit maximization problems of farms is straightforward, as they are price takers. The profit of the farm sector is

$$\Pi_{at} = A_{at}{L_{at}}^{\theta} - w_{at}L_{at} \tag{11}$$

where w_{at} is the wage rate. Farms choose L_{at} to maximize equation 11. This yields the standard first order condition

$$w_{at} = \theta A_{at}(L_{at})^{\theta-1} \tag{12}$$

Total profits (or land rents) are thus,

$$\Pi_{at} = (1-\theta)A_{at}(L_{at})^{\theta} \tag{13}$$

and profits per unit of time worked, π_{at}, are .

$$\pi_{at} = (1-\theta)A_{at}(L_{at})^{\theta-1} \tag{14}$$

2.3 Household Sector

Households live for one period. At the beginning of period t there is measure N_t households.

2.3.1 Preferences.

A household derives utility from children, n_t, consumption of the agricultural good, c_{at}, and consumption of the differentiated industrial goods, $\{c_{vt}\}$, where $v \in V_t$. There is a subsistence level of agricultural consumption $c_{\bar{a}} \geq 0$, such that the household's utility depends on the amount by which c_{at} exceeds the subsistence quantity. Within the set of industrial goods preferences are based on Lancaster's (1979) model of ideal varieties. In that construct, each household has an ideal variety of the differentiated industrial good it prefers over all others, that is given by location on the unit circle. The further away a particular industrial variety v lies on the unit circle from a household's ideal variety $\tilde{v}$, the lower the utility derived from consuming a unit of variety v.

Preferences are Cobb-Douglas between agricultural goods, industrial goods and children. More specifically, the utility of a household with ideal variety $\tilde{v}$ located on the unit circle is

$$U = [(c_{at} - c_{\bar{a}})^{1-\alpha}[g(c_{vt}|v \in V_t)]^{\alpha}]^{\mu}(n_t)^{1-\mu} \quad (15)$$

The subutility function $g(c_{vt}|v \in V)$ is

$$g(c_{vt}|v \in V_t) = \max_{v \in V_t}[\frac{c_{vt}}{1 + d^{\beta}_{v,\tilde{v}}}] \quad (16)$$

where $d_{v\tilde{v}}$ denotes the shortest arc distance between variety v and the household's ideal variety $\tilde{v}$. The term $1 + d^{\beta}_{v\tilde{v}}$ is known as Lancaster's compensation function, and can be interpreted as the quantity of variety v that gives the household the same utility as one unit of its ideal variety $\tilde{v}$. The parameter $\beta > 0$ determines how fast a household's utility diminishes with the distance from its ideal variety.

2.3.2 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. There are no barriers to migration, so that a households is free to work in either sector. Households are also endowed with claims to the profits or land rents of farms. Without loss of generality, we assume that the amount farm profits that accrue to a household depends on the time he works on the farm.[7]

2.3.3 Demographics

The law of motion for the population is determined by the number of children each household has as well as by the measures of the population that end up working in the farm sector and the industrial sector. Denote by N^f_t and N^x_t the measure of households employed in agriculture and industry. Thus,

$$N_t = N^f_t + N^x_t \quad (17)$$

[7] We make this assumption rather than the alternative ones where either farm workers or all households receive a lump-sum payment from the farm sector because we prove algebraically that the economy converges to a balanced growth path equilibrium. This assumption, however, is not important for any of the numerical experiments we report.

The split of the population between the two sectors is important because the cost of child rearing differs across sectors. Let τ^i denote the time cost per child for an adult employed in sector $i \in \{f, x\}$ and n_t^i the number of his children. We assume that $\tau^x \geq \tau^f$, as there are many reasons to think it is more costly to raise children in the city than the country.[8]First, it is easier to watch children while tending vegetables in a field than in a factory. Additionally, as pointed out by Tamura et al. (2007) the infant mortality rate up to the 20th century was much higher in cities than countries.[9]

The law of motion for the population is thus,

$$N_{t+1} = n_t^f N_t^f + n_t^x N_t^x \tag{18}$$

2.3.4 Utility Maximization

The differential cost of rearing children in the city and on the farm implies that household income will be different for an industrial and agricultural worker even though households are free to move across sectors. We therefore distinguish between an agricultural household's income per unit of time worked, y_t^f, and an industrial household's income per unit of time worked, y_t^x. Given the assumption that farm profits are paid out based on the amount of time an agent works at the farm, the income per unit of time worked of an agricultural household is $w_{at} + \pi_{at}$, and the income per unit of time worked of an industrial household is just w_{xt}. Then the budget constraint of the household working in sector $i \in \{f, x\}$ is

$$y_t^i(1 - \tau^i n_t^i) = c_{at}^i + \sum_{v \in V} p_{vt} c_{vt}^i \tag{19}$$

[8]Rosenzweig and Evensen (1977) and by Hansen and Prescott (2002) make this claim.

[9]While it is tempting to interpret this higher rearing cost as an education or human capital cost, it is not appropriate because a child reared in the agricultural sector in the model can work as an adult at the same productivity as someone reared in the city.

Maximizing (15) subject to (19) yields the following first order necessary conditions:

$$c^i_{at} = \mu(1-\alpha)(y^i_t - c_{\bar{a}}) + c_{\bar{a}} \quad (20)$$

$$\sum_{v \in V_t} p_{vt} c^i_{vt} = \mu\alpha(y^i_t - c_{\bar{a}}) \quad (21)$$

$$\tau^i n^i_t = (1-\mu)(1 - \frac{c_{\bar{a}}}{y^i_t}) \quad (22)$$

We make assumptions on the values of initial agricultural TFP, A_{a0}, and the initial average industrial technology, A_{x0}, that ensure that $y^i_t(1-\tau^i n^i_t) > c_{\bar{a}}$ for all $t \geq 0$.

The subutility function (16) implies that each agent consumes a single industrial variety. The variety v' that an agent with ideal variety $\tilde{v}$ buys is the one that minimizes the cost of an equivalent unit of the agent's ideal variety, $p_{vt}(1 + d^{\beta}_{v\tilde{v}})$, so that

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

Using (21), a household with ideal variety $\tilde{v}$ and working in sector i therefore buys the following quantity of variety v':

$$c^i_{v't} = \frac{\mu\alpha(y^i_t - c_{\bar{a}})}{p_{v't}} \quad (23)$$

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

3 Equilibrium

As is standard in this literature, we only focus on symmetric Nash equilibria. In such an equilibrium, all firms use the same technology, and all goods are equally spaced along the unit circle. The section consists of three parts. In the first part, we derive the aggregate demand for each industrial good in the case of this type of symmetry, and use this to simplify the first order profit maximization conditions. In the second part, we define a symmetric equilibrium. In the last part, we prove that the equilibrium is unique and converges to a balanced growth path with proper restrictions on parameter values.

3.1 Aggregate Demand

We first determine the aggregate demand for each industrial good in the case where firms are equally spaced around the unit circle, use the same technology, and choose the same price and quantities. To do this, it is necessary to assume that the measure of agricultural households and the measure of industrial households, N_t^f and N_t^x, are each uniformly distributed around the unit circle in terms of ideal varieties.

Since in a symmetric Nash equilibrium all varieties produced are equally spaced along the unit 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 unit circle. Let d_t denote the distance between two neighboring varieties in period t. The distance between varieties is inversely proportional to the number of varieties, namely,

$$d_t = \frac{1}{m_t} \tag{24}$$

As the nearest competitors to the right and to the left of the firm producing variety v are each located at the same distance d from it, we do not need to differentiate between them, and thus denote each competitor by v_c and their prices by p_c. The agricultural household who is indifferent between buying varieties v and v_c is the one whose cost of a quantity equivalent of one unit of its ideal variety in terms of variety v equals the cost of a quantity equivalent of its ideal variety in terms of variety v_c. Consequently, the agricultural household who is indifferent between v and v_c is the one located at distance d_v from v, where

$$p_c[1 + (d - d_v)^\beta] = p_v[1 + d_v^\beta\ ] \tag{25}$$

Given this indifference condition applies to agricultural households both to the right and to the left of v, a share $2d_v$ of agricultural households consumes variety v. As agricultural households are uniformly distributed along the unit circle and each household spends $\mu\alpha(y_t^f - c_{\bar{a}})$ on the industrial good, it follows that agricultural households will consume C^f units of variety v where

$$C_{vt}^f = 2d_{vt} N_t^f c_{vt}^f = \frac{2d_{vt} N_t^f \mu\alpha(y_t^f - c_{\bar{a}})}{p_{vt}} \tag{26}$$

This is the demand for v by agricultural workers. By analogy, total demand by industrial workers is

$$C_{vt}^x = 2d_{vt} N_t^x c_{vt}^x = \frac{2d_{vt} N_t^x \mu\alpha(y_t^x - c_{\bar{a}})}{p_{vt}} \tag{27}$$

Given that all firms are spaced evenly in the symmetric equilibrium, it follows that $2d_{vt} = d$. Hence, aggregate demand for variety v, C_{vt}, is

$$C_{vt} = d_t(N_t^f c_{vt}^f + N_t^x c_t^x) = \frac{d_t \mu \alpha (y_t^f N_t^f + y_t^x N_t^x - N_t c_{\bar{a}})}{p_{vt}} \tag{28}$$

With these demands in hand, we can solve for the price elasticities in a symmetric Nash equilibrium. This can be done in in two steps. Recall that d_v is the shortest arc distance between the firm and the indifferent customer, and d is the shortest arc distance between the firm and its nearest competitor. First, it is easy to derive from (28) and (1) that

$$-\frac{\partial C_v}{\partial p_v}\frac{p_{\ v}}{C_v} = 1 - \frac{\partial d_v}{\partial p_v}\frac{p_v}{d_v} \tag{29}$$

Next, we solve for the partial derivative $\partial d_v / \partial p_v$ by taking the total derivative of the indifference equation (25) with respect to p_v. This yields

$$\varepsilon_{vt} = 1 + \frac{[1 + d_v^\beta]p_v}{[p_v \beta d_v^{\beta-1} + p_c \beta (d - d_v)^{\beta-1}]d_{\ v}} \tag{30}$$

Given that $p_v = p_c$ and $2d_v = d$, (30) reduces to

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

Equation (31) together with equations (6) and (7), provide the key to understanding the model's results and the importance of the address construct. From equation (31) it is apparent that as the number of varieties increases, and the distance between firms decreases, the price elasticity of demand increases. From equation (6), it follows that an increase the price elasticity of demand brings about a smaller markup. This 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. Larger firms find it easier to bear the fixed costs of R&D, leading to more innovation.

3.2 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, for the benchmark technology, and for TFP in the farm sector. In addition to the profit maximizing and utility condition characterized above and the market clearing conditions, households must be indifferent between working in the farm sector and the industrial sector. More specifically, for any given household with an ideal variety v the utility associated with the consumption and children is the same across sectors, namely

$$U(c^f_{vt},\ c^f_{at}, n^f_t) = U(c^x_{vt},\ c^x_{at}, n^x_t) \tag{32}$$

Additionally, it must be the case that firms in the industrial sector earn zero profits in an equilibrium. Thus,

$$p_{vt}Q_{vt} - w_{xt}[\kappa e^{\phi g_{vt}} + \frac{Q_{vt}}{A_{xt}(1+g_{vt})}] = 0 \tag{33}$$

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

We now define the dynamic *Symmetric Equilibrium.*

Definition of Symmetric Equilibrium. *A Symmetric Equilibrium is a sequence of household variables* $\{c^f_{vt}, c^f_{at}, n^f_t, y^f_t, N^f_t, c^x_{vt}, c^x_{at}, n^x_t, y^x_t, N^x_t\}$*, a sequence of farm variables* $\{Q_{at}, L_{at}, \pi_{at}\}$*, a sequence of industrial firm variables* $\{Q_{vt}, L_{vt}, p_{vt}, g_{vt}, \varepsilon_{vt}, A_{vt}\}$*, and a sequence of aggregate variables* $\{V_t, w_{xt}, m_t, w_{at}, d_{vt}, N_t, A_{xt}, A_{at}\}$ *that satisfy*

(i) utility maximization conditions given by equations (20)

(ii) farm profit maximization conditions given by equations (8), (12), and (14)

(iii) industrial firm profit maximization conditions (1), (4), (6), (7), and (31)

(iv) market clearing conditions

a) industrial goods

$$Q_{vt} = d_t(N^f_t c^f_{vt} + N^x_t c^x_{vt}) \tag{34}$$

b) industrial labor market

$$m_t L_{vt} = N^x_t(1 - \tau^x n^x_t) \tag{35}$$

c) farm labor market

$$L_{at} = N_t^f(1 - \tau^f n_t^f) \tag{36}$$

d) farm good market

$$Q_{at} = N_t^f c_{at}^f + N_t^x c_{at}^x \tag{37}$$

(v) aggregate law of motion for A_{xt} given by (3); for N_t given by (18); and for A_{at} given by (9) and (10)

(vi) zero profit condition of industrial firms given by (33)

(vii) indifference condition of households given by equation (25) and population feasibility given by (17).

3.3 Properties (incomplete)

We conclude this section by addressing the issue of multiple equilibria and the limiting properties of the model, namely, whether the economy converges to something that resembles a balanced growth path.

Proposition 1. *In the limit, the economy converges to a balanced growth path with zero population growth and constant growth in industrial technology provided that*

$$(\frac{1-\mu}{\tau_a} - 1)(\frac{1-\alpha}{\alpha})(\frac{\tau_x}{\tau_f})^{\frac{1-\mu}{\mu}} + (\frac{1-\mu}{\tau_f} - 1) = 0 \tag{38}$$

This is condition is effectively the condition that guarantees zero population growth in the limit.

Proposition 2. *The equilibrium is unique.*

4 Numerical Experiments

We now analyze the equilibrium properties of the model numerically. We begin by examining whether the model generates a pattern that is roughly consistent with the transition from a Malthusian era to a modern growth era. Subsequently, we analyze how various factors or parameters within the model affect the timing of the industrial revolution. While there are many model parameters that we could analyze, we focus on those for which there is good *a priori* reason to believe they are potentially important in understanding the timing of the industrial revolution. Those parameters are the initial population, agricultural TFP, the fixed cost of operating a firm, and the cost of innovation.

Towards this goal, it is instructive to briefly review the pattern of long-run development. Based on the estimates by Maddison (2008), Table 1 reports the growth rates of GDP per capita and of population between 1500 and 2000 for the United Kingdom and Western Europe. In the last decade, many economic historians have challenged the hypothesis that living standards were stagnant before the industrial revolution. Maddison's estimates reflect this new view. As can be seen, the UK living standard rose between 1500 and 1700 at a rate of 0.28 percent per year. Although between 1700 and 1820 the growth rate of GDP per capita did not accelerate, the growth rate of population did. While between 1500 and 1700 the population grew at an annual rate of 0.39 percent, during the 18th century the growth rate averaged 0.76 percent. Between 1820 and 1880 growth in income per capita accelerated significantly, averaging 1.19 percent annually, and the population also grew faster. During the 20th century growth in living standards continued to increase, while population growth dropped, due to the demographic transition. Between 1940 and 2000 income per capita grew at an annual rate of 1.81 percent, whereas population only increased at an average rate of 0.35 percent, similar to pre-industrial revolution figures.

Both Western Europe and the United States have gone through the same stages of development as the United Kingdom. Taking all factors in consideration, we see the long-run pattern of development to be characterized by an initial era of very low growth in the living standard and the population. This is followed by an industrial revolution with a higher and accelerating growth rate of per capita GDP, and with a rising and then falling growth rate of the population. The final era is characterized by a high rate of growth of per capita GDP and a lower growth of the population.

We now parametrize the model and compute the equilibrium path to see if it gives rise to a development and growth pattern similar to the one documented above. In par-

Table 1: England, Western Europe and the United States, 1500-2000

Country	1500-1700	1700-1820	1820-1880	1880-1940	1940-2000
			GDP per capita		
England	0.28%	0.26%	1.19%	1.14%	1.81%
Western Europe	0.13%	0.16%	1.03%	1.30%	2.35%
United States		0.73%	1.56%	1.32%	2.36%
			Population		
England	0.39%	0.76%	0.82%	0.55%	0.35%
Western Europe	0.18%	0.43%	0.71%	0.59%	0.45%
United States		1.94%	2.74%	1.62%	1.27%

ticular, we seek to examine if the model is capable of generating three distinct phases in long-run development: a Malthusian period, with rising population and essentially constant living standards; followed by an industrial revolution with still low, but accelerating rates of economic growth, and increasing population growth; culminating in a modern era, with higher but constant GDP per capita growth, and falling rates of population growth that eventually level off.

Table 2: Parameter values

$\beta = 0.55$	$\phi = 6.4$	$\kappa = 0.34$	$N_0 = 40$
$\mu = 0.89495$	$\alpha = 0.9$	$A_{a0} = 7$	$A_0 = 1$
$\theta = 0.65$	$\gamma_a = 0.00045$	$\tau_a = 0.0545$	$\tau_v = 0.118418$
$c_{\bar{a}} = 0.22$			

The parameter values used in the benchmark experiment are given in Table 2. Although this parametrization does not follow a precise calibration procedure, it is still useful to motivate our choices. There are two key restrictions we impose in the parametrization. The first restriction is that the Malthusian phase of the equilibrium path be characterized by constant population growth and essentially constant output per worker in agriculture. The second restriction is that there is zero population growth in the limit. These restrictions are important for the the utility share parameters, μ and α as well as the relative costs to rearing children in the two sectors as can be seen by the zero population growth condition (38).

The motivation for the remaining parameter values is as follows. The cost of raising children in the city, τ^x, has been set to 0.118418, in line with estimates of the cost of rearing children in the city by Knowles (1999), Haveman and Wolfe (1995) and Doepke and de la Croix (2004). The cost of rearing children on the farm has been set to the lower value of .0545. The subsistence constraint on agricultural goods, $c_{\bar{a}}$, is chosen so that it is never binding. The parameter value β determines the slope of the decrease in utility as a household consumes a variety farther away from its ideal variety. Its precise value is of limited importance. The fixed cost parameters values, κ and ϕ are set so that industry does not innovate initially and that the rate of growth in per capita GDP in the limit is reasonable.

The agricultural sector technology parameters are A_{a0}, and θ. In addition there is the function that relates TFP growth in agriculture to the rate of technological innovation in industry. For initial TFP, A_{a0}, we set it so to ensure that the economy can produce the subsistence quantity. For θ, we set it to a value that corresponds roughly to historical estimates of labor's share in agriculture. The function Γ is

$$\Gamma(A_{xt}/A_{xt-1}) = \max\{A_{a0}, .90A_{xt}/A_{xt-1}\} \tag{39}$$

4.1 Benchmark

Figures 1 to 6 depict the equilibrium path for the economy along six dimensions. Figure 1 plots the size of process innovation in the industrial sector over time, g_{vt}. As can be seen, prior to the period 83, there is no technological progress in the industrial sector. The industrial revolution begins in that period, and is associated with an increase in the growth rate of technological change for the next 150 periods before leveling off. The path of per capita GDP shown in Figure 2 mirrors this growth in industrial technology. Figure 3 depicts the growth rate of the population and Figure 4 depicts the fraction of the population working in the farm sector. Qualitatively, the model gives rise to a demographic transition and structural transformation. The final two figures, Figures 5 and 6 depict the time paths for the price elasticity of demand and firm size.

Over the first 83 periods, there is no process innovation in the industrial sector, or growth in per capita GDP. This is the Malthusian phase of development. The reasons for this stagnation is insufficient demand for industrial products, due to both the agricultural subsistence constraint and the small population size. More specifically, when the market for industrial goods is small, the economy can only support a limited number of varieties, so that the substitutability between them is small, the price elasticity of demand is low, and the markups are high. This implies that firms are relatively small in equilibrium, so that they are unable to spread the fixed innovation costs over a large enough customer base. However, with at least some population growth in this Malthusian phase, eventually the market for industrial goods expands and with this expansion the price elasticity of demand and firm size reach critical levels so that innovation begins.

Subsequent to the start of process innovation in the industrial sector, the shape of the path of technological progress depends on a number of forces, in particular, the rate of population growth and the responsiveness of the price elasticity of demand to increases in the size of the industrial market. Once technological progress takes off, population growth accelerates on account of the acceleration of agricultural TFP that follows from equation (39), as households experience an increase in living standards and hence are able to afford more children . The larger population, together with higher living standards, give firms greater incentive to innovate. Technological progress accelerates because of the self-reinforcing nature of it: the size of the market increases innovation, and innovation increases the size of the market. The eventual slowdown in technological progress occurs because with the structural transformation and the higher cost of rearing children in the industrial sector, population growth slows down. Additionally, growth slows down because the responsiveness of the demand elasticity decreases as the market becomes larger. With a constant population in the limit, and with the fixed R&D costs being independent of the benchmark technology, firms innovate by the same amount each period.

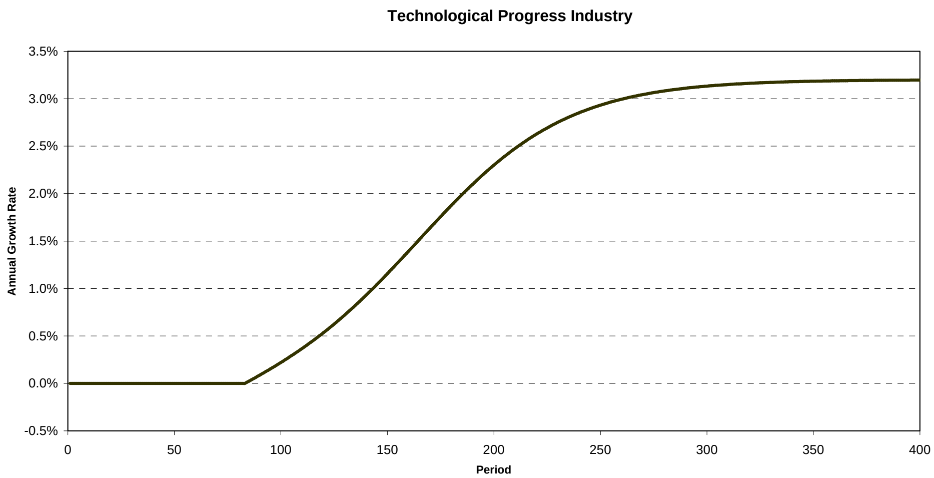

Figure 1: Technological progress industrial sector

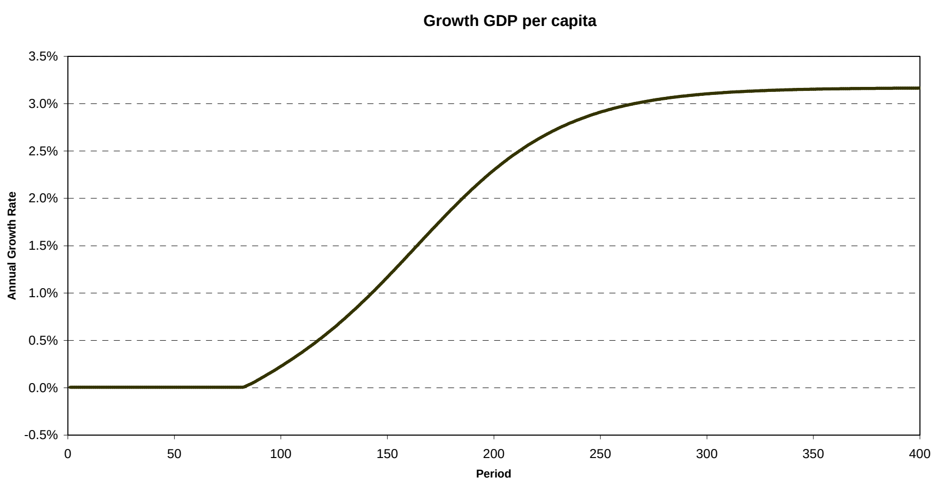

Figure 2: Per capita GDP growth

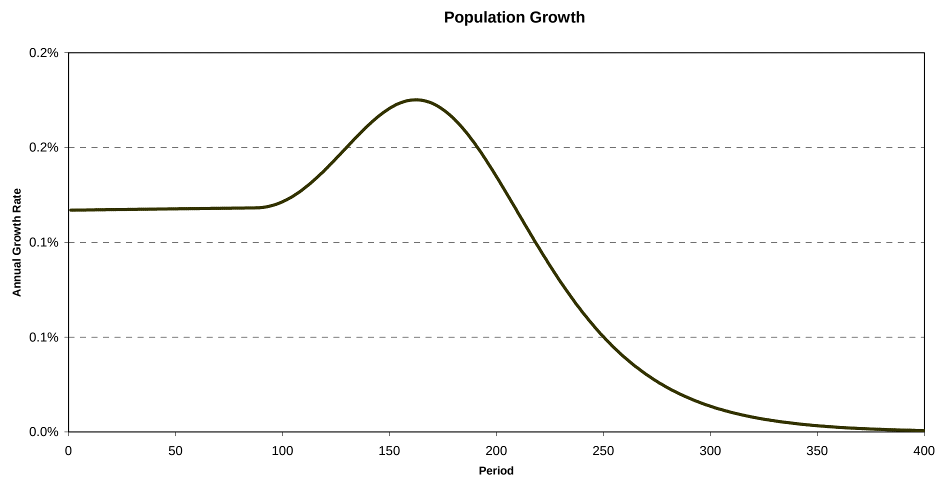

Figure 3: Population growth

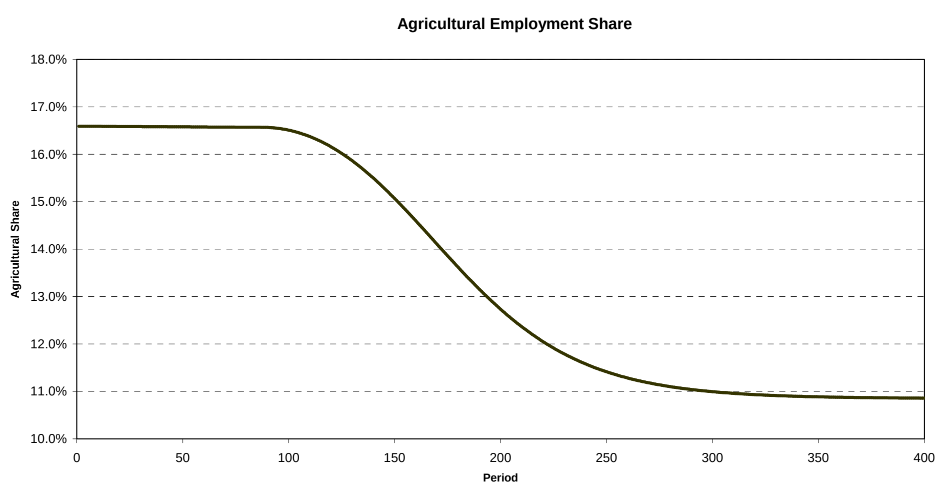

Figure 4: Share of households employed in agriculture

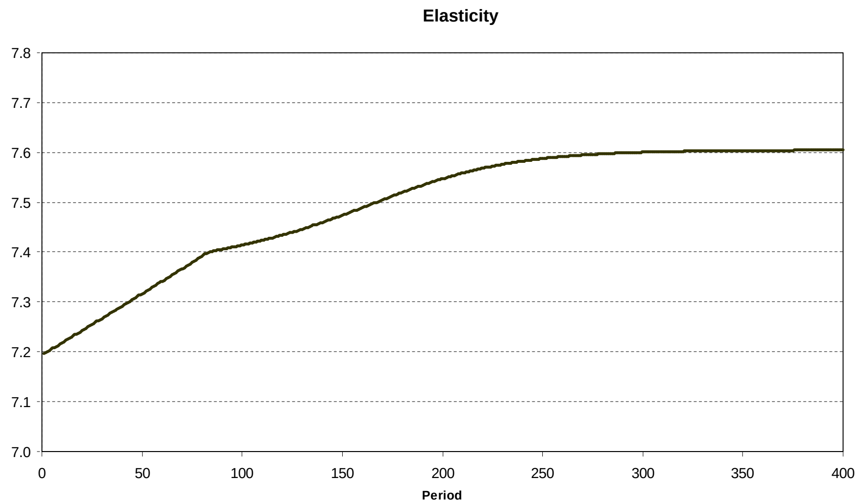

Figure 5: Price elasticity of demand industrial goods

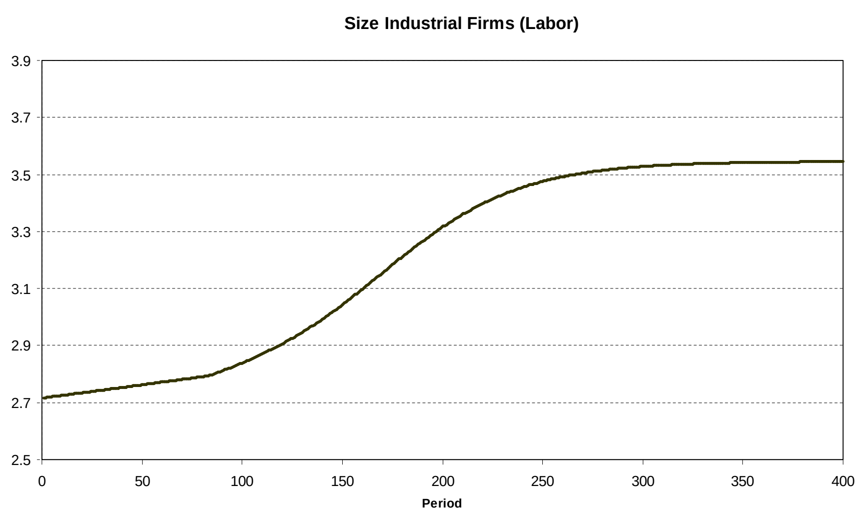

Figure 6: Labor employed in each industrial firm

4.2 No Feedback to Agricultural TFP Growth

In this experiment, we eliminate the feedback from growth in the industrial sector to agricultural TFP growth. We do this to examine the implication of this feedback for generating the demographic transition, the structural transformation, and the transition to modern growth. The existence of this feedback is not important for the start of the industrial revolution as the feedback is only effective when there is innovation in the industrial sector. In the experiment that follows we simply assume that $\gamma_{at} = \gamma_a > 0$.

Figures 7 to 9 depict the path for process innovation, the population growth rate, and the fraction of the population employed in agriculture. Shutting down this feedback is not qualitatively important for generating a structural transformation or for generating an accelerating rate of technological innovation; the same pattern is evident in Figures 1 and 4. With no feedback, the transition phase of the industrial revolution is drawn out. Instead of 150 periods, it now takes far longer before the growth rate of technology levels off.

The critical difference between this experiment and the benchmark lies in the demographic transition. More specifically, without the feedback from industrial innovation to agricultural TFP, there is no increase in the population growth rate that accompanies the start of the industrial revolution. As can be seen in Figure 9, the population growth rate declines monotonically. Hence, we conclude from this experiment that the feedback which is empirically documented and corresponds to the mechanization of farming is important for the demographic transition, but not for the industrial revolution or the structural transformation.

4.3 Poverty Trap

While most countries have undergone an industrial revolution, not all have. Many sub-Saharan countries have either not begun the industrialization process, or have only shown signs of very modest and irregular growth. A poverty trap seems to be a real possibility. In light of this, we examine whether our model can generate a poverty trap, namely, an equilibrium path whereby there is never any innovation in the industrial sector. The

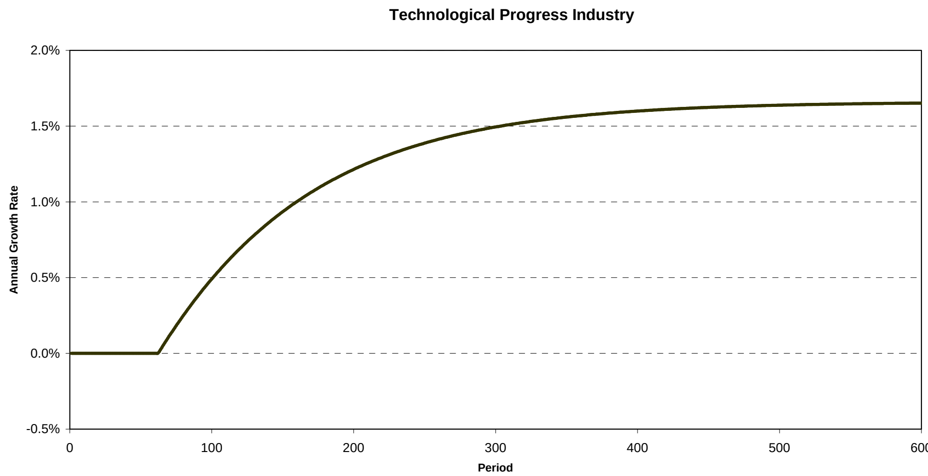

Figure 7: Technological progress (no feedback to agricultural TFP)

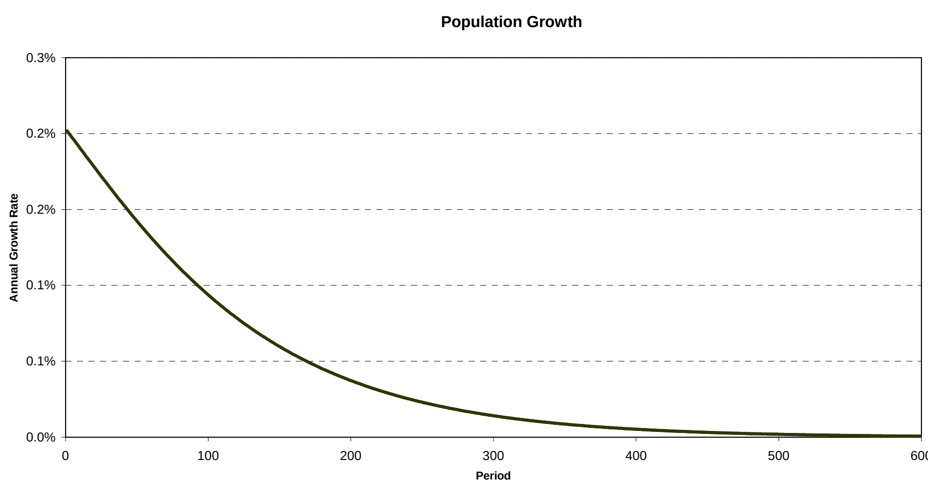

Figure 8: Population growth (no feedback to agricultural TFP)

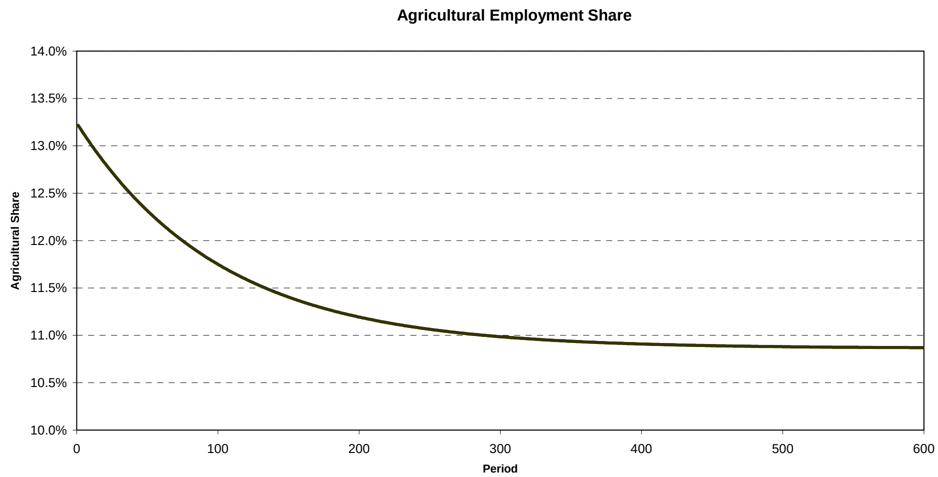

Figure 9: Share of households in agriculture (no feedback to agricultural TFP)

answer is that it can. It is not hard to understand that a necessary condition for a poverty trap is that the population either falls or is constant over time. Without the associated increase in the population, there can be no expansion in markets and firm size to bring about process innovation and the industrial revolution.

The easiest way to generate a poverty trap is by shutting down TFP growth in agriculture. Without growth in agricultural TFP, it is not possible to have sustained increases in the population on account of the diminishing returns to labor in agriculture, (i.e. $\theta < 1$). In this sense the econonomy is truly Malthusian with a constant population in the limit. This perhaps oversimplifies matters because one could get population growth under these circumstances. It simply requires that the economy start with a very small population. In this case, the population will increase for some period before converging to a constant level. If the critical population needed for the industrial revolution to begin is small enough, then an industrial revolution might occur even with no growth in agricultural TFP.

4.4 The Timing of the Industrial Revolution

We now explore how various parameters in the model affect the timing of the industrial revolution. We begin by considering the initial population of the economy. Before doing

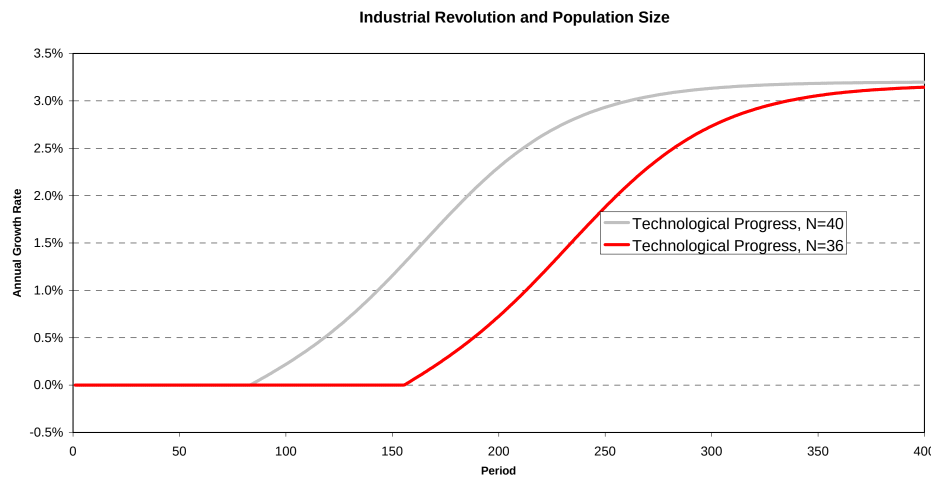

Figure 10: Effect of population size on timing of industrial revolution

so, we emphasize that a country's population is not necessarily a good measure of its market size.[10] More specifically, the real world counterpart of population in the model is the number of people that can access a market. Clearly trade and transportation costs affect this. Although not included in our model, it is easy to show that lower transportation costs or lower trade barriers have the same effect on innovation as an increase in the population.[11]

4.4.1 Population

In this experiment we lower the initial population, N_0, by 10 percent. The effect of this change on technological progress is depicted in Figure 10. As can be seen, a larger population hastens the start of the industrial revolution. The reason for this is straightforward. Since a larger population supports a greater variety of goods, the distance between neighboring varieties is smaller. As a result, the price elasticity of demand rises, and firm size

[10] Voth (2003) is critical of unified growth models that rely exclusively on population size to generate the industrial revolution, and argues that historical evidence points to market size being a more relevant factor.

[11] In Desmet and Parente (2007) we explore the effects of the reduction in trade barriers and the improvement in transportation infrastructure on innovation in a static model with Hotelling-Lancaster preferences. Not surprisingly, we find that freer trade and lower transport costs have the same positive effects on innovation as an increase in population size.

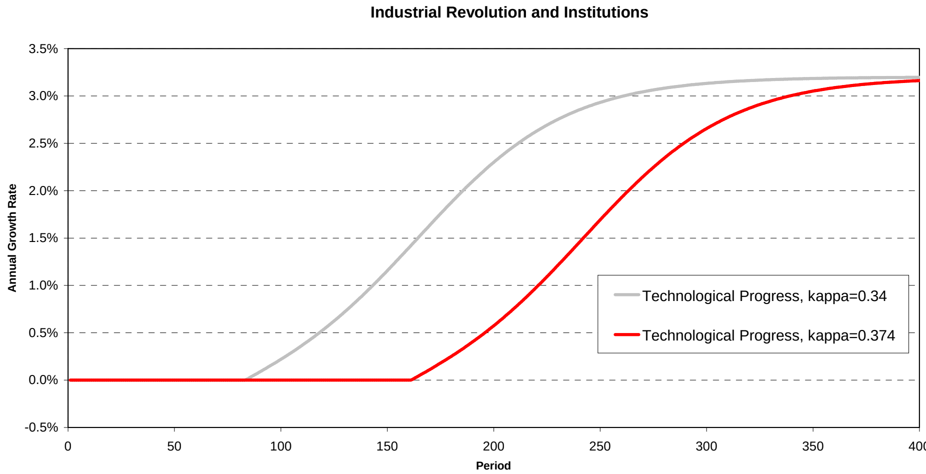

Figure 11: Effect of institutions (fixed cost) on timing of industrial revolution

increases. This makes it easier for firms to bear the fixed costs of innovation, and hence technological progress takes off earlier.

4.4.2 Institutions

We next explore how the timing of the industrial revolution depends on the fixed costs in the model. In the real world, the fixed costs firms incur to operate and to innovate depend to a large extent on institutions and policy. We therefore interpret changes in the parameters that lower this fixed cost to reflect better institutions and policies.

In our model, the fixed cost is made up of two parameters, κ, which determines the fixed cost of operating the benchmark technology, and ϕ, which determines how much the fixed cost increases when adopting better technologies.

Figure 11 shows that if we increase the value of κ by 10 percent, the industrial revolution is delayed nearly 100 years. Worse policy or institutions imply less varieties produced in the economy. As a result, firms are much smaller, and find it optimal to innovate much later on. The effect of an increase in ϕ has the same effect on the economy's development path, and for this reason we do not include a plot. It works in a slightly different manner, however. While it does not affect the number of varieties, and firm size, it does imply that a firm has to be much more bigger to find innovation

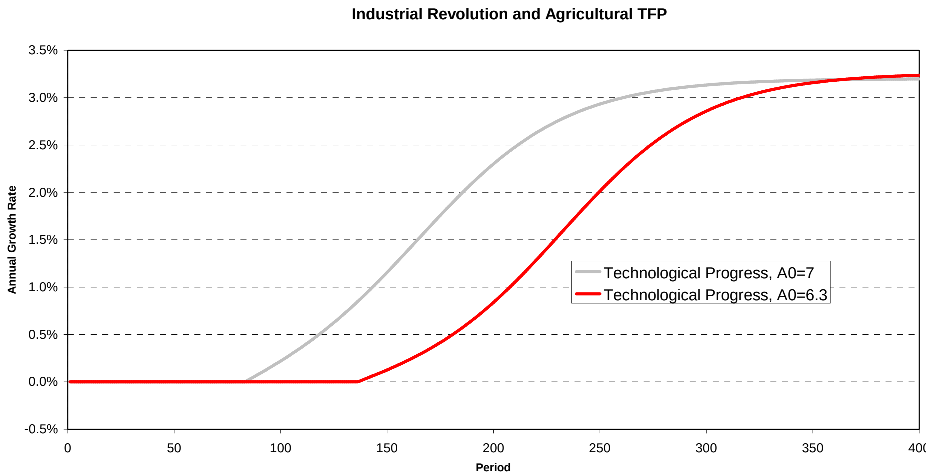

Figure 12: Effect of agricultural TFP on timing of industrial revolution

profitable.

4.4.3 Agricultural Revolution

Some authors, such as Schultz (1971) and Diamond (1997), have argued that an agricultural revolution is a precondition for an industrial revolution. Figure 12 shows that effect of lowering initial agricultural TFP by 10 percent from the benchmark. As the figure clearly shows, this delays the start of the industrial revolution. This is intuitive. It means that more households have to work in agricultural initially, and that they have to spend a greater fraction of their income on the agricultural good. As a result, the demand for the industrial good is lower.

5 Conclusion

This paper proposes a novel mechanism whereby an economy transits from a Malthusian era with stagnant living standards, to a modern growth era, with sustained and regular increases in income per capita. The paper's main hypothesis is markets need to reach a critical size before the returns to innovating are high enough to cover the fixed costs. Market size matters because a larger market can support a larger variety of goods. More varieties mean that goods become more substitutable. As a result, demand elasticity increases and mark-ups fall. To break even, firm size increases. This is critical for innovation as larger firms are more easily able to cover the fixed costs associated with research and development. We have shown within the context of our theory how numerous factors, such as institutions and agricultural TFP, impact the timing of the industrialization and have provided evidence that this mechanism is consistent with the historical record of development.

Clearly, the novelty of the paper lies in the mechanism by which larger markets bring about the industrial revolution, rather than in the idea that markets were critical. Other economists, such as Adam Smith, have argued that market size was important for understanding why England was the first country to experience an industrial revolution. But Smith and other economists who have argued this point have different mechanisms in mind that typically involve increasing returns and specialization. Our mechanism does not rely on either.

We see a number of areas where future research will be valuable. One such area is to make the structure of the model economy richer, say, by allowing for savings, and undertaking a serious calibration exercise. By doing so, we will be able to explore whether our hypothesis is quantitatively plausible. The current model, while generating a structural transformation and demographic transition consistent with the historical record, fails to match the magnitude of the decline in agriculture's share of economic activity or population growth rates. Another area is to explore whether this model is capable of generating divergence, followed by convergence, between countries, as industrialization spreads across the globe.

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