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by

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Structural interactions and long run growth: An application of Experimental Design to Agent Based Models*

Tommaso Ciarli†

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Abstract

We propose an agent-based computational model defining the following dimensions of structural change – organisation of production, technology of production, and product on the supply side, and income distribution and consumption patterns on the demand side – at the microeconomic level. We define ten different parameters to account for these five dimensions of structural change. Building on existing results we use a full factorial experimental design (DOE) to analyse the size and significance of the effect these parameters on output growth. We identify the aspects of structural change that have the strongest impact. We study the direct and indirect effects of the factors of structural change, and focus on the role of the interactions among the different factors and different aspects of structural change. We find that some aspects of structural change – income distribution, changes to production technology and the emergence of new sectors, – play a major role on output growth, while others –consumption shares, preferences, and the quality of goods, – play a rather minor role. Second, these major factors can radically modify the growth of an economy even when all other aspects experience no structural change. Third, different aspects of structural change strongly interact: the effect of a factor that influences a particular aspect of structural change varies radically for different degrees of structural change in other aspects. These results on the different aspects of structural change provide a number of insights on why regions starting from a similar level of output and with initial small differences grow so differently through time.

Keywords: Structural change; long run growth; ABM; DOE
JEL: O41, L16, C63, C99

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1 Introduction

The dramatic increase in output and consumption following the industrial revolution was accompanied by substantial changes in the structure of the economies involved. Countries of late industrialisation and current transition countries are also experiencing dramatic changes (Dasgupta and Singh, 2005). Economists usually refer to structural change as the reshuffling in the share of employment or value added in the three main sectors: agriculture, manufacturing and services (Clark, 1940; Fisher, 1939; Dietrich and Krüger, 2010; Baumol, 2010) which has led to these grand economic shifts to be described as 'industrialisation' and 'tertiarisation' of advanced economies. However, structural changes encompass more than shifts in labour and value added from one sector to another; they include a complex interaction of adjustments in the structure of production, consumption, labour organisation and income distribution, which interact in a continuous evolutionary process. For instance, industrialisation is accompanied by the concentration of production in large capital intensive firms and larger firm size (Desmet and Parente, 2009), an increase in the number of goods available for final consumption (Berg, 2002), closer involvement of science in technological change (Mokyr, 2002), increased use of capital in agriculture and especially manufacturing accompanied by an improvement in the technology embedded in new machines and overall increases in productivity (Kuznets, 1973), greater urbanisation usually accompanied by increased income inequality and changes in social class composition (McCloskey, 2009), and so on. In other words, industrialisation leads to transformations of economies and societies. Thus the definition proposed by Matsuyama, that structural change is "complementary changes in various aspects of the economy, such as the sector compositions of output and employment, the organisation of industry, the financial system, income and wealth distribution, demography, political institutions, and even the society's value system" (Matsuyama, 2008).

To be sure, some changes precede income growth, which then promotes other changes, and there are interactions among the different aspects of structural change. For instance, changes in the distribution of income are related to changes in class composition and patterns of consumption. Changes to class composition, in their turn, are related to the accumulation of capital and the different organisation of labour. The accumulation of capital induces the search of new technologies embedded in more efficient capital goods.

Ideally we would like to explain the changes in each aspect, their co-evolution and their effect on the direction of economic growth and on other dimensions of structural change. We believe that such an investigation is fundamental to shed light on the determinants and dynamics of long-run growth, and to derive policy implication that consider different aspect of economic change. This is especially relevant since traditional explanations of the relation between structural change and growth point to opposing dynamics Matsuyama (2008): i) exogenous changes in productivity in the manufacturing sector – which somehow emerge in the economy – induce labour migration from agriculture to industry; and ii) an increase of productivity in agriculture reduces demand for labour and induces migration to the manufacturing sector where capital investment – characterised by higher increases in productivity per unit of investment – spurs growth; the more investment that is concentrated in manufacturing, the greater manufacturing productivity increases. Both these mechanisms are plausible, although they do not acknowledge the wide array of 'complementary changes' they are conducive to. We believe that a more accurate explanation should include the various economic aspects that accompany the transformation of an economy.

In this paper we heed Matsuyama (2008) definition of structural change and model complementary changes in various aspects of the structure of an economy, namely organisation of production, technology of production, and product on the supply side, and income distribution and consumption patterns on the demand side. However, we also follow Saviotti and Gaffard (2008) suggestion and investigate the microeconomic sources of structural changes. Saviotti and Gaffard (2008, p. 115), in line with Matsuyama (2008), define structural change as a "change in the structure of the economic system, that is, in its components and in their interactions. Components are [...] particular goods or services, and other activities and institutions, such as technologies, types of knowledge, organisational forms etc.". However, departing from Matsuyama (2008), they warn also that: "What does it mean for a system to be in equilibrium when its composition keeps changing due to the emergence of qualitatively different entities" [p. 116].

We take on board these remarks and propose a model of the microeconomic dynamics of structural change as processes that never reach equilibrium, because of the continuous changes to the underlying dimensions of the economy. In order to model these microeconomic interactions and study the emergent structural change and aggregate output, we use computational models and solutions (Colander et al., 2008; LeBaron and Tesfatsion, 2008; Dosi et al., 2010; Leijonhufvud, 2006; Buchanan, 2009; Delli Gatti et al., 2010; Dawid and Semmler, 2010).

We propose an agent-based computational model defining the following dimensions of structural change – organisation of production, technology of production, and product on the supply side, and income distribution and consumption patterns on the demand side – at the microeconomic level. We model their co-evolution in terms of the interactions among the different agents on the supply and demand sides, and the changing behaviour promoted by changes to income and structure. We contribute to the traditional literature on structural change by accounting for 'complementary changes' and in a micro to macro framework, which can be treated exhaustively using agent based computational models.

The model includes two types of firms: capital and final goods producers. Final goods producers produce goods that satisfy different consumption needs, serving different markets. New markets emerge as an outcome of firms' investments in innovation. Consumer goods differ also with respect to their quality. A firm includes many layers of employees (workers and managers at different levels), with each layer earning a different wage. This creates consumers with unequal income distribution. Consumers are grouped into classes that demand different varieties of goods, affecting firm demand. Among other things, this implies that the larger the number of organisational layers required in the firm (organisational complexity), the higher are the differences across consumers, *ceteris paribus*. Each class distributes its consumption differently across the different markets. These consumption shares evolve endogenously as new classes emerge in the economy, representing Engel curves. Growth results from demand expansion, which is a joint outcome of firm selection and technology investment.

The structure of the model is based on Ciarli et al. (2010a) and Ciarli and Lorentz (2010), which discuss the micro economic dynamics that lead to growth in output via endogenous changes in different aspects of economic structure. Ciarli et al. (2010b) discuss the non-linear effects of organisational complexity, production technology and product variety on income growth and distribution. They show that output is negatively related to initial product and demand variety, organisational complexity and faster technological change in capital goods increase output despite higher inequality, and this last, in the form of large earning disparities, leads to lower output growth.

In this paper we build on existing results and assess the relative importance of all the factors that, in the model, determine the initial conditions of structural change and also the pace at which the different aspects of the economic structure evolve. The organisation of production is defined by the structure of labour and earnings disparities. Production technology is defined by the speed of change in capital innovation, the share of resources invested in R&D, and its success. Product technology is defined by the ability of firms to explore new sectors for a given level of R&D investment, improved quality of a new product, and share of resources invested in R&D. Income distribution is studied in relation to profits in capital and final goods firms. Consumption patterns are defined by the speed at which consumption shares change with increases in income and class differentiations and changes in consumer preferences promoted by the emergence of different income classes. Whilst we define each aspect of structural change based on specific factors, most of these factors induce structural change in several aspects of the economy. For instance, the organisation of labour has an impact on the evolution of income classes and, therefore, also on patterns of consumption; the resources invested in R&D reduce the profits available to be shared among firm managers, which affects income distribution; and so on.

We use a full factorial experimental design (DOE) to analyse the size and significance of the impact of the parameters that define structural change, on output growth. We decompose and identify the aspects of structural change that have the strongest impact on growth. We study the direct and indirect effects of the factors of structural change, where indirect effects are those that occur through those variables that also have an impact on income growth. We focus on the role of the interactions among the different factors and different aspects of structural change.

Interactions among factors are of particular interest here, since the early steps in the analysis show that in most cases the effect of one specific factor that influences a particular aspect of structural change varies radically for different levels of the other factors. In many cases, the main effect of a factor defining the economic structure is inverted under different structural conditions defined by other factors. Second, we find that some aspects of structural change, such as income distribution, changes to production technology and the emergence of new sectors, play a major role on output growth, while the roles of others, such as changes in consumption shares, preferences, and the quality of goods, play a rather minor role. Related to this, we find that some factors can radically modify the growth of an economy even when all other aspects experience no structural change, whereas most factors, on their own, do not affect outcomes if all other aspects change rapidly. In other words, one single factor that induces rapid changes in one particular aspect of the economy can induce changes that lead to large growth in output; however, in economies already undergoing structural change in most aspects, slow changes in most other factors have little influence. Finally, we find that, when controlling for other model variables, the effect of most factors on output growth is significantly reduced, showing large indirect effects.

The arguments are organised as follows. First, we describe the model focussing on the main micro dynamics and the main aspects that are mostly affected by the factors that define structural change (2.1). Next we describe the methodology and briefly present the model initialisation and design of experiment (DOE) (Section 3). Section 4 is divided in five subsections. First, we describe the general properties of the model, compare the models output with some empirical evidence, and show how the distribution of world income across countries can be explained by different initial factors, with some caveats. Second, referring to the model, we show how each factor is suited to analysing one or more aspects of structural change. Third, we refer to the literature on DOE and provide a graphical analysis of the main effects and of the interaction (cross) effects among factors. Fourth, we use analysis of variance to analyse the significance of the graphical results. Fifth, we show results from a thorough econometric analysis of the factors to quantitatively assess their relevance in the model, to distinguish direct from indirect effects, and to assess the relevance and direction of the first order interaction between each pair of factors. Section 5 discusses the results and concludes the paper.

2 Model

2.1 Final good Firms

We model a population of $f \in \{1, 2, ..., F\}$ firms producing final goods for the consumer market. Each good satisfies one consumer need $n \in \{1, 2, ..., N\}$. Or, equivalently, each firm produces in one of the $n \in \{1, 2, ..., N\}$ sectors. For simplicity we refer interchangeably to needs and sectors.[1] The firms produce an output addressing a consumer need n with two characteristics i_{j,f_n}: price $p_{f,t} = i_{1,f_n}$ and quality $q_{f,t} = i_{2,f_n}$.

2.1.1 Firm output and production factors

Firms produce using a fixed coefficients technology:[2]

$$Q_{f,t} = \min\left\{Q^d_{f,t}; A_{f,t-1}L^1_{f,t-1}; BK_{f,t-1}\right\} \tag{1}$$

where $A_{f,t-1}$ is the level of productivity of labour $L^1_{f,t-1}$ embodied in the firms capital stock $K_{f,t-1}$. $Q^d_{f,t}$ is the output required to cover the expected demand $Y^e_{f,t}$, past inventories $S_{f,t-1}$, and the new inventories $\bar{s}Y^e_{f,t}$: $Q^d_{f,t} = (1 + \bar{s})\, Y^e_t - S_{t-1}$. The capital intensity $\frac{1}{B}$ is constant.[3]

Firms form their sales expectations in an adaptive way to smooth short term volatility (Chiarella, 2000): $Y^e_{f,t} = a^s Y^e_{f,t-1} + (1 - a^s)Y_{f,t-1}$, where (a^s) defines the speed of adaptation. We assume that the level of demand faced by a firm is met by current production $(Q_{f,t})$ and inventories $(S_{f,t-1} \geq 0)$, or is delayed $(S_{f,t-1} < 0)$ at no cost. Following Blanchard (1983) and Blinder (1982), production smoothing is achieved by means of inventories $\bar{s}Y^e_{f,t}$—where $\bar{s}$ is a fixed ratio.[4]

Given $Q^d_{f,t}$, labour productivity $A_{f,t-1}$ and an unused labour capacity (u^l) to face unexpected increases in final demand, firms hire shop-floor workers:

$$L^1_{f,t} = \epsilon L^1_{f,t-1} + (1 - \epsilon)\left[\left(1 + u^l\right)\frac{1}{A_{f,t-1}} min\{Q^d_{f,t}; BK_{f,t-1}\}\right] \tag{2}$$

where ϵ mimics labour market rigidities. Following Simon (1957) firms also hire 'managers': every batch of ν workers requires one manager. Each batch of ν second tier managers requires a third level managers, and so on. The number of workers in each tier, given $L^1_{f,t}$

[1] In referring to the same good, we prefer to refer to firm innovation in terms of sectors and consumer demand in terms of needs. Establishing a mapping between the two is not one of the aims of this paper and, ultimately, depends on the definition of *sectors*.

[2] For the sake of readability we omit the sector/need index n.

[3] This assumption is supported by evidence from several empirical studies, starting with Kaldor (1957). The capital investment decision ensures that the actual capital intensity remains fixed over time.

[4] We assume adaptive rather than rational expectations. Here we assume an inventory/sales ratio that corresponds to the minimum of the observed values (e.g., Bassin et al., 2003; U.S. Census Bureau, 2008).

is thus

$$\begin{aligned} L^2_{f,t} &= L^1_{f,t}\nu^{-1} \\ &\vdots \\ L^z_{f,t} &= L^1_{f,t}\nu^{(1-z)} \\ &\vdots \\ L^{\Lambda_f}_{f,t} &= L^1_{f,t}\nu^{(1-\Lambda_f)} \end{aligned} \tag{3}$$

where Λ_f is the total number of tiers required to manage the firm f. Consequently, the total number of workers is $L_{f,t} = L^1_{f,t}\sum_{z=1}^{\Lambda_f}\nu^{1-z}$

The firms capital stock is:[5]

$$K_{f,t} = \sum_{h=1}^{V_f} k_{h,f}(1-\delta)^{t-\tau_h} \tag{4}$$

where V_f is the number of capital vintages purchased, $k_{h,f}$ and τ_h respectively the amount of capital and date of purchase of vintage h, and δ the depreciation rate. The firms productivity embodied in the capital stock then is the average productivity over all vintages purchased:

$$A_{f,t} = \sum_{h=1}^{V_f} \frac{k_{h,f}(1-\delta)^{t-\tau_h}}{K_{f,t}} a_{g,\tau_h} \tag{5}$$

where a_{g,τ_h} is the productivity embodied in the h vintage.

Capital investment depends on the expected demand $k^e_{f,t} = (1+u)\frac{Y^e_{f,t}}{B} - K_{f,t-1}$ – where u is the unused capital capacity – and defines the demand for capital good firms:$k^d_{g,f,t} = k^e_{f,t}$. Each firm selects one of the capital producers $g \in \{1;...;G\}$ with a probability that depends positively on g's output embodied productivity $(a_{g,t-1})$, and negatively on its price $(p_{g,t-1})$ and cumulated demand of capital g still has to produce. The delivery of the capital investment may take place after one or more periods, during which the firm cannot make a new investment.

2.1.2 Wage setting, pricing and the use of profits

We model an aggregate minimum wage (w_{min}) as an outwards shifting wage curve (Blanchflower and Oswald, 2006; Nijkamp and Poot, 2005), where unemployment is derived following a Beveridge curve from the vacancy rate (Wall and Zoega, 2002; Nickell et al., 2002; Teo et al., 2004), endogenously determined by firms' labour demand. The minimum wage setting (Boeri, 2009) is related to changes in labour productivity and the average price of goods.[6] The wage of first tier workers is a multiple of the minimum wage, $w^1_{f,t} = \omega w_{min,t-1}$. For the following tiers the wage increases exponentially by a factor b which determines the skewness of the wage distribution (Simon, 1957; Lydall, 1959):

$$\begin{aligned} w^2_{f,t} &= b\omega w^1_t = b\omega w_{min,t-1} \\ &\vdots \\ w^z_t &= b^{(z-1)}\omega w_{min,t-1} \\ &\vdots \\ w^{\Lambda_f}_t &= b^{(\Lambda_f-1)}\omega w_{min,t-1} \end{aligned} \tag{6}$$

[5] Following Amendola and Gaffard (1998) and Llerena and Lorentz (2004) capital goods define the firms production capacity and the productivity of its labour.

[6] For a detailed description of the computation of the minimum wage see Ciarli et al. (2010a).

Price is computed as a markup on unitary production costs Fabiani et al. (2006); Blinder (1991); Hall et al. (1997), i.e. the total wage bill divided by labour capacity:[7]

$$p_{f,t} = (1+\mu)\frac{\omega w_{min,t-1}}{A_{f,t-1}} \sum_{z=1}^{\Lambda_f} b^{(z-1)} \nu^{(1-z)} \tag{7}$$

The tier-wage structure implies diseconomies of scale in the short-run, which is in line with the literature on the relation between firm size and costs (e.g. Idson and Oi, 1999; Criscuolo, 2000; Bottazzi and Grazzi, 2007).

The profits ($\pi_{f,t}$) resulting from the difference between the value of sales, $p_{f,t-1}Y_{f,t}$, and the cost of production, $\omega w_{min,t-1} L^1_{z,t} \sum_{z=1}^{\Lambda_f} b^{(z-1)} \nu^{(1-z)}$, are distributed between (i) investment in new capital $\left(k^e_{f,t}\right)$, (ii) product innovation R&D ($R_{f,t}$) and (iii) bonuses to managers ($D_{f,t}$). We assume that firms always prioritise capital investment when they face a capital constraint, while the parameter ρ determines the allocation of the remaining profits between R&D and bonuses:[8]

$$R_{f,t} = max\left\{0; \rho\left(\sum_{\tau=1}^{t} \pi_\tau - \sum_{h=1}^{V_f} k_{h,f} p^K_{g,h} - \sum_{\tau=1}^{t-1} (R_{f,\tau} - D_{f,\tau})\right)\right\} \tag{8}$$

$$D_{f,t} = max\left\{0; (1-\rho)\left(\sum_{\tau=1}^{t} \pi_\tau - \sum_{h=1}^{V_f} k_{h,f} p^K_{g,h} - \sum_{\tau=1}^{t-1} (R_{f,\tau} - D_{f,\tau})\right)\right\} \tag{9}$$

We assume that bonuses are distributed proportionate to wages, to the manager tiers ($z \in \{2; ..; \Lambda_{f,t}\}$). The overall earnings of an employee in tier z is then $w^z_{f,t} + \psi^z_{f,t}$, where ψ^z_t is the share of redistributed profits to the managers of each tier z.[9]

2.1.3 Product innovation

Firms innovate in two stages: first new products are discovered through R&D, second they are introduced into the market. The R&D activity has two phases: research, i.e. the choice of consumer need/market n' in which to focus the innovation effort, and development, i.e. the production of a prototype of quality $q'_{f,t}$.

The range of sectors $\left\{n^{min}_{f,t}; ...; n^{max}_{f,t}\right\}$ that a firm can search is centred on the knowledge base of the current sector of production n Nelson and Winter (1982) and depends on R&D investment ($R_{f,t}$) and a parameter ι:

$$\begin{aligned} n^{min}_{f,t} &= max\left\{1; n - round\left(\tfrac{N}{2}\left(1 - e^{-\iota R_{f,t}}\right)\right)\right\} \\ n^{max}_{f,t} &= min\left\{N; n + round\left(\tfrac{N}{2}\left(1 - e^{-\iota R_{f,t}}\right)\right)\right\} \end{aligned} \tag{10}$$

[7] This is in line with evidence that firms revise prices once a year, mainly to accommodate inputs and wage costs (Langbraaten et al., 2008).

[8] We are aware of recent empirical evidence which suggest that R&D growth is caused by growth in sales rather than profits Coad and Rao (2010); Moneta et al. (2010); Dosi et al. (2006). Indeed, assuming a fixed markup, in our model profits are a constant share of sales. In other words, we would maintain that R&D is related to sales figures but since the model does not include a credit market we need to constrain R&D investment by the available resources, i.e. profits. Moreover, the model accounts for the case where profits are distributed to managers and not invested in R&D, for a very small ρ, as suggested in some of the literature already cited).

[9] This assumption is inspired by evidence that the exponential wage structure of a hierarchical organisation is not sufficient to explain earnings disparities Atkinson (2007).

Within this set a firm selects the sector n' with the largest excess demand $Y^x_{n,t}$.[10]

The quality of the new prototype developed in sector n' is extracted from a normal distribution where the mean is equal to the quality currently produced by the firm and the variance is negatively related to the distance between the old and the new sectors and positively related to a parameter ϑ:

$$q_{n',f,t} = \max\left\{0; q_{n',f,t} \sim N\left(q_{f,t}; \frac{\vartheta}{1-|n-n'|}\right)\right\} \quad (11)$$

If the innovation occurs in n the new good is maintained only if it is of higher quality than the currently produced good and if it represents an incremental innovation in the market n. Otherwise, the new product is set aside. If it is maintained the new good is introduced in a set Φ of prototypes $q'_{\phi,f,t-1}$. If Φ includes less than three prototypes the new one is added. If $\Phi = \{0; ...; 3\}$ the new prototype replaces the one with the lowest quality as long as its own quality is higher. Otherwise, the new product is set aside.

A firm introduces a new prototype in its market with a probability negatively related to the growth of sales.[11] We assume that a firm introduces in the market its highest quality prototype We assume also that if a firms prototype is for a different sector from the one in which it is currently producing, it will be introduced in this other sector only if the number of firms in that sector is lower than in the current sector of production. In other words, a firm moves to a new sector where there is less competition, or introduces a higher quality product in the current sector of production.

2.2 Capital suppliers

The capital goods sector is formed of a population of $g \in \{1, 2, \ldots, G\}$ capital suppliers that produce one type of capital good characterised by vintage τ_h and an embodied productivity a_{τ_h}.

2.2.1 Output and production factors

In line with the empirical evidence (e.g. Doms and Dunne, 1998; Cooper and Haltiwanger, 2006) we assume that production is just-in-time. Capital suppliers receive orders k^d_{g,f,τ_f} from firms in the final good sectors–where τ_f refers to the date of order–and fulfil them following a first-in first-out rule. The total demand $K^D_{g,t} = \sum_{f=1}^{F} k^d_{g,f,t} + U^K_{g,t-1}$ for a capital supplier is then the sum of current orders and unfulfilled orders $U^K_{g,t-1} = \sum_{\tau=1}^{t}\sum_{f=1}^{F} k^d_{g,f,\tau} - \sum_{j=1}^{t} Y_{g,j}$:

For simplicity, we assume that machinery firms employ labour as the sole input, with constant returns to scale: $Q_{g,t} = L^1_{g,t-1}$; In each period firms sell the orders manufactured:

$$Y_{g,t} = min\{Q_{g,t}; K^D_{g,t}\} \quad (12)$$

Similar to final goods firms, capital suppliers hire a number of workers necessary to satisfy the demand plus a ratio u of unused labour capacity:

$$L^1_{g,t} = \epsilon L^1_{g,t-1} + (1-\epsilon)\left[(1+u)\,K^D_{g,t}\right] \quad (13)$$

[10] Note that as long as some firms are active in a market, and their product reaches the minimum level of quality demanded, excess demand equals zero. We assume that firms give priority to unexplored markets.

[11] For positive growth the probability is 0. We follow the well know Schumpeterian argument that firms innovate to seek new sources of revenues. The probabilistic behaviour captures firms limited forecasting capacity and distinguishes between temporary falls in sales from long term structural downturns which are more likely to require an innovation.

where ϵ mimics labour market rigidities. To organise production capital suppliers hire an executive for every batch of ν_k production workers $L^1_{g,t}$, and one executive for every batch of ν_k second-tier executives, and so on. The total number of workers in a firm therefore is:

$$L_{g,t} = L^1_{g,t} + ... + L^z_{g,t} + ... + L^{\Lambda_g}_{g,t} = L^1_{g,t} \sum_{z=1}^{\Lambda_g} \nu_k^{1-z} \tag{14}$$

2.2.2 Process innovation

Capital firms use a share ρ_k of cumulated profits $\Pi_{g,t}$ to hire R&D engineers. The maximum number of engineers is constrained to a share ν^K of first tier workers:[12]

$$L^E_{g,t} = min\left\{\nu_k L^1_{g,t}; \rho_k \frac{\Pi_{g,t}}{w^E_{g,t}}\right\} \tag{15}$$

The outcome of R&D is stochastic (e.g. Aghion and Howitt, 1998; Silverberg and Verspagen, 2005), and the probability of success depends on the resources invested in engineers and a parameter ζ (Nelson and Winter, 1982; Llerena and Lorentz, 2004):

$$P^{inn}_{g,t} = 1 - e^{-\zeta L^E_{g,t-1}} \tag{16}$$

If the R&D is successful[13] a firm develops a new capital vintage with productivity extracted from a normal distribution centred on its current productivity:

$$a_{g,\tau_h} = a_{g,\tau_{h-1}}\left(1 + max\{\varepsilon^a_{g,t}; 0\}\right) \tag{17}$$

where $\varepsilon^a_{g,t} \sim N(0;\sigma^a)$ is a normally distributed random function. The higher is σ^a the larger are the potential increases in productivity. The new level of productivity enters the capital good produced by the firm for the following period and sold to the final good firms.

2.2.3 Wage setting, price and profits

The price of capital goods is computed as a markup (μ^K) over variable costs (wages divided by output ($Q_{g,t}$)):

$$p_{g,t} = (1+\mu^K)\omega w_{min,t-1}\left(\sum_{z=1}^{\Lambda_g} b_k^{z-1}\nu_k^{1-z} + \frac{\omega^E L^E_{g,t-1}}{Q_{g,t}}\right)$$

where $w^E_{g,t}$ is the wage of engineers. The first tier wage is a multiple of the minimum wage $w_{min,t}$, such as the wages paid to the engineers ($\omega^E w_{min,t-1}$). For simplicity we assume no layer/manager structure among the engineers. Wages increase exponentially through the firms tiers by a factor b identical to the final goods firms.

Profits resulting from the difference between the value of sales $p_{g,t}Y_{g,t}$ and the costs for workers and engineers $\omega w_{min,t-1}\left(L^1_{g,t-1}\sum_{z=1}^{\Lambda_g} b_k^{z-1}\nu_k^{1-z} + \omega^E L^E_{g,t-1}\right)$ are cumulated ($\Pi_{g,t}$). The share not used for R&D $(1-\rho_k)$ is distributed to managers as bonuses, proportionate to their wages:

$$D_{g,t} = max\left\{0; (1-\rho_k)\Pi_{g,t}\right\} \tag{18}$$

where $\Pi_{g,t} = \sum_{\tau=1}^{t-1}\pi_{g,\tau} - \sum_{\tau=1}^{t-1} w^E_\tau L^E_\tau - \sum_{\tau=1}^{t-1} D_{g,\tau}$.

[12] See footnote 8 for a discussion of profits and R&D.

[13] R&D is successful when a random number from a uniform distribution [0; 1] is smaller than $P^{inn}_{g,t}$.

2.3 Demand

The composition of demand depends directly on the structure of production (product technology, firm organisation and labour structure, and production technology) acting as the endogenous transmission mechanism through which structural changes on the supply side affect changes to consumption.

We assume that each tier of employees in the hierarchical organisation of firms defines one (income) class of consumers with the same income (W_z), consumption share ($c_{n,z}$), and preferences (υ_z^i). This is a restrictive assumption, but also an improvement with respect to models that assume two fixed classes (rural and urban) or homogeneous consumers.

2.3.1 Income distribution and consumption shares

The income of each consumer class $z \in \{0, 1, \ldots, \Lambda_t\}$[14] is the sum of wages ($W_{z,t}^w$), distributed profits ($W_{z,t}^\psi$) and an exogenous income ($\bar{W}_{z,t}$):

$$W_{z,t} = b^{z-1} w_{min,t-1} \left(\sum_{f=1}^{F} L_{f,z,t} + \sum_{g=1}^{G} L_{g,z,t} \right) + \sum_{f=1}^{F} \psi_{f,z,t} + \sum_{g=1}^{G} \psi_{g,z,t} + \bar{W}_{z,t} \tag{19}$$

Consumers react to changes in total income, changing total current consumption by a small fraction $\gamma \in [0; 1]$ and postponing the remaining income for future consumption Krueger and Perri (2005):

$$X_{z,t} = \gamma X_{z,t-1} + (1 - \gamma) W_{z,t} \tag{20}$$

Consumers divide total consumption across different needs $n \in \{1; ...; N\}$, each satisfied by a different sector, and allocate to each need a share $c_{n,z}$. The *desired* consumption per need then is simply $C_{n,z,t}^d = c_{n,z} X_{z,t}$ (where $\sum_{n=1}^{N} c_{n,z} = 1$).

Following the empirical literature on Engel curves we allow these expenditure shares to vary endogenously across income classes, representing a different income elasticity for different income classes and different consumption goods (needs in this model). As we move from low to high income classes the expenditure shares change from 'primary' to 'luxury' goods at a rate η:

$$c_{n,z} = c_{n,z-1} \left(1 - \eta \left(c_{n,z-1} - \bar{c}_n\right)\right) \tag{21}$$

where $\bar{c}_n$ is an 'asymptotic' consumption share of the richest theoretical class, towards which new classes of workers (with higher income) emerge endogenously (see equations 3 and 14) tend. The 'asymptotic' distribution is defined as the consumption shares of the top income centile in the UK in 2005 for the ten aggregate sectors (Office for National Statistics, 2006)–which we assume satisfy ten different needs–ordered from smallest to largest (Figure 1).[15] For reasons of simplicity (and lack of reliable data) we assume that the consumption shares of the first tier class, 2000 periods before–the initial period in the model, are distribute symmetrically (Figure 1).[16]

If the goods available on the market satisfy only a limited number of needs – since new goods are discovered through firms' R&D – consumers adapt consumption shares

[14] Where Λ_t is the number of tiers in the largest firm in the market, and $z = 0$ is the class of engineers in capital sector firms.

[15] We thank Alessio Moneta for these data.

[16] Maddison (2001) provides qualitative evidence to support this assumption about changes in household expenditure shares.

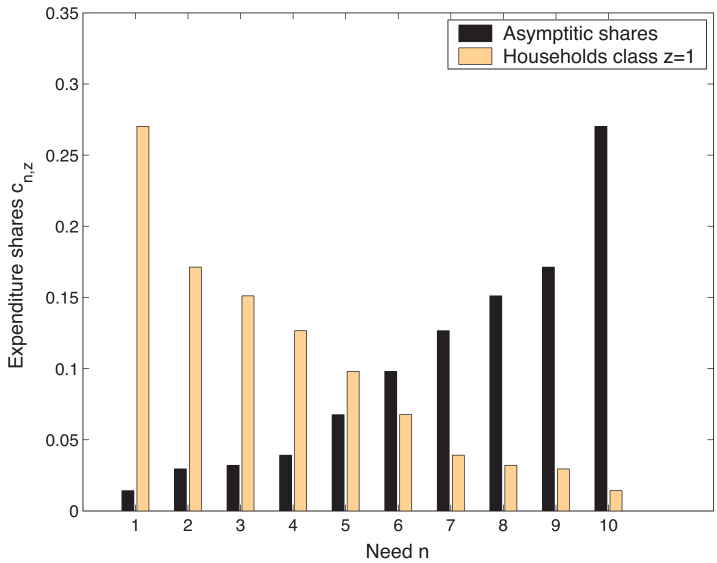


Figure 1: ***Expenditure shares: initial and asymptotic***. *The distribution of the asymptotic level of shares corresponds to current expenditure shares for the highest percentile of UK consumers. For simplicity, initial shares are assumed to be distributed symmetrically.*

accordingly, redistributing the shares for non available needs to the needs that are available, proportional to the consumption shares of their existing needs. The demand for non available needs is defined as excess demand, which works as the signal for final goods firms to choose which sector in which to innovate:

$$Y^x_{n,t} = \sum_{f_n} Y_{f_n,t} p_{f_n,t} - \sum_z c_{n,z} X_{z,t} \tag{22}$$

2.3.2 Consumer behaviour and firm sales

We model consumers who purchase a number of goods in each of the available markets with lexicographic preferences. In line with the experimental psychology literature (e.g. Gigerenzer, 1997; Gigerenzer and Selten, 2001) we assume also that consumers have imperfect information on the characteristics of goods, and that they develop routines to match a satisficing behaviour, leading to the purchase of goods equivalent to the optimal good.

Consumer classes access the market in sequence and demand a non negative quantity of goods from each firm. Firm demand is defined as follows. Consumers in a class z are divided into $m = \{1, H \in N^+\}$ identical groups with an equal share of the class income $\frac{X_{z,t}}{H}$. First, a consumer group m screens all the goods on offer from all the firms in the market (need) and observes their characteristics $i^*_{j,f_n,t} \sim N\left(i_{j,f_n,t}, \sigma^i_j\right), \forall j = \{p; q\}$, where σ^i_j measures the extent of incomplete information, which differs for quality and price Celsi and Olson (1988); Zeithaml (1988).

Consumer preferences are modelled here as degree of tolerance over shortfalls with respect to the best good available in the market in terms of its characteristics $\hat{i}^*_{j,f_n,t}$. That is, given the tolerance level $\upsilon_{j,z} \in [0, 1]$ a consumer is indifferent towards all of the goods that have a quality above $\upsilon_{2,z}\hat{i}^*_{2,f_n,t}$ and a price below $\upsilon_{1,z}\hat{i}^*_{1,f_n,t}$. In other words, for a very large $\upsilon_{j,z}$ a consumer buys only from the best firm in the market, while a small $\upsilon_{j,z}$ indicates indifference towards a large number of goods that differ in terms of price and quality. We assume also that preferences change across income classes: first tier workers have a high tolerance towards quality differences ($\upsilon_{2,1} = \upsilon^{min}$) and very low tolerance towards price differences ($\upsilon_{1,1} = \upsilon^{max}$). As we move to higher income classes, tolerance towards price differences increases and tolerance towards quality differences reduces by a factor ς:

$$\begin{aligned} \upsilon_{1,z+1} &= (1-\varsigma)\upsilon_{1,z} - \varsigma\upsilon^{min} \\ \upsilon_{2,z+1} &= (1-\varsigma)\upsilon_{2,z} + \varsigma\upsilon^{max} \end{aligned} \tag{23}$$

Then, a consumer group selects the subset of firms that matches its preferences: $\hat{F}_{n,m,t} \mid (1-\upsilon_z)\hat{i}^*_{j,f_n,m,t} > |i^*_{j,f_n,m,t} - \hat{i}^*_{j,f_n,m,t}|, \forall j = \{p;q\}$, and purchases are equally distributed among selected firms. Then, the total demand of a firm in market n is the sum of sales across all groups and classes:

$$Y_{f_n,t} = \sum_{z=1}^{\Lambda_t} \sum_{m=1}^{H_{n,z}} \frac{1}{F^*_{n,m,t}} \frac{c_{n,z} X_{z,t}}{H} \tag{24}$$

3 Methodology

The main aim of this paper is to assess the relative effects of the parameters that define the different aspects of structural change. The model is agent-based and has no analytical solution, but we can study its properties with a systematic numerical analysis. We do so using a simple experimental design We describe the initialisation of the model, and then the method of analysis.

Table 1 presents the initial conditions and the value of the parameters not included in the DOE.[17] For these parameters we also report the data ranges available from empirical evidence. While we are not calibrating the model to any specific economy, all parameters are within the ranges observed across countries and over time.

In $t = 0$ firms produce goods in the first two sectors, and consumers can satisfy only those two needs.[18]. Final goods firms differ only with respect to the quality of the good produced, which is extracted from a uniform distribution ($i_2 \sim U\left[\underline{i_2}, \overline{i_2}\right]$). All capital goods firms are identical. All firms are small, requiring only one manager; capital good firms also hire engineers. This labour structure defines three initial classes of consumers: engineers, first tier workers, and one manager tier.

3.1 Experimental Design

To analyse the effect of the parameters that define the structure of the economy (Table 2) we make use of the simplest DOE, the 2^k full factorial design. It consists of analysing k factors at two different levels (typically High and Low), simulating all possible combinations of both levels Montgomery (2001); Kleijnen et al. (Summer 2005). 2^k factorial designs are appropriate for the purposes of this paper: to study the main effects of a large number of factors, and to identify the factors that are more influential on the model behaviour from those that are less relevant; to study a large number of interactions of different orders, between factors; and to, at the same time, minimise the number of simulation runs required to study a large number of factors in a complete design (Montgomery, 2001).

In particular, we analyse the effect of the ten factors that define the initial structure of the economy and the scale at which it changes through time. To each parameter we

[17]The remaining factors are presented in Table 2.

[18]The remaining sectors may emerge as a result of firms product innovation.

Parameter	Description	Value	Data
$\underline{i_2}$	Initial min quality level	98	Analysed
$\overline{i_2}$	Initial max quality level	102	Analysed
a^s	Adaptation of sales expectations	0.9	// [a]
$\bar{s}$	Desired ratio of inventories	0.1	[0.11 - 0.25] [b]
u^l	Unused labor capacity	0.05	0.046 [c]
u	Unused capital capacity	0.05	0.046 [c]
δ	Capital depreciation	0.001	[0.03, 0.14]; [0.016, 0.31] [d]
$\frac{1}{B}$	Capital intensity	0.4	B = [1.36, 2.51] [e]
ϵ	Labor market friction (final firms)	0.9	0.6; [0.6, 1.5]; [0.7, 1.4]; [0.3, 1.4] [f]
ω	Minimum wage multiplier	2	[1.6, 3.7] [g]
$1-\gamma$	Smoothing parameter	0.2	[.04, .14]; [.06, .19] [h]
σ^i_j	Error in the consumer's evaluation of characteristics	$j = 1$: 0.05; $j = 2$: 0.1	// [i]
ω^E	Engineers' wage multiplier	1.5	[1.2, 1.4] [j]
$\upsilon^{min} = \upsilon_{2,1}$	Highest = first tier quality tolerance	0.1	//
$\upsilon^{max} = \upsilon_{1,1}$	Lowest = first tier quality tolerance	0.9	//
F	Final good firms	100	//
G	Capital good firms	10	//
H_z	Consumer samples	100	//
N	Number of needs	10	//

[a]Empirical evidence not available: the parameters has no influence on the results presented here. [b]U.S. Census Bureau (2008); Bassin et al. (2003). [c]**?** with reference to the 'optimal' unused capacity. [d]Nadiri and Prucha (1996); Fraumeni (1997) non residential equipment and structures. We use the lower limit value, (considering 1 year as 10 simulation steps) to avoid growth in the first periods to be determined by the replacement of capital. [e]King and Levine (1994). [f]Vacancy duration (days or weeks) over one month: Davis et al. (2010); Jung and Kuhn (2011); Andrews et al. (2008); DeVaro (2005). [g]Ratio with respect to the average (not minimum) wage in the OECD countries Boeri (2009). [h]Krueger and Perri (2005); Gervais and Klein (2010). [i]No empirical evidence available to the best of our knowledge. Parameters set using the qualitative evidence in Zeithaml (1988). [j]Relative to all College Graduates and to accountants Ryoo and Rosen (1992)

Table 1: ***Parameters setting****. Parameter's (1) name, (2) description, (3) value, and (4) empirical data range*

assign 'Low' and 'High' values (Table 2), which we consider to be the theoretical extreme values (observed infrequently).

We test all 2^{10} combinations of Low and High values of the factors. We run 20 replicates for each combination for 2000 periods.[19] We then totalise a sample of $i = 1, ..., I$ factor responses y_{ijlt} where $j = \{1, ..., 1024\}$ is the number of designs – combinations of the different parameters, $l = \{1, ..., 20\}$ is the number of replicates, and $t = \{1, ..., 2000\}$ is the time periods.[20]

We focus on aggregate output and analyse the responses using various methods, taking into account the violations of normality and constancy of variance in the responses (Kleijnen, 2008)[21]. First, we illustrate the effect of the factors graphically. We then assess the

[19]Our model is a non terminating simulation, which requires us to choose a cut-off point when the simulation enters a "normal, long run" regime Law (2004). For some responses, such as output, under a large number of factorial combinations the model does not reach a steady state. For others, such as output growth and market concentration, the model reaches a "long-run steady state" before 2000 periods.

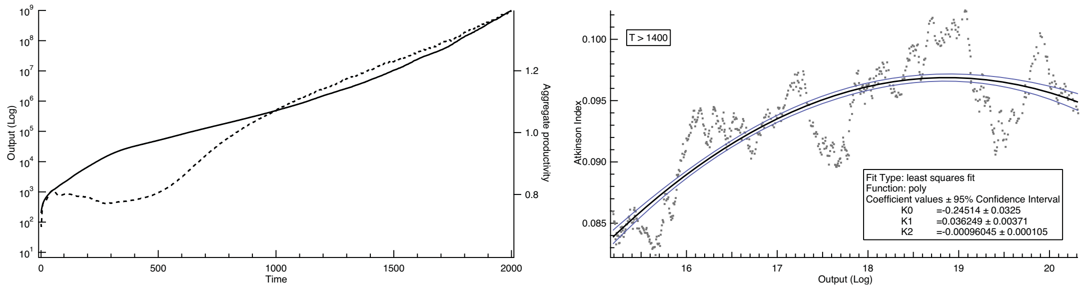
[20]20,480 simulation runs and 40,960,000 observations.

[21]Our model and simulation procedure satisfy the remaining properties outlined in Kleijnen (2008). See also Montgomery (2001) for a comprehensive treatment of the analysis of experiments in simulations.

significance of these effects and their main interactions with an analysis of variance. Third, we study the relative effects of each factor and their interactions, controlling for the effect of a number of variables on output, using Least Absolute Deviation (LAD) regressions.

4 Results

Using the baseline configuration (simulated for 200 replicates) the model generates long term endogenous growth in output with a transition from linear growth to exponential growth (Figure 2 (a)) – occurring here around $t = 1400$ – (Maddison, 2001). Output growth is preceded by an increase in aggregate productivity. We provide evidence of the



(a) Output and productivity

(b) Kuznets curve

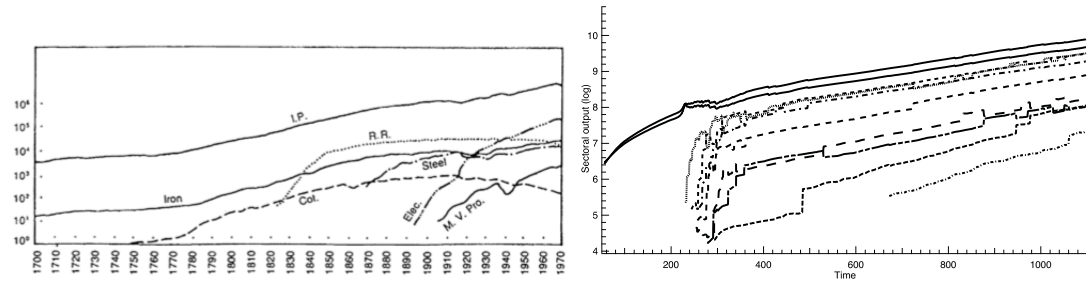
Figure 2: ***Model properties: output (log), productivity and Kuznets curve****. In graph (a) we plot the time series of output in log scale, and aggregate productivity in linear scale. In graph (b) we plot the relation between output (log) and the Atkinson index (dotted line), and the polynomial curve fit (full line) with confidence intervals (blune lines), for the period 1400-2000*

often observed non-linear relation between inequality and income (Kuznets curve) for the period from before take off to the end of the simulation (Figure 2 (b)).[22]

For given values of the extent of exploration of new sectors, the model qualitatively reproduces the s-shaped curve characterising the growth in sectoral output from birth to diffusion in the economy (Figure 3).

Table 7 reports the results of a Vector Autoregressive (VAR) analysis on 10 period growth rates, and coefficients estimated using LAD – with bootstrapped standard errors. The VAR shows the relations between output (1), aggregate productivity (2), average price (3), the inverse Herfindahl index (4) and the Atkinson index of inequality (5). Results are in line with the expected macro dynamics. All variables show a strong cumulative process with one lag. Inequality growth has an immediate positive effect on output (1 lag) which becomes negative after three lags. Similarly, an increase in market concentration has an immediate negative effect on output (1 lag), which becomes positive after two lags. Market concentration also determines an increase in prices and inequality. The effect of productivity on output in this short-run analysis is captured through price reduction, which has an immediate positive effect on output (1 lag). A detailed discussion on the

[22] Inequality is computed using the Atkinson index: $\mathcal{A}T_t = 1 - \frac{1}{\sum_{z=1}^{Z} \frac{W_{z,t}}{L_{z,t}}} \left[\frac{1}{\sum_{z=1}^{Z} L_{z,t}} \sum_{z=1}^{Z} \left(\frac{W_{z,t}}{L_{z,t}} \right)^{1-\varrho} \right]^{\frac{1}{1-\varrho}}$ where $W_{z,t}$ is the total income of consumer class z, $L_{z,t}$ is the total number of workers in class z and ϱ is the measure of inequality aversion. As we are not measuring an empirical level of inequality, we use an intermediate value of $\varrho = 0.5$.



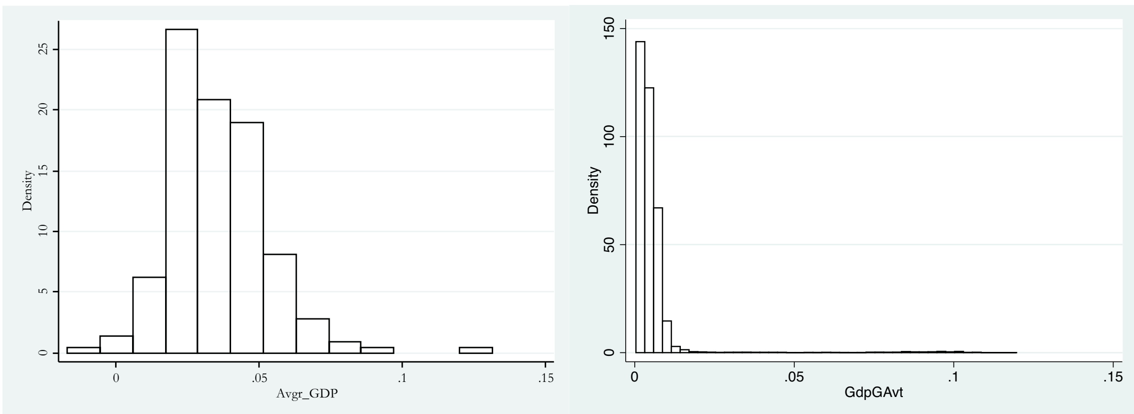
(a) Observed (b) Simulated

Figure 3: ***Sectoral output: industrial production in Britain and simulation results***. *(a) Sectoral output (log scale) computed by Rostow (1978) (cited in Aoki and Yoshikawa (2002)); (b) sectoral output (log) from the model results with* $\iota = 0.005$

short and long run dynamics of a previous version of this model can be found in Ciarli et al. (2010a) and Ciarli et al. (2010b).

4.1 Distribution of income across countries

We now move to the analysis of the model for the 2^k combinations of factors. We compare the distribution of average growth rate of GDP from 1980 to 2010 across countries with the distribution of average growth rate of output from 1 to 2000 across factorial designs (Figure 4). Each combination of factors in the model can be interpreted as a different country with different initial conditions. The distribution is definitely more skewed in our



(a) Observed (b) Simulated

Figure 4: ***Income growth distributions – world Vs simulation***. *Graph (a) plots the distribution of income growth (averaged over 1980-2010) across world economies (Source IMF); graph (b) plots the distribution of output growth (averaged for 1-2000) across different combinations of factors*

simulations across different combination of factors than across world economies. There are three main reasons for this. First, a trivial one: we look at 2000 periods, which includes long periods of stagnation that precede take-off (see above), while the IMF data refer to the the period between 1970 and the present. Second, we are analysing the model under extremely 'stressful' conditions, i.e. for extreme values of the parameters not generally observed in the real world (see Table 2). For some factor combinations no investment occurs, and the economy stagnates over the 2000 periods. For example, take the variance in the distribution that determine an increase in the productivity of capital (σ^a), the wage differentials between classes (b), the probability of process innovation (ζ), and the markup (μ). Figure 5 plots the density of these four parameters when the level of output (log) is larger than 36 (the top bin of the world income distribution according to IMF data). For these extremely high levels of output we observe almost one single combination of factors: σ^a is high with probability 1,[23] b is low with probability around .95, ζ is high with probability nearly 1 and μ is high with probability .95.

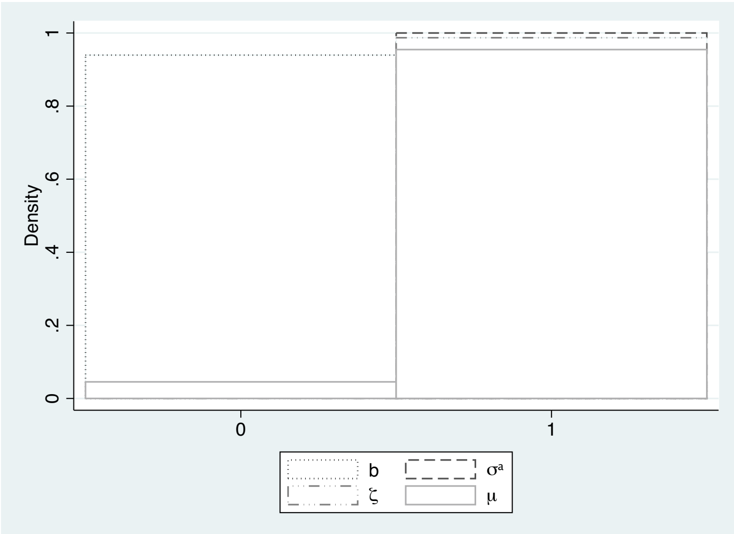


Figure 5: ***Density of some parameters when Log output*** $>$ ***36***. *0 denotes a low value of the parameter and 1 denotes a high value. For extremely high values of output the parameters take almost always the same value*

The third reason for the atypical distribution of output growth in our model simulated across the 2^k different factor combinations is due to the DOE: in Figure 4 (b) we are overlapping distributions from different data generation processes, where each combination of the High and Low values of the parameters represent one process. We show below that some parameters have a dramatic effect on the output variables. The distribution of output variables differs enormously when these parameters switch from one state to another. We show this again by comparing the distributions in the simulated data. Figure 6 plots the distribution of output for different combinations of some influencing parameters with High and Low values. It is sufficient to compare the support of the total distribution (for all values of the parameters) with the support of any other distribution which represents a combination of different High and Low values (0,1) of $\sigma^a, \mu, \iota, \nu, b$. In only one case the support is the same. In most cases, the support is radically different (lower by a factor 10 or 30).

[23]We denote the low level of the parameters a 0 and the high level of the parameter as 1.

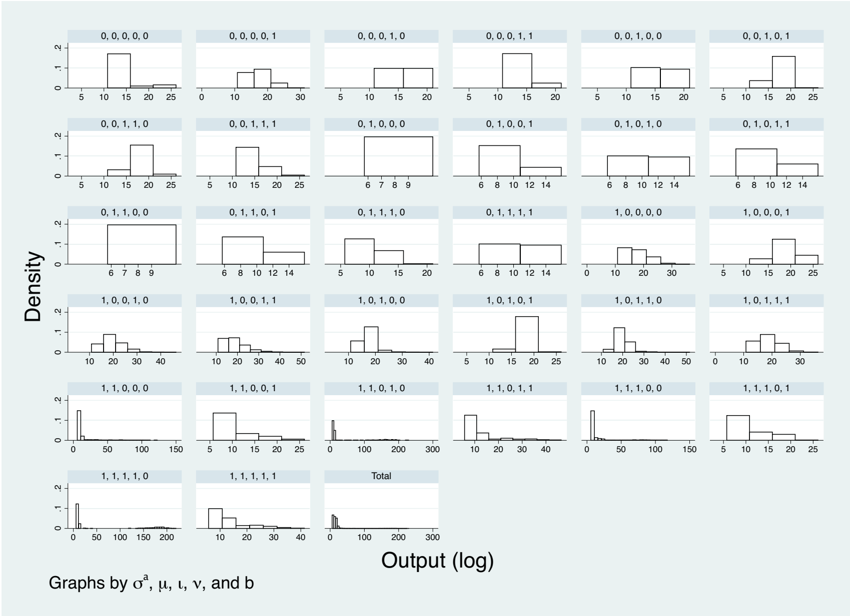


Figure 6: ***Distribution of output (log) for different High and Low values of the parameters.*** *$\sigma^a, \mu, \iota, \nu, b$; 0 denotes a low value and 1 denotes a high value*

To sum up, the overall distribution of output variables, such as output in the final period, and the average rate of output growth over periods, cannot be approximated completely by any theoretical distribution, the closest would be the Pareto distribution.

The above discussion suggests that economies endowed with different factors that determine the initial structural conditions and the way in which structural changes in different aspects of the economy unfold (or not), experience very different growth path. By testing extreme values of these conditions we see that a limited number of economic aspects – different from the beginning – produce dramatic differences in growth. Also the way that these different aspects of structural change interact seems to be relevant.

The rest of the paper provides a detailed analysis of the (main, interactive, direct and indirect) effects of these factors on the final distribution of output across economies with very different starting conditions.

4.2 The factors of structural change

Before analysing factor responses we briefly summarise the effect of the different factors (parameters) that define the initial structure of the economy and the dynamics of structural change.[24] We group them with respect to the aspects of structural change they capture directly: product technology, production technology, organisation of production (which refer mainly to the structure of employment), income distribution and consumption patterns.

Product technology: ι, ϑ, ρ. All these factors have an effect on the variety in the final goods market, ι determining the pace at which new goods are discovered, ϑ influencing the rate of change in the quality of new goods and ρ altering the resources employed by the firm for the exploration of new goods. ι and ϑ play no other role in structural change;

[24] The terms factors and parameters are used interchangeably.

ρ influence the distribution of income through the share of profit not redistributed as bonuses and used for R&D.

Factor	Equation	High/Low	Low	High	Main Economic aspect	Main indirect aspects
ι	10	+	.001	.3	3	–
ν	3	–	3	50	1	4, 5
b	6	+	1	3	1	4
σ^a	17	+	.01	.2	2	1
η	21	+	.1	3	5	–
$\rho = \rho^k$	8, 15	+	.05	.95	3, 2	4
ϑ	11	+	.01	10	3	–
ζ	16	+	.1	1000	2	1
ς	23	+	.05	.9	5	–
$\mu = \mu^K$	7, 2.2.3	+	1.01	2	4	2,3, 1

1: Organisation of production; 2: Production technology; 3: Product technology; 4: Income distribution; 5: Consumption patterns

Table 2: ***Effect of parameters on structural change****. A + indicates that the High value of the parameter induces relatively more structural change*

Production technology: σ^a, ζ, ρ^k. Large values of σ^a and ζ directly modify the capital structure of the economy, determining the pace at which innovation occurs in the capital goods sector; ρ^k has the same effect as ρ in altering the resources devoted to R&D. All three factors have a number of indirect effect on other aspects of structural change. Similar to ρ, ρ^k influences the income distribution. σ^a and ζ in addition to altering the productivity of the final goods firm, modify the demand for production factors (labour and capital), affecting firms' labour structure (through changes in size). Also, given the different pace at which different firms change capital vintages, σ^a and ζ change the distribution of prices in the final goods market, allowing consumers to select based on their price preferences.

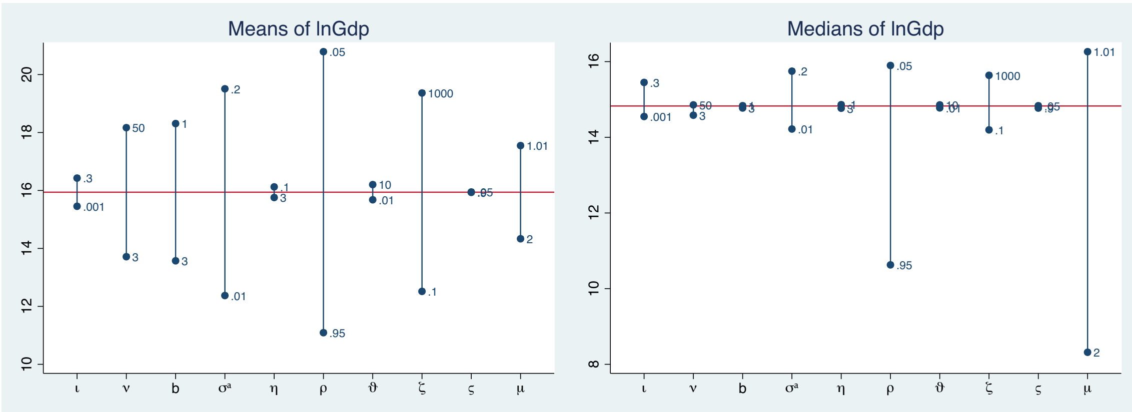
Organisation of production: ν and b. Both parameters define the way in which a firm is organised: a very low ν means that a corporation needs a large number of tiers to organise a small pool of workers, whereas for a large ν a single manager can deal with a large production unit (few changes as the size of the corporation increases). b tells us simply how the different levels of workers and managers are paid (and bonuses are distributed). Both parameters have a strong bearing on the distribution of income as they implicitly determine the number of income classes (ν) and their wage income. Indeed, ν indirectly influences also at least one other aspect of the economy – changes in consumption patterns – by altering the pace at which new classes with different consumption styles endogenously emerge.

Income distribution: μ, μ^k. For a small ρ and low capital investment a large μ implies a redistribution of income from all consumers to higher classes. Indeed, an increase in μ also increases the resources available for investment in R&D – thus it increases the pace at which product and production technology change. Finally, differences in markups indicate different market structures, from competitive to oligopolistic.

Consumption patterns: η, ς**.** High level of both factors induce faster change in consumption behaviour. A high η implies a very fast change in expenditure shares from basic needs to the asymptotic distribution that of the top income centile of UK consumers in 2005. ς changes the consumer preferences in a given classes, for a given expenditure share: a large ς implies that the tolerance for relatively lower quality (higher price) goods decreases (increases) at a faster rate moving towards the high income classes.

4.3 Graphical analysis: main and cross effects

We first show the effect of each factor on the value of output (in logs) in the last simulation step (average across 100 replicates), for any value of the other parameters. A crude comparison of mean differences across the populations defined as Low (L) and High (H) values of the factors (Figure 7.a) provides some initial hints about the relative importance of the parameters – see Table 2 for the Low and High values. First, the parameters that define



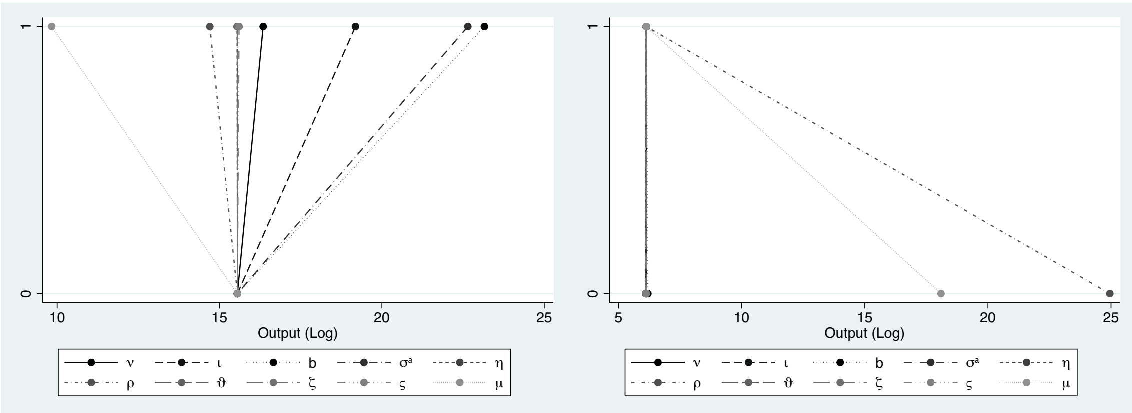
(a) Mean (b) Median

Figure 7: ***Mean and median differences in Output for different values of the factors**. (High and Low)*

technological change in the capital sector (process innovation) have an extremely large impact: the effectiveness of R&D in the production of new machinery (ζ), the variance of the distribution that rules the increase in the productivity of new capital (σ^a), and the ratio of profits devoted to R&D rather than wage premia (ρ and ρ^k). While σ^a and ζ are clearly positive, the effect of a nearly total redistribution of profits from managers to R&D is negative. Second, the parameters that define the organisation of production and the associated distribution of income have a large impact: the gradient of the organisation pyramid (ν), wage differences across the levels of an organisation (b), and the markups (μ and μ^k). Note that both distributional factors (b and μ) have an overall negative effect on output. Finally, the parameters related to product innovation and changes in consumption patterns have a negligible impact: the probability of exploring new sectors (ι) has a small effect, the rate of convergence to the asymptotic 'high income' expenditure shares (η), the variety in the quality of new products (ϑ), and the changes in preferences (tolerance levels) (ς) have a negligible impact.

The results differ when we consider the median, which is less affected by extreme values (Figure 7.b). Process innovation based on capital has a strong impact, mediated through the distribution of resources (generation of profits and their allocation to research); the exploration of new products remains unchanged; and all other parameters seem to have a negligible impact.

We proceed with a graphical analysis of the output response to the single factors for a given state of the other parameters in order to identify the effects of each factor under particular states of the world (all other factors L or H), and to show whether responses change across states, and whether the factors induce an independent response or interact. Figure 8 plots each factor response (L Vs H),[25] against output (Log), when all other factors are L (a) or H (b) – from Table 2 and the discussion in Section 4.2 we know that moving from L to H means increasing structural change for all factors except ν. Figure



(a) All factors Low (b) All factors High

Figure 8: ***Main effect of parameters on Output (Log) for High (a) and Low (b) values of all other parameters***. *0 = L and 1 = L*

8(a) shows the effect of one factor inducing large structural change in one dimension of the economy, when all the others induce little or no structural change (except for ν): indeed, under these conditions most factors have a relevant effect on the level of output. The wage multiplier (b) and a higher variance of the productivity shock (σ^a) have the strongest positive effects, followed by the exploration of new goods (ι), and to a lower extent organisational complexity (ν); a few factors play no role: η, ϑ, ς, and ζ; the negative effects of ρ and μ are confirmed even when the other dimensions of structural change are very low, although the effect of ρ is much lower than in Figure 7. These results show that, starting from an overall low income state, with no changes in other aspects of the economy, radical changes in any aspect among production technology, labour structure and the generation and use of profits engender large differences in output growth, with the signs discussed above. While large changes in the quality of the final good and in consumption patterns, on their own, do not have an influence on growth. The null impact of ζ is due by construction for low investment in R&D.

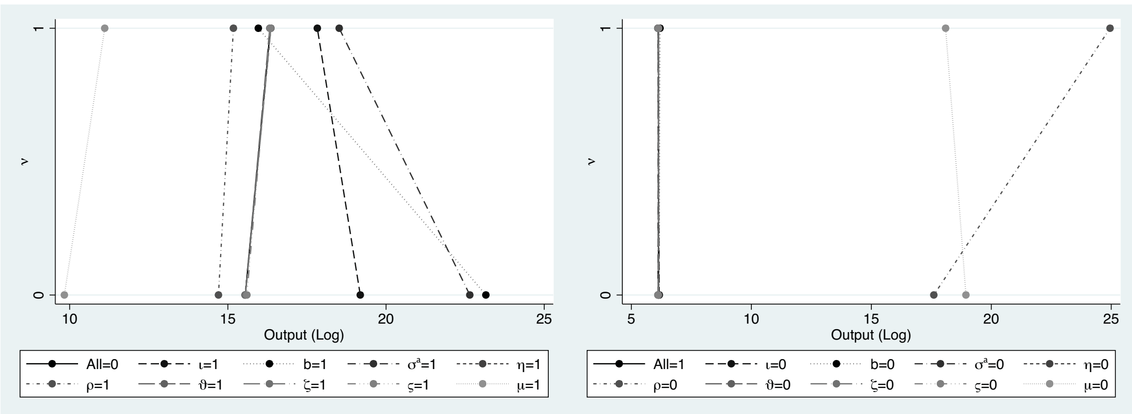
We next examine the opposite case of when most factors are set to induce large structural changes. Does a single aspect of structural change modify the results on growth? This is depicted in Figure 8(b): except for μ and ρ we observe little effect on output, of the factors – changing from High to Low – when they all induce large structural change. We note also that when either μ or ρ is high, output is relatively small, and their effect dominates. The response to the other factors is diminished by the very large structural change in all other aspects of the economy.

However, the relation between factors and output is much more complex than the

[25] See table 2 for the high and low values of each parameter.

extreme conditions of all High or all Low levels of the parameters. We next study the effects of one particular factor, e.g. ν, when all other parameters change from Low to High. This provides preliminary evidence on the interactions among the factors analysed. For example, what is the effect of a more or less complex organisational structure (ν) under varying wage regimes (b), or the varying likelihood of inventing a new product (ι)? Is the effect of ν on output still the same (slightly positive if all other factors are Low, and null if all other factors are High)?

In Figure 9 we plot the log of output against the High and Low values of ν, for changing combinations of the values of the other parameters. The first scatter plot in (a) (*All=0*) shows the same small positive effect of the base case, when all other parameters are Low (Figure 8(a)). We then switch the other parameters, one by one, from Low to High. A few factors – η, ϑ, ς, and ζ – do not change the response induced by ν on output, as shown by the fact that the segments representing their influence on the change in the effect of ν on output coincide with the segment for $All = 0$. ρ and μ do not seem to interact with ν, but they induce a negative level effect of ν on output when they are High, i.e. for both high and low values of ν (as shown by the parallel shift to the left). ι, b, and σ^a, in turn, change the sign of the effect of ν: when they are Low, an increase in ν has a mild positive effect on output (main scatterplot $All = 04$); when they are High, an increase in ν has a strong negative effect on output (the last three lines on the right). This means that highly complex organisations (which require many organisational layers, i.e., many employees receiving different levels of remuneration, for a given number of workers in the first tier) have a positive impact on output growth when markets diversify quickly (High ι), when firms can recover the higher organisational costs (reflected in higher consumer prices) through increased productivity growth, and when wages differ between organisational layers. The rapid vertical growth of firms in fact creates classes of workers with different



(a) All factors Low

(b) All factors High

Figure 9: ***Cross effects of parameters on output (Log) for High (a) and Low (b) values of all other parameters: the case of*** ν*. 0 = L and 1 = L*

consumption shares and different preferences, i.e. consumers that buy more goods from markets that firms still need to discover (with a High ι) and that are ready to buy goods at higher prices. However, the higher organisational costs translate into lower aggregate demand. The net effect on output is positive only if either product innovation brings results in rapid time to market for goods to satisfy the emerging classes of consumers, or when rapid change in product technology compensates for increasing prices (or possibly if both conditions hold).

Graph (b) (Figure 9) plots the effect of an increase in ν on output, when the other parameters switch from H to L. When most of the parameters induce large structural change, as noted above, changing other aspects of structural change, one at a time, has no effect on output. With the exception of markup and the ratio of profits invested in R&D this is the case depicted in this figure. When μ is Low, there is a large positive effect on output for both L and H values of ν (no interaction). While a change in ρ from H to L induces both a level effect (higher output irrespective of ν) and an interaction effect: an increase in ν also considerably increases the output.[26]

In this section we explored graphically the main effects and some of the interaction effects. For simplicity, we explored two extreme cases – out of the thousand possible states of the world analysed in this paper – and found that, in the case where parameters induce low structural change in all dimensions of the economy, a single factor inducing high structural change is sufficient for a strong effect on output. However, this does not apply to all factors and especially not to those that determine changes in the structure of consumption. On the other hand, if all the parameters induce high structural change in all dimensions of the economy, then just two of the parameters inducing low structural change will have an effect on output. We found also that the effect of each parameter in many cases is not monotonous; the signs change if some of the other factors change from inducing low to inducing high structural change.

In order to assess the statistical validity of these results we analyse whether the variance within a particular experimental design is lower than the variance across designs.

4.4 Analysis of variance: the significance of factors' interactions

In order assess the statistical significance of the graphical results discussed above, and the joint significance of the different factors on output, we run an ANOVA on the 20 replicates for each combination of parameters. The results in Table 3 show that apart from η and ς – respectively the speed of convergence of the expenditure shares and of the change in the preferences of consumers for a good's characteristics – all parameters have a significant main effect, even when tested jointly. We can confirm that, when considering the effect of the parameters for all possible states of the world (High and Low values of the other factors), b, σ^a, ι, ρ and μ induce changes to the structure of the economy that have a significant impact on output growth, while the changes induced by η and ς are not significant. With respect to the graphical analysis in Figures 4.3 we find that the effect of ϑ and ζ on output is significant, and large in the case of ζ.

Due to the blatant departure from normality of the output variable, we check the robustness of the result of the ANOVA by testing one way differences between the samples defined by the parameters High and Low values with a Kruskal-Wallis (KW) equality of population rank test. The results (see Table 8 in the Appendix A) differ only with respect to η, which turns out to have a small but significant negative effect.[27] The one way mean test substantially confirm the results in figure 8: high values of $\iota, \nu, b, \sigma^a, \vartheta$ and ζ are associated with a higher output; high values of ρ and μ are associated with a lower output; and η and ς have a negligible effect.

This makes us confident that the results of the ANOVA for our large sample are

[26] Results are similar if we run the same exercise for other factors, e.g. for ι: some parameters do not affect the role of ι, some have only a level effect and a few (as above) radically change the role of ι on output. Conversely, for the interaction of other parameters with μ we observe no relevant effects: a High markup always has a relatively negative effect on output. The other parameters mainly change the size of this effect. Results available from the author.

[27] However, note that the KW test are one way.

Source	Partial SS	df	MS	F	Prob>F
Model	1.258e+06	9	139790	414.1	0.00
ι	4840	1	4840	14.34	0.00
ν	101546	1	101546	300.8	0.00
b	114912	1	114912	340.4	0.00
σ^a	260782	1	260782	772.6	0.00
η	691	1	691	2.05	0.15
ρ	481609	1	481609	1427	0.00
ϑ	1399	1	1399	4.150	0.04
ζ	240068	1	240068	711.2	0.00
ς	0.821	1	0.821	0	0.96
μ	52954	1	52954	156.9	0.00
Residual	6.909e+06	20469	337.5		
Total	8.168e+06	20479	398.8		
Number of obs = 20480; Root MSE = 18.37; R-squared = 0.154; Adj R-squared = 0.154					

Table 3: ***ANOVA – single effects***

informative, and we proceed to analyse the significance of the first order interactions between all factors. As discussed for example in the case of ν in Figure 9, ι, b, and σ^a modify the effect of the organisation structure on output. We analyse these interactions more systematically in Table 4, which summarises the results of the ANOVA that includes all the main effects and first order interactions (i.e. all possible interactions between two different factors). Table 4 confirms the intuition – from the analysis of distributions and

	(1) ι	(2) ν	(3) b	(4) σ^a	(5) η	(6) ρ	(7) ϑ	(8) ζ	(9) ς	(10) μ
ι	0									
ν	**	***								
b	***	***	***							
σ^a	0	***	***	***						
η	**	0	0	0	0					
ρ	***	***	***	***	0	***				
ϑ	0	0	0	0	0	**	0			
ζ	**	***	***	***	0	***	0	***		
ς	0	***	*	0	0	0	*	0	0	
μ	**	***	***	***	0	***	0	***	**	***

Note: Values on the diagonal refer to the factor main effect. ***Prob > F < 0.01; **Prob > F < 0.05; *Prob > F < 0.1; 0: Prob > F > 0.01

Table 4: ***ANOVA – first order interactions***

from the graphical analysis – that most factors induce structural changes that have a significant effect which differs (in size or direction) for different combinations of the other factors, that is, which is subject to the structural changes induced by the other factors. In other words, the different dimensions of structural changes induced by the factors, significantly interact in determining the aggregate behaviour of the economy.

For example, what would be the effect on growth of increasing the opportunities for R&D in the capital sector (σ^a)? As discussed with reference to Figure 8, σ^a alone has an apparent impact on output, when all other factors trigger no or limited structural change. However, Table 4 shows that the role of the production technology crucially depends on many other structural aspect of the economy, such as the organisation of production (ν, b), and especially the share of profits invested in R&D and its effectiveness on the innovation result (ρ, ζ). Its strong effect on output is relatively independent of the introduction of product variety in the consumer market (ι, ϑ)and of the structure of demand for more variety (η, ς).

To better to discriminate among the different aspects of the structure of an economy we perform a regression analysis that allows us to quantify the effect of factors across designs and time.

4.5 The relative influence of the different aspects of structural change

We run quantile regressions (with bootstrapped standard errors) to estimate the relative impact and significance of each factor and their first order interactions on output.. We distinguish between direct and indirect impact Table 5 reports estimates for the factors (1), for a number of control variables, most of which are correlated to the factors (2), and for the parameters when the least correlated control variables are included – a sort of reduced form of the model (3).[28] Table 6 reports the estimates for the parameters and their first order interactions, with and without control variables (respectively bottom-left and top-right triangular matrix).

On average, when abstracting from the different structural change regimes (column 2), the model shows that aggregate labour productivity (A) – measured as output per worker – is strongly and positively correlated to output as well as average expenditure on R&D (across firms and time periods) (R). As noted elsewhere (Ciarli et al., 2010a; Ciarli and Lorentz, 2010), product variety (averaged over the full period) – σq and σp, respectively for quality and price – and the selection that they enable also positively affect output; but their effect is weak when controlling for inequality and productivity, which is a prime cause of price differences. Inequality ($\mathcal{A}T$), averaged over the whole period, has an overall negative effect on output.

Variables	(1) Factors	(2) Contr Var	(3) F & CV
ι	0.692***		1.063***
	(0.056)		(0.071)
ν	0.009***		-0.012***
	(0.000)		(0.000)
b	0.107***		-0.061***
	(0.008)		(0.007)
σ^α	3.242***		0.966***
	(0.088)		(0.083)
η	-0.023***		-0.016***

[28]The estimated sample is the result of the simulations for the last period for 20 replicates of each combination of parameters.

	(0.006)		(0.004)
ρ	-4.900***		-3.947***
	(0.024)		(0.036)
ϑ	0.013***		0.003**
	(0.002)		(0.001)
ζ	0.001***		0.000***
	(0.000)		(0.000)
ς	0.040**		0.021*
	(0.019)		(0.011)
μ	-9.330***		-9.510***
	(0.018)		(0.021)
A		1.201***	2.900***
		(0.071)	(0.057)
$\mathcal{A}T$		-3.809***	3.523***
		(1.109)	(0.109)
σp		0.119*	-0.092***
		(0.065)	(0.004)
σq		0.001	0.000***
		(0.001)	(0.000)
R		0.779***	
		(0.048)	
Constant	28.301***	12.944***	29.424***
	(0.043)	(0.380)	(0.075)
Observations	20,480	20,480	20,480
Pseudo R^2	0.43	0.09	0.48

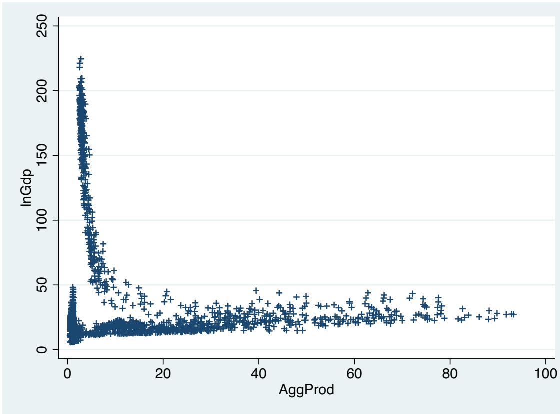
Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 5: ***The relative impact of factors and main variables on output***. *LAD estimates with s.e. obtained from bootstrapping (400); the dependent variable is (Log) output*

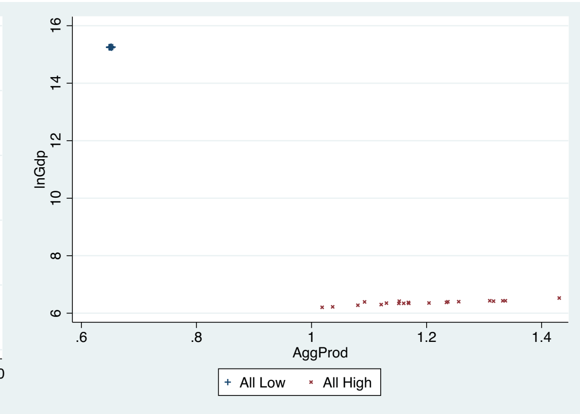
The estimated effect of factors on output is very close to what was discussed in relation to the graphical analysis (Section 4.3). On their own, the parameters that determine structural changes with the strongest (negative) effect on output are ρ and μ, followed by σ^{α}, ι and b. ι shows a much stronger effect and b a much lower effect than in the graphical analysis where we did not control for all these factors together. Related to σ^{α}, ζ also has a positive and significant effect. The least relevant are the structural changes induced by ν, ς (positive) and η (negative).

The factors determining structural change also influence the dynamics of a large number of variables. Therefore, the estimated effect of a variable on output (Table 5) is likely to differ for different levels of the parameters. Likewise, the use of control variables in the estimation of parameters allows us to estimate the direct effect of the factors on output, depurated from the indirect effect through the control variables.

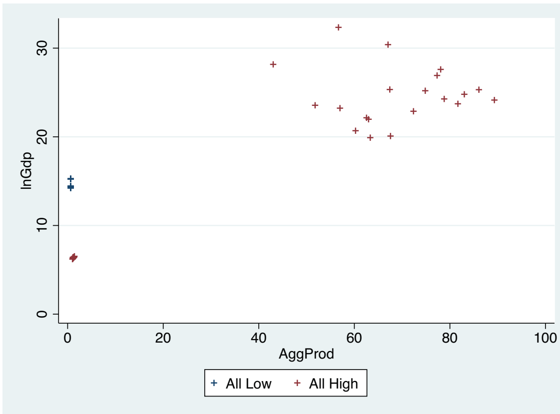
To show this, Figure 10 plots the relation between an independent variable, aggregated productivity, and output (Log), for different values of the parameters. In panel *a*



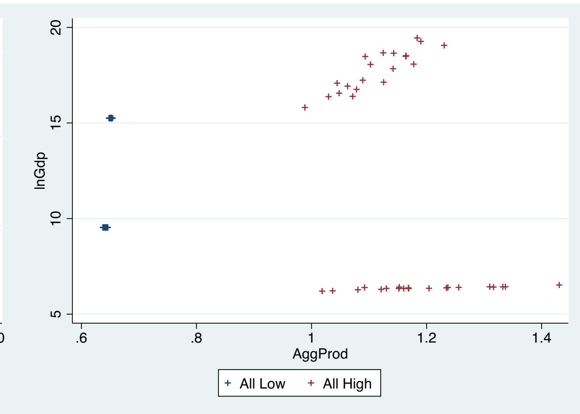
(a) No restrictions on factors



(b) All factors **L**ow or **H**igh



(c) All factors **L**ow or **H**igh, except ρ



(d) All factors **L**ow or **H**igh, except μ

Figure 10: ***Aggregate productivity Vs output (Log).*** *T=2000, aggregate productivity on the x-axis and output on the y-axis.*

no restrictions on parameters are imposed, and the relation between the two variables is distinctly non-linear. More importantly, panel *a* shows that the relation between productivity and output could be reduced to different functional forms, depending on the combination of factors. In panel *b* we restrict all factors to either the high or the low value: aggregate productivity does not show any significant effect on output under either condition. Results are different if we allow the parameters that are strongly related to aggregate productivity to fluctuate. In panel *c* all factors are either high or low, except for ρ, which takes both values. Although the relation between the two variables is not so clear cut, the scale is radically different – the small dot in the bottom left of panel *c* is the flat relation that we observe at the bottom right side of panel *b*. Alternatively, for different levels of markup (μ) the relation turns from null to positive, for high values of all other parameters (panel *d*).

Returning to Table 5, column (3) shows estimates for the direct effects of the factors and for the effect of the least correlated variables. First, the sign of the two factors defining the organisation of production are inverted. A high ν reduces the number of (organisational) workers per good produced, increasing labour productivity. When we control for labour productivity, though, the lower number of tiers for a given number of shopfloor workers reduces the pace at which firms grow in size and diversify by adding different levels of workers and managers (see Eq. 3 and 14). The effect on structural change is a slower increase in the aggregate demand and its variety, and a negative impact on output growth. Large wage differentials (b), increase inequality, which has a negative effect on output, *ceteris paribus*, but which in our model is associated also with larger aggregate demand (Eq. 19); thus the inverted sign of $\mathcal{AT}$ when controlling for the factors. Second, the direct effect of σ^{α} is strongly reduced when controlling for aggregate productivity. Third, the estimated effect of a few variables change their sign and significance as we control for different combinations of the factors determining structural changes.

As already mentioned, the effect that each of the factors induces on structural change depends also on other structural aspects. The relevance of the interaction among several factors is established in the results of the quantile regression where all first order interactions are estimated together with the main effects, with and without the control variables (Table 6). We estimate the effect of the high value of factors, using the low value as the reference case. Estimates that do not include control variables are reported in the top-right triangular matrix and those that include control variables are reported in the bottom-left triangular matrix. On the diagonal we report the main effects. We discuss the estimates obtained when including the control variables. First, the results in Table 6

	(1) ι	(2) ν	(3) b	(4) σ^{α}	(5) η	(6) ρ	(7) ϑ	(8) ζ	(9) ς	(10) μ
ι	1.51	0.16	-0.09	-0.31	-0.01	-0.55	0.03	-0.18	0.04	-0.97
	1.38									
ν	0.28	0.33	-0.95	0.69	0.23	-0.56	-0.08	0.62	0.12	0.20
		-0.81								
b	-0.10	-0.16	1.14	-0.24	-0.15	0.11	-0.05	-0.34	-0.28	0.10
			0.10							
σ^{α}	-0.37	0.68	-0.34	1.51	0.00	-1.58	0.09	2.26	-0.12	-0.73
				1.39						
η	0.04	0.28	-0.21	-0.03	-0.18	0.00	-0.02	-0.04	0.08	0.10
					-0.26					
ρ	-0.52	-0.35	0.31	-1.00	0.00	-0.56	-0.57	-1.42	0.01	-2.51
						-0.98				
ϑ	-0.05	0.01	-0.08	0.18	0.00	-0.61	0.55	0.10	0.20	-0.17
							0.58			
ζ	-0.14	0.42	-0.34	1.18	0.03	-0.88	0.08	1.24	-0.14	-0.39
								1.05		
ς	0.05	0.23	-0.20	-0.03	0.11	-0.06	0.20	-0.12	0.17	-0.37
									0.10	
μ	-0.98	-0.24	0.37	-1.27	0.12	-1.61	-0.56	-0.96	-0.31	-6.06
										-6.22

Note: Values on the diagonal refer to the factor main effect. Standard errors computed with 400 bootstraps. Reference case is the low value of factors, for all main and interaction terms.

p<0.01 p<0.05 p<0.1

Table 6: ***LAD regression – the effect of first order interactions on output.*** *The top-right triangular matrix shows estimates without control variables; the bottom-left triangular matrix shows estimates with control variables. The dependent variable is output (Log)*

show that the main effects are strongly significant, despite the inclusion of the interaction terms. Second, most of the first order interaction terms are also significant, particularly when they include a factor shown to be relevant to output. We proceed by discussing the effect of the different aspects of structural change, following the classification in Table 4.2.

Product technology The effect on output of rapid emergence of new sectors is large and positive on average, but (with the exception of the factor that defines consumption patterns) is always negative when other factors induce strong structural change. That is, for fast changes in consumption shares and/or preferences the high level of ι has a positive effect, although this is weakly significant. We note also that the interaction between the two main factors of product technology, ι and ϑ – respectively needs and quality – do not interact.

Production technology The main factors that affect changes in production technology, σ^{α} and ζ, also have a pervasive effect, interacting with all other aspects of structural change, except those that define changes to consumption patterns. In particular, the relation with organisational factors is negative: for an increase in organisational complexity or wage differences, fast changes in technology reduce output growth. The interaction with production technology is negative with respect to the discovery of new sectors, and positive with respect to changes in product quality. With reference to the factors determining changes in the income distribution, the interaction again is negative. It is in this perspective that we should interpret the interaction with the factors defining organisational changes: rapid changes in the productivity component of capital have a negative effect on output in the presence of high markups, large wage differences and multiple organisational tiers which amplify wage differences. Economies that experience fast changes in productivity grow at a lower pace if the structure imposes as well an unequal distribution of the productivity gains. Finally the two main factors affecting changes in production technology are strongly and positively related to increased output.

Organisation of production A large number of layers required to manage an organisation (ν) and large wage differences (b) between these layers have a negative impact in the presence of strong structural change in all other aspects except those affecting income distribution, μ and ρ. Even in the presence of rapid changes in consumption patterns, higher wage inequality reduces output growth.

Income distribution A large markup generating high profits in our model has a negative impact under almost all aspects of strong structural change, except for the organisational aspects discussed above, and changes in expenditure shares.

Consumption patterns As already noted, the factors determining structural changes in consumption play a minor role in output growth. The interactions with many other aspects of structural change are not significant. Also as already discussed, the main effects of consumption patterns are visible when structural change occurs in product technology and the distribution of income. Indeed, the emergence of new products is a requirement for changes in consumption to have a role on output. The two main aspects of consumption patterns, η and ς interact positively.

5 Conclusions

A large wealth of research has investigated why regions starting from a similar level of output grow so differently through time. Which are the initial apparently small differences that diverge so markedly? In this paper we build on the idea that the initial differences that determine growth divergence are those that define the structure of an economy and the way in which this evolves through time. We maintain that structural change occurs in different aspects of the economy, such as the structure of production, consumption, labour organisation and income distribution. These different dimensions of structural change interact in a continuous evolutionary process, and are not independent from the growth pattern. For example, one could not think at the industrial revolution without considering aspects such as changes in knowledge and technology, changes in the patterns of consumption, changes in trade patterns and extraction of resources through colonial power, and institutional changes. In turn, changes in knowledge and technology may be driven by changes in the demand, as well as by changes in labour relations (e.g. increase in the cost of labour). Similarly, changes in transportation and military technologies are not independent from changes in technological knowledge. Changes in consumption patterns are also related to increased trade. And so on.

We propose a model of the microeconomic dynamics of structural change and their interactions, abstracting from the institutional aspects. The model defines the following related aspects of structural change: organisation of production, technology of production and the emergence of new sectors on the supply side, and income distribution and consumption shares (Engel curves) on the demand side. Ten different parameters in the model account for these five dimensions of structural change.

In this paper we investigate which of these five aspects of structural change play the most significant role in economic growth, and how the different aspects interact. We analyse the relative importance of each aspect of structural change, after having identified each one with a parameter of the model. We acknowledge that some aspects are likely to have a sizeable impact on economic growth only when complemented by other aspects of structural change, while in other cases different aspects can be substitutes. For example, changes in consumption patterns may not occur if there is no change in the sectoral composition of the economy, or if there is no change in income. We therefore use the model to study the interaction among the different aspects of structural change.

For each of the ten parameters defining the different aspects of structural change we assign a high and a low value, respectively identifying large and small structural change – in a specific aspect – as the economy grows. We then define a DOE that accounts for all possible combinations of the parameters' high and low values.

In other words, we define 2^{10} different economies, all starting from the same initial conditions,except for one of the aspects of structural change. On one extreme we have an economy that experiences negligible structural changes in all economic aspects, and on the other extreme an economy that experiences large structural changes in all economic aspects. In between are all other possible combinations. We study the impact of the five different aspects of structural changes in a number of ways: graphically, with an analysis of variance, and running quantile regressions on the cross design – cross country – sample.

We find that almost all aspects of structural change – proxied with the different factors – are significant determinants of the differences in the growth rate of output. However, some aspects of structural change, such as income distribution, changes to production technology and the emergence of new sectors, explain a great deal of output growth differences, while changes in consumption shares, preferences, and the quality of goods are barely significant, and changes in the organisation and compensation of labour lay in between. This result holds when the different factors are analysed *ceteris paribus* as well as when they are analysed jointly. Moreover, the most relevant factors of structural change play a determinant role even in the presence of negligible structural changes in all other economic aspects. While the opposite case is rarely true: the output growth of economies that are set to experience large structural changes in all aspects except for one, is not affected if one of the changes is only negligible.

Concerning the complementarity of different aspects, we find that most factors of structural change interact strongly. This result is extremely relevant, suggesting that we always need to account for a large number of economic aspects to understand long term patterns of across-countries divergence. For example, we find that technological progress is strongly relevant, but quick technological advances have a negative effect on output growth when they are accompanied by structural changes in the organisation of labour that leads to large inequality among a large number of emerging classes. Economies that experience fast changes in productivity grow at a lower pace if the structure imposes as well an unequal distribution of the productivity gains. Or, as discussed above, changes in the composition of sectors available in the market are more relevant when consumption patterns also experience strong structural changes.

Without needing to sum up the results in detail, the model and the analysis of the experimental design we proposed in this paper clearly show that to explain long term growth we need to look at the way in which a large number of structural changes interact at the microeconomic level. It is not unlikely to find that some aspects of structural change were determinant for some regions, and detrimental for others (such as the pay structure at the beginning of the industrial revolution in Europe). Although some of the interactions between the different aspects are relatively known, many interactions instead suggest avenues for future research on the relation between growth and structural change.

Among the implication for future research with this and similar models, two limitation in the analysis of this paper suggest two future steps. First, here we do not consider the deeper determinants of the initial differences in the factors that determine structural change, which are mainly related to institutional aspects – in a broad sense – and to the intricate relation between knowledge, technology, and institutions. In future work we want to build on the sizeable literature that uses the case of the industrial revolution(s) to investigate the relations between knowledge, technology, and institutions to shed more light on the origins of the structural difference that we model here. Second, having studied here which are the most relevant aspects in determining the output response with a very simple DOE, the next step is to focus on those aspects and analyse whether their effect on output is linear and monotonous, as assumed in the DOE.

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A Tables

Variables	(1) ΔY	(2) ΔA	(3) ΔP	(4) ΔIHI	(5) $\Delta \mathcal{A}T$
$\Delta Y(1)$	0.986***	-0.021**	0.014	0.189	0.247***
	(0.037)	(0.010)	(0.009)	(0.145)	(0.076)
$\Delta A(1)$	0.016	0.735***	-0.045***	-0.284	-0.273*
	(0.026)	(0.029)	(0.013)	(0.237)	(0.161)
$\Delta P(1)$	-0.697***	0.049	1.058***	0.718	0.165
	(0.063)	(0.058)	(0.062)	(0.746)	(0.405)
$\Delta IHI(1)$	0.010***	0.019***	-0.011***	0.624***	-0.249***
	(0.003)	(0.004)	(0.003)	(0.043)	(0.026)
$\Delta \mathcal{A}T(1)$	0.020***	0.001	-0.001	0.065	0.941***
	(0.005)	(0.006)	(0.003)	(0.049)	(0.035)
$\Delta Y(2)$	0.081	0.024	-0.012	-0.384**	-0.165*
	(0.051)	(0.016)	(0.011)	(0.192)	(0.088)
$\Delta A(2)$	0.049*	0.044	0.025	-0.085	0.228
	(0.026)	(0.039)	(0.017)	(0.272)	(0.228)
$\Delta P(2)$	0.771***	-0.001	0.054	-1.045	-2.385***
	(0.092)	(0.082)	(0.072)	(0.981)	(0.690)
$\Delta IHI(2)$	-0.014***	-0.026***	0.005*	0.237***	0.247***
	(0.004)	(0.004)	(0.003)	(0.053)	(0.032)
$\Delta \mathcal{A}T(2)$	-0.001	0.006	-0.000	-0.032	0.013
	(0.007)	(0.008)	(0.003)	(0.057)	(0.045)
$\Delta Y(3)$	-0.069**	-0.006	0.000	0.213*	-0.080
	(0.035)	(0.011)	(0.006)	(0.127)	(0.052)
$\Delta A(3)$	0.000	0.085***	0.005	0.138	-0.015
	(0.023)	(0.029)	(0.014)	(0.271)	(0.177)
$\Delta P(3)$	-0.052	-0.083	-0.131***	0.247	2.104***
	(0.056)	(0.066)	(0.051)	(0.775)	(0.528)
$\Delta IHI(3)$	0.006*	0.005	0.005	0.098*	-0.010
	(0.003)	(0.004)	(0.003)	(0.054)	(0.029)
$\Delta \mathcal{A}T(3)$	-0.014***	-0.008	0.002	0.018	-0.019
	(0.005)	(0.005)	(0.002)	(0.042)	(0.029)
Constant	-0.000	0.000***	-0.000***	-0.001	-0.000
	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)
Observations	1,950	1,950	1,950	1,950	1,950
Pseudo R^2	0.98	0.61	0.84	0.71	0.67

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 7: ***Vector autoregression analysis of the main macro variables***. *Results from LAD estimates of 10 periods growth rates, and bootstrapped standard errors (400). (1) ΔY: output growth; (2) ΔA: Aggregate productivity (3) ΔP: price; (4) ΔIHI: inverse Herfindhal Index (5) $\Delta \mathcal{A}T$: Atkinson inequality index. The numbers in parenthesis indicate the number of lags*

Parameter	Obs	Rank Sum	chi-squared	df	Prob
ι					
0.001	10240	1.010e+08	76	1	0.00
0.3	10240	1.090e+08			
ν					
3	10240	1.020e+08	34.94	1	0.00
50	10240	1.070e+08			
b					
1	10240	1.030e+08	17.54	1	0.00
3	10240	1.070e+08			
σ^a					
0.01	10240	9.120e+07	1048	1	0.00
0.2	10240	1.190e+08			
η					
0.1	10240	1.060e+08	8.621	1	0.00
3	10240	1.040e+08			
ρ					
0.05	10240	1.310e+08	3744	1	0.00
0.95	10240	7.900e+07			
ϑ					
0.01	10240	1.030e+08	15.88	1	0.00
10	10240	1.070e+08			
ζ					
0.1	10240	9.220e+07	902.3	1	0.00
1000	10240	1.180e+08			
ς					
0.05	10240	1.050e+08	0.334	1	0.56
0.9	10240	1.050e+08			
μ					
1.01	10240	1.480e+08	10452	1	0.00
2	10240	6.160e+07			

Table 8: ***Kruskall-Wallis rank test.*** *Main parameter effects*