Structural Change of Production and Consumption: A Micro to Macro Approach to Growth

Tommaso Ciarli[*], André Lorentz[†], Maria Savona[‡], Marco Valente[§]

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1 Introduction

This paper investigates the relation between structural changes in the organisation and composition of production, changes in income distribution and the evolution of consumption, as affecting patterns of economic growth. Although these dynamics are strongly inter–linked, few contributions have systematically investigated their co–evolution, both in theoretical and applied literature. Even more so, the analysis of the micro-to-macro mechanisms behind these processes has been greatly overlooked by both mainstream and non–mainstream literature.

The ambition of this work is therefore to provide (agent–based) micro–foundation to the link between structural change and growth by accounting for firm–level organisational and technological changes, the impact of these latter on the structure of earnings and income of workers–consumers

[*]University of L'Aquila and University of Bologna, Italy, tommaso.ciarli@unibo.it
[†]Max Planck Institute of Economics, Jena, Germany, lorentz@econ.mpg.de
[‡]University of Lille 1, France and University of Cambridge, UK, M.Savona@cmi.cam.ac.uk
[§]University of L'Aquila, Italy, valente@ec.univaq.it

and the consequent changes in consumption patterns. We propose a model which articulates the links between innovation and production on the supply side and the endogenous evolution of income distribution and consumption 'needs' on the demand side. We let these links interact to identify via numerical simulation different scenarios of changes in the production composition of economies and aggregate growth as emerging properties of evolutionary micro–dynamics of innovation, skill and functional composition of employment, income distribution and consumption patterns.

This work adds therefore to the literature on growth and structural change in two main respects. First, from a theoretical point of view, we embrace structural change of production and consumption in the belief that both should be accounted for in any attempt to explain growth dynamics, in line with the classics of Pasinetti (1981). Second, from a methodological point of view, we do so by carefully crafting firms and consumers micro–behaviours and identifying the resulting macro–level scenarios of structural change and growth.

A second intended, and much needed, contribution of this work with respect to the existing literature is the explicit introduction of income distribution as one of the main channels between changes in the organisation of firms and production structure on the one hand and changes in the consumption patterns on the other one. We do so in three main respects. First, we model an explicit relation between technological change and the organisation of production, which goes beyond the well–known skill bias effect, in determining the distribution of income (via earnings and profits share). Second, we suggest and model the relation between changes in income distribution and changes in consumption. Third, by endogenising the role of income distribution we are able to provide a valuable tool to extend the use of the model and derive normative implications through policy experiments.

The remainder of this preliminary work is organised as follows. Next section locates the contribution of this work within the context of a selected sketch of both theoretical and empirical, firm– and macro–level streams of literature relevant to the mechanisms explained by the model. In Section 3 we focus on the methodological issues revolving around the use of agent–based simulation modelling *vis á vis* quantitative analysis. Section 4 stylises the functioning of the model and provides the formalisation of it.

2 Literature background

There is still a considerable hiatus between what economic theory is able to explain and what actually happens in economic reality. Streams of economic theories still clash with respect to the range of phenomena investigated, the formulation of the main hypotheses, the justification of these latter, and, finally, the methodology employed. We go back to this latter issues more in depth in Section 3, which focuses on the rationale behind the use of simulation modelling *versus* quantitative analysis. The present section reviews the relevant pieces of literature and the empirical stylised facts which support the choice of our assumptions and the selection of the main mechanisms formalised in Section 4. In what follows we attempt therefore not to enter in the never–ending (and sterile) debate between mainstream (i.e. neo–classical) and etherodox scholars when searching for and formalising the ultimate determinants of countries' different patterns of economic growth. Cross–country divergence in growth rates has been a solid empirical stylised fact for decades (Denison, 1967; Denison, 1979; Maddison, 1987; Barro, 1991), what is left is to assess to what extent the (change in the) sectoral composition of economies is responsible for it and, ultimately, what determines changes in the production structure.

Technical change, changes in the production structure and the evolution of demand might disrupt the sectoral composition of the economy (Pasinetti, 1981) and the steady path of macroeconomic growth. Very few scholars have attempted to look at both the supply– and demand–side as determinants of growth and structural change (Verspagen, 1993; Verspagen, 2002; Montobbio, 2002; Llerena and Lorentz, 2004; Ciarli and Valente, 2005; Ciarli, 2005; Lorentz and Savona, 2006). Each of these contributions proposes models of economic growth which encompass both technical change and demand. However, none of them attempt to specifically look at the interaction between structural changes in the production and organisation of firms and structural changes of consumption needs to derive results on how changes in the composition of the economy affect aggregate growth.

Recent contributions (Saviotti and Pyka, 2004; Saviotti and Pyka, 2006) have looked at economic growth driven by structural change of the economy, in particular as a result of the emergence of new sectors, a phenomenon which is labelled interchangeably as the creation of product variety. Despite being greatly welcome as one of the very few attempts to focus on this issue, we still feel uncomfortable with the representation of structural change as limited to an increased product variety, with no explicit reference to whether and to what extent the evolution of consumption 'needs' and firms' effort to invent and innovate do interact in producing novelty.

A much needed stream of evolutionary literature is developing around the issue of how consumption 'needs' evolve, drawing upon evidence and theory derived from psychology (Valente, 1999; Witt, 2006; Witt, 2001). The importance of these contributions is two-fold. First and foremost on a theoretical level, insofar demand is looked at through the lenses of consumer behaviour and psychological drivers. Further, on a methodological level, as an explicit micro–foundation of consumption theory is proposed. Yet, demand both constraints is constrained by the supply's response to it. Changes in the structure of demand, however driven by psychological incentives, finds its natural interlocutor in whether and how firms respond to it – i.e. to what extent consumption 'needs' are met by the invention and successful commercialisation of new product on the market, as dear old Schumpeter had already emphasised long time ago.

To our knowledge, no one single contribution has explicitly disentangled at the micro–level the role of distributional changes as the natural channel of the evolution of consumption 'needs' into the evolution of actual demand, i.e. changes in the signals which firms receive from the market and which they respond and adapt to. Rather, the large and consolidated literature on the two-sided link between economic growth and income distributional change remains confined to macro–level analyses, since the seminal Kuznet's curve and the works by (Stiglitz, 1969; Tinbergen, 1975), greatly enriched later on (Atkinson, 1997; Aghion, Caroli, and García-Peñalosa, 1999; Aghion, 2002; Galbraith, Lu, and Darity, 1999; Galbraith, 1999)[1].

As for the macro–evidence on the two–sided relation between growth and distributional changes (i.e. increase in income inequality) Aghion, Caroli, and García-Peñalosa (1999) presents an extensive review on this issue. The authors look at both *wealth* and *wages* inequality and provide evidence and theoretical support looking at three competing explanations of wage inequality: **i)** trade (and especially import of intermediate goods from developing countries); **ii)** skill bias (which seems to prevail over trade, although there

[1]Surprisingly, the role of distributional changes is greatly overlooked within the evolutionary stream of literature.

is also evidence of large inequality within educational classes), considering both *disembodied* (see also Aghion, 2002) and *embodied* technical change. Within homogeneous educational classes inequality is attributed to learning and inter–sectoral mobility; and **iii)** changes in firms organisation (and skill experience), though not further defined. In line with Tinbergen (1975), wage dynamics and inequality are argued to follow the competing game between demand and supply of skills. Up to the 70s skills supply has increased more than demand pushing down the relative wages. In the following period the demand for skills has increased and so have done the relative wages. The authors assume though that the only force driving the demand for skills is technical change.

A different view is proposed by Galbraith, Lu, and Darity (1999) and Galbraith (1999), according to whom inequality in income, and in earnings, is due to the country economic structure. The Keynesian approach hints at the Kuznets hypothesis and the specialisation effect on a global market. In arguing his point, Galbraith openly criticises the overrated explanation of wage inequalities led by skills [2]. Wage distribution ultimately depends on the specialisation of the economy, both at the international level (Prebish–Singer hypothesis) and at the national level (á la Kaldor).

Conversely, a great deal of micro–level literature has looked at (changes in) firms' size and organisational structure as affecting the (skill and organisational) composition of workers and executives and the wages structure, since the seminal contributions by Simon (1957), Lydall (1959), Rosen (1982) and further extended (among others, Waldman, 1984; Abowd and Margolis, 1999; Prescott, 2003).

The key–words of this stream of contributions are therefore firm size, number of and complexity of organisational layers internal to the enterprise, the proportion of executives and workers and the structure of pay (and wage premiums). The interesting feature of this literature (see for instance Prescott, 2003) is that, in line with what Galbraith suggests at the macro–level of analysis, the role of skills differentials is not over–emphasised with respect to other factors, in determining earnings and income inequality. For instance, Caroli and Van Reenen (2001) suggest that there is a dynamic other

[2] According to Galbraith it is not the use of the computer *tout court* which is responsible for wage increases. Rather, it is the working condition in which it is used, which makes an entirely new working class to emerge (computers should make jobs easier). The difference is not between users and non–users of technology, but between users and producers.

than skill bias technical change which depends on the organisational change and affects wage and earning distributional change. Namely, an increased decentralisation of production and work organisation demands higher responsibility to a single executive and an increase in wage compensation of executives follows. Technical change, especially ICT–related, requires complementary organisation change in order to be effective, therefore increasing demand for higher shares of higher skilled executives.

This stream of literature, however, at the cross-road between economics and management, excludes from the domain of analysis the impact of changes in the wage structure on the evolution of consumption, both in terms of (average) disposable income and of preferences.

Our conjecture, summarised in 4, is that changes in the economic structure and (trade and sectoral) specialisation have been accompanied by changes in the organisational structure of firms and both have brought about changes in the wage and earning structure. Both micro– and macro–level mechanisms are therefore behind changes in the consumption patterns, which in turn affect changes of the production structure both at the firm and sectoral level. We turn to the representation of these mechanisms in 4, once having justified in the next section the choice of the methodological tools employed in this work.

3 Economic Analysis and Simulation Models

The first step in order to address the ambitious issues mentioned above is to determine a methodological framework able to guide the development of the analysis and, ultimately, provide a test to assess the validity of the purported results.

Standard scientific methodology — as, for example, used in traditional physics — mandates that the major test to assess the validity of a model must rely on quantitative similarities between the values predicted by the model and those observed empirically: the fittest the theoretical data to the empirical data set the better is the model.

Unfortunately, this approach must be ruled out when dealing with socio–economic phenomena, and the aim of the analysis is to look for explanations rather than representations of their happening. Economics is one of the *artificial sciences* (Simon, 1969) whose elements are not behaving blindly, following ascertained (possibly complex) rules of nature, irrespective of the results produced. Rather, as it is well known (though not always taken into account), economics is interested with sentient entities (individuals or organizations) that pursue one or more aims, adopting the instruments they are able to put in use. Therefore, predicting the results of economics' objects of study needs a careful analysis of the environment in which they act, which heavily influences the behaviour of otherwise identical entities.

Such a consideration would not be worth much attention (after all, any science analyses objects whose environment can influence their behaviour), if it were not that the economic environments that we can observe empirically are constantly changing. The conditions in which a consumer, a company, any economic actor, is called to make a choice, can become radically different in respect of even minor differences of location or time. And even more crucial, the complexity of the tasks, together with the limited ability of economic actors to face them and to acquire and elaborate the necessary information, results in the substantial possibility that the very same actor, in the same environmental conditions, ends up taking totally different actions. Consequently, economic systems (either macro–economic system or smaller systems as a firm or an individual households) can be understood only conditional to their complex, volatile environments.

Note that such systems have radically different properties compared to *natural* systems (in Simonian terms). For instance, physical systems (say Newtonian astronomy) studies the *most frequent* behaviour. For example, the gravitational force is observed as applying equally to *almost* any type of weight, and the relevant theory duly describes what must happen if *all* weights behave according its law. In practice we may observe extremely rare circumstances in which the *general* case leaves (little) room to *exceptions*. Say, for example, a metal object floating above a strong magnetic field. Such an observation can be ignored, as far as gravitational theory is concerned. But this is not the case for complex systems in social sciences. If Economics had to follow the same rule, we should (for example) be concerned with the majority of companies that go bust within a few months from their birth, rather than studying the more exceptional case of a firm surviving decades and becoming a multi–billion dollars multinational.

Therefore, sciences concerned with natural worlds rely on a substantial correlation between the characteristics that describe them. For example, two objects of roughly the same size, shape, colour and weight, are likely to have the same material composition. For what concerns the present discussion, though exceptions are found, we can safely assume that, comparing two physical entities, when most measures coincide, also the remaining ones will be quite similar. In Economics this is not the case. Taking any short set of variables, two firms with identical values along these measures may widely differ on any other one. Indeed, any economic entity, in order to be represented properly for *all* its effects on the system, needs to be described in such detail to result, eventually, unique, that is, non–comparable with other entities. And most relevant, the uniqueness does not concern the *values*, but the very *variables* relevant to identify the entity.

It follows that quantitative measures of such complex and 'unstable' (socio–economic) systems, cannot be considered valid representations of a system's properties, although, as we claim below, they have a crucial role. In fact, entities represented as quantitative measures need to drop their uniqueness, since they are assumed to share the same set of dimensions (variables). As a result, the same outcome measure can be obtained from two, totally different, systems as well as two very similar systems, with similar properties, may produce radically different outcomes. And this variability would be the result of deterministic effects of ignored dimensions and unobserved variables, rather than the result of randomness, subject to statistical analysis.

Such considerations may appear, once we accept them, as undermining the very possibility to make any objective, scientific assertion concerning economic phenomena, at least for those phenomena where complexity and uniqueness of entities matter most. This is not necessarily the case: ruling out quantitative invariances does not mean that other types of invariances cannot be found.

First we acknowledge that, although economic systems have radically different properties in different time and places, some (actually, many) aspects can be qualified as stable, though their combined effects may vary between observations. Take for example the desire of agents to increase their wealth; or the effects on prices by excesses of demand or supply. Economists have collected a huge amount of knowledge concerning *ceteris paribus* reactions of economic entities to given stimuli. Above we claim that there is no actual possibility to observe the *ceteris paribus* clause in the real world, and therefore no possibility to predict in detail quantitative patterns, or explain in detail aggregate phenomena.

Second, we acknowledge that scientific knowledge, whatever format is used to embody it, must be able to answer 'simple' questions concerning its domain like: what happens to a given system under certain circumstances? Answers can be more or less detailed and reliable, and scientific investigation pursues exactly increments of details and reliability. Economics does not differ: we can claim to *know* something of a system if we can *explain* (with some details and reliability) how different aspects of the system relate and/or how it is likely to develop in time.

On the inductive side we conceive that, as explained above, the information available to economists — experience of experts, historical records, or data sets — cannot provide an exact representation of systems, but they can undoubtedly provide invaluable information on partial aspects of systems — unobservable in their entirety. It follows that details on any observation may be incremented calling for a mix of stable aspects,[3] and many idiosyncratic events. Statistical analysis can be used, in certain circumstances, to separate one from the other, but in many cases this is difficult, or impossible.

On the symbolic side, the evolution of an economic system — or its observable aspects in each point in time — depends on the behaviour of entities acting at different aggregation levels (micro ones, which aggregate in larger groups, which in turn aggregate in still larger groups, and so on). A complex system is one in which each aggregate's behaviour depends on its components, while it constraints the components' behaviour (or selects on components' behaviour without ruling them). In other words, such systems generate aggregate properties called *emergent properties* (Lane, 1993) that depend on, possibly simple, interaction mechanisms, but whose non linearity makes them difficult to describe, predict, or control.

Difficult needs not to mean impossible. Removing some levels of the system makes the system simpler, and the complexity reduction we obtain by slicing off system elements is larger the more complex is the original system, i.e. the larger the number of interactions. Investigations of a simple enough system (however unrealistic) provides knowledge on how the original system would behave, if the removed elements did not exist. Once this 'toy sub–system' is well understood, it can be expanded adding one of the

[3]What we can consider as *laws*.

elements previously sliced off, removing a *ceteris paribus*, 'if' condition. System behaviour is likely to change, but we can now attribute the difference to the new element introduced — and how they affect the initial setting. Re–instating more and more elements to the system is likely to reach a level in which crediting changes to specific elements becomes impossible. But, before this critical level is reached, we are likely to have built a *toy* system that is well understood — and its mechanisms explained, and whose difference with real one is limited to a relatively small set of elements.

Simulation programs assist the study of such complex systems in several respects, if used properly. Firstly, forcing the modeller to use a rigorously logical programming language, it is not possible to ignore elements, or overlook the details of certain dynamics. A program needs to be perfectly and consistently defined (in logical terms) to execute it. Since we have, from our observation, only a few hints of the actual behaviour of real–world entities, then the necessity to use a programming language is a disciplinary instrument, forcing to clarify overlooked aspects and solve unspotted inconsistencies.

Secondly, even relatively simple models (or programs) can generate unexpected, apparently bizarre results. Sometimes (well, frequently) these are *programming bugs*. But frequently unexpected results are surprising consequences of hidden implications of apparently innocent assumptions made on the unknown bits of the system. These *logical* bugs, once tracked, generate, by definition, further knowledge about what we assumed to now. In fact, a logical bug or, better, an unexpected result, can either induce a re–thinking in the definition of elements and mechanisms, or vary the set of results that we know the model can produce. Both cases are knowledge increments that could not be obtained without running, and analysing, a simulation run.

Thirdly, simulation models are representations of sub–systems that can be gradually adjusted to improve their performance. Although a simulation model is by no means able to reproduce exactly the whole set of properties we can observe in its real–world counter part, it is anyway the expressions of a sub–set of the forces acting in the real world, if the assumptions are reliable, and thus can be used for a *ceteris paribus* analysis. We can use the model to predict the effects of given elements, by running simulations with different parameter sets. Using an abductive approach the study of the simulation runs tell us if and, most crucially, *how*, changes in the parameters affect the properties of the model. The mechanism by which the changes occur can be fully and unambiguously understood in the simulated system, given our capacity to inspect any aspect of the simulation at any moment. Crucially, empirical evidence can be collected to find out whether average and 'exceptional' mechanisms at work in the real world — not final outcomes — are similar to those envisaged in the simulated system. Whatever the result of such comparison, we can increase our knowledge, and put this increment to work into the model: if the mechanisms are similar, our model increases its reliability to represent evidence; if the mechanisms differ, then we know how our model differ from reality, and we can adjust it to include (if relevant) the previously overlooked elements. We can then proceed to expand the virtual system by adding new elements and reducing the ceteris paribus space.

Lastly, a simulation model is a ready–to–use instrument for normative purposes. It allows to test scenarios and the likelihood of policies to reach given goals, and to weight indirect effects. Crucially, a simulation model tells not only *what* would happen, but *why*. The explanation of the channel by which a given initiative affects a system is a more reliable and useful information, in respect of a probability distribution of how targets react to hits.

In the following section we begin the exploration of the relation between structural changes in production and consumption by proposing a first version of a model (a sub–system in the terminology used above) containing basic elements that, we believe, are crucial to the investigation of this phenomenon. In other words, we propose a way to reconcile the crucial elements described in section 2 with the understanding of their complex interactions. Although the model describes macro phenomena at the most aggregate level, as previously mentioned in this section, we aim to explain their emergence via the representation of the subjacent micro–economic mechanisms. In presenting the model we are not claiming that it is a universal model, apt to represent any event in any economic system. Rather, we consider it as the initial element of a sequence of *toy* models, all of them *unrealistic* in any quantitative meaning of the term, but, we hope, increasingly able to produce and explain more and more complex phenomena.

4 The Model

This section provides a stylised description of the main mechanisms and assumptions behind the model, which is formally reported in the following subsections.

Following existing Schumpeterian growth models (see, among others Verspagen, 1993; Leon-Ledesma, 2000; Llerena and Lorentz, 2004) we consider economies composed of a consumers sector and a capital sector. Unlike the existing literature, we account for the whole set of innovation strategies for a firm: process, product and organisational innovation. Such extension allows to endogenising a number of mechanisms that are shown to be responsible for the skewed (Pareto) distribution of incomes (e.g. economics of superstars, profits sharing, and supply of skilled labour, in line with the work of () Lydall, 1959; Rosen, 1982; Rosen, 1981; Prescott, 2003).

The micro–dynamics of both consumption patterns and innovation rely on the products defined as vectors of characteristics, which provide services to the users. This draws upon the work by Ciarli and Valente (2005) and is in line with the Lancasterian and post–Lancasterian approach to consumer theory (Gallouj and Weinstein, 1997; Lancaster, 1966; Saviotti and Metcalfe, 1984).

First, changes in the production processes are modelled as investment in different capital vintages. Firms belonging to the final and capital good sectors make use of unskilled, skilled and engineering labour force, with differentiated wages, dividends and consumption preferences. By changing vintage, firms' strategies alter the capital/labour composition of their technology, affecting the composition of the labour market and the income distribution in the consumers market. We also model the vertical relation between buyers and suppliers. Aggregate demand is therefore a result of the micro–dynamics of consumption patterns, which in turn depend on the (skill) composition of employment and income distribution dynamics.

Second, product changes are considered as a bi–univocal relation between changes in consumers preferences and budget constraints on the one hand, and firms' technological competition to acquire oligopolistic shares of the market on the other hand.

Third, organisational changes affect the relative economic importance of executives by altering firms' governance structure, therefore inducing changes in the income distribution and consumption behaviour. The latter is in fact linked to preferences formation within working classes and imitation across classes.

Further, consumers' demand affects firms' expectations in terms of market shares and, accordingly, constraints their plans of production and R&D investment decisions. Consumption behaviour draws on both economic and psychological evidence collected from marketing studies, and adapts the theoretical construction developed by Valente (Valente, 1999) in previous works. Demand comes from a number of wage classes. The composition of each class defines a distribution of 'needs', from basic to luxury goods. Finally, the distribution of consumers' preferences over the goods' characteristics (price enters as a threshold characteristic, given the budget constraint) defines the demand curve and firms' production shares.

4.1 Final Good Firms

4.1.1 Product, Sales and Stocks

Each firm produces only one product at the time. Each product is characterised by a vector of quality that assign a given quality level $i_{n,m}$ to the product for each consumer need $n \in [1; N]$, and sub–characteristics of this need $m \in [1; M]$:

$$\begin{pmatrix} i_{1,1} \\ \vdots \\ i_{n,1} \\ \vdots \\ i_{n,m} \\ \vdots \\ i_{n,M} \\ \vdots \\ i_{N,M} \end{pmatrix} \tag{1}$$

The number of goods order to the firm by the consumers (Y_t) is covered by the firm's stocks (S_t) or if firm's stocks are not sufficient remain as an order. These orders are collected as backlogs (Bl_t). Firm's stocks correspond to the actual production (Q_t) and the remaining stocks (S_{t-1}) minus the remaining orders to be covered (Bl_{t-1}).

$$S_t = max\left\{S_{t-1} + Q_t - Y_t - Bl_{t-1}; 0\right\} \tag{2}$$

$$Bl_t = -min\left\{S_{t-1} + Q_t - Y_t - Bl_{t-1}; 0\right\} \tag{3}$$

To plan their actual production firms' compute their expected sales (Y_t^e) using an adaptive decision rule:

$$Y_t^e = a^s Y_{t-1}^e + (1 - a^s) Y_{t-1} \tag{4}$$

4.1.2 Production

At each time step, the production level planned (Q_t^d) by the firm corresponds to the difference between the actual and desired stocks ($\bar{S}$) plus the expected sales (Y_t^e) and the remaining orders (Bl_{t-1}) to be covered:

$$Q_t^d = min\left\{\bar{S} - S_t + Y_t^e + Bl_{t-1}; 0\right\} \tag{5}$$

The actual production level (Q_t) is constrained by the production capacities of the firm in terms of available work force ($A_{t-1}L_{t-1}$) and machinery capacity ($\bar{B}K_{t-1}$)

$$Q_t = min\left\{Q_t^d; A_{t-1}L_{t-1}; \bar{B}K_{t-1}\right\} \tag{6}$$

The available labour capacity depends on the work force available defined as the number of workers employed and hired the last period (L_{t-1}) and the labour productivity embodied in the machinery available (i.e. the capital stock accumulated until the last period)

The work force of the firm is composed by Λ layers of skills.[4] The number of workers in each layers depends on the number of unskilled workers L_t^0:

$$\begin{gathered} L_{t-1}^1 = L_{t-1}^0 \nu_{t-1}^{-1} \\ L_{t-1}^2 = L_{t-1}^1 \nu^{-1} = L_{t-1}^0 \nu_{t-1}^{-2} \\ \vdots \\ L_{t-1}^{\Lambda-1} = L_{t-1}^0 \nu_{t-1}^{1-\Lambda} \end{gathered} \tag{7}$$

$$L_{t-1} = L_{t-1}^0 \sum_{l=0}^{\Lambda-1} \nu_{t-1}^{-l} \tag{8}$$

where ν_{t-1} represents the ratio of skilled workers of a given layer requested by the use of the previous layer's workers.

[4]Note that as for now the model only includes 2 layers of skills: namely unskilled and skilled workers.

The firm hires workers according to there planned sales (expected sales Y_t^e and the uncovered demand i.e. backlogs Bl_t), the labour productivity of the firm as embodied in their capital stock A_{t-1}, the parameter ν_{t-1} and, a degree of unused capacity (u^l) to cover unexpected demand:

$$\begin{aligned} L_t^0 = \epsilon_L L_{t-1}^0 + (1-\epsilon_L)\left[\left(1+u^l\right)\frac{1}{A_{t-1}\sum_{l=0}^{\Lambda-1}\nu_{t-1}^{-l}} min\{Q_t^d; \bar{B}K_{t-1}\}\right] \\ \vdots \\ L_t^l = L_t^0 \nu_{t-1}^{-l} \\ \vdots \\ L^{\Lambda-1} = L_t^0 \nu_{t-1}^{1-\Lambda} \end{aligned} \tag{9}$$

Unit production costs (c_t) therefore correspond to the wage bill of the firm divided by the production level ($Q-t$). Wages are set as follows:

- a coefficient ω^u is applied to the macro-level minimum wage w_{t-1}^m to define the wage of the lower worker layer:

$$w_t^0 = \omega^u w_{t-1}^m \tag{10}$$

- the wage for each skill layer is linked to the specific layer which their position belongs to.

$$\begin{aligned} w_t^1 = b w_t^0 \\ w_t^2 = b w_t^1 = b^2 w_t^0 \\ \vdots \\ w_t^{\Lambda-1} = b^{\Lambda-1} w_t^0 \end{aligned} \tag{11}$$

  where b is the fixed ratio between the salary of any executive and the salary of its immediate subordinates.

- the unit production cost c_t can then be computed as follows:

$$c_t = \frac{\sum_{l=0}^{\Lambda-1} w_t^l L_{t-1}^l}{A_{t-1} L_{t-1}}$$

$$c_t = \frac{w_t^0 L_{t-1}^0 \sum_{l=0}^{\Lambda-1}\left(\frac{b}{\nu_{t-1}}\right)^l}{A_{t-1} L_{t-1}} \tag{12}$$

4.1.3 Pricing and Profits

Prices (applied at period t are set at the end of $t-1$) p_{t-1} are set applying a mark-up (μ_{t-1}) on the unitary production costs (c_{t-1}). Yet the mark-up remains fixed (changes to be thought about). Profits (π_t) corresponds to the difference between total monetary sales ($p_{t-1}Y_t$) and total production costs.

$$p_{t-1} = (1+\bar{\mu})c_{t-1} \tag{13}$$

$$\pi_t = p_{t-1}Y_t - c_tQ_t \tag{14}$$

Profits are the only resources available for the firms to invest, in capital goods and in product R&D, and to be redistributed into dividends. Firms devote fixed shares (respectively ι, ρ and $(1-\iota-\rho)$) of their profits to these three components. Hence R_t^I, $R_t^{R\&D}$ and R_t^D representing respectively the resources available for investments, R&D and dividends are computed as follows:

$$R_t^I = \sum_{\tau=0}^{t} \iota\pi_\tau - \sum_{\tau=0}^{t-1} p_{\tau-1}^k k_\tau \tag{15}$$

$$R_t^{R\&D} = \sum_{\tau=0}^{t} \rho\pi_\tau - \sum_{\tau=0}^{t-1} RD_\tau \tag{16}$$

$$R_t^{Div} = +\sum_{\tau=0}^{t}(1-\iota-\rho)\pi_t - \sum_{\tau=0}^{t-1} Div_\tau \tag{17}$$

where $p_{\tau-1}^k k_\tau$ represents the expenditures in capital good at time τ, RD_τ the expenditures in R&D, and Div_τ the dividends redistibuted to the shareholders.

4.1.4 Capital and Investment

The accumulation of capital goods allows to (i) increase the production capacity of the firm ($\bar{B}K_{t-1}$), (ii) increase the efficiency of the production process, increasing labour productivity due to the embodied nature of technical change, (iii) modifies the structure of the work force employed due to the organisational changes required by the use of new capital goods. The capital intensity of a firm ($\frac{1}{B}$) remains fixed.

The capital stock of the firm at the end of period t (K_t) correspond to the sum of the stocks k_τ of capital the capital vintages bought at period τ

net of the loss due to capital depreciation (δ):

$$K_t = \sum_{\tau=0}^{t} k_\tau (1-\delta)^{t-\tau} \tag{18}$$

The actual labour productivity of the firm is embodied in the capital accumulated by the firm. At the end of period t, the latter corresponds to the average productivity embodied in each capital vintages (a_τ) weighted by their share in the capital stock:

$$A_t = \sum_{\tau=0}^{t} \frac{k_\tau (1-\delta)^{t-\tau}}{K_t} a_\tau \tag{19}$$

The labour composition (i.e. ratio between the skill layers) is function of capital. Each capital vintage τ is characterised by a degree of skill-bias (ν_τ), or minimum ratio of skilled workers required to use the machinery. The labour composition ν_t at the end of time t therefore corresponds to the average ratio attached to each capital vintages ν_τ weighted by their share in the capital stock:

$$\nu_t = \sum_{\tau=0}^{t} \frac{k_\tau (1-\delta)^{t-\tau}}{K_t} \nu_\tau \tag{20}$$

Hence if $\nu_t \rightarrow 0$ skills are substituted with machinery; if $\nu_t \geq 1$ as capital is accumulated, more skilled workers are required, technical change is therefore skilled-biaised.

Firms accumulate capital through investment. The investment decisions are constrained by the resources available for investment as a share ι of the profits accumulated through time. If the capital stock of the firm does not allow to cover the expected sales ($Y_t^e + Bl_t$) the firm invests in capital goods these needs k_t^e:

$$k_t^e = \left(1 + u^k\right) \frac{Y_t^e + Bl_t}{\bar{B}} - K_{t-1} \tag{21}$$

u^k is the degree of unused capital to cover unexpected demand

Firms then place an order of k_t^d units of capital goods to a producer of capital good with a compatible technology. The number of unit ordered is constrained by the resources of the firms (R_t^I).

$$k_t^d = min\left\{\frac{R_t^I}{p_{t-1}^k}; k_t^e\right\} \tag{22}$$

p_{t-1}^k corresponds to the price applied by the machinery firm chosen.

The probability for a firm to choose a given capital supplier increases the higher the level of embodied productivity (a_τ), the lower the price (p^k_{t-1}), and the lower the waiting time before completion of the order are with respect to the average among all capital suppliers.

The actual unit of capital (k_t) acquired by the firm in t then corresponds to the part of the order covered by the machinery firm. k_t can either equal k^d_t if the order has been completed of 0 if the order is still to be completed. The firm wait completion of their previous order to renew their investments.

4.2 Machinery Firms

4.2.1 Capital goods

Each capital goods is characterised by its vintage τ, an embodied level of productivity a_τ, the skills ratio ν_τ required to use it and a technology type θ:

$$\begin{pmatrix} \tau \\ a_\tau \\ \nu_\tau \\ \theta \end{pmatrix}$$

The technology type constrains the number of final good firms able to use the capital goods produced. Only the firms using a technology of the type θ are able to use capital goods of the same type (i.e. a producer of textile products cannot use the exact same technology as a computer producer). The characteristics embodied in the capital goods (a_τ, τ) are an outcome of the R&D activity of the machinery firms.

4.2.2 Producing capital goods

The total demand for capital goods at a given period t (K^d_t) corresponds to the sum of the orders addressed to the machinery firm at the same period (k^d_j, t) and the orders uncovered by the production at the previous period (U^d_{t-1}):

$$K^d_t = \sum_{j=1}^{J_t} k^d_{j,t} + U^d_{t-1} \tag{23}$$

where j correponds to the arrival order; Jt then corresponds to the last order arrived and therefore the number of orders at time t.

The production of a machinery firm aims to cover its demand and is constrained by its production capacity ($\bar{A}^k L^k_{t-1}$). The capital orders of the final good firms are treated in order of arrival and orders are never delivered if partially completed. Hence the production level of the capital good firm Q^k_t correspond can be defined as follows:

$$Q^k_t = min\left\{K^d_t; \bar{A}^k L^k_{t-1}\right\} \tag{24}$$

The total sales (Y^k_t) by a machinery firm for a given period therefore corresponds to the sum of the order completed ($k_{z,t}$) during this period:

$$Y^k_t = \sum_{z=1}^{Z_t} k_{z,t} \tag{25}$$

where Z_t is the number of orders completed at time t, so that:

$$\sum_{z=1}^{Z_t} k_{z,t} = \begin{cases} K^d_t \text{ if } K^d_t \leq \bar{A}^k L^k_{t-1} \\ \\ U^d_{t-1} + \sum_{j=1}^{\bar{J}} k^d_{j,t} \text{ for } k^d_{\bar{J},t} \text{ last order before capacity constaint} \end{cases} \tag{26}$$

Hence, the order remaining to cover U^d_t can be computed as follows:

$$U^d_t = \sum_{j=\bar{J}}^{J_t} k^d_{j,t} \tag{27}$$

The production capacity of a machinery firm corresponds to its fixed labour productivity ($\bar{A}^k$) time the labour force available for production. The latter corresponds to the work force employed and hired at the previous period (L^k_{t-1})

Machinery firms hire workers (L^k_t) to increase their production capacity to cover all their orders (K^d_t) and to keep a share (u^m) of unused workers to cover some unexpected demand.

$$L^k_t = \epsilon^M L^k_{t-1} + (1-\epsilon^M)\left[(1+u^m)\frac{K^d_t}{\bar{A}^k}\right] \tag{28}$$

4.2.3 Prices and Profits

The price for capital goods p^k_t are set using a mark-up (μ^k) on the production and development costs of the machinery firm:

$$p^k_t = (1+\mu^k)\left(\frac{w^k_{t-1}}{\bar{A}^k} + \frac{w^E_t L^E_{t-1}}{\bar{A}^k L^k_{t-1}}\right) \tag{29}$$

Production and development costs are link to the wages paid to worker (w_t^k) and to engineers (w_t^E). These wages are set by firms applying a coefficient (ω^k and ω^E respectively) to the minimum wage set at the macro-level (w_{t-1}^m):

$$w_t^k = \omega^k w_{t-1}^m \tag{30}$$

$$w_t^E = \omega^E w_{t-1}^m \tag{31}$$

The profits π_t^k are then redistributed as dividends to their shareholders (Div_t^k).

$$\pi_t^k = p_{t-1}^k Y_t^k - w_t^k L_{t-1}^k - w_t^E L_{t-1}^E \tag{32}$$

4.2.4 R&D and Innovation in Machinery

Machinery firms aim to improve the characteristics of their products through their R&D Activity. The outcome of this activity is stochastic.

The probability (p_t^{inn}) of success of R&D increases with the number of engineers employed in R&D (L_{t-1}^E):

$$p_t^{inn} = 1 - e^{-zL_{t-1}^E} \tag{33}$$

The R&D investment by machinery firms therefore consist in hiring engineers. Firms correlated the engineers pool to their profits in the range of a fixed share ρ of cumulated profits constrained by a fixe ratio ν^k of engineers by workers (L_t^k):

$$L_t^E = min\left\{\nu^k L_t^k ; max\left\{\rho^k R_t^E ; 0\right\}\right\} \tag{34}$$

The costs induced by the engineers pool is then included to the production cost of the next periode.

Formally the R&D activity is represented by the following algorithm:

1. Firms draw a number from a Uniform distribution on [0 ; 1].

2. If this number is contained in the interval [0 ; p_t^{inn}], the R&D is successful.

3. If R&D is successful, the characteristics of the newly developed vintage are randomly drawn as follows

$$a_\tau = a_{\tau-1}\left(1 + max\{\varepsilon_t^a ; 0\}\right) \tag{35}$$

$$\varepsilon_t^a \sim N(0;\sigma^a) \tag{36}$$

$$\alpha_\tau = \alpha_{\tau-1}\left(1+\varepsilon_t^\nu\right) \tag{37}$$

$$\varepsilon_t^\nu \sim N(0;\sigma^\nu) \tag{38}$$

4.3 Wages and Income Settings

4.3.1 Minimum wage

All wages are set at the level of firms applying a fixed rule to the minimum wage negociated at the macro-economic level. This minimum wage w_t^m is indexed on a smoothen growth of aggregate productivity (Aa_t) , a smoothen rate of inflation in the final good sector and a proxy for the rate of unemployment. We moreover assume the minimum wage to be flexible in increases but rigide to decreases so that:

$$w_t^m = w_{t-1}^m\left[1+\epsilon^A\left(max\left\{\frac{\Delta Aa_t}{Aa_{t-1}};0\right\}\right)+\epsilon^P\left(max\left\{\frac{\Delta P_t}{P_{t-1}};0\right\}\right)-\epsilon^U\left(max\left\{Um_t;0\right\}\right)\right] \tag{39}$$

The smoothen growth rate of aggregate productivity is computed as follows:

$$\frac{\Delta Aa_t}{Aa_{t-1}} = \beta^A\left(\frac{Aa_t}{Aa_{t-1}}-1\right)+(1-\beta^A)\frac{\Delta Aa_{t-1}}{Aa_{t-2}} \tag{40}$$

with:

$$Aa_t = \frac{\sum \frac{p_{t-1}}{P_t^p}Q_t + \sum \frac{p_{t-1}^k}{P_t^p}Y_t^k}{\sum\sum_\Lambda L_{t-1}^{Lambda} + \sum L_{t-1}^k + \sum L_{t-1}^E}$$

where P_t^p corresponds to the production price index computed as:

$$P_t^p = \sum\left(\frac{p_{t-1}Q_t}{\sum \frac{p_{t-1}}{P_t^p}Q_t + \sum \frac{p_{t-1}^k}{P_t^p}Y_t^k}\right)p_{t-1} + \sum\left(\frac{p_{t-1}^kY_t^k}{\sum \frac{p_{t-1}}{P_t^p}Q_t + \sum \frac{p_{t-1}^k}{P_t^p}Y_t^k}\right)p_{t-1}^k$$

The rate of inflation is measured as the average rate of change in the sum of firms prices in the final good sector weighted by their market share, as follows:

$$\frac{\Delta P_t}{P_{t-1}} = \beta^p\left(\frac{\sum z_t p_{t-1} - \sum z_{t-1}p_{t-2}}{\sum z_{t-1}p_{t-2}}\right)+(1-\beta^p)\frac{\Delta P_{t-1}}{P_{t-2}} \tag{41}$$

where z_t represents the market share of a given firm in the final good sector.

We assume here that the labour market is perfectly elastic and the labour supply not bounded. We then proxy the unemployment rate as follows:

$$Um_t = 1 - \frac{\sum\sum_{\Lambda} L_{t-1}^{Lambda} + \sum L_{t-1}^{k} + \sum L_{t-1}^{E}}{mEmp} \tag{42}$$

where $mEmp$ represents the maximum employment level reached in time:

$$mEmp_t = max_{\tau}\left\{\sum\sum_{\Lambda} L_{\tau}^{Lambda} + \sum L_{\tau}^{k} + \sum L_{\tau}^{E}\right\} \tag{43}$$

4.3.2 Income distribution

Households total income T_t is composed of both wages (W_t) and dividends ($TDiv_t$):

$$T_t = W_t + TDiv_t \tag{44}$$

$$W_t = \sum\sum_{\Lambda} w_t^{\Lambda} L_{t-1}^{Lambda} + \sum w_t^{k} L_{t-1}^{k} + \sum w_t^{E} L_{t-1}^{E} \tag{45}$$

$$TDiv_t = \sum Div_t + \sum Div_t^k \tag{46}$$

This income is then distributed around consumer classes to fund their expenditures: Each consumer class κ gets a respectively a share χ_{κ}^{div} and χ_{κ}^{w} of dividends and of wages. The income available for each consummer class (T_t^{κ})is therefore:

$$T_t^{\kappa} = \chi_{\kappa}^{div} TDiv_t + \chi_{\kappa}^{w} W_t \text{ with } \forall\kappa \begin{cases} \sum_{\kappa} \chi_{\kappa}^{div} = 1 \\ \sum_{\kappa} \chi_{\kappa}^{w} = 1 \end{cases} \tag{47}$$

Moreover the ratio between wage and dividends income is increases with the lower consummer classes.

4.4 Final Demand

4.4.1 Demand structure

Aggregate demand is composed by classes defined by:

- Number of consumers in the class;
- Average disposable income per consumer;
- Percentages of income devoted to the different uses;
- Set of preferences and other consumer's specific properties of the consumption function.

4.4.2 Consumers' choices

The demand function needs to respect several conditions:

1. The higher the quality of firm i's product, the higher its market shares;
2. The higher the qualities of firms j's products, the lower the market shares of firm i;
3. The higher the qualities of products, the higher the absolute level of sales.

Such simple requirement make difficult to build a sensible aggregate function turning qualities into sales. The more so if we want to control the function behaviour by means of realistic parameters, that is, meaningful measures of some real-world aspect. That is, cross-elasticities of prices and qualities do not exist, though we may measure it, since people's behaviour provides inconsistent values (e.g. highly volatile through time). Instead, there is ample empirical evidence from market research students and psychology, showing (broadly) how people actually take decisions, and therefore which parameters influence their choice, which can be directly observed.

Therefore, we use an agent-based function, representing the behaviour of a single consumer purchasing a product to be chosen among a set of existing alternatives. The parameters governing this routine, that have a clear influence on the choices made, clearly indicate well-defined classes of consumers, e.g. expert vs. casual consumers, highly segmented vs. generalist market, etc.

Consider a set of potentially available products each defined over a vector values, representing different qualities (e.g. "cheapness", robustness, consumption, durability etc.). Without loss of generality, we assume that all qualities are positive, therefore the highest values are more desirable.

The routine for purchasing is the following:

1. Replace the true quality level for each product and each quality with an **observed** value, a random value drawn from a random function centered on the true quality and with variance proportional to a *ignorance* parameter. The larger this parameter, the wider the distribution of sales, and the less selective will be the demand sector as a whole.

2. Determine a **viable** set of options by removing from all existing products on offer all the products scoring too low in respect of one or more qualities. If no product satisfies the minimum requirement, do not make any purchase (this provides the possibility of having increasing sales with increasing qualities).

3. Consider a threshold for **tolerance**, or equivalence: a product scoring more than the fraction τ of the best product is considered equivalent to the maximum.

4. Apply the **Take-The-Best** algorithm, selecting out all products that are inferior in respect of the sequence of qualities considered. The order of the characteristics make up the consumers' preferences.

5. When a single product remains, choose it. If more than one product remain after all characteristics have been used, choose randomly, with the same probability, over all the products remained.

4.4.3 Demand model

We consider the routine defined at the level of the *use* for each demand class (i.e. not for the single consumer). That is, for each use in each demand class, the demand routine provides the products chosen by the average consumer in the class for that use. When the routine is completed for all classes and uses, we thus have sales, share etc.

Notice that we consider that global expenditure by demand (i.e. by all classes), as loosely dependent on employees income. The idea is that consumers' style are quite sticky in respect to salaries, implicitly assuming that savings absorb the volatility of salaries in respect of the stability of consumption patterns. In any case, eventually, wages level determines expenses.

Each demand class is defined by:

- Share of disposable income;

- Shares of expenses for each use

- Consumers' preferences for each use, that is: order of characteristics, minimum requirements, selection tolerance, variance of the random observation function.

Each property above is currently defined by constants, though, obviously, they can be endogenized at a later stage.

The routine for demand by classes is a modification of the TTB described above for the single consumer. The only change is that when more than one product remains after all characteristics have been used to filter available products, all of these remaining ones are considered as purchased by some consumers in the class.

Technically, the routine works as follows, for each demand class and each use:

- Compute the expenditures for the specific class and use. This is the amount of expenses the routine needs to allocate over all products on sale.

- Apply the modified TTB several times, each time re-drawing the random observation of products' quality.

- For each application of the TTB, add a counter to all products not discarded by the routine.

- When each application is completed, spread the total expenditures to the products proportionally to the counters recorded.

The routine above ensures that the money spent by demand classes for each use follows a TTB pattern. When all the total expenditures of the system are allocated, for each product with positive sales, divide the allocated expenditures to the product by its price, generating the absolute level of sales for that product. Stocks (or backlogs), make up the difference between production and sales.

5 Summary of the findings and conclusions

To be completed

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