Learning, Market Selection and the Evolution of Industrial Structures*

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ABSTRACT. Industrial economics is a rich source of 'puzzles' for economic theory. One of them – certainly the most discussed – regards the co-existence of firms (and plants) of different sizes, displaying rather invariant skewed distributions. Other 'puzzles', however, concern the sectoral specificities in industrial structures, the persistence of asymmetric corporate performances and the dynamics of entry and exit. The paper reports some preliminary results on evolutionary modeling of the links between the microeconomics of innovation, the patterns of industrial change and some observable invariances in industrial structures.

First, the paper reviews a few of these empirical regularities in structures and in the patterns of change. Second, the paper discusses the achievements and limits of interpretations of the evidence based on equilibrium theories. Finally, it presents a model where these regularities are explained as emergent properties deriving from non equilibrium interactions among technologically heterogeneous firms. Moreover, simulation exercises show that also the intersectoral variety in the observed industrial structures and dynamics can be interpreted on the grounds of underlying specificities in the processes of technological learning – which is called 'technological regimes' – and of the processes of market interactions – i.e. 'market regimes'.

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I. Introduction

Industrial economics is a rich source of 'puzzles' for economic theory. One of them – certainly the most discussed – regards the co-existence of firms (and plants) of different sizes, displaying rather invariant skewed distributions, approximately Pareto-distributions for manufacturing as a whole.

Other 'puzzles', however, concern the sectoral specificities in industrial structures, the persistence of asymmetric corporate performances and the dynamics of entry and exit.

This paper reports some preliminary results on evolutionary modeling of the links between the microeconomics of innovation, the patterns of industrial change and some observable invariances in industrial structures.

At each of these levels of analysis many remarkable regularities have emerged, in principle demanding some unified account joining together what we know about the processes by which firms are born, grow, die – on the one hand – and what we know about some aggregate statistics (e.g. on size distributions) – on the other.

As an illustration, consider the puzzle provided by the coexistence of (a) an approximate stability of some skewed distribution of firm- (and plant-) sizes; (b) quite high degrees of market 'turbulence' (i.e. instability of market shares over time); (c) persistently high rates of entry and death; (d) persistence of non-average performances of individual firms (as measured by e.g. rates of innovation, production efficiency, profitability) in

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industrial structures. How can one reconcile the relative stability in the latter with apparently much more 'messy' microdynamics?

Conversely, from a cross-sectional point of view, how does one interpret the inter-industrial variety in structures (for example, significant departures from the aggregate size distribution) and also in underlying microbehaviours (for example, rates of innovation, entry, death, etc.)?

In the economic literature, the prevailing interpretations of observed industrial structures – described in term of size distributions of firms, and, less often by the rates of entry – fall within two major categories. The first include those models which assume the lack of any persistent effect of size, or for that matter any other systematic variable, upon growth and, thus, account for the observed size distributions as the outcome of a frequent, 'small' and unpredictable shocks on growth rates: 'Gibrat-type' processes of firm growth come under this heading (cf. Ijiri and Simon, 1977). The second category tries to interpret whatever observed structure as an equilibrium realization of some mechanism of optimal allocation of scarce managerial talents (Lucas, 1978), or of heterogeneous individual abilities under imperfect information (Jovanovic, 1982).

In this work, we depart from both approaches in many significant respects.

Neither of them, we suggest, is consistent with a few 'stylized facts' on the microeconomics of innovation and growth. For example, the former can hardly accommodate phenomena of persistence in individual corporate performances, and appears also to be at odds with cross-sectional observations on structural diversities. The latter approach, in our view, appears even more demanding on the microeconomics which generates aggregate observations, and, until now, has shown no easy way how to accommodate firm-specific innovations and the purported equilibrium dynamics in structures.

In the following, we shall try to interpret the regularities in industrial structures as emergent properties[1] deriving from non-equilibrium interactions amongst technologically heterogeneous firms. Here, we define 'structures' in terms of a set of statistics, including, of course, (i) size distributions, but also, (ii) degrees of asymmetries in performance among firms (which we shall define below); (iii) rates of entry and exit; (iv) 'turbulence' in market shares.

Particular 'structures', we shall argue, can be interpreted on the grounds of underlying characteristics of the processes of technological learning – which we call *technological regimes* – and of the processes of interaction – i.e. *market regimes*.

Our general conjecture is that a few 'stylized facts' concerning time-series invariances in structures and their cross-sectional variety can be given an evolutionary explanation, as far-from-equilibrium outcomes of particular regimes of learning and market selection.

In Section II we review some empirical regularities and 'puzzles'. Section III discusses the achievements and limitations of economic theory in interpreting those regularities. Section IV sets forth an evolutionary account of industrial dynamics; a formal model is presented in Section V and some results are discussed in Section VI.

II. Some empirical regularities in industrial structures and dynamics

1. *General patterns*

Although the phenomena which we are going to review are quite familiar to the practitioners of the discipline, a fresh look at the theoretical issues involved in their interpretation is a good introduction to the rationale of the model which follows.

For the purposes of this work, it seems useful to distinguish between those empirical regularities which emerge in most or all industrial sectors and those which display a marked industry-specificity, and therefore differentiate different types of structures and different processes of industrial change.

Let us start from the former.

Skewed distributions and their stability

It is certainly the most known 'fact' in industrial demography: skewed distributions of both firm- and plant-sizes in manufacturing as a whole, following approximately Pareto distributions, appear relatively stable over all the industrial history for which data can be estimated. More technically, it remains rather controversial whether the cumulated distribution presents a concavity (while the theoretical Pareto distribution presents a straight line),[2] and it is also controversial how stable the distribution remained over time.[3] Two phenomena are in any case remarkable. First, the skewness implies the steady coexistence of plants and firms of different sizes, and with rather stable relative frequencies. Second, the relative stability of the distribution itself – despite the secular growth of industrial output and despite the secular tendency toward technical specialization among production tasks (i.e. an increasing division of labour) – implies also the approximate stability of the proportion of the activities of production and exchange occurring within organizations as compared to those mediated through the market.

Clearly, all this raises major questions concerning the nature of production technology and innovation. For example: what are the restrictions on returns to scale necessary to support the coexistence of widely different sizes of plants and firms? How plausible is an hypothesis of constant returns? What are the processes of innovation and diffusion consistent with the stability, in the aggregate of manufacturing, of particular skewed size distribution?

And other major questions relate to the processes of growth of individual firms.

Firms' growth

In principle, three fundamental mechanisms govern changes in firms' sizes, namely, first, variations in the market shares; second, variations in the size of the markets in which firm operate (holding shares constant); and, third, mergers, acquisitions, vertical integration/disintegration, horizontal diversification. While not much attention has been given to the separate effects of these mechanisms on firms' growth (or decline), a long tradition of studies, as known, has investigated the 'synthetic' statistical properties of firms' growth – the bench-mark being Gibrat's 'Law of Proportionate Effect'. In its simplest formulation the 'Law' states that growth rates are i.i.d. random variables independent from size. A handy property of the Law is that it generates log-normal or, under suitable modifications, Yule or Pareto distributions.[4]

In brief if $x_i(t)$ is the log of size of firm i at time t

$$x_i(t) = \alpha + \beta_i x_i(t-1) + \varepsilon_i(t), \tag{1}$$

where α is a growth component common to all firms and $\varepsilon(\cdot)$ is a random term. Gibrat's law assumes that $\varepsilon(\cdot)$ is i.i.d. and the restriction $\beta_i = 1$, $\forall i$.

The evidence with respect to the Gibrat process is mixed, but it mostly tends to reject it, or restrict its applicability to particular size classes. Recent studies have found that both firms' growth rates and their variance tend to fall with size and with age (Hall, 1987; Evans, 1987a, 1987b; Bianco and Sestito, 1992). (However, Audretsch, 1995 finds some corroboration for the Law by including in the sample also firms exiting the industry.) Moreover, Gibrat's Law seems a more appropriate description of the growth process of relatively big firms.[5]

The statistical properties of growth dynamics add to the questions facing the theory. For example: under what circumstances is it safe to assume that randomness – whenever detected – simply means that differential growth is an outcome of a multiplicity of 'little' factors with low persistence? Does the evidence on the negative correlation between size and growth imply some form of decreasing returns – e.g. in production technology or managerial control? Or does it mainly reflect strategic traits of bigger firms (for example, higher desired mark-ups as in Nelson and Winter (1982) or in Sylos Labini (1967)). Does the negative correlation between age and growth reveal, from an evolutionary point of view, a fall in the 'average fitness' of firms in changing environments as time goes by? Further, how does one account for those outliers possibly too rare to show up in aggregate statistics but crucial archetypes in business economics – e.g. the Intels, the Sun Microsystems, or, on the opposite side, the British Leylands – which present persistent (positive or negative) differentials in growth rates?

Certainly, underlying whatever statistical regularities one detects in aggregate size distributions, a much more 'messy' microeconomics appears with respect to entries, exits and changes in market shares.

Entry, exits and market turbulence

A general 'stylized fact' concerns the significant degree of turbulence in all industries, due to entry, exit and changing shares of incumbents (Acs and Audretsch, 1990; Beesley and Hamilton, 1984).

In particular, gross entry is a pervasive phenomenon. Birth rates are quite high in most industries, even in those characterized by high degrees of capital intensity (Acs and Audretsch, 1989, 1991).

Most entrants are small firms, far below any measure of efficient minimum scale and a large percentage of new entrants exits the industry within few years after entry. However, an important source of entry are incumbents firms operating in other industries or countries which diversify. In this case, entry often occurs via acquisition of existing plants. The role of this second type of entry is limited in terms of number of firms, but much more important in terms of share of output or employment.

It must be remarked that we know very little about the degree of turbulence in the 'core' of the industry among large firms. Older studies (Kaplan, 1964; Collins and Preston, 1961; Mermelstein, 1969; Bond, 1975) suggested a relative stability in the hierarchy of large firms: rates of turnover among the largest corporations appeared to be small and declining over time. Acs and Audretsch (1991) confirm that turbulence among small firms is higher than among large firms by 35% in the 247 manufacturing industries included in their sample.

Mortality is however high too, so that the rates of net entry are much smaller than gross entry and significant turbulence characterizes industrial evolution. In general, the probability of survival appears to increase with age and with size.[6]

An interpretation of this evidence is that turbulence is primarily a characteristic of the fringe of each industry. This seems corroborated by the observation that substitution of 'old' firms with 'new' firms occurs to a much larger extent among small, young firms which are relatively similar to each other. In other words, entrants in the fringe often are not more efficient than the incumbents. Turbulence is much lower in the core of the industry and among larger firms. The latter appear to be relatively sheltered from selective pressures (Levinthal, 1991). In any case, one does not have yet any robust theory of what determines the birth of new firms: why do firms continue to enter despite their low probability of survival? Why is entry so high even in capital intensive sectors? Is current profitability driving entry? (Which does not appear to stand empirical scrutiny.) Or is it the perception of some unexploited opportunity of innovation? What determines entry in new industries via diversification of existing firms?

Persistence of asymmetric performances

Whatever dynamics one observe, this is grounded in a collection of firms displaying persistent differences with each other. These differences (which we call elsewhere *asymmetries*, Dosi (1984)) concern significant differentials in productivity and costs (Nelson and Winter (1982), Contini and Revelli (1990), Baily (1987)); profitability (Mueller (1990), Geroski and Jacquemin (1988), Yamawaki (1970)); innovative output (Freeman (1982), Jaffe (1986), Griliches (1986), Patel and Pavitt (1991)).

What is particularly intriguing is the persistence of these asymmetries, so that, for example, firms enjoying higher (lower) profits can be expected to earn higher (lower) profits also in the future: that is to say, profits do not seem to converge to a common rate of return (and the same applies to e.g. rates of innovation).

It is hard to say to what extent the observed persistence in profitability differentials reflects the persistence of differential 'efficiencies' which are not eroded away by the competitive process or, conversely, the sluggishness of the competitive process itself. (However, the evidence seems to indicate that the adjustment of profits to their firm-specific 'permanent' values is rather quick, although a significant variability is observed across different countries.) Indeed, persistent asymmetries amongst firms – although no big news for business economists and practitioners – entail puzzling questions for the theorist. What are their sources? Why don't competitive interactions wither them away? And, also, what are their consequences for industrial dynamics?

'Life-cycle' patterns

The properties of industrial structures and dynamics discussed so far pertain to broad aggregates, such as 'manufacturing', or 'industries' – the way they are defined by conventional statistics, say, at 2- or 3-digit levels. However, the locus of innovation, competition, entry and exit is to be found at a much more disaggregated level of observation: it is not e.g. 'chemical' or even 'pharmaceuticals', but, say, 'antibiotics', 'β-blockers', or, within other industrial codes, 'integrated circuits', 'laser-printers', etc. Within micro sectors, one has identified some typical patterns of evolution along what is sometimes called the 'life cycle' of a particular technology or group of products.[7] These patterns (not entirely uncontroversial) are summarized by Klepper (1992) as follows:

(i) There is an initial period of fairly steady growth in the number of producers followed by a period in which the number of producers declines sharply;
(ii) the time path in the number of entrants up to the peak number of producers does not follow a common pattern for all new products, with the number of entrants sometimes rising up to the peak whereas in other instances it reaches a maximum well before the peak. For all products, though, entry tends to peak at or before the peak in the number of producers and then falls off sharply and stays below exit throughout the shake-out;
(iii) the number of major product innovations tends to reach a peak during the period of growth in the number of producers and then falls over time;
(iv) during the period of growth in the number of producers, the most recent entrants account for a disproportionate share of product innovations;
(v) over time, increasing effort by producers is devoted to process relative to product innovation;
(vi) over time, the rate of change of firm market shares slows. (Klepper, 1992, p. 7).

2. *Sector-specific phenomena*

Given these relatively general regularities in industrial structures and in the processes of change, at a finer level of detail one observes also significant cross-sectional differences.

Variety of industrial structures
Probably the oldest, albeit crude, exercise of sectoral classification has focused on the widely different degrees of concentration across sectors. Must likely, an undue emphasis has been put on the relationship between concentration and performance, but, still, the Schumpeterian question concerning the determinants of observed variety of industrial structures remains a crucial one.

In this respect, note also that the more disaggregate the observations on industrial structures are and the more likely is that one will observe size distributions departing from theoretical Pareto density functions.[8]

Moreover, industries widely differ in (a) the intensity of their innovative efforts and the ways they pursue innovation – as reflected, for example, by different propensities to undertake R&D; (b) their measurable innovative output – e.g. patents; and (c) their rates of productivity growth (for an interpretative survey, cf. Dosi, 1988).

Recently, sectoral taxonomies have been developed based on the size and organizational characteristics of innovating firms (Pavitt, 1984) and the nature of innovative opportunities, learning processes and appropriability conditions (Levin *et al.*, 1987; Malerba, 1992; Malerba and Orsenigo, 1990, 1992, 1993).

Different dynamic properties
Sectoral specificities appear to affect the processes of firms' growth, too. For example, Acs and Audretsch (1990) – one of the few recent studies which on average lends support to Gibrat's Law – find that growth rates are significantly different across firm-size classes in about 40% of the industries considered in their sample (and it is not intuitive to find together in the 'non-Gibrat group' a lot of sectors from e.g. petroleum, leather, paper, plastic; and in the 'Gibrat group', furniture, chemicals and transport equipment . . .).

Turbulence differs a lot across sectors, and tends to be relatively lower in industries characterized by high rates of innovation, high advertising, high capital intensity, low concentration, low growth (Acs and Audretsch, 1991).[9]

By further disentangling the sources of 'turbulence', it appears that, for example, advertising is a greater barrier than capital intensity to both gross and net entry, irrespectively of firm size. However, concentration inhibits entry of small firms but not of large companies. Similarly, high rates of innovation do not necessarily deter small firms from entry. On the contrary, in certain industries, in which small firms account for a significant share of total innovative activities, birth rates are rather high.

Evidence is less clear about the role played by variables like industry growth and profitability. The latter variable does not seem to have any significant effect in attracting entry, whilst mixed results are obtained for industry growth (in fact, the estimates of Acs and Audretsch (1990) would suggest that turbulence is higher in high-growth industries, but might be lower in high-profitability industries . . .).

Regarding the probability of survival of new small firms, it appears to be lower in capital-intensive industries, and in sectors characterized by high rates of innovation and high economies of scale. However, a further distinction needs to be made. Concentration, scale economies and capital intensity actually seem to be positively correlated with survival in the short run, but not in the long run. Indicators of innovativeness does not affect survival in the short run, but only in the long run. Moreover, survival is also easier in those industries in which small firms are important sources of innovation.[10]

Finally, it must be noted that surviving firms have either a higher initial size or higher growth rates. Bigger initial size implies lower growth, but higher survival probabilities. Surviving new firms tend to growth in the short run: surviving firms tend to grow faster in the early periods, but this property fades away in the long-run.

3. *Empirical puzzles and economic theory*

Many of the empirical regularities surveyed above are 'puzzles' for the theory in their own right – for example the relative aggregate stability of Pareto-type distributions. However, even more challenging is the explanation of how these different 'stylized facts' can stick together.

In very general terms, these puzzles have to do with a few major analytical questions, namely:

(i) *The 'driving forces' of firms' growth.* Are they multiple, small and temporary? Or conversely, can one identify deeper, more persistent factors? And, what is the role of technological and organizational innovation in all that? What are the degrees of forward-looking rationality that one should attribute to firms in their choice of entry, exit, expansion? And, does it matter, after all?

(ii) *Microheterogeneity and invariances in some aggregate statistics.* For example, how does one keep together the observations of persistent asymmetries among firms with that of relatively stable aggregate Pareto-type size distributions? How does one reconcile 'life-cycle' patterns at microsectoral level with apparently more stable structures at higher levels of aggregation?

(iii) *Cross-sectional variety in industrial structure and in the processes of change.* What determines these observed differences? Can one find some underlying variables which shape different evolutionary patterns? And, in that, what is the relative importance of technological factors, mechanisms of competitive interactions and demand conditions?

III. Industrial dynamics and economic theory

It is straightforward that the interpretation of foregoing regularities involves some underlying theory of production technology and innovation. In this respect, let us group the models proposed in the literature into three major approaches, which we shall call (a) neutral equilibria; (b) 'optimal control' equilibria; (c) (special) evolutionary equilibria. (In the next section we shall develop upon a fourth approach, namely, far-from- equilibrium evolution.)

Neutral equilibria

As already mentioned, one candidate theory for the interpretation of some aggregate invariances in industrial structures rests on the 'Law of Proportionate Growth' and has been explored, in different versions, by Herbert Simon and associates (cf. Ijiri and Simon, 1977).

The 'structure' (i.e. the relative invariant size distribution which data reveal) can be theoretically generated by some random process with little or no past memory, plus some auxiliary restrictions (such as on birth and death rates). In this case, the random process stands for a multiplicity of little factors which temporarily make one firm more (less) efficient than the competitors but are not persistent over time (these considerations, mutatis mutandis, apply also to stochastic models based on serial correlations of growth rates with decaying effects over time). Alternatively, one could also interpret the random process applied to growth rates not as the outcome of a multiplicity of small efficiency related 'shocks', but rather as random variations in corporate strategies. Relately, the most likely candidate for a theory of production compatible with Gibrat-type models implies constant returns to scale: no persistent scale-biased factor influences growth opportunities (an exception being Kalecki's model (Kalecki, 1945) with increasing constraints to growth related to financial factors). At the extreme, all possible conditions between organizations and market are neutral equilibria. That is, all possible distributions of industrial structures, ranging from monopoly to perfect competition, can be expected ex-ante to show identical efficiency properties.

As we see it, there are three major difficulties with this interpretation. First, we are rather sceptical of a general 'neutrality' hypothesis (i.e. 'all forms of industrial structures are identical in terms of efficiency'). To trivialize, it is difficult to image a Boeing aircraft produced with the same efficiency in an Italian industrial district by thousands of family-run firms, or, conversely, a (now defunct) East German Kombinat producing fashion garments with the same efficiency and creativity as an Italian district . . . More generally: microeconomic evidence, admittedly quite impressionistic, seems to suggest that in each industrial activity there are some 'typical ways' of organizing production. They can be more than one, but not very many. That is, there can be a few combinations between organization and markets that are 'neutral' in terms of efficiency, but the set is small and possibly not dense . . .

Second, and relatedly, at a disaggregated level, one does not often find either the structure or the Gibrat-type growth that one may observe in the aggregate (indeed, as discussed earlier, even for the manufacturing aggregate the evidence supporting a 'law of proportionate growth' is hardly overwhelming).

Third, it follows from the underlying theory of production that firms ought to almost identical – with scaling up or scaling down only affecting size – but, in turn, there seem no easy way to reconcile this assumption with the evidence on persistence of inter-firm asymmetries in revealed performances and – even more important – in innovative capabilities (cf. the foregoing section).

'Optimal control' equilibria

In Simon-type models of firm-size distributions, with the related Gibrat processes of growth, it does not make sense to ask whether the observed structure is the 'optimal' one: indeed, the implicit constant-return cum continuum of neutral equilibria hypothesis entails that the observed structures are some statistical outcome of history with nothing remarkable to be said for or against their allocative properties. And this is likely to fall well short of satisfaction for the true believer. Lucas (1978) handles the problem. He start with an optimal allocation problems, given a usual two-inputs production function to which one adds another factor ('managerial talents'), unevenly distributed across the workforce. This, together with ad-hoc auxiliary assumptions on managerial technology and on the distribution of such talents, yields the optimal size distribution of firms and the Gibrat-law as an empirically testable restriction on the production function.[11] With regards to the 'Gibrat restriction', we have already discussed above its likely empirical inconsistencies. More generally, it would take us too far to discuss the bizarre, albeit elegant and fashionable, epistemology involved in those modeling endeavours whereby the core assumptions of rationality and equilibrium are *ex hypotheses* shelved from refutation and the burden of the 'proof' is laid on testing some restrictions imaginatively derived on the grounds of some unobservable . . .

Let us just suggest that one does not seem to learn much more from these kind of exercises in rationalization than we didn't already know from 'inductive' observations (except, possibly, some Panglossian contentness, for those who can feel it). And, even more important for our purposes here, these exercises seem strictly unsuited to account for those phenomena of entry, exit, innovation and non-equilibrium learning which seem central in contemporary industrial change.

(Special) evolutionary equilibria

Recently a class of models has been proposed, which is explicitly dynamic and tries to explain the observed patterns of industrial dynamics as the (equilibrium) outcome of processes of learning and selection.

Jovanovic (1982) attempts to explain the observed regularities in size distribution, together with the patterns of entry and exit as the result of a stochastic process of convergence to optimal techniques under imperfect information. New firms continuously enter the industry, with rational technological expectations but uncertain about their own production efficiency. By producing they acquire noisy information about their productivity. Those firms who discover that their efficiency exceeds their expectations expand their scale of output, while those who receive unfavourable signals contract or even exit from the industry. Thus, industry evolution is driven by noisy selection which fosters the growth of efficient firms and the decline of inefficient ones. Pakes and Ericson (1987) have extended this model to consider the possibility that firms can affect their productivity by investing in learning (e.g. R&D) activities, the outcome of which is however random. In the same vein, other models (Lambson, 1991) examine industry evolution and explains some of the stylised facts discussed above as the result of changing exogenous market conditions.

We have called these models as 'special evolutionary equilibria', because while they embody some evolutionary account of imperfect learning and market selection amongst heterogeneous agents they maintain stationary 'fundamentals' as far as best-practice technologies are concerned: biologists would say that the 'evolutionary landscape' upon which evolution occurs is fixed (another way of putting the same property is by assuming that changes in the evolutionary environment arrive at a rate that is much lower than that at which agents adjust to them). A consequence of all this, however, is that the models can hardly accommodate innovative processes, in general, and especially whenever they are idiosyncratic and firm-specific. Moreover, one finds difficult to accept that evolutionary pressures are so strong that each observation of e.g. size distributions, entry, exit, etc. is (nearly) an equilibrium one. Finally, the way selection dynamics works in e.g. Jovanovic (1992) heavily rests on very demanding assumptions on the rationality and forecasting abilities of individual agents (one is not at all sure what the dynamics would be if every agents did not have rational technological expectations – indeed, a very heavy requirement in an evolutionary set-up).

Indeed, it might be worth exploring the properties of evolutionary models which are not constrained to particular equilibrium representations and which take full account of heterogeneous processes of innovation. This is what we shall try to do in the next section.

IV. Technological regimes, selection and industrial structures: far-from-equilibrium evolution

The evolutionary interpretation that we shall pursue in this work of empirical regularities discussed in section (ii) above, focuses on the nature of learning activities and on market interactions as selection mechanisms. It has in common with 'special evolutionary models' mentioned earlier the emphasis on microeconomic heterogeneity. However, it departs from them in several ways. First, it assumes that innovation – rather than adjustments to some unchanged technological landscape – is the driving force of industrial change. Second, it tries to specify an explicit market dynamics rather than assuming some limit state of the dynamics itself. Third, it conjectures that aggregate regularities are indeed the outcome of disequilibrium fluctuations.[12]

Let us start by characterizing learning activities. As emphasized especially by evolutionary and 'organizational' theories of the firms, the rates and direction of innovation depend on the competences that firms embody, on the internal and external knowledge they can draw upon, and the procedures by which they do it (see Nelson and Winter, 1982; Dosi, 1988; Teece *et al.*, 1993).

In particular, it has been suggested that various activities present different degrees of technological opportunity, that is a different scope for improvements in products and processes on the grounds of a given knowledge base, and also a different 'ease' in achieving these improvements. (One way of formalizing these differences is in terms of the probability distributions of achieving an $x\%$ improvement in some performance characteristics of a product or a process, given some search effort, say a one dollar investment in R&D.)

Technologies and sectors have also been found to differ in terms of appropriability conditions, i.e. the effectiveness through which innovations can be shielded from imitation by competitors.

According to the features of the process of innovative search and the knowledge upon which it draws, the innovative success of individual firms may show varying degrees of serial correlation, often referred to as the cumulativeness of innovative activities. Moreover, the degrees of tacitness and specificity of knowledge (or conversely, its universality and serendipity) influence the ease of access of entrants as compared to incumbents (Winter, 1984).

Finally, it has been argued elsewhere that radical changes in the knowledge bases, procedures and directions of technological change, i.e. a change in the 'technological paradigm' (Dosi, 1992) imply also significant changes in the relative innovative capabilities and growth potentials of firms embodying 'old' or 'new' competences.

In brief, we shall call particular combinations of these features of technological knowledge as *technological regimes* (Winter, 1984).

In line with Nelson and Winter (1982), Winter (1984), Dosi and Salvatore (1992), one of our central hypothesis is that these specificities of learning have a direct link with the explanation of why industrial structures are what they are and how they change. More in detail, some implications can be easily seen by comparison with the stochastic representation of firms' growth described by Equation (1), above.

(a) Differences across industries in technological opportunities (assuming some positive correlation between innovation and growth) imply different values for the constant and different means and variances of the stochastic term in Equation (1). Moreover, if 'opportunities' change over the development of each technology, one should also expect correlated change in the distribution of the ε_t.

(b) Appropriability of innovation, cumulativeness of technological advances, specificity of some elements of technological knowledge imply some firm-specificity in the factors which foster or hinder growth. The findings from the economics of innovation, as well as complementary findings from business studies, suggest that neither the stochastic process nor the β in Equation (1) can be assumed to be identical across firms. Some firms may be persistently 'better' or 'worse' than others. In turns, that means that any evolution of industrial structures must not only be interpreted in terms of a multiplicity of little transitory shocks on individual growth opportunities, but also account for the interaction among firms that may be persistently different in their technological and organizational characteristics.

(c) Differential degrees of appropriability and cumulativeness, and different characteristics of the knowledge underlying innovative activities are also likely to imply different entry-conditions in each industry.

(d) Abandoning the assumption of single-product firms, the variegated sources and procedures of learning and innovations are bound to affect the corporate patterns of horizontal diversification and vertical integration and also the structure of individual industries and of manufacturing as a whole.

If the characteristics of learning are the first major building block of an evolutionary interpretation, some form of selection is the second one.

The intuition is quite straightforward. Technological (and organizational) heterogeneity implies diverse competitive abilities of each firm: that is, diverse levels of 'fitness' over some evolutionary landscape wherein firm interact (in the model which follows such landscape is restricted only to product-markets, but in actual fact it involves also other interactive domains, e.g. the market for finance). In turn, different competitive abilities affect the size and number of firms, i.e. the dynamics of market shares and of exit (mortality). It is important to notice that in any case the selection criteria are themselves endogenous, in that they are a collective property of the rates and directions of learning of each and every firm (and in more general versions of evolutionary models also of the patterns of learning of customers, suppliers, providers of finance, etc.). We distinguish *market selection regimes* according to the relative speed at which selection occurs – loosely speaking, analogous to what practitioners call 'the intensity of competition' – thus, market regimes determine, other things being equal, the 'intensity' of reward and penalties for the better (worse) competitors and the speed at which such rewards and penalties arrive.

Formally, selection processes are often captured by some dynamics on the unit simplex operating with respect to endogenous 'fitness' criteria.[13] However, irrespectively of the precise theoretical representation, the crucial point is that evolutionary processes generally embody some collective mechanism of ex-post selection amongst heterogeneous technologies, products, behaviours, organizations which can hardly be written out by assuming that agents perfectly anticipate the consequences of their actions and choose *ex ante* reciprocally consistent and symmetric behaviours.[14]

The model which follows formalizes these hypotheses about the dynamics of learning and selection.

V. An evolutionary model

Assume that 'industry' (say, the equivalent in recorded statistics of 'aggregate manufacturing') is composed of several 'sectors', each corresponding to particular technological and market regimes, which shall be defined below. In turn, any one 'sector' is composed of 'microsectors' (groups of relatively homogeneous products or technologies, loosely corresponding to the empirical analyses concerning 'technological cycles' and reviewed earlier in Section II). Hence, one has three levels of observation: most of the 'action' – i.e. learning, changes in market shares, entry and exit – occurs within 'microsectors'; but higher level statistical entities stochastically aggregate into 'sectors' (i.e. regimes) and the overall 'industry' (In fact, as we shall see, there is more than statistical aggregation since, in one of the regimes, firms may diversify across microsectors).

Each firm (j, if it is an incumbent; i, if it is an entrant) is defined by its age, a; size, s; and 'competitiveness', e. Size and competitiveness are endogenous variables dependent on learning, market selection and – regarding size – also on the dynamics of the markets to which the firms belong. 'Competitiveness' is a positive real number which in principle summarizes the technological and organizational capabilities of each firm. Hence, 'learning' yields positive increments to firm-specific competitiveness.

Learning dynamics

Each 'technological regime' is defined by the stochastic processes governing the transition probabilities $P(e_j(t+1)\,|\,e_j(t))$, for incumbents, and the draws on the competitiveness (i.e. the levels of initial knowledge) for entrants, $e_i(t)$.

Let us start with two extreme opposite archetypes, which we shall call 'Schumpeter Mark I' and 'Schumpeter Mark II': they are meant to capture some sort of limit configurations of the learning procedures discussed in the previous section.[15]

Under 'Schumpeter I' incumbents never learn: their competitiveness remains the one of their birth. Evolutionary dynamics is driven by the 'heroic entrepreneurship' of entrants.[16]

The competitiveness of entrants at time $(t + 1)$ is

$$e_i(t+1) = \overline{e}(t)\left[1 - k + \frac{g}{\lambda_1}\right], \qquad (2)$$

where $\overline{e}(\cdot)$ is the average competitiveness of incumbents, weighted with their market shares, f_j, $\overline{e} = \sum_j e_j f_j$, g is a random variable drawn from a Poisson distribution with mean g; k and λ_1 parametrize, respectively entry barriers (which might as well be absent) and levels of generically available opportunities, which, so to speak, 'rescale' the competitiveness jumps drawn from the stochastic process.

In the symmetric opposite model, 'Schumpeter II', learning by incumbents is highly cumulative – in probability, 'success breeds success':

$$e_j(t+1) = e_j(t)(1 + h_j(t)), \qquad (3)$$

$$h_j(t+1) = \left[1 + \ln\left(1 + \frac{e_j(t)}{\overline{e}(t)}\right)\right]\frac{g_I}{\lambda_2}, \qquad (4)$$

where, again, $g_I \approx$ Poisson (the subscript (I) here and throughout stands for incumbents, and (E) for entrants).

New firms enter with competitiveness

$$e_i(t+1) = \overline{e}(t)\left[1 - k + \frac{g_E}{\lambda_3}\right]. \qquad (5)$$

Finally, let us define an 'Intermediate Regime' whereby incumbents learn via

$$e_j(t+1) = \overline{e}_j(t)\left[1 + \frac{g_I}{\lambda_4}\right], \qquad (6)$$

and entrants are characterized by the same process as from Equation (5).

Note, incidentally, that even if learning for incumbents is a Gibrat-type process, this does not carry any straightforward implication for growth dynamics, since, as we shall see, the latter is also the collective outcome of market selection.

Birth of new firms

Let $n(t)$ the number of incumbents in any one microsectors at time t. The number of entrants, $b(t+1)$ is the random variable

$$b(t+1) = n(t)(h + \mu) \tag{7}$$

(approximated to the nearest positive integer), where h (> 0) parametrizes the ease of entry, the possibility of spin-offs from incumbents, etc.; and μ is a random variable uniformly distributed on the support $-1 < -b \leq \mu \leq b < 1$.

Market selection and death rules

Market shares $(f_{(\cdot)})$ of individual firms (both incumbents and entrants) change according to a 'quasi-replicator' dynamic of the form

$$\Delta f_{(\cdot)}(t, t+1) = A\left[\frac{e_{(\cdot)}(t)}{\overline{e}(t)} - 1\right] f_{(\cdot)}(t). \tag{8}$$

subject to the 'death rule'

$$\text{death}_{(\cdot)}(t) = 1 \text{ if } e_{(\cdot)}(t) < \psi\overline{e}(t) \text{ with } \psi \ll 1$$
$$\text{or if } f_{(\cdot)}(t) < \overline{f\varepsilon}. \tag{9}$$

That is, the event 'death' occurs if the competitiveness of the firm is below a certain fraction of the average competitiveness of the industry or if its market share falls below a certain minimum level $(\overline{f\varepsilon})$.[17] The parameters A, ψ and $\overline{f\varepsilon}$ capture the 'market regime': the higher their level, the higher also the 'selectiveness' of a market environment.

'Life cycles of microsectors'

The dynamics of the structure of each 'microsector' is endogenous and dependent on the processes described so far. However, we assume also a 'demand cycle' which determines the absolute size of the microsector itself, which we take as exogenously given. The level of output (i.e. the size of demand) for microsector k at the beginning and the end of its 'cycle' is conventionally set equal to unity and peaks at $T/2$ with $M^k_{\tau = T/2} = m$, where T is the total length of the 'cycle'; we also assume that demand stays at unitary level thereafter.

New 'microsectors' are randomly born every ω times (with ω uniformly distributed on a finite support).

Hence, a cross-sectional observation of demand pattern, say at $t = t^*$, would impressionistically look like the one depicted in Figure 1.

Multi-product diversification

In contemporary economies, a good percentage of firms are multi-product. In Dosi, Teece and Winter

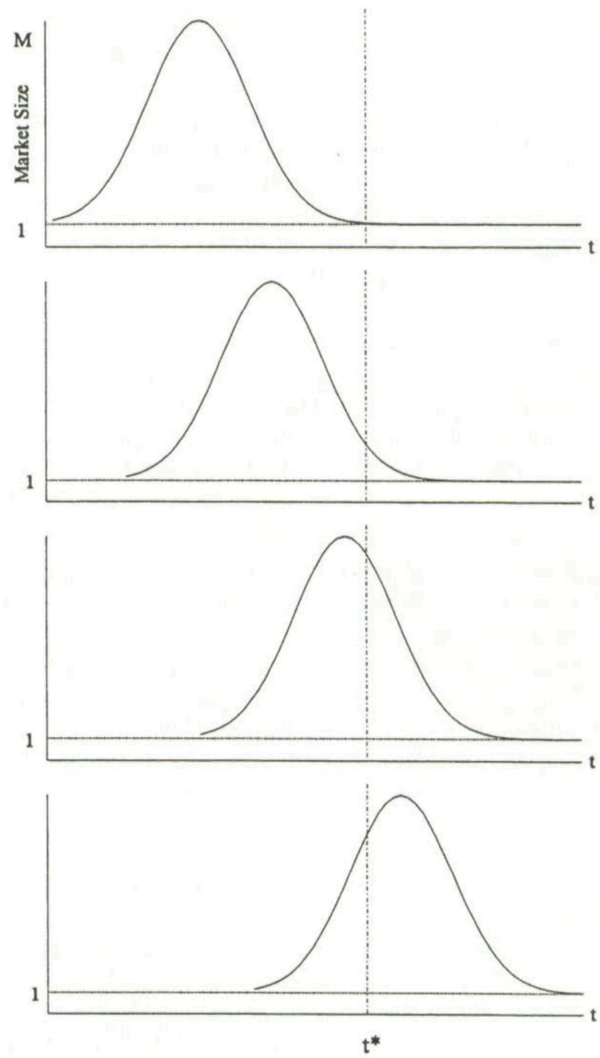


Fig. 1.

(1992), one argues that the patterns of horizontal diversification can be traced back to the 'core competences' which firms embody and to the nature of knowledge upon which the firms principal activities draw. Here we formalize some features of that intuition and assume that in the regime 'Schumpeter II' firms can cumulatively exploit their knowledge across different microsectors via entry and acquisition of incumbent firms.

Calling d, the event 'diversification' of a firm from microsector k,

$$\Pr(d = 1) = 1 - \theta \exp\left\{-\theta \frac{e_j^k}{\bar{e}_k}\right\}. \qquad (10)$$

More successful firms face a higher probability of diversification, while θ captures the degrees of intersectoral 'serendipity' of knowledge.

If the event occurs, the microsector, l, toward which the firm moves is randomly drawn with a uniform distribution[18] over all sectors.[19] More precisely, in the experiments reported below we rule out $k = l$, that is intra-sectoral mergers/acquisitions. The impact of the later is on the agenda for future work. Next, the firm which is to be 'acquired' or 'founded' is selected, with uniform probability over all firms N^l of microsector l (if the firm draw is an incumbent, then diversification occurs via 'acquisition', otherwise it is an entry associated with establishment of a new unit – division – in that market).[20]

Regimes and structural properties

The foregoing model allows the determination of a quite rich set of endogenous variables and statistics characterizing industrial structures and their changes over time at the three levels of aggregation (microsectors, sectors/regimes, 'industry').[21]

For our purposes here we shall focus on the following ones:

(i) size distributions and some statistics of industrial concentrations;
(ii) asymmetries in firms' performances as proxied by some measure of dispersion in the level of 'competitiveness';
(iii) market turbulence (we shall define it in terms of market share changes involving incumbent, entrance and exiting firms: $\sum_{i,j}|f_{(\cdot)}(t+1) - f_{(\cdot)}(t)|$;
(iv) industrial demography indicators – e.g. gross and net entry, number of firms, age distributions;
(v) industrial dynamics indicators – i.e. growth probabilities and death probabilities conditional on age and size;
(vi) measures of persistence in the relative performance of individual firms.

Our basic analytical strategy is to try to 'map' the regularities in structures and dynamics highlighted by these indicators – into the underlying system parameters defining learning and selection regimes. We shall go further than that and claim that such a mapping represents, in a first approximation, also an explanation of the emerging patterns. This claim rests also on some additional – somewhat implicit – additional hypotheses.

First, readers (expecially economist readers) have probably noticed the lack of any behavioural assumption in our model. Quite a few evolutionary models embody indeed an array of ('boundedly rational') stylizations of behaviours (against which many orthodox criticisms dismiss their 'ad-hoc' nature and the unelegantly high number of supposedly 'free parameters'.[22] Here, we take a different methodological route and assume that, for the purposes of determining some general invariances in industrial structures, fine restrictions on microeconomic conducts exert, *on average*, only second-order system-level effects. It is obviously a very strong assumption, which can be justified either in terms of relatively uniform constraints which appear in relation to any one set of technological and market opportunities (i.e. each 'regime'), or in terms of behavioural norms and learning competences which co-evolve with the development of each regime itself (Nelson, 1992; Dosi and Orsenigo, 1988). In fact, we do believe that both processes are at work.

Second and relatedly, our modeling assumptions imply that some modal features of learning are *specific* to each particular 'regime' or, at least, change on a time scale which is longer than the time-scale of supposedly strategic interactions among agents: in our view, the evidence on the microeconomics of innovation supports this point (cf. Freeman, 1982, Dosi, 1982, 1988).[23]

Given both of these hypotheses, let us explore some properties of the co-distributions between regime-parameters and characteristics of industrial structures.[24]

VI. Some simulation results

We present some simulation results of the three 'technological regimes' described earlier, parametrized with technological opportunities $g_{(I)}$ and $g_{(E)}$, ranging in different exercises between zero and 8; and selection between 1 and 5 (that is, the average Poisson draws for incumbents and entrants imply increments in 'competitiveness' between 0 and 8%, and 'selection' is captured by the parameter A in Equation (8).[25]

Microsectors

Number of firms. Not surprising in an evolutionary perspective, the number of firms is endogenous and depends on the characteristics of each 'regime'. Figure 2 presents the average

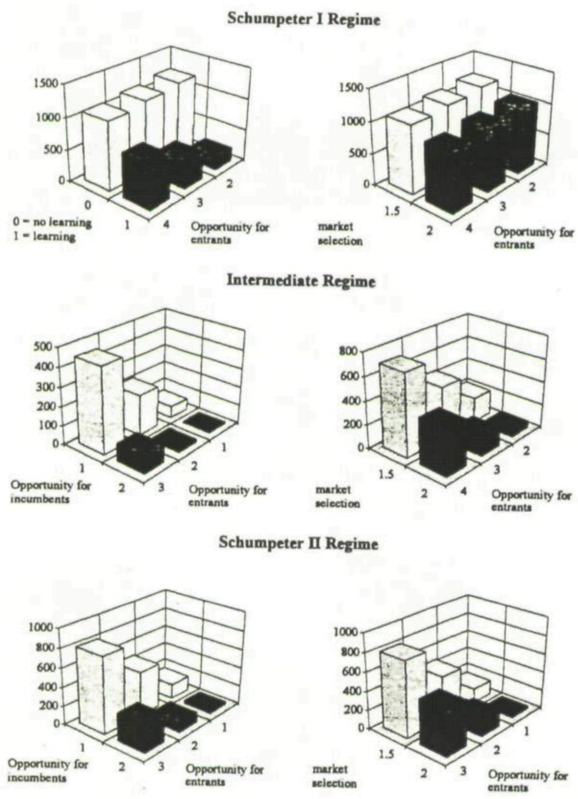


Fig. 2. Average number of firms in different regimes.

number of firms (over 10 simulations and 1000 iterations) under different regimes and parametrizations of learning opportunities and selection. Please note that the upper-left histogram in Figure 2 contrasts the Schumpeter I regime (no learning for incumbents) with the intermediate regime (opportunities for incumbents = 1). Ceteris paribus, those numbers decrease as the opportunities for incumbents grow, and as selection increases. Conversely, the number of firms grows in two out of the three technological regimes together with the technological opportunities for entrants.

All this is intuitively in line with the findings of Winter (1984) on the properties of what he calls 'entrepreneurial' and 'routinized' regimes. However, it is worth noting that, in our simulations, under 'Schumpeter I' – the regimes wherein incumbents do not learn and innovation is entirely associated with entry – greater opportunities are associated with a lower average number of firms. Our interpretative conjecture that increasing opportunities – even holding the selection parameter constant – implies a higher selective pressure by the most successful firms on the environment, and, also higher mortality rates (see below).

Concentration. Industrial concentration[26] is always a positive function of the opportunities of incumbents and of market selection, and, other things being equal, a negative one of the opportunities for entrants (see Figure 3).

Note that here concentration is an outcome of the uneven exploitation of learning opportunities by different firms, and, *ceteris paribus*, grows with the latter:[27] obviously, it has nothing to do in this model with 'market power' or collusive behaviours. Moreover, if the degrees of selection are interpreted as a proxy for 'how well markets work' – in the sense that they quickly reward winners and weed out losers – then more efficient markets tend to yield, in evolutionary environments, *more* concentrated market structures, rather than more 'perfect' ones in the standard sense.[28]

Asymmetries and turbulence. In general, higher opportunities for entrants are associated with higher market turbulence (as defined earlier) and higher interfirm asymmetries.[29] However, our simulations highlight remarkable non-linear inter-

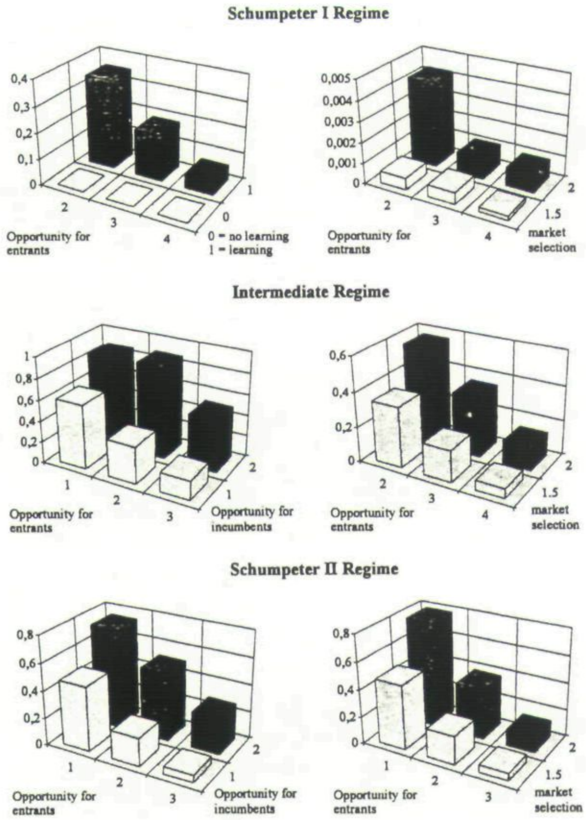


Fig. 3. Degrees of industrial concentration.

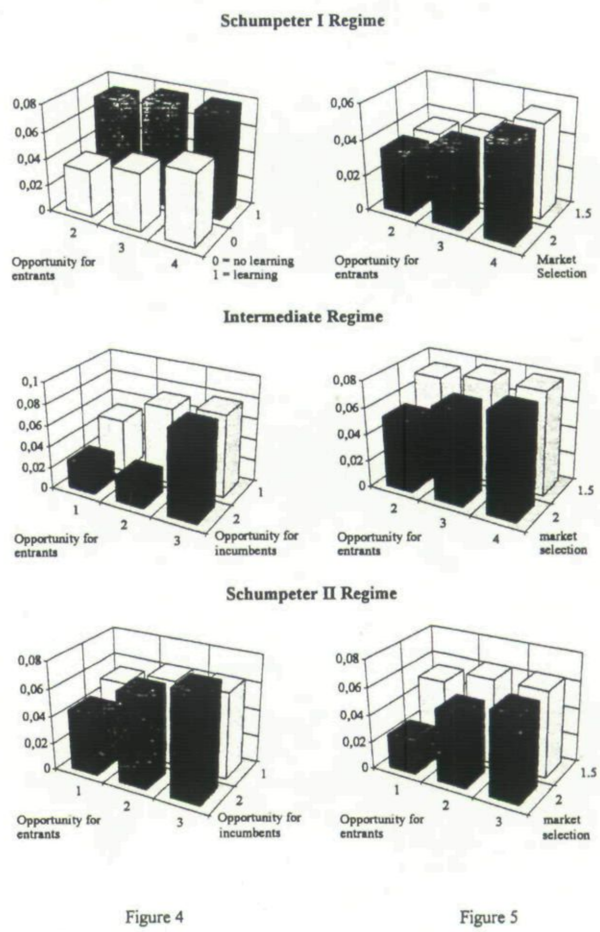
actions between opportunity for entrants; opportunity for incumbents; and market selection. See Figures 4, 5, 6 and 7.

In particular, there seems to be a *negative* effect of learning opportunities for incumbents upon these two statistics which *decrease as general levels of opportunities increases*.

However, there seems to be a threshold in general learning and some 'critical ratio' between the learning potential of entrants *vis-à-vis* incumbents, above which the cumulative abilities of the latter do *not* 'stabilize the market' and do not render its suppliers more homogeneous. On the contrary, cumulative learning in these cases is likely to magnify over time the competitiveness of particularly skillful or particularly lucky entrants and incumbents alike. Let us illustrate the case with an impressionistic example. If these exercises tell something about empirical phenomena, one could argue that there has always been a high probability that IBM, even ruling out its own organizational failures, was going to meet major competitive challenges by some entrants; that the most successful of these new firms would have exploited too the potential of fast and cumulative learning; and that all this would have generated persistent instabilities in market shares and persistent competitiveness gaps within the industry.

The effect of market selection upon these some indicators of industrial performance shows remarkable interactions with opportunities: as the latter grow, the market mechanisms which should supposedly reduce the interfirm variance in efficiency becomes less powerful (Figure 5).

Moreover, above some threshold in opportunities, faster selection appears to generate relatively more market turbulence and greater asymmetries.[30] Using the foregoing example, the intuition is that with rapid market selection – as one manager of a newly found company told one of us some years



Figs. 4 and 5. Degrees of industrial asymmetry.

ago – "soon we'll be able to cut one arm of the IBM giant . . ." Or, putting it another way, high selection jointly with high innovative opportunities make discrete evolutionary jumps easier. ('Jumps', in probability, may be bigger, even if over finite spans of time high opportunity and cumulativeness may well sustain the market dominance of one or few firms.)

Relatedly, it is worth emphasizing that higher degrees of selection – which, as mentioned earlier, formalizes the collective effectiveness of some 'quasi-Invisible Hand' of markets,[31] under circumstances of fast learning, seem to be associated with higher microeconomic disequilibrium and higher technological heterogeneity. That is, the competitive process allowing for fast changing technological fundamentals and relatively easy entry, is likely to bring the system *away* from any equilibrium where micro behaviours are consistent

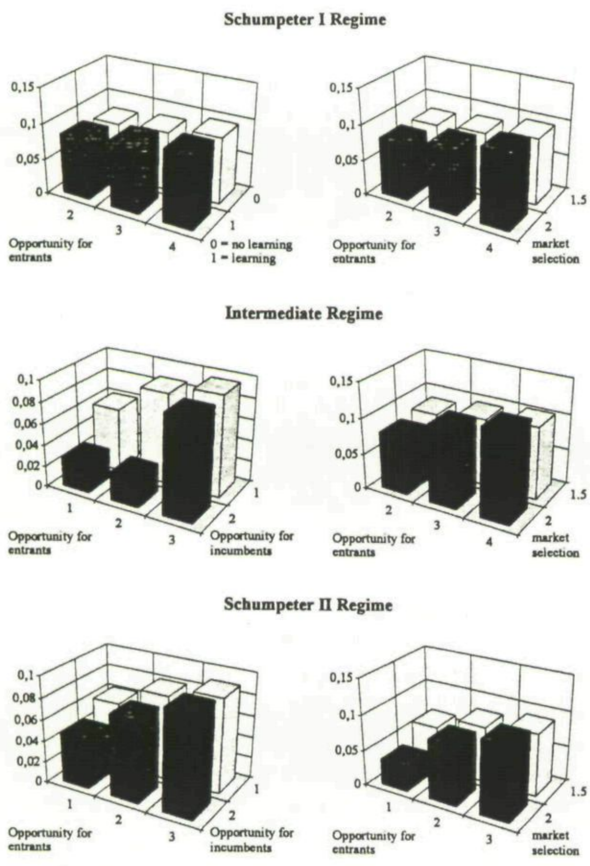


Figure 6

Figure 7

Figs. 6 and 7. Degrees of industrial turbulence.

with each other. On the contrary, the conjecture is that fast selection rapidly rewards 'hopeful monsters', to use a biological analogy. And above some opportunity threshold, these 'monsters' are so frequent that their (temporary) evolutionary superiority destabilizes the incumbent structure, notwithstanding cumulative learning by existing firms. Recall, however, that such a threshold is determined also by the *relative* learning abilities of incumbents and entrants. Thus, the model would predict that in 'high-tech' industries, for given general opportunities, market turbulence would be greater the lower is the ability of established firms to generate and competitively exploit the innovative opportunities. Pushing to the extreme a thesis argued in several works by Keith Pavitt at SPRU, University of Sussex, phenomena like the market volatility of the American electronics industries, the 'Silicon Valley', etc. should be interpreted at least as much in terms of persistent organizational *failures of established firms* to their innovative opportunities as in terms of entrepreneurial success of new firms fostered by favourable context conditions. (Indeed, a comparison with Japan is likely be quite revealing.)

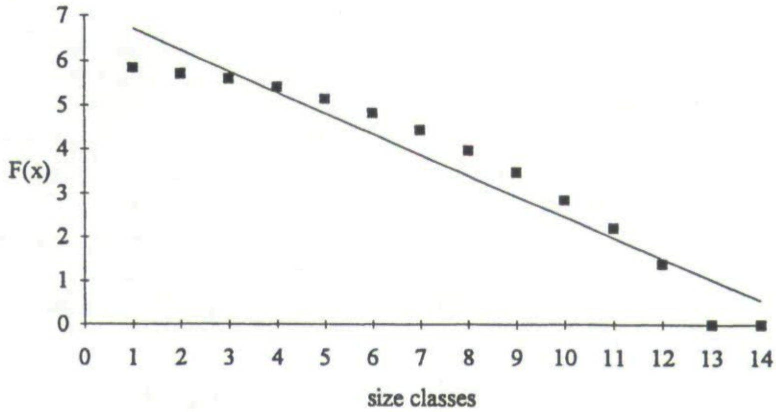
Size distributions. The process of learning and selection modelled here generate skewed distributions of firms by size,[32] which, however, often depart significantly from a Pareto distribution with a density function

$$f(x) = qx^{-(1+q)}$$

and a right-cumulated function

$$F(x) = x^{-q}. \tag{11}$$

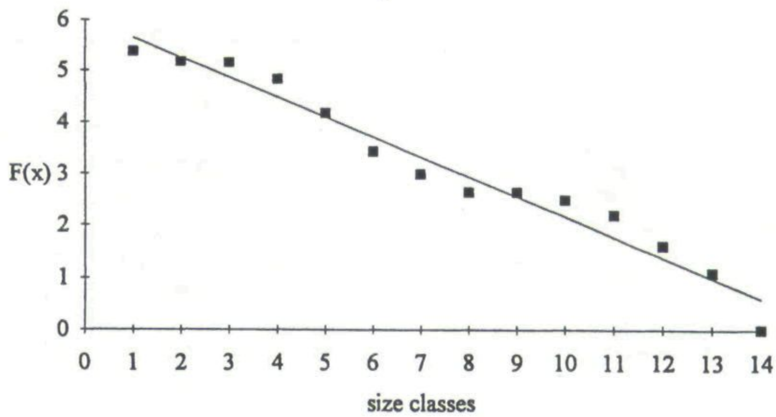
Interestingly, the departures from the theoretical Pareto distribution (a) are systematic, (b) depend on the stage in the 'life cycle' in each micro sector, and (c) can be meaningfully 'mapped' into the underlying regime parameters. These departures are particularly marked at the level of micro-sectors but they carry over to regime-specific aggregations. Figures 8, 9 and 10 present the actual cumulated distribution and OLS estimates of the logs of Equation (11), concerning three somewhat archetypal cases of (i) a 'Schumpeter I' regime with very fast selection and extremely high opportunity for entrants (Figure 8); (ii) an 'intermediate' one with somewhat slower selection and



Schumpeter I (5,0,8)
(i.e.selection:5; opportunity for incumbents: 0; opportunity for entrants: 8)

Constant	Coefficient	Coef.Determination	F-ratio
1,9893	-0,6822	0,9284	155,6911

Fig. 8.



Intermediate (1.5,2,2)
(i.e.selection:1.5; opportunity for incumbents: 2; opportunity for entrants: 2)

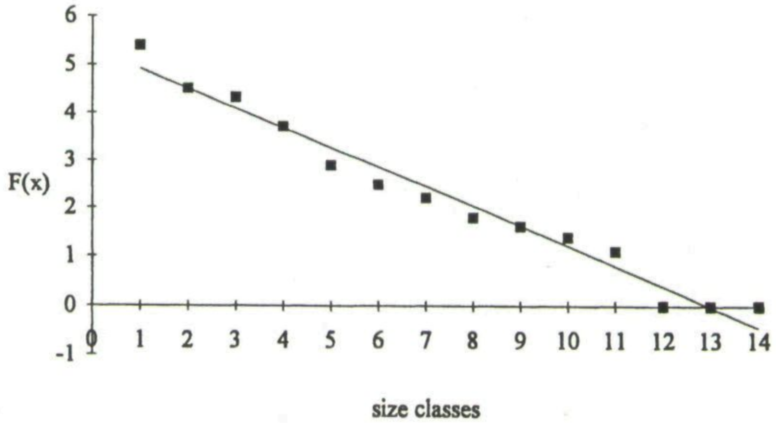
Constant	Coefficient	Coef.Determination	F-ratio
1,7866	-0,5592	0,9600	319,30

Fig. 9.

relatively high opportunity for both incumbents and entrants (Figure 9); and (iii) a regime with a straightforward innovative advantage of incumbents and lower selection (Figure 10).[33]

It would seem, by qualitative inspection of these and other results not shown here, that 'Schumpeter I' regimes tend to display concavity of the actual distributions, yielding to 'double-humpted' ones for regimes where both incumbents and entrant access relatively rich learning opportunities, and, finally, to convex ones under 'Schumpeter II' regimes.

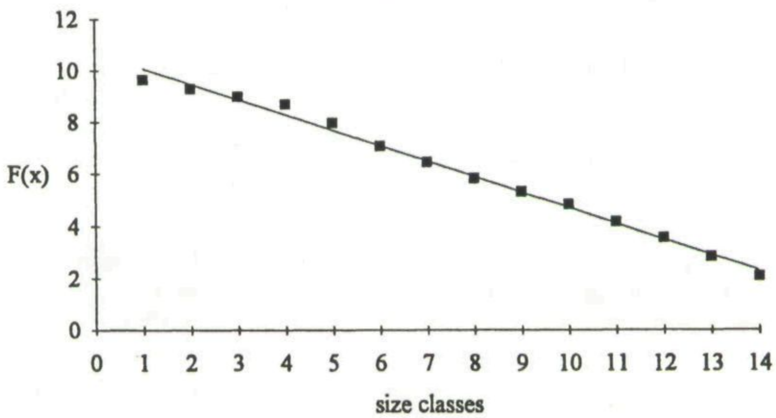
A remarkable property is that random aggregation over different microsectors and different regimes (i.e. 'aggregate manufacturing')[34] *does* display a size distribution quite close to a Pareto one (Figure 11). Our interpretation – already discussed in Dosi and Salvatore (1992) – is that, in the model and in the real world, this is a sheer outcome of aggregation. Moreover, as argued there, that aggregate distribution is likely to remain stable as long as *on average* the conditions of learning and selection do not dramatically change.[35]



Schumpeter II (1,4,2)
(i.e.selection:1; opportunity for incumbents: 4; opportunity for entrants: 2)

Constant	Coefficient	Coef.Determination	F-ratio
0,8151	-0,5934	0,97	408,29

Fig. 10.



Industry

Constant	Coefficient	Coef.Determination	F-ratio
4,1219	-0,8612	0,99	1745,87

Fig. 11.

The invariance in structures. So far our interpretation of the simulation results has focused upon several properties of industrial structures which apply *on average* – over time and across different simulations of microsectors under the same parametrizations. Moreover, the results discussed above hold also for aggregations *within* learning regimes. Admittedly, at this stage of investigation of the properties of the model, we fall short of rigorous robustness tests. Still, standard deviations in the foregoing indicators of 'structures' across simulations turn out to be (surprisingly) low: at least a qualitative assessment of the results supports the hypothesis that relatively invariant, modal, patterns emerge.

Were these regularities corroborated by further modeling results and empirical taxonomic exercises, important theoretical implication would follow, too.

First, the microeconomics underlying the particular invariances in structures and performances appears to be fundamentally inconsistent with technological homogeneity and market equilibria. Rather, the model corroborates the view that it is the very existence of persistent inter-firm asymmetries which drives the process of change and, *together*, accounts for the statistical invariances in structures.

Second, a rather robust taxonomy of 'types' of industries emerge which can be mapped and, in some sense, 'explained' on the grounds of underlying system parameters governing particular regimes (and without invoking any particular behavioural assumption, either of the neoclassical or the 'institutionalist' kinds).

Evolutionary patterns. Another set of phenomena regards the time-series properties of microsectors, the performance over time of individual firms and their demography. Clearly, the matching between such properties of the model and the corresponding 'stylized facts' reviewed above are an important part of its corroboration. And, they also overlap with the predictions of other models suggested in the literature. For example, some relatively invariant non-linear dynamics in the number of firms, following temporally skewed distributions would fit well the prediction of 'organizational ecology' models. Conversely, theories emphasizing extreme cumulativeness and organizational routinization of innovative activities would predict a strong tendency toward monopoly.

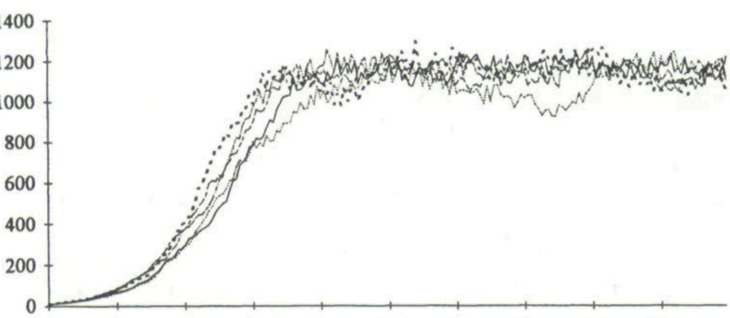
What turns out is that (i) there seem to be relatively invariant patterns of evolution of microsectors, and (ii) they are quite *specific to the technological regimes* defining learning dynamics.

Interestingly, the cases which display an apparent convergence to some intertemporally stable structures are those emerging within a 'Schumpeter I' regime (cf. Figure 12 on the number of firms; similar consideration apply to concentration, asymmetries and turbulence).

As incumbents' learning is introduced, also an (irregular) long-term cyclicity shows up (cf. Figures 13 and 14 on number of firms and concentration within an 'intermediate' regime). The entire set of simulations that we have run suggests that the periodicity of these 'cycles', within each microsector, increases together with learning opportunities. The same applies to our other indicators.

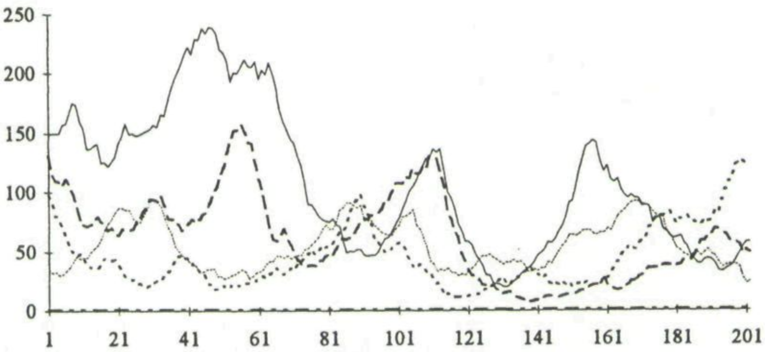
Over sub-periods, the tendency toward oligopoly/monopoly driven by cumulative learning becomes stronger but, with probability one, 'creative destruction' by newly born innovative firms upsets established structures. Under strongly cumulative learning ('Schumpeter II' Regime) the average time that the sector spends in highly concentrated structures increases: 'disruptions' are less frequent but, when they occur, they induce major discontinuities in the statistics describing structures (Figures 15 and 16).

Growth and death of firms. A relatively familiar test concerns the relationships between growth and size, and, sometimes, age (see, for example Evans, 1987). In the literature, the analysis is often meant as a test of Gibrat-type laws of firm growth. Here, of course, we know the 'true law', by construction, but it is informative and theoretically interesting to know what econometric regularities emerge. We have estimated around fifty regres-



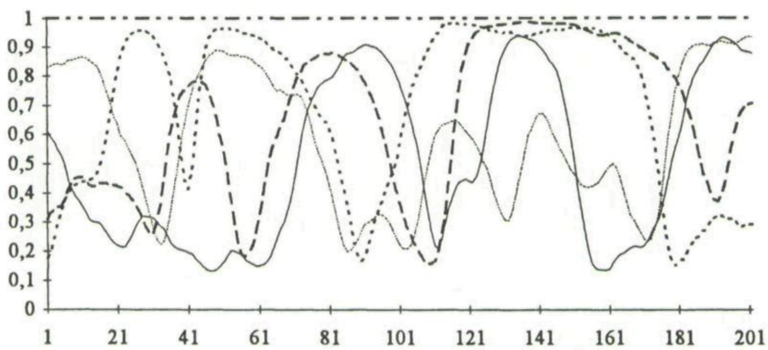
Schumpeter. I (1.5; 0; 3), plot of five simulations

Fig. 12. The dynamics of firms' populations: 'Schumpeter I'.



'Intermediate' (1.5; 1; 1), plot of five simulations

Fig. 13. The dynamics of firms' populations: 'Intermediate' Regime.



'Intermediate' (1.5; 1; 1), plot of five simulations

Fig. 14. The dynamics of concentration: 'Intermediate' Regime.

sions of the form

$$\log(g) = \alpha + \alpha_1\log(s_0) + \alpha_2\log(a_0) + \alpha_3[\log(a_0)\log(s_0)], \qquad (12)$$

where, for each firm, g ($= s_{10}/s_0$) is growth over 10 periods, s_0 is the initial size and a_0 is the initial age.[36]

Table I summarizes the signs and significance of coefficients for microsectors, regimes and 'aggregate manufacturing'.

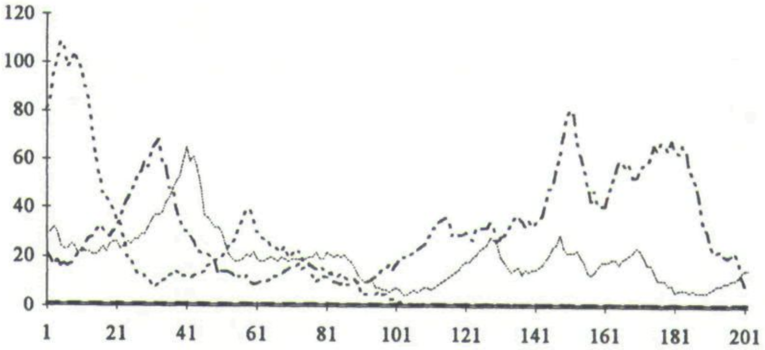
At the level of microsectors a positive correlation often appears between size and growth. The effect is particularly evident under a 'Schumpeterian II' regime, but it shows up somewhat surprisingly also under 'Schumpeter I'. This effect fades away at the level of 'sectors' (i.e. aggregation within regimes) and turns out to be negative at the level of 'aggregate manufacturing'.

The age of firms is either uncorrelated or, much more often, exerts a negative impact on growth. This applies – more so – at higher levels of aggregation.

Regarding the interpretation of these tests, note, *first*, that at least in the aggregate our results correspond to the properties of historical data (see, for example Evans, 1987). That is, the model generates as *emergent properties* those empirical regularities which are often interpreted on the grounds of quite different microeconomics theories (cf. Section III, above).

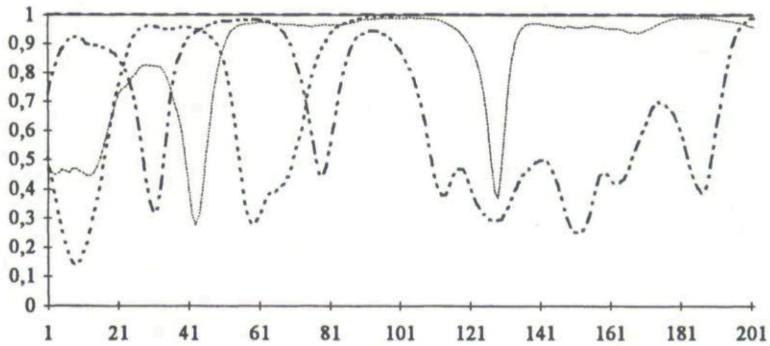
Second, one ought to account for the somewhat puzzling positive links between size and growth which appear in several microsectors and one 'regime'. Of course, nothing in our model determines an advantage of size as such. On the contrary, it is the ex-post outcome of differential innovative success.

However, a particularly high competitiveness exerts its influence over relatively long periods,



'Schumpeter II' (1.5; 2; 1), plot of five simulations

Fig. 15. The dynamics of firms' population: 'Schumpeter II'.



'Schumpeter II' (1.5; 2; 1), plot of five simulations

Fig. 16. The dynamics of concentration: 'Schumpeter II'.

TABLE I
Age, size and growth: a summary of regression results (dependent variable: firms growth over 10 periods)

	Schumpeter I		Intermediate		Schumpeter II		Aggregate manufacturing
	Individual microsectors	Sector	Individual microsectors	Sector	Individual microsectors	Sector	
Initial size ln(s)	*non significant* with low opportunities for entrants; *positive* most often *significant* with high opportunities	negative, significant	*most often non significant, uncertain sign*	*non significant*	*positive, generally significant*	positive, often non significant	negative, not always significant
Initial age ln(a)	negative, non significant with low opportunities; *negative significantly* with high opportunity	*same* as micro-sectors	non significant uncertain sign	*negative, non significant*	negative, often significant	*negative,* significant	*negative,* significant
Interaction age and size ln(s)*ln(a)	non significant		non significant		negative often significant	negative sometimes	negative not always significant

especially in the 'cumulative regimes', but also under 'Schumpeter I', provided that opportunities are high. Hence, over finite spans of observation, one detects a positive link between size and growth which is spurious from a causal point of view, since it simply reveals a long autocorrelation structure in the growth of firms that happen to be at the extremes of the competitiveness distribution. Clearly, the causal link here goes from competitiveness to both growth *and* size.

Different regimes show quite different patterns of evolution of market shares and a different demography. Regarding the former, Figure 17 show the dynamics over 25 years, with some sort of 'Marshallian cycle' characterizing the most innovative entrants (the others die quite soon: see also below). Conversely, with cumulative learning one or few dominant firms emerge (Figure 18).

In these circumstances, the general properties of industrial dynamics are basically driven by an 'oligopolistic core' or a quasi-monopolist with a fringe of more or less numerous small marginal firms. Of course this occurs until with low but positive probability major disruptions in the competitive pecking order occur (as discussed earlier).[37] Even more so under 'Schumpeter II', where the tendency toward monopoly is particularly marked.

More generally, our results appear to suggest that evolutionary processes under most regimes show powerful monopolistic tendencies, curbed by (relatively infrequent) 'radical' innovations, and, probably more important, by the emergence of new microsectors (i.e. new markets and new lines of production activities) often explored by novel firms.

Regarding the demography of firms, Figure 19 show the probability of death conditional on age and Figure 20 conditional on size.

In general, mortality falls with size, but with

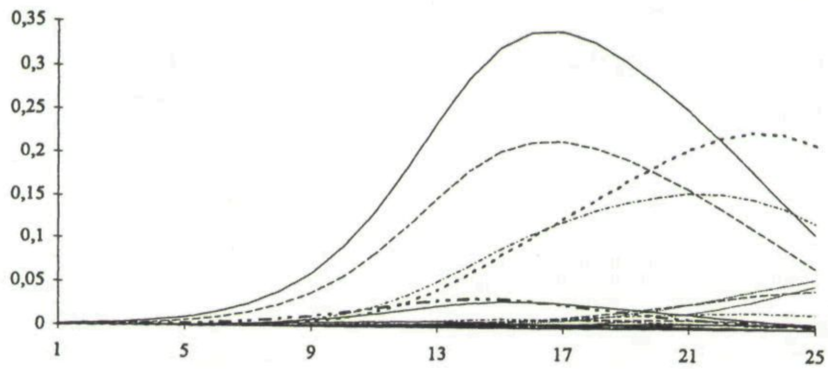


Fig. 17. The evolution of market shares, 'Schumpeter I'.

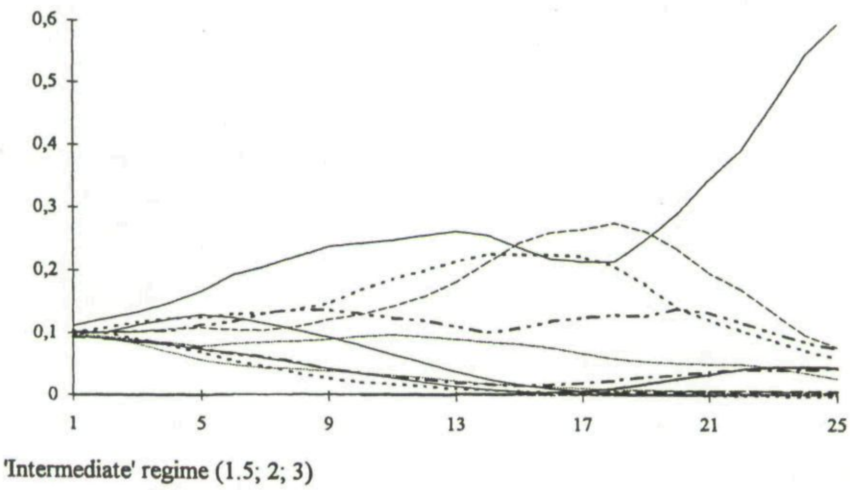


Fig 18. Dynamics of market shares in a 'cumulative regime'.

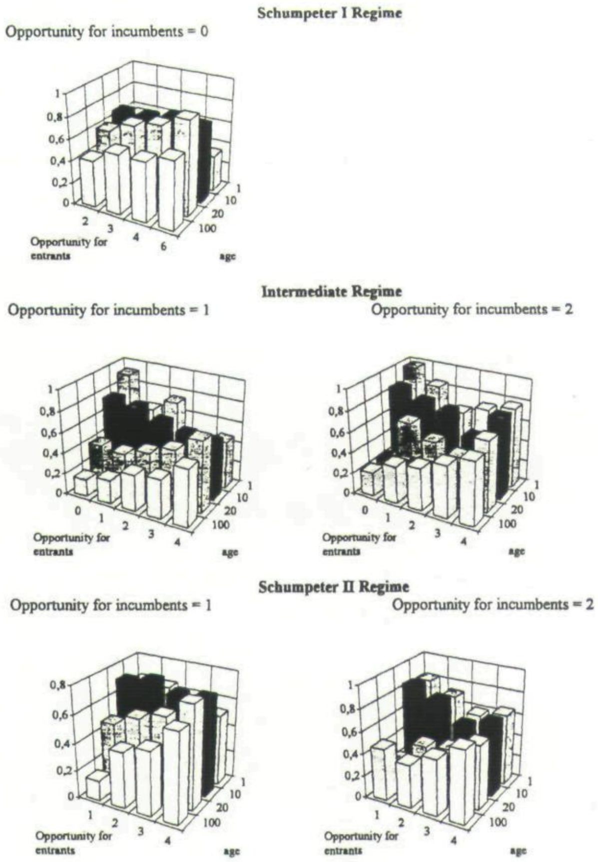


Fig. 19. Probability of death conditional on age.

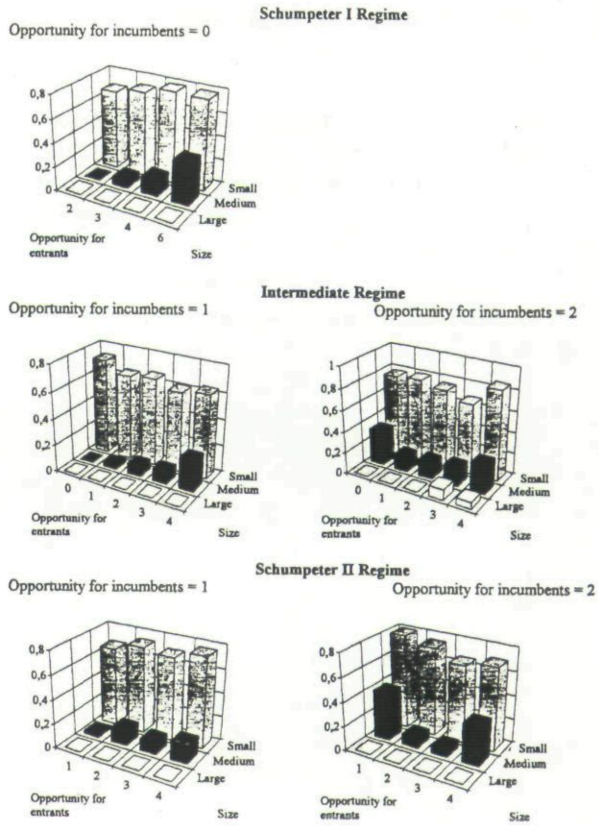


Fig. 20. Probability of death conditional on size.

high learning opportunities also big firms have a positive probability to die.

Under a 'Schumpeter I' regime the probability of death increases during its youth, then falls and eventually starts rising again. Under all other regimes, mortality *falls* with age.

This property, together with the earlier one that growth also falls, loosely corresponds to the phenomena described in population-ecology models as adaptation to particular environmental niches. (Of course in our model there is no such behavioural feature.)

Interestingly, as the opportunity for entrants grows, *short-term* mortality *falls* and long-term one increases (which is also a phenomenon empirically noted by Audretsch (1991)).

VII. Conclusions

On the grounds of a rather simple evolutionary model, we have tried to show, one is able to generate a rich set of 'stylized facts' concerning several statistical invariances in industrial structures and in their dynamic properties, at different levels of aggregation. In the mode of analysis which we have followed here, the 'explanation' rests in the 'mapping' between aggregate properties and the system parameters governing learning processes and market selection, while being totally agnostic about specific behavioural assumptions.

The ability of the model of accounting for a multitude of regularities *together* is certainly a point of analytical strength (which indeed cannot be ascribed to most equilibrium models one finds in the literature). A preliminary comparison between the results of the model and the 'stylized facts' surveyed in Section II is indeed quite encouraging.

Relatedly, this approach can generate a rather long list of propositions that are at least in principle empirically testable, concerning for example the link between opportunities for learning – on the one hand – and size distributions, market turbulence, concentration, etc. – on the other; the links between degree of cumulativeness and market structures; the intertemporal patterns of industrial evolution; and many others. An increasing availability of time-series of micro data in recent years is making them testable not only in principle but also in practice.

In this respect this work ought to be considered only as an introductory exploration of the properties of evolutionary dynamics driven by various forms of learning and occurring, loosely speaking, over an 'evolutionary landscape' which the agents themselves continuously shape.

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We thank Boyan Jovanovic and David Audretsch for their comments during conference presentations of the research, and Laura Porta for her helpful research assistantship.

Notes

1 More on this notion in Lane (1992).

2 Cf. Ijiri and Simon (1977). A detailed discussion is in Marsili (1992).

3 For example, Barca (1985) shows in the Italian case, for the '70s, significant departures from a Pareto distribution, biased in favour of small firms. In Dosi and Salvatore (1992) we show that this could well be a temporary phenomena associated with major technological discontinuities. See also below.

4 For example, Kalecki (1945) assumes a variance of the error term falling with size. Simon and Bonini (1958) account also for entry and Ijiri and Simon (1977) allow for a first-order Markov process on growth rates.

5 For example, Geroski and Machin (1992), on a sample of around 500 British firms while rejecting the null hypothesis that growth rates are random, find also that "one cannot say that the evidence against the null is very impressive" (p. 16). A somewhat contradictory evidence stems from earlier studies: see Hart and Prais (1956), Hymer and Pashigian (1962), Mansfield (1962) Singh and Whittington (1975), Simon and Bonini (1958), Hall (1987).

6 On entry and exit in different countries see Dunne, Roberts and Samuelson (1988), Baldwin and Gorecki (1991), Cable and Schwalbach (1991), Bianco and Sestito (1992), Aldrich and Auster (1986), Acs and Audretsch (1991) and (1992), Phillips and Kirchoff (1989), Audretsch and Mahmood (1991), Mahmood (1992), Geroski and Schwalbach (1991)).

7 On various features of the dynamics of entry, exit, innovation within 'life cycles' see Klepper (1992) and the works surveyed therein: Suarez and Utterback (1991), Klepper and Graddy (1990), R. Henderson (1988), S. J. Lane (1989), W. G. Mitchell (1988).
Overlapping or complementary evidence stems from the growing field of 'organizational ecology': see Hannan and Freeman (1989) and Hannan and Carroll (1992).

8 In terms of plant-sizes, firms' market shares and total firms' sizes.

9 Note that 'turbulence' in the definition here may be low even if rates of gross entry are high, provided that entrants do not make any big impact on market shares – for example because many of them die young.

10 It must be also noted, however, that some studies have shown that mortality rates are much more stable over time and across sectors: the variance in mortality across industries is lower than the variance in birth rates.

11 An extension of the model incorporating different forms of learning is in Calvo and Wellisz (1980).

12 This conjecture, of course, is by no means restricted to the empirical domains one is considering here. On the contrary, it is germane to a general epistemological challenge to the 'equilibrium paradigm' underway in both natural and social sciences: see Nicolis and Pricogine (1989). Indeed, it happens that economics and theology hold out as the two disciplines most resilient to such a methodological shift.

13 In Nelson and Winter (1982) and Winter (1984), this 'quasi-replicator' dynamics is implicitly in the expansion rules of firms. For other examples of selection dynamics, see Iwai (1984a, 1984b), Conlinsk (1980), Gibbons and Metacalfe (1986), Silverberg (1987), Silverberg, Dosi and Orsenigo (1988), Chiaromonte and Dosi (1992). Partly overlapping with this class of evolutionary models, recent studies of 'organizational ecology' have suggested that a selection pattern ('density dependent selection') is relatively invariant in all 'industry life cycles' (cf. Hannan and Freeman (1989) and Hannan and Carrol (1992)). Of course, whether such invariance holds is mainly an empirical question. Let us just note that these models do not involve an explicit learning dynamics. Moreover, they focus primarily on the demography of firms, rather than their characteristics – including their sizes. For our purposes here, 'density-dependence' could be regarded as one of the possible outcomes of evolutionary dynamics, and indeed a very interesting question is: which learning and selection regimes allow it to emerge? More generally, for a discussion of selection dynamics in evolutionary models, see Silverberg (1988) and in ecological models, see Winter (1990).

14 Moreover, even if agents were able to correctly forecast the consequences of their actions, still heterogeneous and changing technologies would imply some selection dynamics.

15 To some extent, this is also a caricatural version of the two quite different views of the innovative process which J. Schumpeter held during his life, cf. Freeman (1982).

16 Another, equivalent, way of saying it is that evolution is driven by mutation rather then by 'Lamarckian' transmission of acquired characters.

17 The modified version of the Fisher-Pry selection dynamics that we adopt in Equation (8) allows notional shares to become negative. Of course, in that case the death rule applies and actual market shares are recursively adjusted.

An advantage of the selection dynamics sub 8. is that, given the non stationarity in the levels of competitiveness, it scales their affects on market shares to the dynamics of the mean: market adjustments are approximately invariant in the log differences in competitiveness.

[18] In a more sofisticated formulation, one should assume that the choice of the sectors of diversification depends on some measures of 'technological distance', as suggested in Dosi, Teece and Winter (1992). Indeed such an hypothesis of non-uniformly random processes of diversification appears corroborated by some preliminary evidence: cf. Teece *et al.* (1993). Here, however, we stick to the simpler, *and empirically false*, formulation since we are not so much interested in issues of internal coherence of firms, but rather on broader statistics on market structures.

[19] More precisely, in the experiments reported below we rule out $k = l$, that is intra-sectoral mergers/acquisitions. The impact of the later is on the agenda for future work.

[20] All the statistics that we shall present below on microsectors will consider such 'divisions' as indipendent firms. A proper account of multi-product firms will be given when describing 'sectors' and, of course, the whole 'industry'.

Moreover, note that the stochastic diversification process is recursively repeated across all microsectors, thus allowing firms to hold a number of activities ranging between 1 and $\nu(t)$ (the total number of microsectors that are active at that time).

[21] It might be worth emphasizing that within the notion of 'structure' adopted here one includes also variables that one would normally consider in industrial economics as describing the performance of particular industries – for example the dynamics and cross firms variances in 'competitiveness' – which can easily be interpreted to represent productivity or some combination between the latter and product innovation.

[22] Which, incidentally, is a quite ill-placed objection given their embeddedness in a well defined structure of interactions.

[23] More in line with microeconomic 'rationality', one could also assume to the same effect that regimes specific restrictions on our Markov processes of change in competitiveness are the outcomes of more sophisticated strategically motivated activities of innovative search: with little doubt, several Ph.D. are there to be written on the rationalization of intersectoral differences in innovation patterns . . .

[24] One should also mention some of the features which are missing in these modelling exercises: first, one does not account for any capital-embodied innovation and vintage-effect; second, the model does not account for any process of inter-firm imitation. Given these drawbacks, results on persistence concerning both sector-wide structures and firm-specific performance ought to be considered as sorts of lower bounds for the 'true' values, had one accounted for these additional sources of hysteresis and interdependences.

[25] Correspondinghly in the following, we shall describe each simulation by three indicators (A, $g_{(I)}$ and $g_{(E)}$).

[26] The index user here is $\{n_{(t)}\sum_i[f_i(t)]^2 - 1\}/[n(t) - 1]$ which is bound in [0; 1]; n is the number of firms and f_i are the market shares.

[27] The *ceteris paribus* implies also that the *relative* ability of entrants and incumbents is held constant.

[28] A line of inquiry which we cannot pursue here concerns the normative implications of these results: it is straightforward, for example, that for anti-trust purposes market share concentration measures might be highly biased indicators of the probability of collusion, while traditional pro-competition policies might imply 'perverse' effects on long-term improvements in products and processes of production, and competitiveness. In general, major normative questions concern the possible dilemmas between 'static' and 'dynamic' efficiency and one is only beginning to explore them (cf. Nelson and Winter (1982) and Dosi, Pavitt and Soete (1990)).

[29] The measure of asymmetry is the standard deviation in the degrees of competitiveness of the firm at t, $\sigma(E_{(t)}/\overline{E}_{(t)}$. This statistics is bound between zero and a finite value determined by one of the 'death rules': cf. Equation (9).

[30] Another direction of inquiry which, again, it is not possible to explore here concerns the link between selection on the product – and on the finance – markets. In Dosi (1991), one conjectures that, ceteris paribus, a higher 'efficiency' in the markets for ownership titles and corporate debt might lead to systematically lower rates of innovative exploration, given a plausible biased distribution of search effects toward mistakes. The model presented here neglects this issue by simply assuming – quite irrealistically – that the learning dynamics of individual firms is independent from finance.

[31] The 'Hand' is invisible in the sense that we assume that no agent explicitly tries to strategically influence its own payoffs, but, it might be quite 'visible' since 'atomlessness' hypotheses on the size of the agents *vis-à-vis* the market are largely violated and, ex-post, individual firms may well turn out to influence the selection process.

[32] Here, size is measured by the turnover of each firm.

[33] Each regime aggregates over five microsectors observed at different stages of their 'lifecycle' (i.e. different 'ages' of the microsectors themselves).

[34] The 'manufacturing aggregate' adds up over 80 'microsectors' randomly drawn from the three regimes.

[35] In Dosi and Salvatore (1992) we experiment with a generalized discontinuity in technological knowledge – an economy wide change in technological paradigms. This yields indeed an aggregate departure from a Pareto-type distribution, somewhat similar to that shown by actual data in the '70s in some countries. However, we also show that such a departure is likely to be a temporary phenomenon, unless one expects these generalized shocks to occur with high frequency.

[36] The tests exclude the firms which die within the 10-iteration period.

[37] Incidentally, note also that within the 'oligopolistic core', over finite periods, there might be *positive* correlation between age and growth for these outliers, but this property does not hold for the universe of firms.

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