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Mariana Mazzucato
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Mariana S Mazzucato

Dr Mariana S Mazzucato
Economics Discipline
The Faculty of Social Sciences
The Open University
Walton Hall
Milton Keynes MK7 6AA
Email: m.mazzucato@open.ac.uk
Abstract

The paper explores structural and random determinants of industry market structure. The former is studied in the context of different Schumpetarian debates on the relationship between firm size and innovation (dynamic returns to scale), and the latter is studied in the context of studies that emphasize the role of idiosyncratic events, path-dependency and initial conditions in industry dynamics. The object is to better understand the determinants of empirical regularities in market share patterns by varying the type and strength of dynamic returns to scale and the size of shocks to costs.

Keywords: market structure, economies of scale, innovation, random events.
JEL Classification: L11 (Market Structure: Size Distribution of Firms),
O30 (Technological Change)

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1 Introduction

The paper explores structural and random determinants of industry market structure. The former is studied in the context of different Schumpetarian debates on the relationship between firm size and innovation, and the latter is studied in the context of studies that emphasize the role of idiosyncratic events, path-dependency and initial conditions in industry dynamics. A stochastic component of firm costs captures the idiosyncratic aspect of innovation projects, advertising campaigns and daily managerial decisions (e.g. Henry Ford’s personality did affect the market structure of the US automobile industry). The object is to better understand the determinants of empirical regularities in market share patterns by varying the type and strength of dynamic returns to scale and the size of shocks to costs.

The study is motivated by two empirical regularities widely documented in industrial dynamics: (a) the “skewed-size distribution” of firms found to exist across different types of industries (Ijiri and Simon, 1977; Klepper and Simons, 1997; Sutton, 1998), and (b) the periodic increases in market share instability during an industry’s life-cycle (Cable, 1998; Gort, 1963; Hymer and Pashigian, 1962; Klein, 1977). Examples of such patterns are illustrated in Fig. 1a. for the US automobile and aircraft industries: in both there has been a prevalence of market concentration, accompanied by alternating periods of market share instability:

Figure 1a. Market shares in the US automobile industry and delivery shares in the US aircraft industry

The large variation in market shares is seen even more clearly in Fig. 1b. below where market share instability in the US automobile industry is measured via an instability index devised by Hymer and Pashigian (1962). This index is defined as:

\[ I = \sum_{i} [s_i - s_{i-1}], \text{ where } s_i \text{ is the market share of firm } i \text{ at time } t. \]
Figure 1b. Instability and concentration in the US automobile industry

Similar patterns have been found in the television set industry (Datta 1971), the semi-conductor industry (Malerba 1985, Gruber 1994), and the tire industry (French 1991). The patterns suggest that it may be important to study the determinants of industry concentration and market share instability simultaneously, and that industry concentration should not be used as the sole measure of market structure and competition.

Theoretical explanations regarding the cause of concentration have focused on three main processes, each with an implication for market instability: 1) the optimal allocation of scarce factors of production, where an optimum firm size emerges from the underlying U-shaped cost curve; 2) the random nature of firm growth patterns; and 3) the path-dependent dynamics of technological change and increasing returns. In the traditional approach, based on the U-shaped average cost curve, market concentration arises due to economies of scale and market share instability arises (if at all) as a transient phenomena during the process of convergence towards the optimum size, or also if the optimum size is continuously disturbed by changes in exogenous variables (e.g. technology shocks). In its extreme version, the latter interpretation is in fact the stochastic approach: firm size is simply the accumulation of random historic events.

The stochastic approach arose due to the dissatisfaction among industrial economists with the strong behavioral assumptions underlying the traditional theory of firm size, and the inability of the latter to produce empirically relevant firm growth rates and to account for firm-specific differences in growth rates. This approach makes no behavioral assumptions and assumes only that the size of a firm at time t+1 is a function of its size at time t subject to random variation. The random process most studied in this regard is Gibrat’s Law of Proportionate Growth which states that firm growth rates are i.i.d. random variables independent of firm size (Gibrat, 1931; Kalecki, 1945; Simon and Bonini, 1958; Ijiri and Simon, 1977; Sutton, 1997). The principle result in such models is that although firms begin ex-ante with equal growth prospects, random events soon cause them to diverge in size and a skewed size distribution (log-normal) to emerge. Market share instability arises due to the indiscriminate impact of the shocks but is the highest early on when concentration has not yet occurred. An obvious problem with this approach is that it makes market
structure solely a result of random factors, which as is claimed by Geroski et al. (1997): "... may be more an artifact of the models than of the data itself." The full reliance on randomness ignores empirical case studies which refer to specific economic mechanisms which might generate such patterns (e.g. the dynamics of innovation). It also ironically ignores the specific role of randomness itself, a topic we explore in Section 3.

The third approach emphasizes how positive feedback mechanisms, such as that between firm size and R&D (Klepper, 1996) and between firm size and advertising (Sutton, 1991), cause markets to become concentrated. In both cases, the advantages incurred to large firms cause a "success breeds success" dynamic. This approach predicts that industries, or periods in the industry life-cycle, characterized by different degrees and types of positive feedback will be characterized by different levels of concentration. Market instability occurs through the arrival of new innovative entrants and/or periods of product innovation which disrupt the more stable and path-dependent dynamics of process innovation.

The current study explores the determinants of market structure by using various insights provided in all three approaches. Structural determinants of market structure are explored by embodying different Schumpetarian assumptions on the relationship between firm size and innovation in a dynamic returns to scale setting (Abernathy and Wayne, 1974; Klein, 1977; Rothwell and Dodgson, 1996). The object is to see how positive and negative feedback mechanisms between firm size and innovation affect market concentration and instability. Random determinants of market structure are explored by studying the effect of shocks on firm costs during periods of positive and negative feedback. The firm-specific and industry-specific conditions under which shocks have the most impact on the underlying (non-linear) deterministic dynamics are examined (David, 1985; Arthur, 1990; Klepper, 1996).

Before presenting the model in Section 3, we first review the relationship between firm size and innovation, and the formalization of this relation via dynamic economies of scale.

## 2 A Dynamic-Stochastic Relationship between Firm Size and Innovation

### a. Firm size and innovation

The relationship between firm size and innovation is a complex one due to the fact that both variables affect each other. Although many studies relating innovation to market structure are inspired by the writings of Joseph Schumpeter, they sometimes do not heed Schumpeter’s own position that firm size is endogenous to the innovation process via “creative destruction” (Schumpeter, 1942). It is the feedback embodied in this complex relationship that is responsible for the inconclusiveness of many econometric results on the topic (Scherer and Ross, 1990).
The mechanism by which firm size affects innovation is tied to the relative advantages of large/small firms during the process of innovation. Reasons why large size can be advantageous for innovation include: capital market imperfections which give preference to large firms due to the greater stability of their internally generated funds; higher returns from R&D due to greater volume over which to spread costs (hence greater incentive to develop internal process improvements); higher productivity of R&D due to the greater complementarities between manufacturing, marketing, and financial planning; and the lower risk incurred from any one R&D project due to the more diversified portfolios of large firms. Both Schumpeter and Galbraith are known for their writings on the advantages associated with the large enterprise:

"What we have got to accept is that [the large-scale establishment or unit of control] has come to be the most powerful engine of [economic] progress ... In this respect, perfect competition is not only impossible but inferior, and has no title to being set up as a model of ideal efficiency.”

(Schumpeter, 1942: p. 106)

Reasons why small size can be advantageous for innovation include: greater managerial control and flexibility of small firms since research in large labs may become over-organized; the greater flexibility and motivation of small firms in foreseeing future changes in demand; and the ability of small firms to attract scientists and entrepreneurs who are disillusioned by large bureaucratic firms. In this line of thought, Schumpeter warned that the bureaucratization of inventive activity (to a certain extent more characteristic of large firms) could undermine capitalist development:

"A system - any system, economic or other - that at every given point in time fully utilizes its possibilities to the best advantage may yet in the longer run be inferior to a system that does so at no given point in time, because the latter's failure to do so may be a condition for the level of speed of longer-run performance.”

(Schumpeter, 1942)

Empirical evidence suggests that there is no one answer to whether it is small or large firms which are more innovative; the relationship between firm size and innovation is sensitive to various factors such as the type of industry being considered, the underlying knowledge-base of the technology, and the specific phase in the industry life-cycle. Thus:

"...the appropriate question is not 'which size firms have the relative advantage in innovation?', but rather 'Under which circumstances do large or small firms have the relative innovative advantage?' "

(Acs and Audretsch, 1987).
In attempting to answer this question, Acs and Audretsch (1987) find that small firms tend to have a relative advantage in industries which are highly innovative, which use a large component of skilled labor, are low in R&D intensity, and which tend to be composed of a relatively high proportion of large firms. Other studies have also found that small firms have a relative advantage in innovation when innovation is radical as opposed to incremental, when the environment is characterized by strong uncertainty, and when production is more skill intensive rather than capital intensive (Abernathy and Wayne, 1974; Klein, 1977; Jovanovic and MacDonald, 1994a; Klepper, 1996). Uncertainty is especially high in situations of volatile changes in demand, prices and technological progress. Uncertainty is also high during the early stage of the industry life-cycle, when the product design has not yet been standardized and demand is unstable. In this phase, the flexibility of small new firms allows them to be the main sources of cost reduction and innovation (causing high rates of entry); while during the mature stage of the life-cycle, when the product and market demand have stabilized, economies of scale favoring large firms are strong and innovation becomes increasingly path-dependent, leading to a more stable oligopolistic structure (Audretsch, 1995; Klepper, 1996).

Ways in which the causation runs the other way around, i.e. innovation affects firm size, is related to how innovation affects market structure, especially through entry/exit dynamics. Innovation could be concentration-increasing if successful innovators rise to market dominance and can defend themselves successfully from imitators; or if vigorous innovation increases the variance of firms’ growth rates under many versions of Gibrat’s law. Innovation can also affect market structure by increasing or decreasing the minimum efficient scale of production; if an innovation causes the MES to grow more rapidly than demand, then concentration will increase. This has been found to hold in electric power generation, chemical industries, cement, brewing, refrigerators, paints, and batteries (Cohen and Levin, 1989).

The intensity (speed, vigor, opportunity) of innovation has been found to be an important factor in the relationship between innovation and market structure. In the model developed in Section 3, we refer to it as the level of “technological opportunity”, i.e. the ease of innovation. Geroski (1987) finds that vigorous innovative activity reduces concentration, and Mukhopadhyay (1985) finds concentration to fall in high opportunity industries. Dosi (1984) finds that the semiconductor industry is more concentrated in countries which are not at the vanguard of technology. Lunn (1986) finds that product innovation, which is more radical (hence more vigorous) in nature than process innovation, tends to lead to a less concentrated market structure than process innovation. Also life-cycle studies find that entry rates are much higher than exit rates in the early stage of the life-cycle when product innovations are more important that process innovations (Klepper, 1996; Gort & Konakayama, 1982).

b Modeling dynamic economies of scale

We explore some of the above issues regarding the relationship between firm size, innovation and market structure through a model of dynamic returns to scale: the effect of size on the rate of cost reduction (i.e. innovation). We refer to dynamic decreasing and increasing returns to scale as dynamic negative and positive feedback. Negative/positive feedback means that as a firm grows,
its speed of innovation falls/increases (the intuition behind both assumptions is found in the discussion above). Economists interested in disequilibrium dynamics have studied positive feedback due to their interest in explaining the existence of multiple equilibria and the reasons why initial conditions matter (Arthur, 1989; David, 1995). These studies have, however, mainly looked at static feedback: the effect of size on the direction of costs. Due to the unique equilibrium results produced by static negative feedback (e.g. a unique optimum firm size), and due to the fact that these studies are interested in disequilibrium dynamics, they have explicitly ignored any type of negative feedback. On the other hand, less theoretical and more descriptive management studies often highlight the role of negative feedback in generating market share turbulence. For example, Klein (1977) claims that the instability of market shares which can be observed in the early history of many industries and/or in certain industries more than others is due to periods of “dynamic efficiency” in which firms are required to explore new frontiers of production to remain competitive. Since small firms are usually more flexible and hence potentially better at exploring new frontiers (reasons discussed above), periods of dynamic efficiency tend to be characterized by market share instability. Instead periods of “static efficiency,” in which firms are required to exploit existing techniques of production to remain competitive (e.g. learning curve strategies), are characterized by market share stability since large firms are better at exploiting existing leadership positions.

Mazzucato (1998) uses ideas from the life-cycle literature to construct an evolutionary model of dynamic feedback and finds that negative feedback does, under certain conditions, lead to turbulence in market share patterns as often described in the management literature. We review this model now briefly since the stochastic model in Section 3 builds upon it.

If we take \( s_i \) and \( c_i \) to denote the market share and cost of firm \( i \) respectively, and \( \bar{c} \) to denote the weighted average industry cost, we can describe the evolution of market shares through Eq. (1) which states that the market share of firm \( i \) increases (decreases) if its cost is below (above) the weighted average industry cost:

\[
s_i = \gamma \cdot s_i (\bar{c} - c_i) \quad \text{where} \quad \bar{c} = \sum c_i s_i \quad \text{and} \quad \sum s_i = 1
\]

Equation (1) is a replicator equation describing an evolutionary “distance from mean” dynamic: when \( c_i = \bar{c} \) for all \( i \), there is no change in market shares. The parameter \( \gamma \), representing the speed at which market shares adjust to cost differentials, is assumed to always equal one because variations in its value are not relevant to the current analysis (Geroski and Mazzucato [1999] study changes in the degree of selection by varying this parameter). The advantage of using replicator dynamics to study market structure is that replicator dynamics, like all evolutionary methodologies, explicitly focus on the evolution of variety between agents as opposed to the characteristics of one “representative” agent. And a study of industry concentration and instability is precisely a study of the evolution of variety between firms in an industry.

To study the dynamic positive and negative feedback discussed qualitatively above, the cost terms in Eq. (1) are explored through different assumptions regarding the effect of size on the rate at which firms reduce their costs (e.g. innovation):
Equation (2a) describes the case of dynamic negative feedback: an increase in market share causes a firm’s rate of cost reduction to fall. Equation (2b) illustrates the case of dynamic positive feedback. The parameter \( a \) is an industry-specific parameter that can be interpreted either as the degree of technological opportunity (ease of innovation) in the industry or as the average rate of cost reduction in the industry. We prefer the latter interpretation. The exact rate of cost reduction of any one specific firm depends both on the value of \( a \) as well as on its market share via Eq. (1). The value of \( a \) might depend on the “tacitness” of the knowledge base in an industry, on the patent system, and on other industry-specific and technology-specific factors which affect spillovers and diffusion (Pavitt, 1984). We can combine the two cost equations into a single equation by putting weights on the different feedback mechanisms:

\[
\frac{c_i}{c_i} = \beta(1 - s_i) + (1 - \beta)(-\alpha s_i)
\]

(3)

where \( \beta = \frac{-\alpha}{n-1} \) and \( n \) is the number of firms in the industry. When \( \lambda = 1 \), costs evolve via dynamic negative feedback, while when \( \lambda = 0 \), costs evolve via dynamic positive feedback. In what follows we refer to the parameter \( \beta \) for the case of dynamic positive feedback and to the parameter \( \alpha \) for the case of dynamic negative feedback.

1 Because equation (2a) and equation (2b) embody different average rates of cost reduction, it is necessary, when setting the value for \( \alpha \) in the two equations, not to introduce a bias into the model. The average rate of cost reduction for equation (2a) is equal to \(-\alpha(n-1)\), while for equation (2b) it is equal to \(-\alpha\). To control for this difference, the parameter \( \alpha \) must be set differently in the two equations so that for any given value of \( \alpha \) in equation (2a), the average rate of cost reduction is the same in the two equations. We do this by replacing the average rate of cost reduction for equation (2b), i.e. \(-\alpha\), with the term \(-\beta\) and by setting the two average rates of cost reduction equal to each other: \( \beta = \alpha(n-1) \). This means that the value chosen for \( \alpha \) in the phase of dynamic positive feedback must always be \( 1/(n-1) \) times the value chosen for \( \alpha \) in the phase of dynamic negative feedback.
Figure 2a illustrates the results from the simulation of Eqs. (1) and (3) with $\lambda = 1$ (i.e. only dynamic negative feedback) and with different values of $\alpha$. In each case, market shares begin equal while costs instead begin randomly distributed (with mean 1 and variance $\gamma$).

Figure 2a  
**Negative Feedback: Simulation of Eq. (1) and (3) for n=2 firms with $\lambda=1$, $\gamma = .4$ and different values of $\alpha$**

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>Market Shares</th>
</tr>
</thead>
</table>
| .001     | ![Graph](image)
| .02      | ![Graph](image)
| .5       | ![Graph](image)

Figure 2b illustrates the deterministic results from the simulation of Eqs. (1) and (3) with $\lambda = 0$ (i.e. only dynamic positive feedback) and with different values of $\beta$.

Figure 2b  
**Positive Feedback: Simulation of Eq. (1) and (3) for n=2 firms, $\lambda = 0$, $\gamma = .4$ and different values of $\beta$**

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Market Shares</th>
</tr>
</thead>
</table>
| .1      | ![Graph](image)
| .2      | ![Graph](image)
| .5      | ![Graph](image)
The simulation results indicate that dynamic returns to scale, unlike static returns to scale, does not lead to a predictable market structure. In this more dynamic conception of returns to scale, we find that even negative feedback leads to multiple equilibria; the particular market structure in each case is sensitive to the industry-specific average speed of innovation (or technological opportunity) and to the variance of the initial random distribution of costs (γ). The results are summarized and interpreted below (for further details see Mazzucato, 1998):

- In both the case of dynamic positive and negative feedback, when the industry average rate of cost reduction is set very low (i.e. inertia), the market structure which emerges is highly concentrated due to the overpowering effect of selection (Eq. 1). This result confirms the empirical studies reviewed in Section 2 which find the “intensity” of innovation to significantly affect market structure: when the rate of innovation is very slow, innovation tends to lead to a more concentrated market structure (Geroski, 1990; Dosi and Orsenigo, 1987); concentrated markets are more conducive to innovation in low “technological opportunity” industries in which the science base moves relatively slowly and predictably (Comanor, 1967; Scherer, 1984); radical innovation and product innovation tend to produce less concentrated market structures (Lunn, 1986).

- In both dynamic positive and negative feedback, with a very high value for α, the emergent market structure is less concentrated since the fast speed of convergence between firms weakens the ability of the different feedback regimes to select between firms. In neither of these extreme cases (a high/low α) do market shares undergo changes in rank: the initially most fit firm predictably remains the market leader. This result confirms the empirical finding that in any given industry, market structure tends to be less concentrated in countries characterized by fast rates of innovation than in those characterized by low rates of innovation (Dosi, 1984; Acs and Audretsch, 1987) and that vigorous innovation tends to be more concentration reducing than increasing (Geroski, 1990; Mukhopadhyay, 1985).

- The case of dynamic positive feedback with an intermediate level of α, leads simply to an “in-between” result (as compared to the two extremes), again with the initially most efficient firm remaining the market leader and the exact value of α determining how many other firms co-exist with the leader. In the case of dynamic positive feedback, on the other hand, the results with an intermediate level of α are qualitatively very different. A turbulent switching pattern emerges due to the alternating advantages of firms; when a firm’s market share increases, the firm becomes less innovative and is surpassed in share by smaller more innovative firms. The final ranking of firms is unpredictable since the changes in rank continue until costs reach their lower bound, causing market shares to reach a steady state. This result confirms the empirical finding that market share instability tends to be higher during periods in which small firms have relative advantages in the innovative process, such as the early phase of the life-cycle and in industries characterized by “dynamic efficiency” (Acs and Audretsch, 1990; Klein, 1977; Klepper, 1996).
• The higher is the initial variance of costs, the greater is the degree of market share instability and the longer it takes for market shares to reach an equilibrium value. This result confirms the empirical finding that low levels of initial asymmetry in firm characteristics allow more firms to compete and a less concentrated market structure to emerge (Dosi and Orsenigo, 1987).

The results confirm the hypothesis found in Abernathy and Wayne (1974) and Klein (1977) where it is postulated that periods of dynamic efficiency lead to market share instability and periods of static efficiency lead to stability and concentration. The contribution of the model is to outline exactly under which conditions this hypothesis holds. We learn that processes of negative feedback should not be ignored by economists interested in disequilibrium dynamics!

In Section 3 we add shocks to the model to study the interaction between random and structural determinants of market structure. The question asked is “under what conditions do shocks have the most impact on market structure?”.

3 Modeling the Effect of Idiosyncratic Events on Positive/Negative Feedback

The validity of using a deterministic model to understand market structure comes into serious question when confronted with the increasing empirical and theoretical literature on the role of initial conditions and idiosyncratic events in influencing industry dynamics (Klepper and Graddy, 1990; Nelson, 1995). An empirical example can be found in Klepper and Graddy (1990) where industrial regularities are reproduced in a model which emphasizes how factors governing the early evolution of industries may shape their market structure at maturity. Stochastic concepts in this framework have a qualitative effect on the model, beyond adding “noise,” interacting with the underlying structural economic mechanisms. Under such conditions, it is impossible to know apriori which of many different possible market structures will emerge in any given run. Rather, one can:

“... record the particular set of random events leading to each solution and study the probability that a particular solution would emerge under a set of initial conditions.”

(Arthur, 1990)

Including a random element to costs allows us to partially capture the effect of uncertainty faced by firms in their production and innovation activities. In a non-linear system characterized by positive and negative feedback, shocks may determine early winners and losers and thus have a strong influence on the resulting dynamics:
“In the real world, if several similar-size firms entered a market at the same time, small fortuitous events - unexpected orders, chance meetings with buyers, managerial whims - would help determine which ones achieved early sales and, over time, which firm dominated. Economic activity is quantified by individual transactions that are too small to observe, and these small "random" events can accumulate and become magnified by positive feedbacks so as to determine the eventual outcome. These facts suggest(ed) that situations dominated by increasing returns should be modeled not as static deterministic problems but as dynamic processes based on random events and natural positive feedbacks, or nonlinearities.”

(Arthur 1990, p. 5)

We now test the different feedback regimes explored in Section 2b are tested below for how robust they are to such shocks. Given the results in the deterministic analysis, we should expect the turbulence produced by the phase of dynamic negative feedback to be more sensitive to shocks than the phase of dynamic positive feedback since even without shocks the industry structure and ranking of firms which emerges from negative feedback is unpredictable (with an intermediate \( \alpha \)). The market structure generated from positive feedback is probably more resistant to shocks since the force of selection is strongly biased towards the initially most efficient firm. Yet the presence of shocks should prevent, at least in the beginning, any one firm from getting too far ahead of other firms.

To examine the effect of a stochastic component on costs we embody different size shocks to Eq. (3):

\[
\frac{c_i}{c_{i-1}} = \lambda \cdot (-\beta (1- \varepsilon_i)) \varepsilon_i + (1- \lambda)(-\alpha \varepsilon_i) \varepsilon_i
\]  

(3*)

where \( \varepsilon_i \) is an i.i.d random variable drawn, at each moment in time for each firm \( i \), from a normal distribution with mean = 1. To study the effect of different size shocks on the model, we vary the variance level (\( \sigma \)) of this distribution. We experiment with values \( \sigma = 0, .05, .1, \) and .2. If, for example, we increase \( \sigma \) from .05 to .1, this means that the possible size of the shocks has increased although at any moment in time the shock might be small.

For each size shock, the simulations are run with a given initial distribution of costs with mean \( 1 \) and variance \( \gamma \) and with a given speed of cost adjustment parameter (\( \alpha \)). For each set of parameters, the results from 50 simulation runs are documented. We will assume that the reader knows that \( \lambda \) in Eq. (3*) is 0 in the positive feedback case and 1 in the negative feedback case. The results are presented both graphically as well as through tables. While the graphs serve to illustrate “typical” patterns from the simulations, the tables document the average statistics from the 50 runs with each set of parameters. For each set of parameters (\( \alpha, \gamma, \sigma \)), we first calculate the time period (TC) in which market shares settle down to a constant value. This is determined by the period in which the instability index (defined in Section 1) reaches the value .002. The
following data is then calculated at that time period: the herfindahl index (HI2), the cumulative instability index (II2: the integral of the instability index from $t = 0-TC$), the surviving number of firms (n), and the number of times the ranking between firms changed (R). The value of the instability index and the herfindahl index at the midway point (TC/2) are also calculated (under the heading III and HII). The values in the table for each of these statistics correspond to the average value which emerges from 50 simulation runs using the same set of parameters. Turbulence in market structure is portrayed through the combination of the instability index and the number of times firm ranking changes. The latter has been used by Gort (1963).

For each simulation we display four graphs; the first displays the market shares for the whole simulation run; the second displays market shares for a shorter time period so that the path of very early market share dynamics is more evident; the third displays the evolution of concentration through the changing herfindahl index; and the fourth displays the evolution of turbulence through the changing instability index. We always begin with the deterministic case for comparison. The economic interpretation of the results and a comparison of the results to those in similar studies (Arthur, 1990; Klepper and Graddy, 1990) are left to the conclusion in Section IV.

### a Stochastic Dynamic Positive Feedback

Whereas the deterministic simulation of the two different types of feedback allowed us to explore the hypothesis regarding innovation and instability found in Abernathy and Wayne (1974) and Klein (1977), adding shocks to the positive feedback scenario allows us to explore the life-cycle hypothesis described in Klepper (1996) and the path-dependent dynamics described in Arthur (1990). Both of these hypotheses state that early turbulence in market shares can result from the effect of idiosyncratic events on increasing returns. Although positive feedback will eventually cause a concentrated market to emerge, shocks will prevent this from happening monotonically.

We add a stochastic component to the case of positive feedback with the objective of observing whether and how the results found in the deterministic simulation of dynamic positive feedback (Figure 2b above) are altered. We begin again with the case of a low industry average rate of cost reduction. We recall that in the deterministic case, a very low $\alpha$ (inertia in costs) causes the force of selection to dominate industry evolution and thus the herfindahl index to always equal 1 and the firm with the initially lowest cost to predictably always become the market leader.

Figure 3 below illustrates the market patterns which emerge from stochastic dynamic positive feedback with a relatively low value of $\beta$ (=.02), a low variance of the initial cost distribution and different size shocks ($\sigma = 0, .05, .1, .2$):
Figure 3  Stochastic Dynamic positive feedback with $\beta=.02$, $\gamma=.1$, different $\sigma$

3a. $\beta=.02$, $\gamma=.1$, no shock

3b. $\beta=.02$, $\gamma=.1$, $\sigma=.05$
3c. $\beta = .2$, $\gamma = .1$, $\sigma = .1$

![Graphs showing Market Shares and Herfindahl Index for different scenarios.](image)

3d. $\beta = .2$, $\gamma = .1$, $\sigma = .2$

![Graphs showing Market Shares and Herfindahl Index for different scenarios.](image)
We see that in the stochastic positive feedback case, with a low value of $\beta$, it is still a concentrated market structure which emerges (as in the deterministic positive feedback case), yet the process towards concentration is not smooth as in the deterministic case but instead turbulent (in the deterministic case it was only with negative feedback and with a mid-level value for $\alpha$ that turbulence arose). It is thus not possible to know ex-ante which firm will become the market leader.

Table 1 in the Appendix illustrates that a *mid-size* shock ($\sigma = .1$) with a low $\beta$ causes the most turbulence and least concentration ($CI2 = 2.48, 4.04, 2.6; R = 2.3, 5.3, 3, HI2 = .98, .86, .90$). Instability first increases with shocks because the existence of shocks disrupts the force of selection caused by positive feedback. But if the shock is too big, turbulence decreases and concentration increases because the degree to which one firm can get shocked upwards or downwards is larger and hence so is the shakeout of firms. The mid-size shock also produces the longest time period before which market shares settle to a steady state ($TC = 63, 161, 76$). Except for the case of the very large shock, a higher variance of the initial cost distribution ($\gamma = .2$) causes the level of instability to be lower than with a lower variance level ($\gamma = .1$). This is because the higher is the degree to which firms are different from each other at the beginning, the stronger will be the early shakeout and the fewer firms there will be to experience the instability, and the shorter the time period in which the instability lasts ($TC = 63, 161, 76$ vs. $TC = 44, 43.5, 58$). This might be because the higher initial variance in firm efficiencies makes the market structure less vulnerable to shocks due to the stronger force of selection.

To conclude, the results indicate that shocks applied to dynamic positive feedback with a low industry average rate of cost reduction $\beta$ (or technological opportunity), cause the smooth and monotonic movement toward concentration in the deterministic case to be replaced with a more turbulent movement toward concentration, and that this is most true for *mid-size* shocks and a low initial level of variance between firm efficiencies.

Figure 4 illustrates the simulation results with a higher industry average rate of cost reduction: $\beta = .2$. We recall that in the deterministic case with a mid-level value for $\beta$, the final market structure is more competitive than with a very low $\beta$ (i.e. more than one surviving firm) but that firm ranking is still predictable (no market share switching):
Figure 4  Stochastic Dynamic positive feedback with $\beta = .2$, $\gamma = .1$, different $\sigma$

4a. $\beta = .2$, $\gamma = .1$, no shock

4b. $\beta = .2$, $\gamma = .1$, $\sigma = .05$
4c. $\beta = .2, \gamma = .1, \sigma = .1$

Market Shares

Herfindahl

4d. $\beta = .2, \gamma = .1, \sigma = .2$

Market Shares

Herfindahl

mstats
As was found in the deterministic case for both types of feedback, a faster average rate of cost reduction in the industry makes the market structure less concentrated than in the case of a lower level (compare the values of HI2 in the first, second and third columns of Table 1). Although the emergent market structure is always relatively concentrated, the shocks have the effect of creating turbulence in the process towards concentration. Yet unlike the case with a small $\beta$ (Fig. 3 above), shocks with a mid-size $\beta$ increase the number of surviving firms. This is because the larger $\beta$ causes selection to be much weaker than in the case of strong inertia (low $\beta$). As before, an increase in the shock size causes the market to be more concentrated (HI2 = .82, .84, .90) due to the effect of large shocks on the shakeout of firms. As in the case with a small value of $\beta$, the market evolution is most turbulent with mid-size shocks (CI2 = 2.08, 2.37, 2.04; R = 1.5, 5, 4).

A higher variance in the initial distribution of costs causes the market structure, with a given value of $\beta$ and $\sigma$, to be less concentrated (HI2 = .51, .62, .72) and less turbulent (CI2 = 1.78, 1.98, 2.3; R = 0, 1.6, 3.2). As in the case with a low value of $\beta$, increases in shock size cause an increase in the level of concentration and instability. This differs from the results with a low level of initial cost variance, in which concentration is lowest and instability highest with a mid-size shock.

To save space we describe the results for the case with a very high $\beta$ (=2) only verbally. In the deterministic case, the fast industry average rate of cost reduction causes market shares to converge to a steady state before switching has time to take place (HI2 = .29, CI2 = 1.37, R = 0, n = 5). There, the asymptotic market structure is one where several firms co-exist and where firm ranking is determined by the initial hierarchy of efficiency levels. In the stochastic case with a high value of $\beta$, the cumulative instability index is larger yet it decreases as the size of the shock increases (CI2 = 1.75, 1.67, 1.6; R = 1, 3.2, 2.6, n = 1, 3.2, 2.6). Shocks cause concentration to increase (HI2 = .46, .44, .53). Hence while the deterministic case with a high level of $\beta$ causes the market structure to be relatively competitive, in the stochastic case it is more concentrated due to the effect of market instability on the shakeout of firms. This might imply that in industries in which all firms' costs fall relatively quickly (due to a high level of technological opportunity) idiosyncratic events might prevent a relatively competitive market from emerging, as would instead be the case in the absence of those events.

A higher variance in the initial distribution of costs causes the herfindahl index to be larger than in the case of the lower variance (HI2 = .46, .44, .53 vs. HI2 = .660, .628, .725) and the level of turbulence to be lower. For any given level of $\beta$, a higher variance of the initial distribution of costs ($\gamma$) causes more turbulence and concentration. We document the summary statistics for the case of dynamic positive feedback in Table 1 of the Appendix and interpret the results in more detail after exploring the case of dynamic negative feedback below.

**b Stochastic Dynamic Negative Feedback**

In the deterministic model it was found that the market structure which emerges from dynamic negative feedback depends on the industry-specific average rate of cost reduction ($\alpha$) and the variance of the initial cost distribution ($\gamma$). When $\alpha$ is very low or very high, results similar to the case of deterministic dynamic positive feedback emerge. It is when average costs are falling at an
intermediate level, that the richness embodied in dynamic negative feedback is revealed; firm market shares undergo turbulence in the form of switching since as soon as a firm becomes large, its rate of cost reduction falls, and it is surpassed by a faster growing small firm. For any given level of →, the higher is the variance of the initial distribution of costs (•), the more turbulent and concentrated is the emergent market structure.

We start as usual with a low industry average rate of cost reduction and recall that in the deterministic case, when α is very low there is no turbulence in market shares; inertia overwhelms the dynamic and only the initially most fit firm survives. Figure 5 displays results with a relatively low speed of cost adjustment (α=.002), and a relatively low variance of the initial cost distribution (γ=.1).

Figure 5  Stochastic Negative feedback with α=.002, γ=.1, different σ

5a. α=.002, γ=.1, no shock
5b. $\alpha=.002, \gamma=.1, \sigma=.05$

5c. $\alpha=.002, \gamma=.1, \sigma=.1$
The dynamics illustrated in Fig. 5 indicate that, as in the case of stochastic dynamic positive feedback, the addition of a stochastic component to costs does not alter the emergence of concentration, it alters the path towards concentration and the final ranking of firms. However, unlike the deterministic case where turbulence and switching occur only with a mid-level value of $\alpha$, switching here emerges even with a low $\alpha$, and although concentration always results due to the effect of selection on inertia, the final leader is not (necessarily) the initially most efficient firm. This result was also found with a low level of $\alpha$ in the case of stochastic positive feedback.

The effect of different size shocks can be seen clearly in Table 2 of the Appendix. As the shock increases in size, the final herfindahl index decreases ($HI^2 = .98, .892, .77$) and the number of surviving firms increases ($n = 1, 1.2, 1.6$). A larger shock also makes the cumulative instability index rise ($CI^2 = 2.76, 4.08, 6.35$) and the number of changes in rank rise ($R = 3, 5, 6.2$). Larger shocks thus make the market more competitive on its way towards monopoly. Lastly, we note that with a given $\alpha$ and $\gamma$, increasing the size of the shock first makes the convergence time increase very much and then decrease ($TC = 70, 157, 137$). The convergence time is thus the longest with a mid-size shock. This is because a shock that is very large causes a strong shakeout of firms, while a shock that is not very large allows the selection mechanism to remain strong and hence one firm to dominate quickly; a mid size shock has the effect of increasing the path of turbulence and hence delaying the time of convergence to a steady state.
As was also noted in the deterministic case, with a given value of $\alpha$ and $\sigma$, the larger is the variance in the initial distribution of costs (except in the case with large shocks), the more concentrated and more turbulent is the resulting market structure ($H2 = .95, .97, .98; CI2 = 2.9, 5.57, 2.63; R = 2, 6, 4.3$).

Figure 6 illustrates the results with a mid-level value of $\alpha$. We recall that in the deterministic negative feedback case, a mid-level value of $\alpha$ causes the market to experience turbulence in market shares; switching and general instability emerge due to the effect of alternating advantages between firms.

**Figure 6**  Stochastic Negative feedback with $\alpha = .02$, $\gamma = .1$, different $\sigma$

6a. $\alpha = .02$, $\gamma = .1$, no shock
6b. $\alpha = .02, \gamma = .1, \sigma = .05$

6c. $\alpha = .02, \gamma = .1, \sigma = .1$
6d. \( \alpha = .02 , \gamma = .1 , \sigma = .2 \)

With the addition of a stochastic component to costs, instability is even stronger; shares do not only switch, as in the deterministic case, but also experience longer more frequent and jagged ups and downs. In Table 2 we see that as shocks increase, concentration rises (HI2 = .39, .71, .74) while instability falls (CI2= 4.6, 4.2, 4.58; R = 7, 5, 4). We also see that with a given value of \( \alpha \) and \( \gamma \), the larger is the shock the quicker market shares converge (TC = 296, 182, 166). This is different from the case of a very low level of \( \alpha \), where instead an increase in shock size caused the convergence time to first increase and then to decrease. The difference here is that the mid-size \( \alpha \) causes the market to be turbulent even in the deterministic case, and hence the increase in shock size causes the market to become excessively turbulent, “shaking” many firms out. This can also be noted by the fall in number of surviving firms as the shock gets larger (n = 3.6, 2.6, 2.2).

A higher variance in the initial cost distribution (\( \gamma = .2 \)) has the effect of increasing the instability of market shares in both the deterministic and the stochastic case.

To save space, we again omit the figures for the case with a very fast rate of cost reduction and describe the results verbally. In the deterministic case, a high \( \alpha \) caused the asymptotic market structure to be characterized by a relatively low level of concentration and no switching or changes in rank to occur. This was due to the fact that the effect of convergence (caused by costs falling very quickly for all firms) outweighed both the effect of selection and of negative feedback. We find that when the fast innovation regime is subjected to shocks, the shocks are not able to greatly alter the deterministic pattern; no switching, survival of all firms, and low concentration. This is different from the cases of a very low and mid level value for \( \alpha \) where instead shocks cause turbulence and changes in rank to emerge even when the final market structure is a monopoly. The inability of shocks to alter the deterministic pattern in the case of a
high $\alpha$ is due to the fact that convergence dominates both the process of selection and the two processes creating variety (negative feedback and shocks). Although this was also noted in the case of stochastic positive feedback, the impenetrability of the deterministic case with a high $\alpha$ is greater in the case of dynamic negative feedback.

In Table 2 we see that as the shock size increases, concentration increases but not by very much ($H_{i2} = .1, .127, .16$); turbulence increases ($C_{i2} = .307, .604, .822$; $R = 0, 2.3, 3$); and the convergence time increases ($T_{iC} = 19, 23, 27.3$). These same relationships emerge with a higher variance of the initial cost distribution ($\gamma = .1$).

**Summary of stochastic dynamic feedback:**

We summarize the results for the case of stochastic feedback below:

- Under stochastic positive feedback with *any* value of $\alpha$ (industry average rate of cost reduction), and under negative feedback with a *low* $\alpha$, although concentration still tends to emerge (in the former due to path-dependency and in the latter due to inertia), the process towards concentration is very different; turbulence precedes concentration, and the final leader is not necessarily the initially most efficient firm.

- The presence of shocks always renders unpredictable which firms will finally lead the industry: information regarding initial efficiency levels does not provide information on final ranking.

- When $\alpha$ is very high, the deterministic results are less affected by the presence of shocks. This is due to the fact that when the industry average rate of cost reduction is high, convergence dominates both the process of selection as well as the negative/positive feedback process creating variety between firms. This result is even stronger in the case of negative feedback. This implies that in industries in which the average rate of cost reduction is very high, idiosyncratic events have less of an impact on industry evolution. The stochastic case with a high $\alpha$ produces a less competitive market structure than the deterministic case with a high $\alpha$. *This implies that in industries with a fast average rate of cost reduction, the occurrence of shocks (idiosyncratic events) might produce a less competitive market structure than the case in absence of those “events”.*

- Market share instability is greatest with mid-size shocks since small shocks are not very “disturbing” and large shocks cause too large of a shakeout and hence early concentration. In the stochastic negative feedback case with a mid-level speed of cost reduction parameter, instability is higher than in the deterministic case; shares do not only undergo changes in rank and switching but also experience longer more frequent and jagged ups and downs. *Emphasis should thus not be placed only on large radical events affecting change but also and especially on minor events.*
• In the case of stochastic negative feedback with a low $\alpha$, although the market tends to become concentrated (as in the deterministic case), as the shock size increases, the degree of concentration decreases and the instability index rises. Larger shocks thus make the market more competitive on its way to monopoly.

• In the case of stochastic dynamic positive feedback, a higher variance of the initial cost distribution, causes the level of instability to be lower than with a lower variance. This might be because the higher degree of initial differences between firms makes the market structure less vulnerable to shocks due to the stronger force of selection.

• In both types of feedback, when costs change very slowly convergence to stability (instability index $= .002$) takes the longest time to occur with a mid-size shock. This is because large shocks cause many firms to exit, while small shocks cause the selection mechanism to remain strong. The mid-size shock has the effect of increasing turbulence and hence delaying the time of convergence to a steady state. This result does not hold under decreasing returns with a mid-level $\alpha$, where instead an increase in shock size causes the convergence time to first increase and then to decrease. This is because the mid-size $\alpha$ under negative feedback causes the market to be turbulent even without a shock, hence the increase in shock size causes the market to become excessively turbulent.

5 Conclusion

The stochastic analysis allows us to better understand the particular role of randomness in industry evolution. A deterministic and a stochastic version of the model were developed separately so that the interaction between structural and random factors could be explored. As opposed to studies which make all underlying dynamics based on stochastic shocks (e.g. firm growth modeled as a Gibrat process), economic change occurs in the model due to the interaction between initial conditions, shocks and the underlying non-linear structural dynamics related to firm size.

The patterns that emerge from the stochastic model shed light on Klepper’s (1996) hypothesis that market share turbulence during the early phase of the industry life-cycle, and/or in certain types of industries, might be the result of idiosyncratic (random) events which disrupt the path-dependent effects of selection under positive feedback:

"The result (of increasing returns) is a world in which initial firm differences get magnified as size begets size... The starkness of the model precludes any departures from this evolutionary pattern. This can be remedied by allowing for random events that alter the relative standing of incumbents and potential entrants. If cohorts differ in terms of the distribution of their innovative expertise or if the innovative expertise of incumbents is undermined by certain types of technological changes, then later entrants may leapfrog over the industry leaders and the firms
that eventually dominate the industry may not come from the earliest cohort of entrants."
(Klepper 1996, p. 581)

We explored the degree to which shocks affect the path-dependent pattern under different types of conditions. The industry-specific conditions included the type of feedback regulating the relationship between firm size and innovation, the average rate of cost reduction in the industry (or technological opportunity), and the different level of initial asymmetry between firms.

The deterministic analysis indicates that when small firms are favored in the process of innovation (dynamic negative feedback), the market structure tends to be more unstable (with switching in firm ranking) and less concentrated. When instead it is larger firms that have the innovative advantage (dynamic positive feedback), the emergent market structure tends to be more concentrated and stable (concentration emerges without any switching in firm market shares). The exact patterns are determined by the industry-specific speed of cost reduction parameter ($\alpha$) as well as by the parameter describing the initial variance between firm efficiencies ($\gamma$).

In the stochastic version of the model, new results emerge. Under positive feedback, and under negative feedback with a very low speed of cost reduction parameter, although concentration still tends to emerge, the process towards concentration is very different from the deterministic case. Market share switching and general instability precedes concentration, so that observers only interested in the asymptotic level of concentration risk missing important qualitative information regarding industry evolution. That is, to fully understand market evolution, one should not only look at the level of concentration at one point in time, but also the process of instability and concentration which leads up to that state. The stochastic model illustrated that the empirical regularities can be reproduced by those life-cycle studies which emphasize the effect of idiosyncratic events on positive feedback (Klepper and Graddy, 1990; Klepper, 1996; Arthur, 1990).

It was found that when the speed of cost adjustment parameter is very high, the deterministic results are less affected by the presence of shocks. This implies that in industries in which the rate of diffusion is very high (for example in industries with a "codifiable" knowledge base), idiosyncratic events have less of an effect on industry evolution. In both types of feedback, turbulence (as measured by the instability index and the rank index) was found to be the highest with mid-size shocks since small shocks are not very "disturbing" and large shocks cause too large of a shakeout and hence early concentration. In the stochastic negative feedback case with a mid-level speed of cost reduction parameter, instability was higher than in the deterministic case: shares do not only undergo changes in rank and switching but also experience longer more frequent and jagged ups and downs. Emphasis should thus not be placed only on large radical events affecting change but also and especially on minor events.
APPENDIX

For each size shock, Table 1 (positive feedback) and Table 2 (negative feedback) document the average statistics from 50 simulation runs with each set of parameters. The parameters include $\sigma = \text{the variance of the distribution from which the shocks are chosen}$, $\beta$ and $\alpha = \text{the industry specific speed of cost reduction under positive and negative feedback}$, and $\gamma = \text{the variance of the initial cost distribution}$. First, the time period (TC) is calculated as the time period when market shares settle down to a constant value (i.e. when the instability index reaches the value of .002). Then the following statistics are calculated at TC: the Herfindahl index (HI2), the Instability index (II2), the Cumulative Instability Index (CI2=the integral of the Instability index from $t=0$-TC) the surviving number of firms (n), and the number of times the ranking between firms changes (R). The value of the first three statistics at the mid-way point (TC/2) are also calculated under the heading HII, II1, CI1.
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In 1999, approximately £250,000 million worth of externally funded grants (3 from the ESRC) were held by discipline members, some of whom also act as consultants to national and international bodies. Approximately half a dozen students are currently reading for doctorates with members of the discipline and we are always interested in proposals from colleagues or potential students who would like to do research with us.