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The economics of path-dependence in industrial organization[1]

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Abstract

Path-dependence defines the set of dynamic processes where small events have long-lasting consequences that economic action at each moment can modify yet only to a limited extent. Path-dependence is analytically generated by the overlapping of irreversibility, indivisibility and structural actions of agents. It makes it possible to allow both for the effects of past behaviour of agents on the structure of the environment and the Lamarckian survival of agents by learning and adaptation to the character of the environment; hence it provides a framework to understand and to model the effects of historic time on the behaviour of agents which are able at each point in time to modify their evolution. © 1997 Elsevier Science B.V.

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1. Introduction

Path-dependence defines the set of dynamic processes where small events have long-lasting consequences that economic action at each moment can modify yet

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only to a limited extent. The trajectory of a path-dependent process however cannot be fully anticipated on the basis of the original events. Path-dependence is different from past-dependence because the former is able to accommodate the consequences of actions at each point in time. Path-dependence analysis is systemic and dynamic because it focuses attention on the process of change that is generated by the interaction of a plurality and variety of agents whose behaviour is constrained by their localization in time. Path-dependence is analytically generated by the overlapping of irreversibility, indivisibility and structural action of agents as opposed to parametric behaviour.

In this context irreversibility and indivisibility assume a radical new flavour. Although irreversibility and indivisibility per se are well known tools for economists, their combination with structural action uncovers a new area for economic analysis. Irreversibility and indivisibility per se are at the origin of well known classes of market failures. The overlapping of the different classes of indivisibility and irreversibility with structural action however generates dynamic processes that display their effects over time with important effects in terms of multiple equilibria and discontinuity. The transition from out-of-equilibrium conditions towards equilibrium can be impeded or delayed for ever.

Irreversibility is well known to industrial economics. It can be defined as the difficulty of changing a given behaviour or choice. Hence it can be measured by the opportunity costs that arise at time $t+1$ from any attempt to change a commitment to a given behaviour or choice taken at time t. A variety of phenomena can be classified under the heading irreversibility: (i) switching costs for both consumers and producers when facing the opportunity to change the mix of products or production factors that enter their current bundle; (ii) all classes of sunk costs associated with the difference in the market value for assets ex ante and ex post their purchase.

Indivisibility among production factors leads to a variety of well known phenomena such as technical and pecuniary economies of scale, externalities and economies of scope. Indivisibility and irreversibility are highlighted when economic analysis focuses attention on the role of information as an economic good. Reputation is the outcome of irreversibility and information impactedness. Transaction costs are clearly the outcome of a special class of indivisibility. Low levels of appropriability and learning can both be portrayed as aspects of the more general problem of indivisibility. In turn inappropriability has important dynamic implications in terms of interdependence among innovators and users–producers interactions which leads to clustering of innovative activities in technological districts and industrial filieres and spillovers, that is opportunity of imitation and technological recombination and hence free rider behaviour.

Standard economics is built on strict assumptions about the scope of economic action. Economic agents are induced to act only by optimization procedures and their action is strictly parametric in that it consists only in adjustments of prices to quantities or quantities to prices. Structural action, that is the intentional change of either the technology in the production function or tastes in the utility function is out of the scope of economics standards. Tastes and technologies can change but strictly in response to exogeneous forces.

When structural action is allowed for, tastes and technology become endogenous variables that are determined by the interaction of agents who can purposely change their own production functions and utility functions. Learning processes play a major role among the determinants of structural action. Learning consists of a peculiar class of indivisibility in that agents while manufacturing or selling also learn about technologies and market conditions. A large body of literature has explored the different categories of learning: (i) learning by doing; (ii) learning by using; (iii) learning by consuming; (iv) learning to learn (Arrow, 1962; Stiglitz, 1987; Malerba, 1992). Moreover the utility and production functions of each agent can be influenced by the actions, both intentional and unintentional, of other agents. Hence structural change can be viewed as the outcome of an autonomous effort of learning agents as well the result of a change in conduct induced by the action of other parties. In this approach firms do more than adjust prices to quantities and vice versa; they are also able to manipulate interactively the basic structure of the system. Technologies and tastes at time t are the outcome of the interaction in the marketplace of agents at time $t-1$. Hence, market interaction determines not only quantities and prices but also new technologies and tastes.

The analysis of the interactions and combinations of the different specifications of irreversibility and indivisibility provides elements for building a new approach to understanding industrial change and more broadly economic change; one where they are the building elements of an evolutionary process of change in which historic time matters instead of the factors of some well circumscribed classes of market failures.

When economic growth is path-dependent, stationary state theory is not an adequate analytical framework (Rosenstein Rodan, 1934; Abramovitz, 1938). Agents are exposed to changes that take place in such a way that their behaviour and their expectations are deeply affected. Path dependence in fact should be considered a macroeconomic process, of which each agent does not necessarily have a full understanding and clear command of the sequence and timing of each stage. So far time matters as a source of uncertainty about the consequences of each action. Second, when path dependence is at work time matters because of irreversibility; the sequence of growth stages in fact cannot be reversed and the time profile of each action has important effects. Consequently time matters because it affects selection processes: the 'tendency' towards equilibrium is in fact dramatically altered by changing market conditions. Finally time matters because the outcome of any adjustment process of market dynamics is dependent upon the characters of the initial conditions of market forces and the behaviour of agents at any point of time. When path-dependent growth is at work, stationary economics has little to say about the real dynamics of market forces and the behaviour of firms for given initial conditions of disequilibrium.

In the industrial organization tradition economic agents are assumed to be able to change the basic structure of their system, that is production functions and utility functions. A variety of models and empirical studies has explored the effects of research and development expenditures on the growth of total factor productivity of firms, the relation between demand pressures and the direction of technological changes, the effects of changes in the relative prices of production factors as inducement mechanisms to foster the rate of introduction of innovations as well as their direction in terms of factor intensity. A large body of literature has assessed the effects of advertisement expenditures on the elasticity of demand curves for the products of firms.

Industrial structures are featured by high levels of heterogeneity of sectors in terms of rates of growth and firms in terms of size, age, organization, innovation and learning capabilities, input costs, market conduct and most importantly in terms of performance such as profitability, productivity and output growth. Such diversity is persistent and self-reinforcing. Industrial organization has explored in significant detail a variety of partial dynamic processes that help to understand the causal factors behind the evidence of the variety of cumulative growth processes that characterizes industrial economies. Yet it often fails to provide a general framework that accommodates such a variety of partial analyses. Path dependence can help to constitute a general framework to study the evolution of industries and firms.

2. Dynamics in industrial economics

Industrial economics has long analyzed the implications of the interactions of the different classes of structural action, indivisibility and irreversibility and has generated a variety of important models that are usually found dispersed in different chapters of textbooks.

The basic classes of dynamic phenomena that have been so far detected in this rich literature can be classified in two categories. The dynamics explored by industrial economics in fact consists of two different processes: the endogenous processes of change and the endogenous persistence of out-of-equilibrium behaviour. Both reveal that the system is characterized by a plurality of attractors and forces that go well beyond the limits of standard equilibrium analysis (Greenwald and Stiglitz, 1989).

More specifically important models have been built on the interaction between different classes of structural action, irreversibility and indivisibility in the theory of the firm, in the theory of demand, in the theory of markets, in the economics of structural change and industrial dynamics, in the economics of regions, in the economics of innovation and new technology. More generally industrial economics has tried many times to appreciate the relevance of the overlapping of irreversibility and indivisibility so as to produce a theory of industrial dynamics that could integrate their effects rather than listing them as special classes of market failure. Significant attempts so far have been developed along four axes:

1. The diffusion of innovations and the selection of new technologies.
2. The notion of economies of growth in the theory of the firm.
3. The structure-conduct-performance approach and its dynamic applications.
4. The structural change and industrial dynamics approach.

Let us review them in turn.

2.1. From the diffusion of innovations to the selection of new technologies

The diffusion of innovations has long provided the basic field of analysis to appreciate the long-lasting effects of increasing returns and irreversibility (Mansfield, 1961).

The diffusion of innovations, that is the distribution of delays in the adoption of new technologies has long been understood in terms of increasing returns due to externalities in the assessment of information necessary to evaluate the new products being introduced in the marketplace. The larger the number of users of a new product is, the lower are the information costs necessary to appreciate the characteristics of the new products. The adoption of new goods among consumers is first delayed by transaction costs originating in the lack of reputation of the new products and the difficulty of assessing their actual utility. Eventually, however, when a critical mass of new consumers has been built up a fast diffusion process among users can take off. The epidemic contagion is the outcome of the flow of information made available in the marketplace by each new user. Moreover increasing returns on the demand side, due to complementarity with other products or skills, favour the reduction of the hedonic prices for products that happened to be selected first, and hence their diffusion. Irreversibility plays a major role in the selection of the new product: switching costs delay the adoption of new technologies that are superior only when sunk costs are not accounted for while increasing returns on the supply side favour the reduction in costs and prices of new products that happened to be selected first, and, hence, their diffusion (Stoneman, 1983).

The diffusion of innovations had long being analyzed as if just one new superior technology had been introduced at each moment. A major shift took place in this literature when it became more and more clear that the diffusion of an innovation is the outcome of a complex process where: (1) a wave of new rival products is introduced in the marketplace, (2) intense competition takes place, (3) progressively a subset of them win out in the selection process against similar rival new goods, and (4) is eventually diffused, that is adopted by large numbers of potential users.

Increasing returns to adoption and positive feedbacks play major roles as determinants of such a process. Increasing returns to adoption stem from the combination of four distinct class of dynamic forces: (i) learning to use and learning by doing; (ii) network externalities; (iii) economies of scale in production; (iv) technological complementarities and interrelatedness. The dynamics of interdependent diffusion of new complementary products on the demand side and of imitation processes on the supply side leads to irreversibility. Technologies that happened to be selected first have greater chances to diffuse faster and eventually become the standard (Katz and Shapiro, 1986; Farell and Saloner, 1985; Foray, 1989). Economic systems may be locked in technological choices that are actually inferior to other possible alternatives (David, 1985; Arthur, 1989; Cowan, 1991).

The new economics of technological choice under conditions of increasing returns, indivisibility and irreversibility makes it possible to grasp the pervasive role of two classes of dynamic processes (Foray, 1997):

1. Excess momentum: i.e. hysteric processes of change and growth. The persistence of dynamic behaviour even when agents are not stimulated to adjust to any exogeneous change is the outcome of some endogenous dynamic forces that cannot be reduced to adjustment processes.
2. Excess inertia and inelastic adjustments, i.e. the lack of proper reactions to given incentives. Behaviours that have been chosen in some circumstances are retained even when the parameters of the system change by some attrition forces that should be properly analyzed.

As a matter of fact however the pervasive role of excess momentum and excess inertia was already well known in the industrial economics literature.

2.2. *Economies of growth in the theory of the firm*

In the theory of the firm the notion of growth economies has been touched upon at different times and with different specifications. The basic argument is that unit costs tend to decrease along with the rates of growth of output. Formally this can be expressed by the following equation:

$$AC = F(\mathrm{d}Y) \text{ with } F' < 0, \tag{1}$$

where AC are the average costs and Y is the output.

This notion is at odds with the received theory in which we have a representative firm that produces near the conditions of equilibrium. In the received theory firms can experience economies of growth only when they are small and the optimum size is large. In this case the faster the growth rates the closer they get to the equilibrium output. Because of growth firms are then expected to be able to shift along a given L-shaped average cost curve with a negative slope that reaches a minimum after which no further economies of scale can be attained. In such a case the relationship between average costs and rates of growth would be clearly a spurious one, hiding the more substantial relationship difference between actual (small) sizes and optimum ones. The evidence on the dynamics of firms size confirms the strong relevance of the so-called Gibrat law according to which growth is proportionate to size independently of the relative size of each firm (Gibrat, 1931). Gibrat's law states that both small and large firms grow at a rate which is simply proportional to their size with no actual convergence in the distribution of sizes towards a given optimum size. In this context there is no trend towards convergence in the size of firm. On the contrary the given initial spread of sizes tends to persist over time. Hence, economies of growth lead to a classic case of excess inertia and hysteresis in the composition of the population of firms in a system (Hart, 1962; Hymer and Pashigian, 1962; Mansfield, 1962).

The evidence of continuing advantages from growth which applies equally to the full spectrum of small and large firms calls for an alternative explanation, one where dynamic forces are at play. The emergence of economies of growth at the firm level seems to be the outcome of an application in microeconomics of the endogenous processes of growth analyzed at the system levels by Kaldor (Momigliano, 1974; Lazonick, 1990). Their analytical foundation consists in rejecting the basic assumptions about the exogeneous and static character of technology in the production function and tastes in utility functions. Endogenous technological change, endogenous formation of consumer tastes learning processes, indivisibility and irreversibility are the analytical blocks on which economies of growth are currently built.

(1) Irreversibility of production factors generates the basic incentives for the firm to grow. Density economies account for economies of growth when substantial expenses are anticipated and sunk not only in fixed capital (Sutton, 1991), but also in reputation, research and development activities, marketing outlays that can be used, with no additional expenses by large quantities of incremental output. Moreover according to Arrow (1974) information channels necessary to manage a firm are the result of long-lasting investments and constitute a substantial piece of dedicated capital stock, highly specific and idiosyncratic which it is difficult to replace or reutilize in different circumstances. Moreover the capacity of communication channels is very large and additional information flows can be carried on with limited levels of additional investments. Once firms have made such an irreversible commitment and poured funds into building communication channels the advantages of making an intensive use of them grow without limitation (Antonelli, 1992). Hence firms have a clear incentive to grow because the larger their size the better use they make of dedicated resources sunk into communication channels that constitute the fabric of organizations. Lazonick (1990) stresses that irreversibility of large amounts of capital stocks sunk into fixed production factors and anticipated in organization and intangible capital accounts for the steep negative slope of average and marginal cost curves. The

larger the output the lower are the costs and the larger is the amount of internally generated funds available to finance new generations of fixed capital and especially to introduce better and more sophisticated technologies and organizational structures (Simon, 1951; Langlois, 1986).

(2) All learning processes favour the emergence of economies of growth. The basic argument here is that the larger are the levels of cumulated output and the larger is the experience acquired by agents, the larger is the reduction in costs. Learning economies have many implications for industrial organization. First of all the age of firms becomes an important issue in understanding the distribution of sizes in the population of firms and their dynamics. The interaction between technical economies of scale and learning leads to variety among firms. Old firms can be small and yet as efficient as young larger ones which benefit from technical economies of scale. Second, for some levels of market prices, sticky in the short term, a self-propelling process of growth takes place. The larger the cumulated output the larger is experience, hence the smaller are the costs and market prices of each learning firms, hence the larger can be the growth in size. Larger size via learning processes induces new reductions in costs, prices and hence increase of output. Thirdly, and most importantly, a variety of learning processes have been detected and each of them stresses different aspects of the behaviour of firms. Learning to do relates the learning process to production activities, learning to use to investment activities, learning to learn to research activities, learning to interact to user–producer interactions. The analysis of the interactions among these different classes of learning opens the way to understanding economies of growth as an interdependent process of organic development of the capabilities acquired in managing the current business (Rosenberg, 1982; Stiglitz, 1987; Cohen and Levinthal, 1989).

(3) The interaction between irreversibility and learning leads to endogenous processes of introduction of localized technological changes along technological trajectories. Irreversibility of the mix of production factors and organization generates switching costs when either relative prices of production factors change or demand increases. Changes in factor costs and demand increases would push firms to adjust their production techniques and size to the new required levels. Switching costs however make adjustments expensive and difficult. Limited information about new techniques adds to the costs of mobility in the techniques space. On the other hand learning by doing and learning by using have generated localized competencies that can be mobilized in order to cope with new economic conditions. In such circumstances the trade-off between the switching costs necessary to adjust within a given technology and the R&D expenses necessary to capitalize upon localized learning induce firms to generate localized technological changes that make it possible to retain factor intensity and size of input, and yet to increase total factor productivity. The interaction between switching costs and localized technological change leads to economies of growth when dimensional switching costs matter. The larger the demand pull the larger the amount of

localized technological change, hence the larger is the increase in total factor productivity and for some given sticky market prices for the products of the firm, the larger the opportunity to increase the levels of output which leads to further increases in total factor productivity growth. Localized technological change pushed by demand growth leads to excess momentum within self-propelling processes. Localized technological change induced by changes in the relative prices of production factors leads to excess inertia in production techniques and factor intensity (Atkinson and Stiglitz, 1969; David, 1975; Antonelli, 1995a, 1996a).

(4) The interaction between economies of scale and economies of scope leads to economies of growth by diversification (Penrose, 1959). According to Chandler (1990) the basic engine of economies of growth consists in the interaction between economies of scale and economies of scope. Production processes are characterised by indivisibilities and bundles of specific and strictly interrelated techniques which exhibit a clear potential for economies of scope. Firms have an incentive to increase their size to reap the advantages of technical economies of scale. The new size however uncovers a potential for hidden economies of scope. The larger the size in one given line of business the larger the incentive to increase the division of labor within the firm and to specialize some production units into some specific production processes originally bundled in with others. Specialization makes it possible to reduce production costs. Each of the production processes so far specified is in turn characterized by economies of scale that push firms to grow in each of the newly specified production processes.

(5) The interaction between inappropriability, learning and economies of scale leads to multinational growth. A specification of the process elaborated by Chandler has been provided by Dunning (1981); Caves (1982) to explain the multinational growth of firms. Here the building of a technological capacity plays a central role together with the notion of transaction costs for technological know-how. Firms are learning organizations that are able to build a technological capacity. Tradeability of technological know-how, especially in international markets, is hindered by inappropriability problems and the related high risks of opportunistic behaviour. Firms are now induced to establish affiliates abroad to take advantage of the technological know-how elaborated while managing current business in domestic markets.

(6) The interaction between growth, investments and anticipated adoption of capital goods provides one more argument to understand economies of growth. Firms with fast rates of growth can fund the high levels of net investment necessary to adjust their production capacity to the larger desired levels of output. The distinction between net and replacement investment, together with a trend in the generation of technological change plays a crucial role here. Net investment can purchase new vintages of capital stock that embody better technologies. Replacement investment instead is slowed by sunk costs of existing capital stocks. Firms with faster rates of growth can embody better technologies, hence

experience a reduction in costs, and for some sticky market prices, increase their output which in turn leads to new investments, faster adoption of new technologies and further reduction in costs. Firms with lower rates of growth are less able to fund investments to expand their production capacity. Replacement of existing capital stock with older vintages in fact is slowed by sunk costs (Salter, 1966; Antonelli et al., 1992).

2.3. Structure-conduct-performance and structure (t+1)

In the traditional structure-conduct-performance analysis the conduct of firms was determined by the industrial structure especially in terms of barriers to entry and concentration. In turn performances of firms were determined by conduct.

This original representation was essentially static and to a large extent it reproduced the basic elements of the neoclassical paradigm assuming that the behaviour of firms could not have any bearing on the structural characters of the system. The original static representation however underwent major changes when the term structure $(t+1)$ was added by Almarin Phillips (Phillips, 1970, 1971) to the traditional sequence. Now the structure of the industry could no longer be regarded as a given exogeneous state but rather as itself part of a dynamic process which was exposed to the effects of the behaviour of agents. A recursive process now emerges in which firms at the same time decide their conduct on the basis of the present features of the structure and select a behaviour that generates performance as well as some changes, both intended and unintended, in the structure of the system.

The introduction of endogenous technological innovations that reshape the cost curve and hence the advantages of incumbents with respect to potential entrants as well as the longlasting consequences of advertisement strategies on the reputation of firms are simple examples of a recursive process of change where the features of the system at time $t+1$ are influenced by the conduct of firms at time t.

When the structure of a market is the endogenous product of the behaviour, both explicit and unintended, of firms the notion of barriers to entry itself needs to be enlarged. Increasing returns and sunk costs associated with reputation reduce the risks of failure for incumbents, hence barriers to exit. Irreversibility and sunk costs reduce mobility of firms across sectors, hence mobility barriers.

More generally the notion of dynamic barriers is re-emerging. Dynamic barriers are the barriers to growth for marginal competitors. Within dynamic barriers marginal competitors have slower and more irregular rates of growth while incumbents are able to take full advantage of economies of growth. In the 1960s in fact a large empirical literature had already documented the advantages for large firms with market power in terms of steady rates of growth as opposed to irregular growth cycles for smaller, marginal firms (Caves and Porter, 1977; Kamien and Schwartz, 1982; Jacquemin, 1985). In such a theory of markets we see the following.

(1) Entry barriers springing from economies of scale and reputation delay the entry of newcomers and hence protect the quasi-rents of incumbents which in turn feed new investments in R&D and reputation-building activities which increase the unit costs for small potential entrants. Barriers to entry are here the outcome of both the conduct and the performances of incumbents. The conduct of incumbents is oriented towards the erection of barriers to entry when strategies that are associated with high levels of sunk costs, learning opportunities and large optimum sizes are selected. They all imply in fact significant asymmetric differential effects for smaller newcomers which can spread the fixed costs over smaller volumes of output. Moreover the selection and endogenous generation of new technologies with large optimum sizes and steep negative portions of cost curves for small firms becomes an essential factor in building the height of new barriers to entry. The performances have structural effects in terms of increasing the height of barriers to entry especially in terms of the interaction between high levels of economic profits and lower constraints due to funding risky and uncertain activities such as R&D when external financial markets incur high information costs to assess the profitability of borrowing for risky undertakings (Mueller, 1986; Stiglitz, 1988; Geroski, 1991).

(2) Increasing returns and sunk costs combined with the introduction of innovations favour the persistence of profits above the norm even with low levels of barriers to entry, if there are significant barriers to imitation. This is the well known Schumpeterian Mark II model where firms that happen to be able to introduce an innovation at time *t* are able to earn profits above the norm for a long period of time. Quasi-rents generated by an early innovation can be partly used to fund high levels of R&D expenditures. High levels of R&D expenditures increase the chances to generate a new wave of innovations and hence the possibility of maintaining the same time high levels of profit and high rates of introduction of innovations simultaneously. Each successful innovation makes it possible to spread the costs of R&D expenses on large quantities of cumulated output and hence to reduce unit costs so to increase further profitability. Barriers to imitation can be built by innovating firms when selecting and generating new technologies with high levels of information impactedness and complexity that reduce the risks of unintended leakage (Sylos Labini, 1962, 1984).

(3) The interaction between barriers to entry, profits above the norm and learning leads to the persistence of innovative activity. Barriers to entry and related quasi-rents make it possible for firms to internally fund high levels of R&D activities. External borrowing for risky undertakings is in fact likely to be hindered by asymmetric information and limited rationality of bankers and the financial markets. Hence R&D activities can be funded only with (or largely with) internal funds. Larger R&D activities, for a given distribution probability are likely to generate faster rates of introduction of technological innovations. When economies of scale in conducting research activities are allowed for a larger R&D budget can generate more than proportionate rates of introduction of technological innova-

tions. Such an outcome is also likely to take place when learning to learn matters. Finally when appropriability is low and market power measured by barriers to entry limits imitation innovators can retain the quasi-rents associated with an early innovation for a longer time span, hence they can fund larger R&D activities and have greater chances to be able to generate faster rates of innovations. Early innovators are likely to experience rates of introduction of innovation persistently above the average (Malerba, 1992; Mueller, 1987).

(4) Endogenous changes of utility functions where tastes are influenced by advertising and other intentional strategies of firms as well as by reputation effects caused by bounded rationality of consumers and 'gregarious' imitation, become relevant. The interaction of economies of scale in advertisement and increasing returns from demand externalities makes for the emergence of a new class of self-sustained barriers to entry. Firms that enjoy the advantages of barriers to entry at time t can invest internally generated funds in reputation building and perpetuate or even increase their profitability and cost advantage over potential competitors. Economies of scale in advertisement play a major role. Reputation engendered by demand externalities moreover can provide long-lasting advantages to incumbents even without advertisement expenses. It is sufficient that learning processes take place on the demand side when tastes are assumed to be endogenous. Such demand externalities can take a variety of forms: (i) the larger the number of consumers of a given product, the larger is the utility each consumer extract from such a product; (ii) the larger the quantity of products sold in the marketplace the larger is the utility each consumer extracts from that product; (iii) the longer the time span over which a given product has been sold in the marketplace the larger is the utility each consumer extracts from it; (iv) the larger the stock of products sold, that is the cumulated quantity of goods still used by other consumers, the larger is the utility each consumer extracts from it. When such conditions apply the demand curve for such products is larger and steeper than that for rival goods. Proper advertisement strategies can add to the processes of endogenous taste formation, so that small amounts of advertisement expenses have long-lasting effects when associated with solid reputation effects engendered by demand externalities. In such conditions self-propelling barriers to entry are generated. The larger the output at time t the larger the reputation at time $t+1$, hence the larger the height of barriers to entry and the larger the quasi-rents that can be partly used to fund advertisement expenses that help to increase further the height of new barriers to entry (Schmalensee, 1986; Spence, 1980; Jacquemin, 1985).

(5) The interaction between externalities, economies of scale, entry and birth rate of new firms favours the clustering of economic activities in limited regions with the emergence of asymmetric dynamic barriers to entry. The dynamics of specialization and division of labor of interrelated production processes push the emergence of regional and industrial clusters. Dynamic externalities play a major role when the natality of firms is explained. New firms are born in clusters and

along technological 'filieres' where new opportunities spilling in the regional and technological system are available. Indivisibility and inappropriability are causal factors of increasing returns both internal and external to firms. The interaction between demand effects exerted by incumbents and externalities spilling from their current activities interact so as to attract new firms in well defined niches, defined either regionally or technologically. The classical conditions for self-propelling processes are again well set. Economies of scale push firms to grow internally and to increase the derived demand for intermediate inputs which provide additional demand for new specialized firms. Interdependence among innovators and user–producer interactions leads to clustering of innovative activities in technological districts and technological systems. Technological, technical and pecuniary externalities favour birth and entry of new firms which in turn are likely to engender new waves of externalities which attract new waves of entrants. Firms outside these clusters experience increasing barriers to entry while firms within clusters face the lowering of barriers to entry (Becattini, 1987; David and Rosenbloom, 1990; Krugman, 1992; Carlsson and Stankiewitz, 1991).

2.4. Industrial growth retardation

The hypothesis of retardation in industrial growth has long been considered in the classic industrial economics literature, and especially in the 1930s. The empirical evidence about retardation shows that industrial growth follows a well defined 'secular' movement according to which three well defined phases can be identified: (I) a first phase of slow growth; (II) a short period of dramatic surge of output; (III) a prolonged phase of slow growth that tends to an asymptotic level of cumulated output. One of the most clear analyses has been provided by Kuznets (1930) who notes that retardation characterizes the growth of single industries: "As we observe the various industries within a given national system, we see that the lead in development shifts from one branch to another. The main reason for this shift seems to be that a rapidly developing industry does not continue its vigorous growth indefinitely, but slackens its pace after a time, and it is overtaken by industries whose period of rapid development comes later" (Kuznets, 1930 p. 5).

The problem of retardation, so clearly identified by Kuznets (1930); Burns (1934), has been substantially overlooked in the post-war literature, except for the applications to the theory of international trade and foreign direct investment termed by Vernon (1966) as the product life cycle. More recently it has been rediscovered to explain the evolution of industrial structures: many growth industries that had characterized the post-war period, such as motor-cars, airplanes, chemicals, have in fact experienced in most industrialized countries since the mid-1970s a significant decline in the rates of growth of output, productivity and employment, after reaching asymptotic levels of cumulated output (Freeman et al., 1982).

The broader approach to structural change and economic dynamics has been built on the retardation hypothesis. The structural change and economic dynamics literature rely on three founding blocks:

1. A theory of endogenous technological change.
2. A theory of demand based on endogenous changes of utility functions where the evolution of consumer tastes is influenced by income levels and by gregarious behaviours.
3. A theory of indivisibility and complementarity in production processes and consumption patterns.

(1) The analysis of Kuznets has received growing attention in recent years and a large body of literature has explored the causes and effects of the distribution of innovative activity within industries. Technological change is inherently characterized by the sequence between product and process innovations because of the features of competition processes in industries and learning in manufacturing (Pavitt, 1984; Sahal, 1981; Metcalfe, 1989).

Innovative activity within firms selected by the competition process is based on the localized knowledge acquired by means of learning by doing and by using and is geared towards the introduction of process innovations that help to beat off competitors mainly in terms of costs reductions (Utterback, 1994). The introduction of process innovation on the supply side and the saturation on the demand side that follows the fast growth of the first periods of the diffusion process pave the way to the retardation process.

In the marketplace two quite distinct dynamics take place along the diffusion process of new goods: (i) from monopoly to competition; (ii) from competition to monopoly (Klepper and Graddy, 1990). When appropriability of process innovations is high, the new market has a strong monopolistic character which eventually degrades into competition via the entry of new firms which are able to invent around, hence to imitate and to introduce process innovations that make it possible to reduce the cost difference, built upon reputation and size, with respect to incumbents (Flaherty, 1980).

When the selection process among many independent innovators is very strong and many parallel product innovations are confronted in the marketplace, the opposite shift from competition to monopoly may take place: process innovations introduced by firms that had a chance to make transient economic profits pave the way to the selection of products and firms so that the market evolves from competition to monopoly.

The outcome of the interdependence between demand diffusion and supply diffusion and the interdependence between processes of innovation and processes of selection are such that process innovations become more and more important as an industry matures, as the number of firms in the industry shrinks and as the opportunities for growth decline.

(2) A theory of demand based on the endogenous evolution of utility functions lies at the heart of the approach to structural change and industrial dynamics. As Kuznets noted, demand plays a major role: retardation in fact is driven by the rate of introduction of incremental innovations, but is actually determined by the inelastic portion of demand curves that is 'necessarily' met by the sequence of lower and lower supply curves. The basic assumption here is that income elasticities are influenced by income levels and by the novelty of products. In a general equilibrium approach in fact stable income elasticities should compensate for the decline of production costs and keep the overall levels of output constant. When however Engel curves matter, the relationship between consumption and income may change according to income levels and hence the endogenous changes in the articulation of consumers' tastes. An industry characterized by a decline of income elasticity, the gregarious behaviour of consumers and by the introduction of incremental process innovations is exposed to a secular decline in output. An industrial system characterized by a block of old declining industries and only a few new emerging ones is also exposed to a secular decline, especially when it is integrated in international markets that provide the new goods at low costs (Pasinetti, 1981, 1988).

(3) Moreover utility functions may change endogeneously because of the gregarious behaviour of agents whose belief is influenced by the aggregate levels of consumption of new goods. Positive and negative externalities play a major role in shaping the evolution of consumers' beliefs especially about the expected utility of new goods: positive externalities induce consumers to attach a greater value to a new good when the number of lead-users is still small and this is perceived as a status symbol or actual complementarities in usage feature the good (this is naturally the case with telephones and generally all communications services). Eventually, however, when the number of users and goods already used increase, congestion effects may reverse the positive effect and actually reduce the expected utility (Marris, 1964).

(4) The analysis of industrial and structural change focuses attention on the strong complementarities and interdependencies among industries and products in the analysis of industrial growth. Industrial structures are characterized as a system of interdependent and specific complementary production activities which rely on each other for the provision and purchase of intermediate production factors. Increasing returns to scale and specific thresholds characterize each industry (David, 1987; Carlsson, 1989; Milgrom and Roberts, 1990). Significant externalities, both pecuniary and technical, spill from one industry to another in the matrix of interindustrial exchanges. For some combinations of values of output in vertically integrated sectors an industrial system may achieve very high levels of efficiency. Complementarities in consumption play a similar role so that the demand for different products is strongly interrelated in that each exhibits positive cross-demand elasticities. Complementarities in production and consumption account for big push effects, i.e. discontinuities in growth rates due to the

emergence of the correct combination of interindustrial linkages. The dynamics of structural change is guided by the endogenous evolution of the technical coefficients in the input–output matrix, the crosselasticities among products, the income elasticities of bundles of complementary products (Rosenstein Rodan, 1934; Hirschman, 1958; Simon, 1951; Durlauf, 1993).

Kuznets was the first economist explicitly to import the logistic curve into the economic literature from the methodology of demography and population studies in the attempt to provide a synthetic and simple statistical treatment to model the dynamics of long-term output growth of industries. The logistic specification proposed by Kuznets to fit empirically the evidence about retardation in industrial growth finds a strong complementarity with the Schumpeterian tradition about the sequence in technological change between the punctuated (Mokyr, 1990) introduction of radical technological innovations and the subsequent, declining rates of introduction of incremental innovations. The logistic specification of retardation can be formalised as follows:

$$P(t) = a - b \cdot Q(t) \tag{2}$$

The revenue equation is:

$$R(t) = P(t) \cdot Q(t) = [a - b \cdot Q(t)] \cdot Q(t) \tag{3}$$

Let us now assume that a share Z of total revenue at each point in time is devoted to fund research and development activities that make it possible to reduce the costs of the output in the ith industry and consequently the market price in that industry:

$$P(t) - P(t-1) = -\lambda \cdot Z \cdot R(t) \tag{4}$$

where $Z<1$ measures the share of revenue devoted to fund R&D activities and λ measures the effects of the research and development activities on production costs and consequently market prices.

Substituting Eq. (3) into Eq. (4) we see that:

$$P(t) - P(t-1) = -\lambda \cdot Z \cdot [a - b \cdot Q(t)] \cdot Q(t) \tag{5}$$

Let us assume that the increase in demand depends on the reduction of prices:

$$Q(t) - Q(t-1) = -B \cdot [P(t) - P(t-1)] \tag{6}$$

if we substitute Eq. (5) into Eq. (6), we have

$$Q(t) - Q(t-1) = \lambda \cdot B \cdot Z \cdot [a - b \cdot Q(t)] \cdot Q(t) \tag{7}$$

which can be easily expressed as:

$$\frac{Q(t) - Q(t-1)}{Q(t)} = B \cdot \lambda \cdot Z \cdot [a - b \cdot Q(t)] \tag{8}$$

Eq. (8) shows that the percentage rate of growth of output is a negative function of the levels of output already reached, that is Eq. (8) reproduces the basic dynamics of retardation. The growth equation with endogenous research and development expenditures, funded with a fraction of the revenue of each time that makes it possible to reduce production costs and market prices for the product of the industry, exhibits an S-shaped process of growth, when expressed in cumulated output. So far it is possible to extract from it an equation which shares the essential character of the logistic curve and is directly obtained with simple hypotheses from the standard demand equation.

Similar conclusions can be obtained when the endogenous formation of the utility function is considered to be the outcome of the gregarious behaviour of consumers. Let us consider a simple Cobb-Douglas utility function with constant returns where the utility elasticity of a good (x) for each consumers i is influenced by the levels of the aggregate stock (X) of the same good already sold. The relationship between the stock and the flow accounts for both positive externalities up to a threshold and negative externalities beyond that level which can be modeled as a quadratic function (Marris, 1964). Hence:

$$U_{it} = f(x_t^{\alpha} y_t^{\beta}) \text{ with } \alpha_t + \beta_t = 1 \text{ and } \alpha = (X_t - X_t^2) \tag{9}$$

Standard maximization of the utility under a budget constraint (I_{it}) leads to the following demand equation for each gregarious consumer:

$$x_{it} = I_{it}(X_t + X_t^2)/P_{xt}(\beta + (X_t - X_t^2)) \tag{10}$$

The equilibrium levels of aggregate demand that each point in time can be considered a flow added on to the stock:

$$\mathrm{d}X/\mathrm{d}t = I_t(X_t - X_t^2)/P_{xt}(\beta + (X_t - X_t^2)) \tag{11}$$

where, once more we see that the rate of growth of the dependent variable is shaped by a quadratic function of the levels of the same variable.

Eq. (8) (and Eq. (11)) have, as their solution, the well known logistic function:[2]

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[2] More precisely the passages are as follows:

$$\int_t \frac{\mathrm{d}Q(t)}{[\alpha - Q(t)]\cdot Q(t)} = -\frac{1}{\alpha}\log\left|\frac{\alpha - Q(t)}{Q(t)}\right| = -\lambda\cdot Z\cdot t + C_1 \Rightarrow \left|\frac{\alpha - Q(t)}{Q(t)}\right| = C_2\cdot e^{\alpha\cdot\lambda\cdot Z\cdot t}$$

for

$$\left|\frac{\alpha - Q(t)}{Q(t)}\right| > 0 \quad Q(t) = \frac{\alpha}{1 + C_2\, e^{\alpha\cdot\lambda\cdot Z\cdot t}}$$

for

$$\left|\frac{\alpha - Q(t)}{Q(t)}\right| < 0 \quad Q(t) = \frac{\alpha}{1 - C_2\, e^{\alpha\cdot\lambda\cdot Z\cdot t}}$$

$$Q(t) = \frac{\alpha}{1 + C_2 e^{\alpha \cdot \lambda \cdot Z \cdot t}} \quad \text{where } \alpha = \frac{a}{b} \tag{12}$$

According to Eq. (12) it is clear in fact that the dynamics of the absolute rates of growth are such that we can identify three distinct regions: for low levels of cumulated output they are very low, they are especially high in a central region and finally they are very low again for high levels of cumulated output.

More specifically, with respect to Eq. (8) we see that industrial growth is retarded, that it follows a distinct product lifecycle along a sigmoid time path shaped by the values of:

- Z, the share of revenue used to fund R&D activities and generate process innovations.
- λ, the effects of R&D activities on production costs and consequently market prices.
- B, the slope of demand.

With respect to Eq. (9) we see that industrial growth is retarded by the alternation between the positive and negative effects of the gregarious behaviour of consumers on the evolution consumers beliefs about the expected utility of new goods and hence of demand, with given levels of income and prices.

The effects of the income elasticity of demand, especially when the Engel Law applies, can be appreciated if a in Eq. (2) is in fact $a(t)$ with, in the inverse demand function, $\mathrm{d}(1/a)/\mathrm{d}t = A$. A measures the effects of the income elasticity in terms of shifts of the demand function over time. The general function Eq. (12) in such a case generates an envelope of logistic paths where each S-shaped process shifts rightward.

When the endogenous aspects of consumer tastes formation are properly taken into account we see that a variety of path-dependent growth alternatives are likely to emerge. According to the endogenous evolution of tastes the distribution of income elasticities for different products will in fact vary across economic systems and with it the growth opportunity for the system itself. The time distribution of all efforts to manipulate the formation of tastes and their outcome plays a central role in such dynamics as well as the matching between endogenous taste formation and endogenous technological change. Moreover the interactions between structural change and the dynamics of industrial markets can lead to a variety of outcomes. Industrial structures also are exposed to structural changes that parallel retardation: in the stages of fast growth rates barriers to entry based on the ratio of minimum efficient size to total demand and R&D and reputation building sunk costs should shrink so that entry is easier and consequently concentration levels lower. In such phases non-price competition is systematically used by firms in order to acquire larger shares of the market. Conversely selection is more severe when retardation emerges and consequently concentration levels rise together with the decline in the number of firms and in rivalry in the marketplace. Along the product lifecycle markets change because of the endogenous changes in technology (Mueller and Tilton, 1969; Vernon, 1966; Winter, 1984).

3. Towards a generalization: path dependence as a general model of evolution and change in industrial organization

The complex dynamics that have been recalled so far have long been known to industrial economists and yet disregarded due to the difficulty of handling their outcome analytically. As Brian Arthur recalls, even Schumpeter pointed out that "multiple equilibria are not necessarily useless but from the standpoint of any exact science the existence of a uniquely determined equilibrium is, of course, of the utmost importance, even if proof has to be purchased at the price of very restrictive assumptions; without any possibility of proving the existence of a uniquely determined equilibrium—or at all events, of a small number of possible equilibria—at however high levels of abstraction, a field of phenomena is really a chaos that is not under analytical control" (Schumpeter, 1954 quoted by Arthur, 1994, p. 4).

Several dynamic models of local interactions have been recently applied to economics, such as Polya Urns, recently generalized to *n* colours, Spin systems including stochastic Ising dynamics, and Markov random fields with multiple absorbing states. The methodological interest of Markov random fields consists in the existence of a plurality of absorbing states where the dynamics of the process stops. The process declines when all the agents converge to the assignments of one of the many elements of the finite set.

Many processes that have been explored by the industrial organization literature can be accommodated by the methodology of Markov chains. A few important distinctions however are necessary here. As Nelson and Winter (1982) recall, a Markov chain describes a process where: "the condition of the industry in each time bears the seeds of its condition in the following period. It is precisely in the characterization of the transition from one period to the next that the main theoretical commitments of evolutionary theory have direct application. However those commitments include the idea that the process is not deterministic; search outcomes, in particular, are partly stochastic. Thus, what the industry condition of a particular period really determines is the probability distribution of its conditions in the following period. If we add the important proviso that the condition of the industry in periods prior to period t has no influence on the transition probabilities between t and $t+1$, we have assumed precisely that the variation over time of the industry's condition-'state' is a Markov process" (p. 19).

Within the broad category of Markov processes a distinction can be made between simple Markov chains and complex Markov processes. This distinction plays a major role in our analysis.

Dynamic processes where the transition from one state to another depends only on the state at time t or time $t-1$ can be termed 'state dependent' and are appropriately accounted for by the methodology of simple Markov chains. Here the events at time $t+1$ can be fully predicted on the basis of knowledge of the state at time $t-1$. The probability of transition from the state at time t to the state at time $t+1$ is not affected by the characters and features of the previous states. These processes are past-dependent but are not path-dependent. In fact the condition of non-ergodicity does not apply in a full sense. A process with such features is partly deterministic: the intentional actions of agents and the conduct of firms are not associated with the probability of transition from one state to another. So far the methodology of simple Markov chains offers some interesting insights into the dynamics of industrial systems, but seems inadequate to represent the complexity of outcomes of the interactions of agents fully embedded and localized in the structural characters of the system, and yet still able to influence the evolution by means of a variety of structural actions (Krugman, 1996).

Dynamic processes where the probability of transition from one state to another is associated with the specific conditions of the state at time $t-1$, $t-2$, $t-n$ are non-ergodic and fully path-dependent. The transition depends clearly on the state at time t but also on the changes that the path to state t has exerted on the probability of transition. Hence it is convenient to apply the methodology of complex Markov processes to this second class of dynamic processes. A path-dependent dynamic process in fact can be described as a process where there is a multiplicity of rest states and the transition from one to another of many cannot be fully predicted on the basis of the conditions of the state at time t alone. Such a definition of a path-dependent process seems appropriate to accommodate the specific self-propelling processes which characterize the growth of firms, and the evolutions of markets and industries that we have identified in the industrial organization literature. In all these processes in fact agents are assumed to be 'state dependent' and yet able to generate structural changes either intentionally and directly or unintentionally and via interactions, which at the same time reflect the conditions of the system at time t and still can modify its evolution in an unpredictable way. The behaviour of agents, via both aggregate and local changes, can modify the probability of transition at each time and can push the system towards a variety of alternative states at each point in time.

The interaction, within complex Markov processes, between natural (simple) Markov chains or routines and global changes, as determined by the collective behaviour of all the agents has already found many applications. Newman and Wolf (1961) elaborated one of the first applications to economics of complex Markov processes to represent the dynamics of industrial selection and adjustment in the Marshallian tradition (Marchionatti, 1992). Newman and Wolf (1961) assume that for each firm the probability of increasing or decreasing output depends upon the levels of temporary equilibrium prices. The transition matrix, that is the probability for each firm of transition from one class of size to another, for a given distribution of firms sizes, is influenced by the interaction between a global variable such as the level of prices, which reflect the levels of aggregate supply, and by the economies of growth internal to each firm. Nelson and Winter (1982) apply complex Markov processes to study the evolution of routines within firms and the introduction of innovations in the Schumpeterian tradition. The introduction of technological and organizational changes is influenced, within the dynamics of Markov chains, by the features of a global factor such as the selection environment in the marketplace. Firms in fact are induced to innovate and hence to alter the reproduction of routines along natural trajectories of growth by the failure of their performances as determined in the marketplace where heterogenous agents confront each other.

Among complex Markov processes special attention has been given recently to local Markov fields. David (David, 1988, 1992a,b, 1993; David et al., 1997) relies systematically on the latter. This class of dynamic processes is characterized by the outcomes of local interactions as opposed to global interactions. In fact a system is now viewed as a network of asymmetric relations among agents (Dalle, 1995, 1996). Economic action shapes the system only via the structure of local interactions. In a local path-dependent process there are three basic ingredients: "(a) a source of local positive feedback that will systematically reinforce the action of agents... (b) some source of fluctuations or perturbations that remain independent of and weak in comparison with the systematic effects of the system... and (c) something causing the progressive diminution in the comparative strength of whatever forces are perturbating the system... " (David, 1988, p. 29). Among the applications of Markov random fields the percolation theory seems especially promising.

3.1. Percolation processes

The dynamics of market selection, the formation of expectations especially in financial markets, technological rivalry, complementarity among industries with respect to input–output interindustrial flows of intermediary inputs, decisions on location of new plants and entry in new industries are all examples of processes where the outcome of the interaction of agents at the global level can be thought to be determined by the specific structural context in which each interaction takes place. More generally all these processes involve some coordination equilibria such that the decision making of the agents is influenced by the coordination with the other neighbouring agents also located in the same economic niche.

The application of percolation methodology to study dynamic processes in economics is based upon the basic assumption that the behaviour of each agent is strictly determined by his or her structural local context of action: the behaviour of each agent depends upon the decisions of his or her neighbours. The outcome of the process at the global level depends upon the distribution of agents' behaviour in a structured context. For small differences in the features of the structure of local interactions the outcome can be either full homogenization or 'hysteresic' differentiation in behaviours. Percolation methodology applies the basic properties of the Markov random fields. Markov random fields can be defined as "interdependent Markov chains with locally positive feedback or additively interacting Markov processes" (David, 1992a,b). Markov random fields capture the dynamics of processes where each agent is exposed to the influence of its neighbours, rather than to the global influence of all the system.

Percolation processes have been studied in physics as the outcome of four classes of forces termed density, external pressure, connectivity and receptivity. For given levels of density and external pressure, the percolation probability is measured by the combined result of receptivity probability and connectivity probability. The methodology of percolation processes can be used to study the probability that flows of exchange of goods as well as exchanges of information and effective communication take place within local networks. A variety of applications can be elaborated ranging from the study of adoption of communication standards (David and Foray, 1994) to the spillover of innovations and the effects of technology transfer on the productivity of the research and learning efforts of each firm in the system (Antonelli, 1996b), or to the evolution of technological cooperation among firms (Antonelli, 1997a,b).

In fact an economic system can be characterized as an information network shaped by connectivity coefficients that is the number of transmission links among firms and receptivity coefficients that is the extent to which each firm is able to absorb the amount of information transmitted. Connectivity coefficients can be lower than $(n-1)n/2$, the maximum number for a system with n firms, and receptivity levels can be lower than 100%, when all firms are able to absorb all the information transmitted.

Percolation probability is the probability that each firm i can effectively communicate with the other firms that are part of the same system that is the joint probability of transmitting and receiving. The percolation probability qualifies the probability that some of the nodes can be more receptive than others and some transmission links can be more effective than others. The basic properties of the system therefore appear to consist in the actual complementarity among firms that takes the form of receptivity and the extent to which each firm is able to interact with the other firms that is translated in terms of connectivity.[3]

Let us define 'G' as a network which consists of a set of nodes or firms 'F':

$$F=(F_1,F_2,\ldots,F_n) \tag{13}$$

each of which is connected to the others by a set of transmission links 'T'

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[3] We follow closely the notation of David and Foray (1994) and Antonelli (Antonelli, 1996b, 1997a,b).

$$T=(t_1,t_2,\ldots,t_n) \tag{14}$$

An operative path in G from a firm f_i to a firm F_j is a finite sequence of the form $(F_1\ t_{12}\ F_2\ t_{23}\ F_3\ \ldots\ t_{n-1}\ F_n)$ where t_{ij} denotes a relational line connecting F_i to F_j. The network G is connected if, for each pair of firms F_i and F_j, there is a path in G from F_i to F_j.

A random maze on G is set when each unit F of G is 'open', or responsive to the influence of any of its neighbours' innovative action, with probability p_f, or closed (unresponsive to local technological externalities) with probability $q_f=1-p_f$. We shall call such a probability the receptivity probability. Similarly each interfirm transmission link t reaches some minimal or threshold density of interactions between i and j (which is sufficient to influence decisively the ith and jth firms' level of innovation output) with probability p_t or it fails to do so with probability $q_t=1-p_t$. Such a probability is termed the connectivity probability. These events are assumed to occur independently of each other.

An operative path d between F_i and F_j is defined as follows:

$$d=(F_1t_{12}F_2t_{23}F_3\ldots t_{n-1}F_n) \tag{15}$$

The operative path between F_i and F_j is said to be 'open' if all its communication links reach the minimum sufficient density, that is the number of agents in a finite space, and all the firms are influenced by externalities in their activity. Thus the probability that the particular path is 'operational' in that sense is given by $(p_fp_t)^{n-1}$

The percolation probability is the probability that activities carried out by each firm can affect the performance (or the conduct) of firms in G. The percolation probability depends also on the levels of external pressure, denoted as R, and the density of firms, denoted as Z, so that the full percolation probability equation reads as follows:

$$P(p_f,p_t,R,Z)=PP \tag{16}$$

For given levels of R and Z, the mixed percolation probability PP is a non-decreasing function of p_f and p_t and $P(0,0)=P(1,0)=P(0,1)=0$. Thus, $P_f(p)=P(p_f,1)$ and $P_t(p)=P(1,\ p_t)$ are, respectively, the node percolation and the connection probabilities of this network.

According to David and Foray (1994) a fundamental mathematical property of the percolation process is that there are some combinations of critical values $p_f>p_f{}^*$ and $p_t>p_t{}^*$ beyond which there will be a positive probability that percolation occurs, and below which the percolation probability is zero.

In other words the system undergoes a 'phase transition' when these underlying critical probabilities are reached. There are corresponding critical values at which the node percolation and the transmission percolation probabilities respectively become positive. These define the endpoints of a region above which a 'mixed percolation process' (one for which it is not certain that either all nodes or all links of the network are open) will have positive probability of achieving complete percolation (David and Foray, 1994). The receptivity of the system is more 'fragile' than the connectivity. The following general property is important:

$$P_f(p) < P_t(p) \text{ whenever } 0 < p < 1 \tag{17}$$

This property suggests that percolation is easier via an imperfect set of connections between receptive nodes than through a completely connected network whose nodes are imperfectly receptive. Another generalization states that:

$$P(p_f b, p_t) < P(p_f, p_t b) \text{ whenever } 0 < p_f < 1, 0 < p_t < 1, 0 < b < 1 \tag{18}$$

This inequality has important economic implications: it suggests in fact that it is more effective to modify the connectivity of members of a population by a factor b than to modify the receptivity with efforts of the same amount.

The percolation properties of a system are relevant to analyze dynamic processes like the diffusion of new products, the adoption of standards, the leakage of spillovers, and the flows of interindustrial externalities. More specifically we see that, according to the properties of percolation systems four factors play a major role: (1) the strength of the external pressure, (2) the receptivity, (3) the connectivity of each firm to the information transmitted, and (4) the density of agents in the maze. Moreover for levels of receptivity and connectivity coefficients that are $p_f < p_f{}^*$ and $p_t < p_t{}^*$ lower than the minimum receptivity and connectivity thresholds, respectively, the general efficiency of the interaction system is severely damaged. Within the network some areas can experience connectivity and receptivity levels that are larger than the thresholds so as to determine 'maculated' networks. Antonelli (1997a) shows that in the real world the distribution of percolation probability in the economic space can vary across technologies, regions, industries, and, most importantly, time. Secondly and most importantly; the features of the system upon which percolation probability depends should not be considered as given and exogeneous. In fact each effective connection requires an effort to be established: hence, effective connections are the outcome of intentional action and can be considered as endogenous. Percolation probability at time t affects the behaviour of agents not only with respect to the levels of their market conduct but also to the levels of intentional action devoted to building connections and receptivity which can enhance their efficiency and profitability. Finally, the dynamics of localized technological change and of percolation processes are interdependent. In fact the higher the percolation probabilities of a given economic system, the higher is the probability that firms facing such changes in their economic environment as an increase in wages or in the price of other production factors, an increase and/or a decline in the demand for their product, react with the introduction of localized technological changes rather than adjusting the levels and composition of inputs to the new conditions within a given technology (Antonelli, 1997b).

3.2. Implications for empirical research

The implications of this approach for developing new applied research strategies are important. As Krugman (Krugman, 1996, pp. 1 and 70) notes, percolation models have been already applied in more than 15 scientific fields and (almost) not yet in economics. Krugman (1996) shows how percolation theory can be applied to business cycles (Scheinkman and Woodford, 1994) and regional economics. In the economics of industrial organization and technological change and more specifically within the 'new empirical industrial organization approach' (Bresnahan, 1989) the economics of path dependence suggests the analysis of the behaviour of agents at any point in time as the outcome of:

1. The structure of events as they were at time $t-1$; and
2. the part of the structure of events that changes through time.

Along these lines two methodological approaches seem most promising: the adaptive recursive approach and the survival methodology. In the first, following Day and Nelson (1973); Day (1986); Day and Eliasson (1986); Foster (1991), (1993) an evolving system characterized by path dependence can be described as follows:

$$X_t = X_{t-1} - Z_t + W_t \tag{19}$$

where: X_t = the structure of events that is analyzed at time t; X_{t-1} = the structure of events as they took place at time $t-1$; Z_t = the part of the X structure exposed to decay over time t; W_t = the part of the X structure that is new due to new actions that have been undertaken over period t.

With such an adaptive recursive methodology it appears possible to capture the structural dynamics that underlies the time distribution of events under the control of the behavioral factors that both reinforce and contrast it. Nonlinearity in the dynamics of the process can be easily captured with the manipulation and qualification of the relationship between the events at time $t-1$ and the outcome at time t:

$$X_t = (X_{t-1}) - (X_{t-1})^2 - Z_t + W_t \tag{20}$$

According to Eq. (20) past conditions exert their influence on current events along a quadratic relationship that privileges the role of some thresholds before which the relationship takes a positive sign and beyond which it takes a negative one.

In the survival or duration approach, following Kiefer (1988) an evolving system is directly characterized as an entropy process where the duration of an event, or the rate of survival of the same event, are assumed to be conditional upon its state at time 0 and a vector of characteristics that evolve through time. A standard duration approach then takes the following form:

$$L(t;Z) = L_0(0)\exp(Z;b) \tag{21}$$

where: L = the instantaneous rate of failure conditional upon survival to time t; L_0 = an arbitrary and unspecified base-line hazard rate at time 0; Z = a vector of characteristics of the agents; and b is a vector of coefficients.

With a survival methodology it is possible to assess how long it takes before a given behaviour or event takes place and which are the features of the state at time 0 that affect its evolution together with the characteristics of the agents and the structural determinants of the behaviour that is analyzed that are associated with the time distribution of the events.

In sum, it seems that new empirical approaches can accommodate the effects of both inertia hysteresis and evolution to study such dynamic processes' as natality, entry, growth and retardation, profitability, investments and capacity expansion, productivity, integration and specialization, concentration and fragmentation, advertising and marketing strategies, innovation and technological change, that are all influenced by the characters of the environment and yet are likely to affect the evolution of the environment.

4. Conclusions

The analysis of path dependence, as implemented by the methodology of Markov chains, is relevant from two different, and yet complementary points of view: (i) the analysis of the evolution in historic time of the system; and (ii) the analysis of the evolution in historic time of the performances of each agent in the system. The outcome of the latter provides the information to understand the former. According to the values of the parameters of the system described by the different Markov random fields, such as the distribution of agents in the economic space, the number of agents, the density of agents, the quality and quantity of connectivity channels among agents, and their receptivity we have elements to understand the dynamics of the system and the performances of each agent in the system. At any point in time, however, the parameters can be affected and ultimately changed by the conduct of each agent such as entry and exit, investments in connectivity channels and receptivity and new localization in economic space. Hence, the parameters of the system cannot be viewed as exogeneous or given-once-for-ever, but are the outcome of the past conduct of agents as well as of the dynamic properties of the system itself. Because of the stochastic character of Markov random fields one can observe small events that are likely to activate chain reactions that drastically change the parameters of the full system, while in other periods of time and in different contexts of co-action the outcomes of the same efforts can be much smaller. Hence, the character of path dependence where hysteresis and determinism are mitigated by the localized context of action.

The analysis of path dependence provides a general framework into which the evolution of industrial economics, as outlined from the structuralist approach elaborated in the 1960s (Scherer, 1980), through the Schumpeterian developments of the 1960s and 1970s and the evolutionary steps of the 1980s (Dosi, 1988), finds a broader and more structured context to grow into a fully elaborated dynamic structuralism. Such a dynamic structuralism, drawing upon both the Marshallian and the Schumpeterian traditions, makes it possible to overcome the Darwinistic limits of the static structuralism and the standard evolutionary approach. In both in fact for a given distribution of agents differentiated in terms of size, age, production costs and innovation capability, a set of structural factors that are assumed to be exogeneous and not subject to changes, acts as a sorting device and selects the features of the agents that are more appropriate to that given environment. Little scope is allowed for the intentional action of agents and for their capability to modify the environment that emerges over time.

A dynamic structuralism, based upon the notion of path dependence provides instead a more general framework which accounts for both flows of effects in the interaction between agents and structures. It makes it possible to accommodate both for effects of the past behaviour of agents on the structural factors of the environment and the Lamarckian process of survival of agents by learning and adaptation to the characters of the environment. Hence path dependence provides a framework to understand and to model the effects of historic time on the behaviour of agents which however are able at each point in time to modify their evolution (Nelson, 1995; Antonelli, 1995b).

Path dependence in fact appears able to provide a general framework that can accommodate a variety of specific dynamic processes that have always featured a large share of research in industrial economics such as:

(i) The growth and diversification of firms: the dynamics of economies of scale, economies of scope and learning processes, as interacting Markov processes, play a central role in explaining the evolutionary path of firms through markets, products, countries and technologies so as to explain the variety of specialization profiles, and the variety of processes of growth (Chandler, 1990; Dunning, 1981; Egidi and Narduzzo, 1997).

(ii) The interaction between different learning processes, sunk costs and industrial structures, as interacting Markov processes, play an essential role in assessing the evolution of the performances and the strategies of films and hence the persistence of economic profits and innovative activity in the long run (Salter, 1966; Sutton, 1991; Mueller, 1986; Malerba, 1992; Mueller, 1997). The understanding of industrial structures as well as organizations as complex systems characterized by a set of interconnected activities which influence each other opens the way to heuristic applications to economics of neural networks. Neural networks belong to the family of computationally based methods which can be used to explore complex adaptive processes (Calderini and Metcalfe, 1997).

(iii) The determinants of the dynamics of market structures. Market structures can no longer be viewed as exogeneous and fixed but rather as endogenous outcomes of the interaction between selection process and the Lamarckian conduct of firms: at any point in time the levels of the height of barriers to entry, concentration and cost asymmetries among firms depend upon the dynamics of entry, innovation, imitation and diffusion (Geroski, 1991; Klepper and Graddy, 1990; Metcalfe, 1989, 1992; Metcalfe and Gibbon, 1988; Matsuyama, 1995).

(iv) The dynamics of structural change and the evolution in the composition of industries within economic systems follows a product lifecycle determined by increasing returns, complementarities and interdependencies in production and consumption and endogenous evolution of tastes and can be modeled as a clear case of complex Markov processes where different simple Markov chain are interdependent (Vernon, 1966; Pasinetti, 1981; Durlauf, 1993).

(v) The persistence of innovative activities and technological specialization (Malerba et al., 1997).

(vi) The selection of new rival technologies: the dynamics of increasing returns as determined by the flows of introduction of incremental innovations, and by the interaction of economies of scale with supply and demand externalities is likely to affect the selection of new technologies so as to influence the emergence of new technological systems characterized by high levels of complementarity and interdependence among new technologies (Arthur, 1989; Carlsson, 1995; Foray, 1997; Witt, 1997).

(vii) The diffusion of innovations: the interaction between two simple Markov processes such as the epidemic engine of imitation on demand side and the role of learning economies, economies of scale and competitive entry of imitators on the supply side provides a rich approach to study the diffusion of innovations (David, 1975; Metcalfe, 1981; Antonelli, 1995a).

(viii) The dynamics of regional and technological clusters that feed industrial growth by means of systems of localized and dynamic complementarities among firms both with respect to the existing production processes and with respect to new technologies can be nicely analyzed by means of interacting Markov processes where different simple Markov chains are interdependent (Becattini, 1987; Carlsson, 1995, 1997).

(ix) The endogeneous evolution of consumption patterns based on interdependencies in the formation of utility functions (Cowan et al., 1997).

(x) The economics of new information technology and the economics of knowledge, as shaped by the pervasive role of a variety of irreversibilities, complementarities and learning processes.

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