The evolution of competences in a population of projects: a case study

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1. Introduction

This paper explores the idea that the dynamic process through which firms accumulate and diffuse competences is an evolutionary process. Of course, the idea is not new. The literature on adaptive complex systems has much emphasized that evolutionary processes not only shape the dynamics (composition) of populations of agents, but may indeed shape the internal processes through which agents learn and adapt (Holland 1975, 1995; Axelrod and Cohen forthcoming). Similarly, cultural evolution theories have stressed that social systems accumulate an diffuse the results of individual or group experimentation and learning through processes that may be modelled as proper evolutionary dynamics (Cavalli-Sforza and Feldman 1981). Finally, there is now a pretty large stream of research in organization theory suggesting that there may be evidence for intra-firm "Darwinan" cycles of mutation, selection and spread of fittest variants (for a short review see Warglien forthcoming).

The peculiar contribution of this paper is to explicitly model such internal processes and look for empirical support to evolutionary views of the dynamics of firm competences through the analysis of a longitudinal case study. In particular, the paper reconstructs the intra-organizational evolutionary dynamics of design competences in a large european microelectronics firm, over a time span of about 20 years (1973-1993). This requires some careful definition of the intra-firm units of analysis and of the dynamic interactions among them, in order to organize data collection and allow proper analyisis of such data. Section 2 shortly presents the case study and defines the units of analysis of the intra-firm population under study (a population of about 2.000 projects).

In order to study evolutionary processes, one must be premiminarily able to show the existence of selective pressures affecting life events in the populations under study. Section 3 shows that the population of projects considered here exhibits significant density-depedence of birth and mortality rates. An analysis of the age-dependence of mortality shows interesting phenomena of intra-organizational inertia at work.

Section 4 moves from Malthus to Darwin, analysing patterns of traits generation and diffusion in terms of exploration and exploitation trade-offs, using an "evolutionary activity" metric derived from artificial life studies. Section 5 further analyses patterns of new traits diffusion. Using a dynamic model of competences diffusion, I estimate how competition between competence families shapes their diffusion over time, supporting a view consistent with evolutionary theories. A few conclusions are drawn in section 6.

2. The units of analysis

It has been often claimed that firms adapt to their environments following a "Darwinian" logic of evolutionary change . For example, Herbert Simon has suggested (1962) that processes of search and discovery in individuals and organizations can be framed in terms of a variation/selection model. Karl Weick (1969) has expanded a view of the organization as a web of organising cycles where variety is generated or enacted, it is selected (mostly by internal processes) and it is retained in organizational memories.The metaphor of organizational genetics has oriented important developments in the theory of the firm (Nelson and Winter 1982; Winter 1990) and computer models of how organizations search and learn (Cohen 1981, 1984; Warglien 1995). Contrasting to the radical population ecology approach (Hannan & Freeman 1977, 1989), that emphasises selective processes operating at the population of firms level (thus denying that significant evolutionary processes can happen inside the firm), the evolutionary view of the firm stresses variation and selection processes unfolding *within* the firm (Burgelman 1990), thus allowing more room for organisational change and adaptation phenomena.

A key issue of any "Darwinian" view of organisational adaptation is the definition of the units of analysis, those on which selection operates (Cohen et al. 1996). Which organisational entities are able to replicate themselves? How do they propagate, and how does selection act on them? How can we observe them and track their evolution through time? There seems to be a substantial agreement on identifying organisational competences, or routines, as the organisational replicators or "genes" (Nelson and Winter 1982; McKelvey 1982; Winter 1990). As Winter has emphasised, "in economic evolutionary theory, organizations are viewed as packages of routinized competence" (Winter 1990, p. 280). Such routinized competences are recognisable by repetitive patterns of activity and embodiment in human and physical assets; moreover, they are usually associated to labels that help to identify them. They are inheritable both within and among organizations; they are subject to selection (resulting both in firm growth and in differential reproduction rates of organisational forms) and they can be mutated through innovation or imitation.

However, routines in themselves may be unlikely candidates for developing empirical observations of organisational evolution, especially when analysis over long time periods is needed. Careful recording of routines may be non-existing in archival sources, and their diffusion may be hard to assess (excepted the case in which they are spatially replicated in different plants or units: Winter 1990). Routines seem better suited for laboratory studies (Cohen and Bacdayan 1992; Egidi and Narduzzo 1997) or ethnographic research

(Feldman 1989; Narduzzo et al. forthcoming) than for extensive longitudinal analysis. Empirical analyses of the long-run dynamics of intra-firm evolution are still to a large extent missing (however see Dosi, Nelson and Winter forthcoming for some early attempts).

This paper tries to move some early, albeit partial, steps in such a direction. An operational approach to evolutionary theories of organisational adaptation is sought, enabling data collection strategies and econometric modelling of the empirical observations. The paper is a longitudinal case study (1972-1993) focused on a particular kind of organization, that might be generically defined as *project-based*. The organization is the "Dedicated Products" division of a large european microelectronics firm (ST). As in many R&D based firms, this is an organization where projects are singled out as basic units, so that managerial responsibilities, resource allocation (men, money and equipment), and accounting data are directly or indirectly defined in terms of projects or aggregations of projects. What is the appeal of such kind of organization?

If one puts on Darwinian spectacles and looks at the projects portfolio of such firm, he will see populations of entities (the single projects) that are born, die, compete for limited resources (skilled labor, equipment and financial means), inherit clients, technologies and other traits from preceding generations, and re-transmit them (sometimes modified or innovated) to next generations. One can observe simultaneously hundreds of such entities, and their individual life cycle is usually short enough to allow the observation of many generations in a rather small number of years.

In general, project-based organisations tend to generate more projects than those that arrive at full development. Environmental selection (such as the one operated by the market) or internal selection (such as the one operated by the firm's decision makers on internal resource allocation processes) jointly contribute to shape the evolution of the projects portfolio of the firm. The presence of a potentially exceeding number of projects competing for organisational and environmental limited resources allows significant ecological processes to take place.Thus, one can study age dependence in project mortality, or how density affects the demography of projects. This requires the definition of the basic life events of a project. In this paper, I will define two basic life events. Birth is defined by the first formal assignement of resources to a project. After birth, the project can be suppressed during its development stage ("infant death") or can become a marketed product, in which case it dies only when its production ceases. During early stages, a project tends to be a net resource consumer - but after its market introduction, it starts generating net resources that are pooled in the resource basis of the firm.

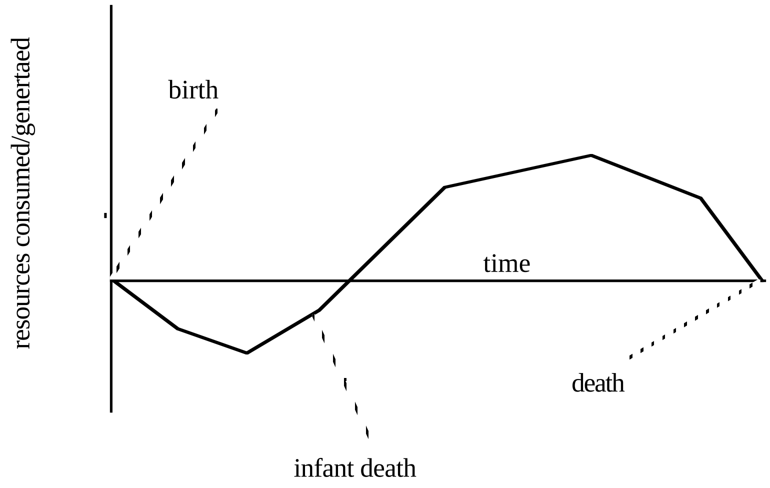

Fig. 1 The life cycle of a project and its net resource consumption/generation over time

Furthermore, each project can be characterized by a certain number of “quasi-genetic” traits (Cohen et al. 1996) such as relationships with some classes of clients or market areas, technologies, critical components, functionality. Traits are the expression of the fundamental competences or routines of the firm, although they are not necessarily competences or routines in themselves.

Technological or marketing traits are easier to observe and track through time than the underlying competences or routines, while their presence witnesses the ustilization of such basic organisational abilities. Moreover, while the growth and diffusion of routines in an organisation is hard to empirically observe over long periods, tracking the diffusion of traits in a population of projects is much facilitated by the fact that most firms keep a record of projects' subject, of technologies, clients and functionality involved.

Traits can usually be inherited from project to project, and they are sometimes modified by project development efforts. By modifying the projects portfolio, a firm also modifies the distribution and combination of such traits - and thus it modifies its positioning in the environment and how resources are exchanged with it. The relative fitness of a project-based organisation heavily relies on the composition of its portfolio, and there is a large evidence that this composition changes through time. This way, firms give rise to a process not too far from that of an animal population that adapts by modifying and recombining its genetic repertoire and the distribution of traits within the population itself. Of course, the underlying process is very different, but the resulting dynamics can appropriately be defined as a form of evolution. This paper will concentrate on the diffusion of technological traits. Such traits are defined as “processes”. A process is a set of phyiscalchemical steps and procedures for generating a chip. It underlies a design kit made of active (transistors) and passive (resistors and condensers) components, and the capability to combine tehm given the understanding of the physical-chemical properties of the semiconductor material (silicon).

Individual processes belong to families of processes (technologies) that are characterized by common underlying design competences. For example, if one finds projects generating a BCD multiplex device for cars, this implies underlying competences in basic processes such as bipolar, CMOS and DMOS technologies, and the ability to combine them in a mixed technology. It will also imply knowledge about mid-range power devices functionality.

Finally, traits also allow us to operationalize a concept of mutation, or innovation. Very naturally, a mutation happens when a new process is introduced in the population.

The following table summarizes the main units of analysis and life events employed in this paper, mapping them into familiar concepts of evolutionary theories. A more detailed description of them will be introduced as needed in each subsequent section of the paper.

Projects	individuals
early resource assignment	birth
the projected is discontinued before being marketed	infant death
the project ceases to consume resources	death
processes	traits
families of processes	trait families
a new process is introduced	mutation

Table 1 mapping units of analysis and evolutionary concepts

3. Selection at work: The simple ecology of projects.

As suggested in the introduction, the first level of analysis focuses on selection dynamics. I have followed a classical approach, trying to find indirect support to the hypothesis that selective pressures drive the long term growth of a population.

The first choice I made was to treat the 2000 projects as a single ecological population. In facts, all the projects share a rather homogeneous resource space. They compete for the same human and financial resources in the firm, and although they address different market niches, they all pertain to a same broad industry segment (the dedicated products one), they share marketing resources, the same production facilities, and they draw from a common technological base.

Second, I have hypothesised that population dynamics could be explained by a simple ecological model. I have thus assumed that the population density might be a good proxy for competition for the existing resources, hypothesising that increases in density would imply increasing death rates and decreasing birth rates (this is a familiar assumption both in standard ecological models and in the population of organizations ecology: cfr.Hofbauer and Sigmund 1988 and Hannan and Freeman 1977).

The usual formulation of growth dynamics assumes positive linear relationships between density and death rate, and a negative one between density and birth rate. All this results in the usual logistic model of population growth, as expressed by the following equation:

$$\frac{dN}{dt} = rN\left(\frac{K - N}{K}\right)$$

where *N* is population density, *r* is the intrinsic growth rate, and *K* is the environmental carrying capacity.

Finally, I have defined life events as follows. A project is born when it first applies for an assignment of resources. Usually, this happens after early conception efforts. This might imply important information losses. Fortunately, the resource assignment process in the firm I have analized forces early tracking of project conception (even early feasibility studies have to be recorded). Thus, most of the R&D effort is captured well before the manufacturing start-up begins (on average, this amount to about two years). A project is dead when it stops using the firm's resources - i.e. when it constitutes no more a source of development or manufacturing costs.

Figure 2 shows the growth of the population over the 1972-1993 period. It clearly suggests logistic growth. The non-parametric, montecarlo Pollard test of density-dependence (Pollard et al. 1987) actually confirms this impression, by supporting the density dependence hypothesis at the 0.001 significance level.

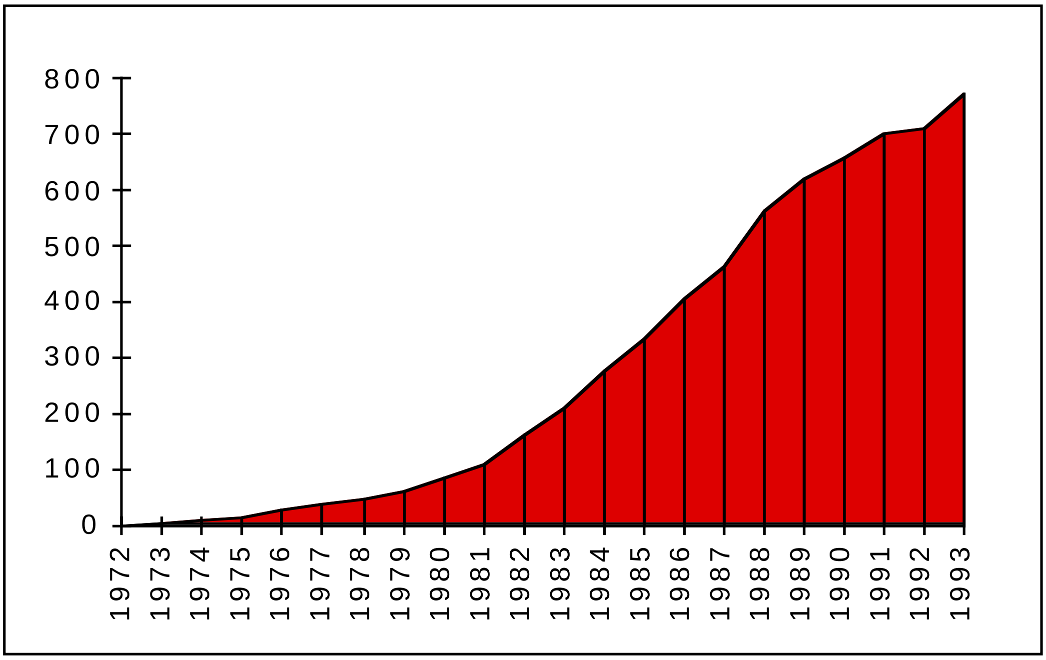

Fig. 2 Population numerosity, 1972-1993

However, to be more accurate, on has to conside separately birth and death processes. The analysis of death and birth rates (data reliability forced me to limit the analysis to the 1982-1993 period) provides even more meaningful results. Figg. 2 and 3 plot birth and death rates against the population numerosity. For each year, the death rate is computed as the ratio of dead projects to the population numerosity; similarly, the birth rate is computed as the ratio of births to the population numerosity.

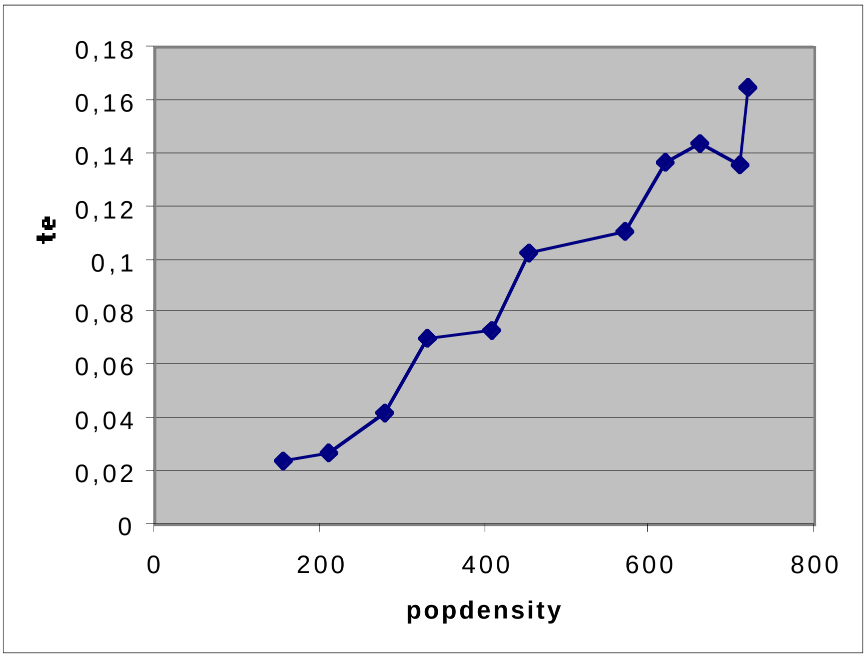

Fig. 3 Death rates and population density (sample 1982-1992)

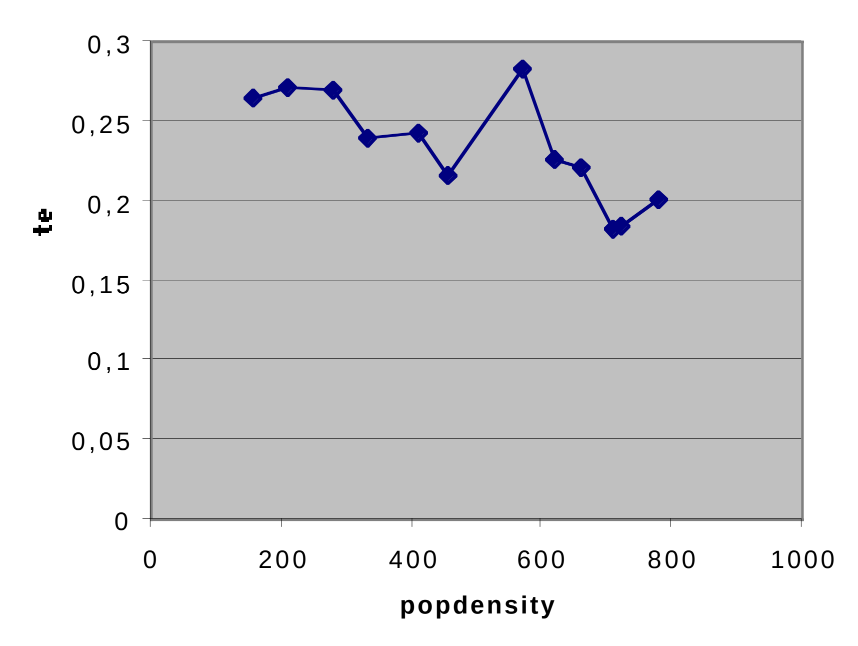

Fig. 4 Birth rates and population density (sample 1982-1993)

Plain OLS regression analysis reveals a striking linear relation between density and death rates (fig. 5, plotting actual and fitted values for each observation). The R^2 is 0.97; furthermore, all usual tests of correlation, normality and heteroschedasticity are passed.

coefficients	Value	Std.error	t-value	t-prob	Part.R^2
constant	-0.019617	0.005875	-3.3339	0.0087	0.5534
Density	0.0002427	1.1656e-005	20.823	0.000	0.9797

R^2=0.979666   F(1,9) = 433.61   p= 0.000744988 DW = 2.85

Similar results are obtained with birth rates (fig. 6), although a dummy variable has to be introduced for 1988, due to a merger that abruptly multiplied the number of exisiting projects (r^2=0.919).

Coefficients:	Value	Std.error	t value	Pr(>| t |)
(Intercept)	0.3877	0.0137	28.3592	0.000
Density	-0.0003	0.0000	-9.5064	0.000
Dummy	0.0821	0.0212	3.8769	0.0037

Multiple R-squared: 0.9195 F(2,9): 51.42, p=0.0000119

Thus, density does matter. The indirect support it provides to the hypothesis that selection drives population dynamics is strengthened by qualitative interviews with the management and designers of the division, that help us outline some sources of competitive pressure related to density. While there seems to be no direct competition for the financial resources of the firm (the capital budgeting process doesn't seem to be very effective at the level of individual projects), there is instead competition for human resources and the use of existing facilities. Design resources appear to be critical because overcrowding of projects over existing engineering resources can result either in impossibility of starting new projects (which might affect birth rates), or in delays in their manufacturing start-up, with negative consequences on their life expectancy.

Even more stringent appear to be the limits of available equipment, which can create bottlenecks especially in the final phases of engineering and in pre-production. Finally, marketing resources are limited, and the success of a project may critically depend upon the effort, attention and commitment of the marketing force. External resource constraints are obviously relevant, too. On one hand, they affect the growth rate of the firm, and thus the pool of resources available for nurturing the projects population. On the other, customer commitment appears to be very critical for a project's survival since its early days. As projects crowd environmental niches, they can meet resource limitations also from this side (moreover, different generations of projects can compete for a same customer). Finally, overcrowding can result in development delays, with infant mortality due to the loss of clients for time-to-market requirements violation.

Finally, the existence of external long term constraints (the environmental "carrying capacity") is witnessed by fig. 7, reporting the log of the cumulatd number of market niches occupied by the population over time. The tendential "saturation" of potentially available niches is easily seen.

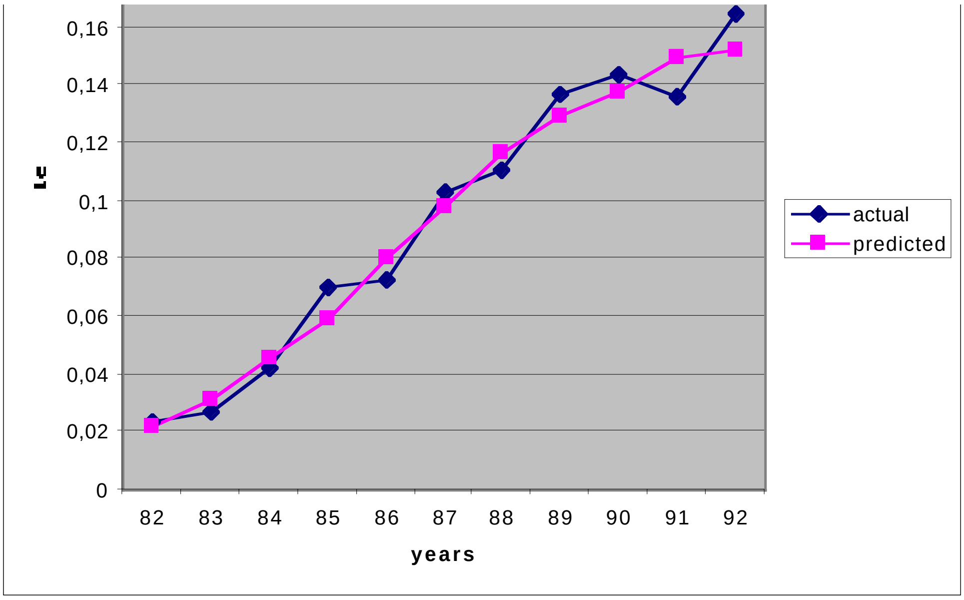

Fig. 5 Death rates and population density, fitted and actual data

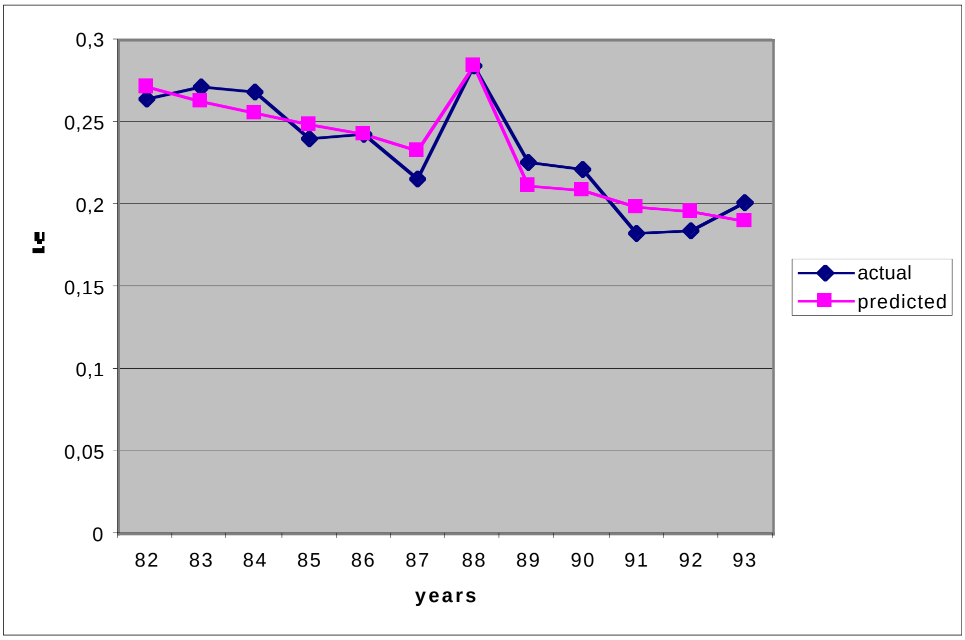

Fig. 6 Birth rates and population density, fitted and actual data

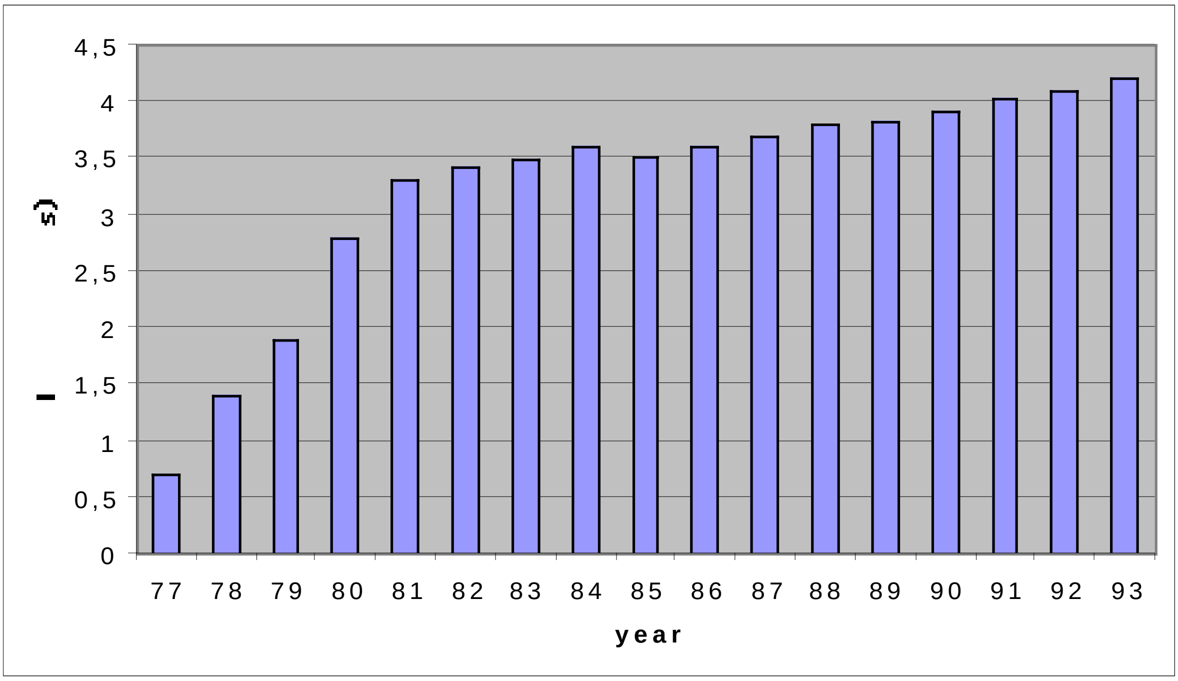

Fig.7 Log of cumulated market niches, 1977-1993

A second important ecological property is age dependence in mortality rates. The population ecology of organizations has put a special emphasis on the hypothesis that chances of survival for organizations are lowest in their earliest periods of life, and increase with time - a property often referred to as "liability of newness", after Stinchombe's (1965) pioneering analysis. Does liability of newness also apply to projects?

Again, our data suggest that such a familiar ecological property holds true. If there is age dependence, the cumulated hazard function must grow at decreasing rates, thus showung that mortality risk is decreasing as project age increase. This is clearly exhibited by fig. 8. The hazard function derived from the integrated hazard function, expressing the mortality probability in single age points, makes this property even more visible. The hazard rate neatly declines as projet age increases (fig.9), showing a negative correlation between mortality and age.

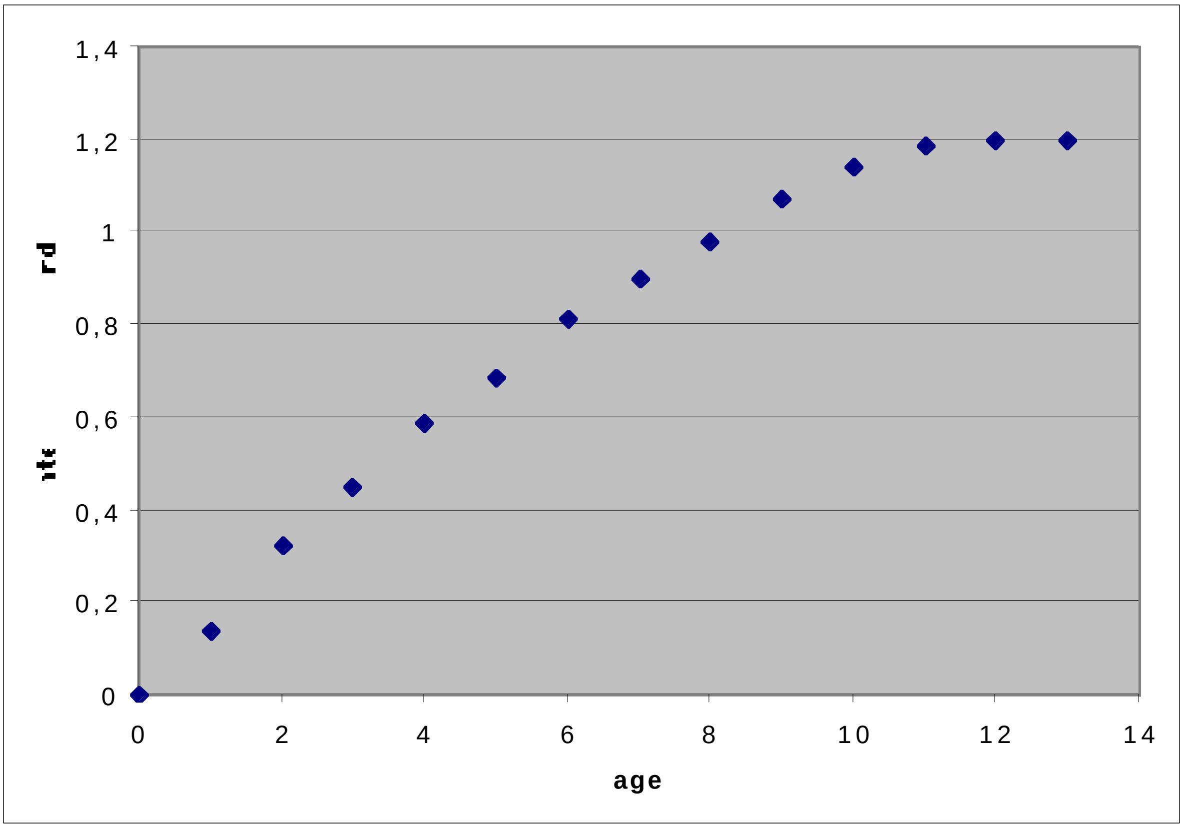

Fig. 8 Integrated hazard function (Meier-Kaplan estimator)

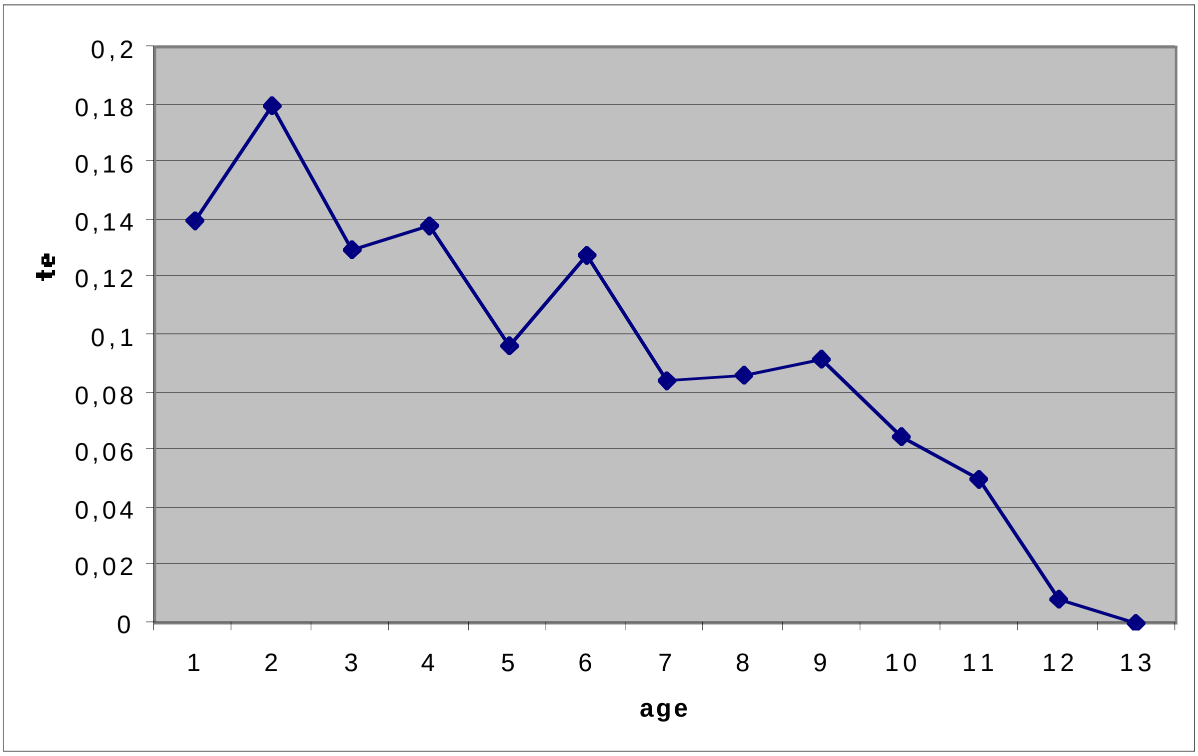

Fig. 9 Hazard rate

Once the hazard function has been reconstructed, one may try a parametric analyisis that allows to test different models of the process. Among the different tested models (Gamma, log-logistic, Weibull, Gompertz) data analysis (performed with TDA) indicates as the best candidate the Gompertz model, that brings to a determination coefficient of about 80% - again, a good result given that just one eplanatory variable is employed. The Gompertz model assumes that the hazard rate is an exponential function of age (in other words, this implies that the log of the hazard rate is a linear function of age):

$$h(t)=\lambda e^{-\rho t}$$

	Coeff.	St.error	t-stat.	Signif.	Covariate
Const	-1.6600	0.0775	-21.4320	1.000	1.000
Const	-0.0812	0.0765	-1.0612	0.7114	1.000
Age	-0.0342	0.0094	3.64341	0.9997	1.000

R^2=0.80061

Notice however from fig. 9 that the peak in the death rate is reached at the second year - this shows a projects population analog of a familiar phenomenon in organisational ecology, labelled as " honeymoon", that protects new-born entities from death (Fichman and Levinthal 1988).

It is controversial whether the liability of newness may be considered a consequence of selective pressures when organizational populations are concerned. The selectionist point of view states that it depends on the fact that organizations with higher age are those that have survived the selection process thanks to their superior fitness - and it is this superior fitness which lowers their probability of dying off. There have been two objections to such argument. From an "adaptationist" point of view, the liability of newness may result from learning processes: the older the organisation, the more likely it is that it has learned to better fit the environment, thus reducing death rates. Finally, it has been suggested that the same curve may be the outcome of simple random walk processes (Levinthal 1990): if each organisation has an initial limited stock of resources and dies off when such resources are exhausted, mere random walk in its performance can generate the liability of newness effect.

However, these objections do not hold true in the case of project populations within a firm. First, once the project has been frozen in a product, its adaptation opportunities are very limited, if not nil. Second, projects do not fail when they exhaust an individual resource stock: they can draw on the firm's pooled resources to overcome temporary fluctuations in performance. Thus, it seems reasonable to argue that age dependence in death rates is another significant hint of selection processes (again, interviews support this remark). Moreover, these effects seem to be strong enough to contrast the opposite forces of technological obsolescence, that tend to increase mortality as age grows.

4. Innovation and evolutionary activity:

In order to highlight evolutionary phenomena in a population of projects, a mere demographic analysis wouldn't suffice: we also need to look at ways in which projects' characteristics (their "traits") are generated and diffused. In this section I present again some simple empirical evidence suggesting the unfolding of an evolutionary process. Next section will analize the competitive dynamics of competences underlying such process.

It is important to distinguish between two related processes: the generation of new traits and their diffusion. In fact, the evidence that new traits are generated doesn't by itself point to the existence of an evolutionary process (Bedau and Packard, 1992). These new traits must be absorbed within the population and used. The analysis of innovation rates needs to be complemented with the analysis of their diffusion process. Later in this section I will discuss a simple measure of a system's evolutionary activity that combines these two kind of analyses and will apply it to our projects' population.

Innovation waves

It is often reasonable to assume that in nature mutation rates within a population are constant in the short run. In social systems, and especially in firms, strong reasons suggest some cautiousness in adopting such an assumption. The innovation effort is in fact a variable that on one hand can be partly influenced by managerial choices, and on the other hand depends on a multitude of individual choices at the research and development teams level. Both kind of behaviours are affected by current evaluations of past experience and by perception of development opportunities. We can thus safely assume the existence within the population of some endogenous regulation of the trade-off between exploration of innovative opportunities and exploitation of existing capabilities (March 1991). Early computer modelling and empirical analyses (Warglien 1995; Warglien and Gasparini 1994) allow us to hypothesise that the propensity to innovate (i.e. to generate new traits) exhibits a waveform behavior. Such dynamics may be explained by the fact that the discovery of a new, fitter "basin of opportunities" will reward innovative behaviours and will enhance their diffusion through resource allocation and imitation. As opportunities are saturated, the same processes of resource allocation and behaviour diffusion will induce a come-back of more exploitation-oriented strategies (Warglien 1995).

A measure of innovation effort within a population of projects is its "mutation rate", i.e. the percent of new projects showing new traits. Being constrained to technology only, we have defined as a "new trait" each new process used by a device. Fig. 10 shows the rate from 1977 to 1993. Two major innovation waves can be observed with peaks in 1979 and 1986.

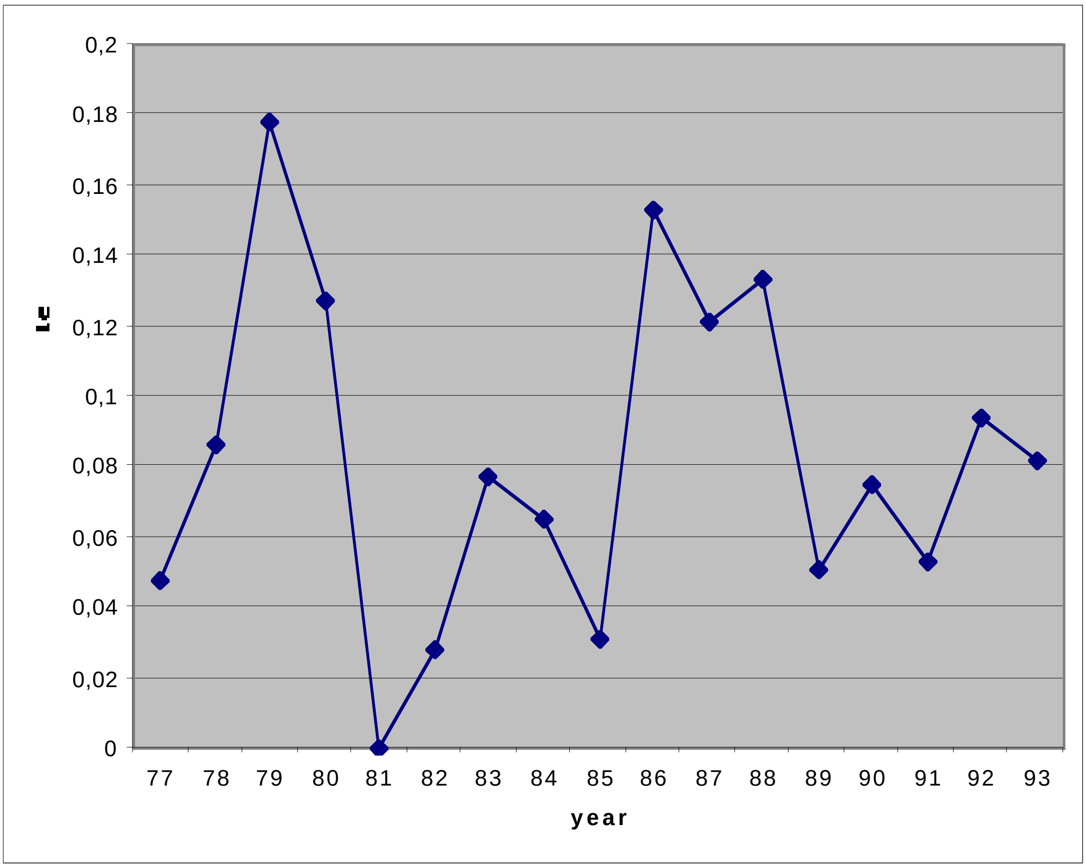

Fig 10 Mutation rate, 1977-1993

It is important to stress that these are true innovation waves, and not mere random fluctuations. I tried to know more on the second wave by analysing technologies and interviewing relevant organisational actors. In short, the wave gets its start from the internal development of a new design capability, related to mixed technologies (i.e. technologies which hybridise digital and analogic processes). The new processes wave is fundamentally spawned by the exploration of the new kind of technology. Interviews have underlined the importance of imitative behaviours in R&D teams in diffusing such technologies and a higher propensity to innovate: "As soon as mixed technologies were developed, there has been a rush among engineers to the development and use of new processes embedding such technologies", as a senior manager reported.

It is also interesting to remark that, as predicted by computer simulations (Warglien 1995) there seems to be a corrspondence between innovation waves and the liability of newness. In particular, an examination of the "infant" mortality of projects (the percent of new projects that die off within two years) shows that rising waves of innovation rates tend to be followed by rising waves of infant mortality, with a delay of one to two years. Moreover, phases of higher mutation also correspond to an accentuation of the joint innovation of both technology and markets, i.e. maximum diversification. Clearly, both phenomena subsume an increased risk propensity, that characterizes exploration phases (March 1990).

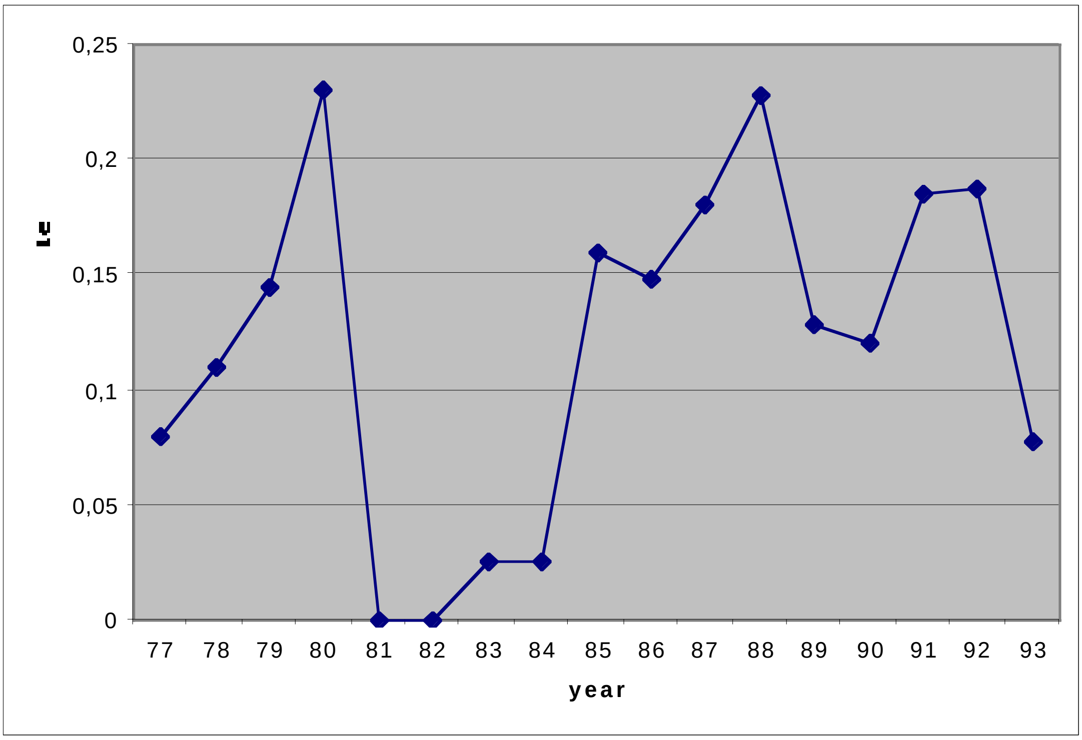

Fig.11 infant death rates, 1977-93

Activity waves

We are thus led to the second main question: do innovation waves generate evolutionary waves in the population? One can easily imagine innovation waves that die off soon without leaving any trace in the system's behaviour. As suggested above, innovations must generate patterns of persistent usage of new traits in order to give rise to significant evolutionary phenomena. In other words, innovation must be followed by diffusion. From this point of view, the discriminating criterion is whether new traits are being persistently used in subsequent generations of projects.

On the basis of similar considerations, Bedau and Packard (1992) have defined some basic usage statistics that answer the need to measure the "evolutionary temperature" of a system. Referring to simplified "artificial life" systems, they choose <u>cumulated usage</u> of genes in a population as the fundamental indicator of absorption of genetic material. Thus, a usage distribution function is defined as follows:

$$N(t,u) = \frac{1}{N_g} \sum_{i,j} \delta(u - u_{i,j}^t)$$

where N_g is the number of genes in the population, u^t_{ij} is the usage that a gene g_{ij} (the j^{th} gene of the i^{th} individual) has accumulated by time t, and $\delta(u - u_{i,j}^t)$ is the Dirac delta function (equal to 1 if $u = u_{i,j}^t$ 0 else). At time 0, all genes will have zero usage. But after some time, as useful genes enter the population, the function will become positive for positive values of u. As cumulative usage of genes in the pool increases over time, there will be a moving wave in the distribution, that will appear over the time/usage plane. Sometimes these waves may be interrupted by extinction of genes. Bedau and Packard define such waves as waves of evolutionary activity, or activity waves.
In the case of projects, the measure is defined in terms of cumulative usage of a specific process: the more projects embed a given processes, the larger the usage number. The distribution function associates to each usage level u_n the number of processes that have been used n times.

Bedau and Packard have suggested a second statistic of evolutionary activity, that measures the flow of genes over a usage threshold. Intuitively, one wants to measure the rate at which new genetic materials are absorbed within the population by observing their passage from a single point of cumulative usage. A measure of such flow is based on the measure P of the proportion of genes at t that have at least usage u_0:

$$P(t,u) = \sum_{u=u_0}^{\infty} N(t,u_0)$$

If a rising wave is passing through a point u_0 at a constant rate, there will be no modifications in the level of P. If it is increasing, then P will decrease because of the passage of genes to the upper values of u. Thus, the flow of genes through the usage point u_0 can be measured by the negative of the derivative of the measure P(t,u) with respect to t.

$$A(t) = -\left[\frac{\partial \mathrm{P}(t,u_0)}{\partial \mathrm{t}}\right]$$

Of course, the choice of the level of the reference point u_0 will be to some extent critical. Although slight changes in u_0 may not be crucial, u_0 must be chosen high enough to avoid recording the passage of useless genes. Interviews with the firm management and analysis of data suggests that 12 may be a good candidate for such treshold..

Fig. 12 plots the activity waves as recorded by A(t) in our projects population. Again, two waves can be observed: the first (of which fig. 12 captures the decline) is probably a continuation of the wave triggered by the innovation burst of the late seventies, while the second is related to the introduction of mixed technologies.

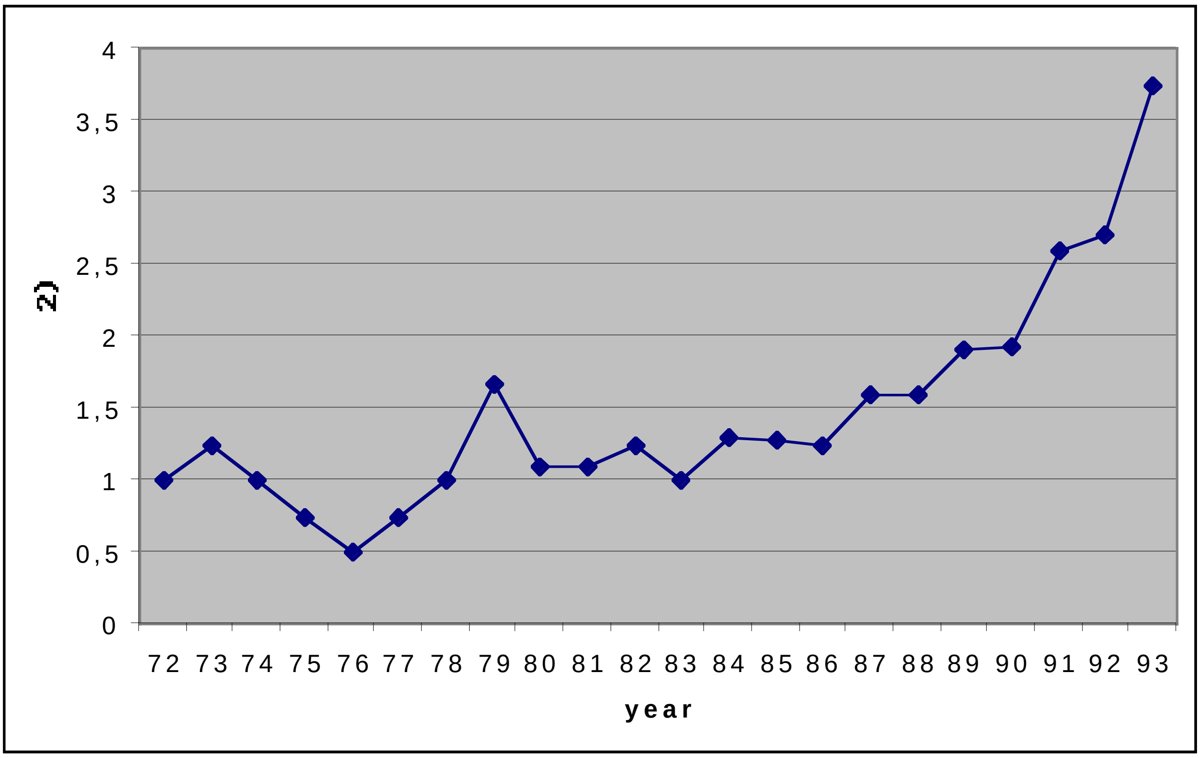

Fig. 12 activity waves, 1972-93

A comparison with mutation rates suggests that the ability to translate innovation into traits diffusion has been increasing over the deployment of the second actiovity wave - a clear symptom that the initial exploration efforts have involved higher risks and that innovation reliability has been increasing as the new technological family has become better understood. The ability to exploit innovation seems thus to increase as the poulation departs from the early exploration phases of the activity wave.

5. The evolution of competences: traits diffusion

The results of the previous sections legitmate futher investigation of the diffusion of traits as an evolutionary process. As a matter of fact, there are deep analogies between the analysis of the diffusion of a fitter variant and the diffusion of an innovation. As remarked in Cavalli-Sforza and Feldman (1981), the basic hypothesis that fitter mutants reproduce themselves at exponential rates makes models of "diffusion of the fittest" isomorphic to models of diffusion of innovation (and to those of epidemiologic spread): both predict a logistic diffusion curve when the population composition is considered. In our case, however, things are significantly complicated by the fact that diffusion has to be studied as a multivariate diffusion process, rather than as a univariate one, as in conventional diffusion studies. The problem is to understand how competition among technologies drives diffusion patterns: this brings us closer to Lotka-Volterra-like models of competition, in which interaction coefficients among competing variants have to be taken into account together with intrinsic growth rates (auto-correlated components). Furthermore, one needs to model a process in which new traits enter the competition as time elapses: in other words, the dimensionality of the model varies over time. To make things worse, there is no a-priori reason to believe that interaction coefficients are stable over time: technological innovation and learning efects may significantly alter how single technological traits compete with other ones.

To deal with such an uncomfortable condition, a reasonable approach seems to give up with the assumption that parameters of the model are unknown fixed quantities, and treat instead parameters as random variables, assuming that the researcher has prior beliefs over those variables, expressed in probabilistic form; as new observations are introduced, they will allow the researcher to update such beliefs. This shifts us in the realm of bayesian inference. The advantage is that both changing dimensionality and variability in the competition coefficients can be more naturally arranged within such framework.

The basic idea, derived from the Quintana and West (1988) Dynamic Multivate Regression (DMR) model, is that diffusion can be modelled through two systems of equations (see Pastore and Warglien, in prep., for technical details).

The first system, the observation equations, models the composition of the population at each time t:

$$\mathbf{Y}(t)= \mathbf{F}(t)\ \Theta(t)+ \nu(t)$$

where the dynamics of the parameters array $\Theta(t)$ are modelled through the evolution equation

$$\Theta(t)= \mathbf{G}(t)\ \Theta(t-1)+\boldsymbol{\Omega}(t)$$

$\mathbf{Y}(t)$= observations array at time t
$\mathbf{F}(t)$=Matrix of independent variables at time t
$\Theta(t)$ = parameters matrix

G(t) system matrix
$\nu(t)$, $\boldsymbol{\Omega}(t)$ normal random variable arrays

The bayesian update of the parameters array $\Theta(t)$ is obtained through application of the recursive Kalman algorithm. The DMR model is applied to compositional data by log/logistic transformations of data. (Aitchison 1986).

What prior beliefs are needed to run the model? The only needed assumption is that the researcher has some (diffuse) priors regards the possible emergence of a given new trait. Basically, one has to use a prior distribution with low mean (and high variance) about the percent of projects adopting hjte new tehnology in the first adoption year. The model turned out to be quite robust to changes in the prior distributions.

Figures 13-14 plot the results of the DRM model. One can see the good predictive performance (one year ahaead) obtained (r^2 ranging from .91 to .96 for the different traits: see Pastore and Warglien, in prep.). Predicted compositions match pretty well the actual observations, with errors ranging mostly within a ± 5% interval (with the exception of a few points, mostly related to the introduction phase of new technologies). However, the good fit might be not surprising given the high number of parameters as compared to the low number of observations. Although the risk of overfitting cannot be denied, a closer analysis of the parameters shows that most parameters assume values very close to 0. In other words, the model seems to have selected a few parameters as relevant, suggesting a more parsimonious model. Given the quite cumbersome amount of information needed for a close analyisis of the model, in what follows I will give only a summarized report of the main results, and refer to Pastore and Warglien (in prep.)for a more detailed analysis.

What needs to be stressed is that the few competition parameters selcted by the model are indeed those that make sense from a technological and market point of view. in particular, the model singles out strong competitive effects from the bipolar to the standard family, and from the mixed technology to the bipolar one. This is exactly what the perception of inside actors confirms. There are also competitive effects from the MOS family to the bipolar one (and weaker ones from MOS to mixed technologies). The dynamics of the MOS competitive parameters are however affected by early design failures and by an injection of digital design capabilities with the merger of 1987, which gives them a neat two-phases behavior..

A closer look at the two most interesting competition parametres - bipolar vs. standard and mixed techs vs. bipolar -and to the second phase of the evolution of the MOS vs. bipolar competition parameter shows another interesting feature. As expected, competition coefficeints are not constant over time. But a naive expection might be that as the firm gains experience with a new technology, its competition coefficient should *increase*; this is not what happens. On the opposite, competition coefficients of the newer technology vs the older tend to *decrease* over time. Despite this may seem a counter-intuitive result, it has strong consonancies with the resuls of the age-dependence analysis performed in section 3. Different projects embedding a same technology have different fitness. Newer technologies can initally easily wipe out weak individuals form older technologies. But as the weaker individuals have been substituted, competition is with the surviving stronger individuals, and the diffusion of newer technologies is slowed down. Thus, the same "inertial" factor affecting the population demography seems at work in the diffusion process.

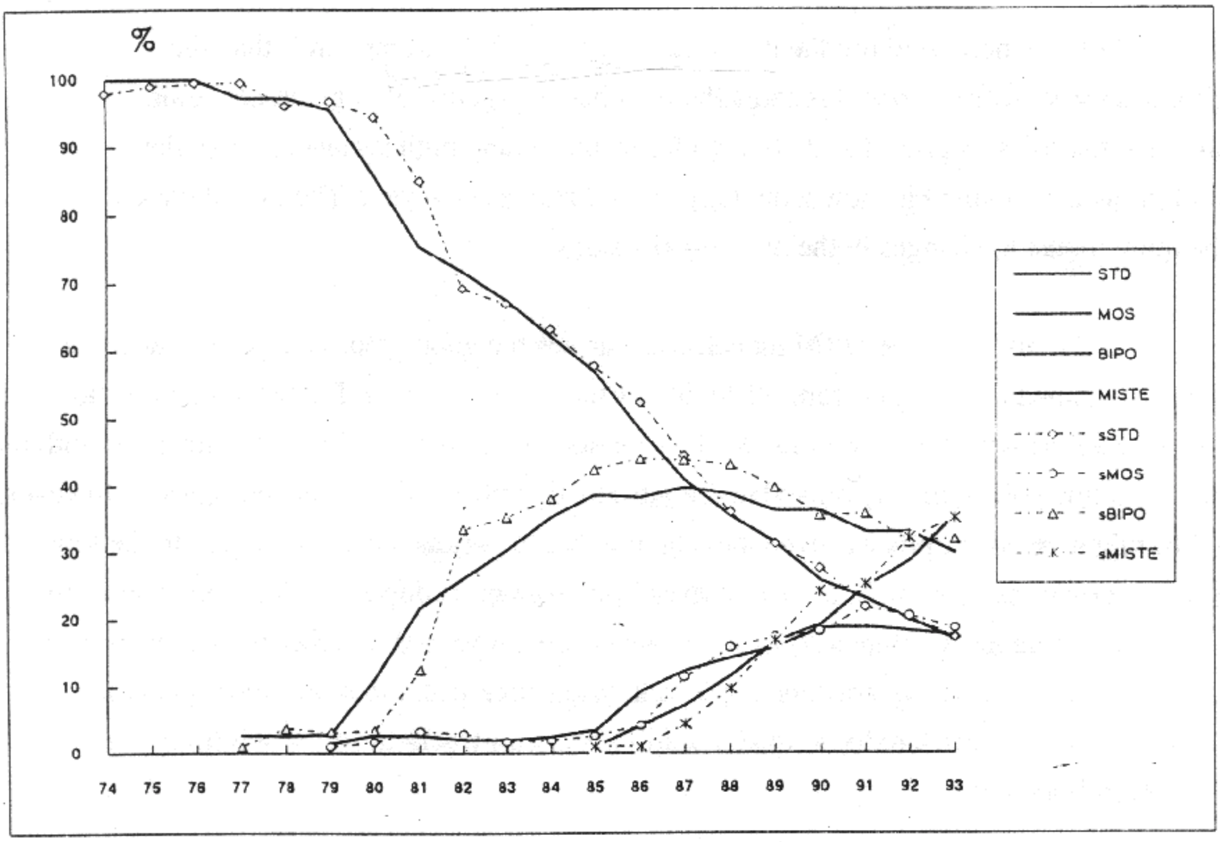

Fig. 13 DRM, predicted and actual observations

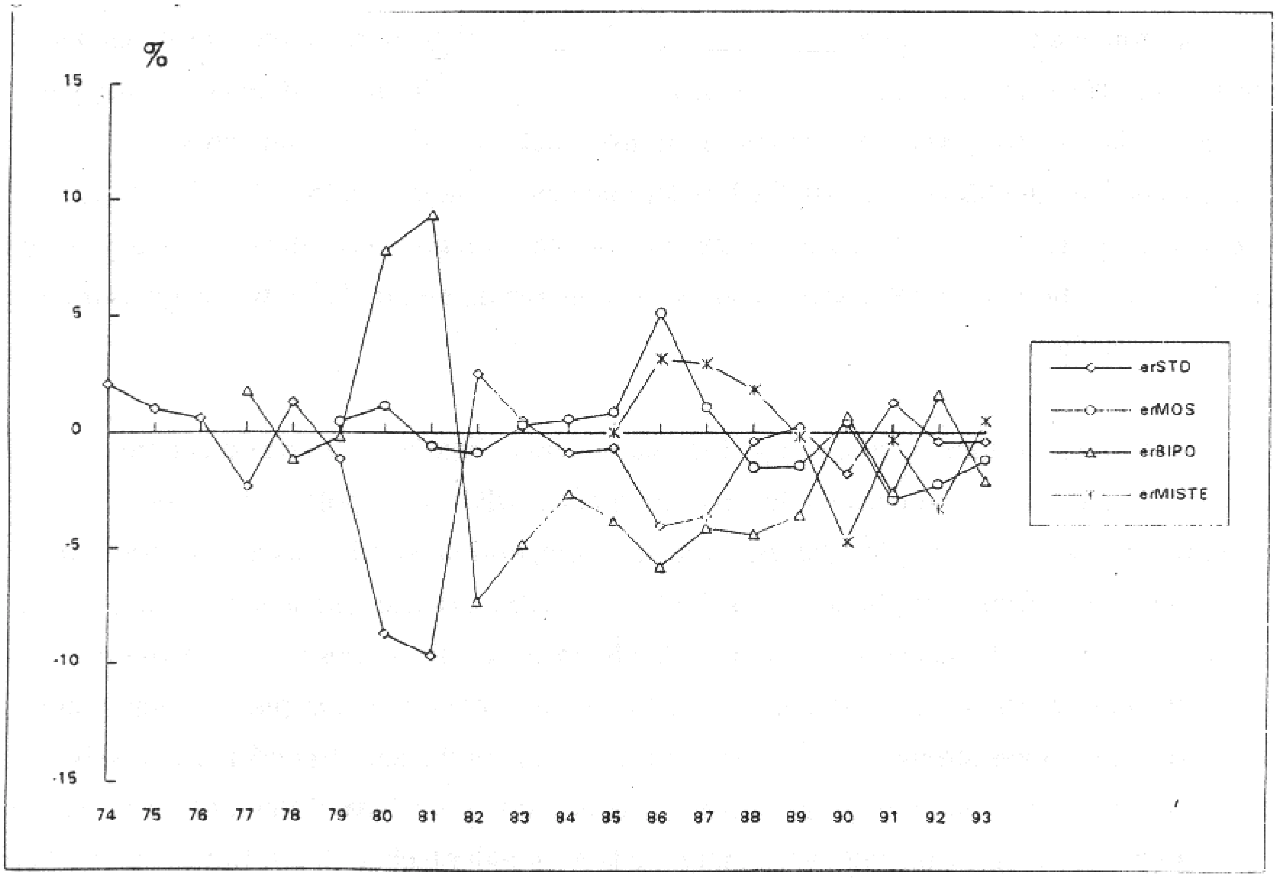

Fig. 14 DRM, prediction errors

6 Concluding remarks

The first aim of this paper is to show that firms' competences evolve over time following evolutionary processes. This is done through a longitudinal case study of more than 20 years of a the dynamics of design competences in a major European miocroelectronics firm.

Tracking directly over time the generation and diffusion of competences may be prohibitively hard – but one can obtain reasonably accurate information from the study of traits that express underlying competences. In the case study analized in this paper, design competences can be meaningfully related to the processes embedded in products' design. This provides a simple key for the research design, helping to single out a population of units carrying such traits (the population of product design projects) and suggesting to analize the long term dynamics of such population.

The study has two main empirical parts. The first one can be properly labelled as "ecological analysis", while the second one is more directly concerned with evolutionary issues.

The first part is an analysis of selective dynamics in the population of projects. This analysis has a value per se, as an example of ecological modelling of intra-firm processes; but it is also necessary in order to establish the premises for the subsequent evolutionary analysis. This part brings two essential results on density- and age-dependence.

Density-dependence is generally acknowledged as the most fundamental property of populations subject to selective dynamics. I show that density dependence characterizes the growth of the population of projects, affecting both the birth and the death process.

Age-dependence is a more problematic feature; in the context of microelectronic devices design, it can be interpreted as resulting form the contrasting effects of obsolescence (positive age dependece) and inertia (negative age-dependence). This study shows that even in short life-cycle industries such as microelectronics inertia matters.

After the existence of selective pressures has been established in the first part of the study, the second part deals with the evolutionary dynamics of competences. First, the paper shows that the rates of innovation have waveform behavior over time, and affect the risk of early mortality of new projects. This suggests that there are “schumpeterian” internal cycles of regulation of the exploration/exploitation trade-off within the firm. I propose the application of a new metric of evolutionary activity (mutuated from research in the artificial life domain) to gain further insights in the regulation of such trade-offs. Such metric highlights the existence of processes of learning to diffuse new design competences. Finally, the paper shows that the analysis of competitive dynamics between competences supports a Lotka-Volterra like modelling strategy. This strategy is implemented through the use of a Dynamic Multivariate Regression bayesian model. The analysis of the behavior of competition coefficients over time confirms the relevance of inertial phenomena in the process of competence diffusion.

Besides these research results, this study has some potentially relevant implications for the management of innovation. Broadly speaking, the results obtained point to the necessity of managing competences in a dynamic perspective which emphasizes the control of the parameters regulating evolutionary processes, rather than looking at single projects. I suggest that the ability to tune the evolutionary process is a genuine dynamic capability of the firm, affecting its long term success.

First of all, the study reveals a need to govern the selection process. Data reveal a strong impact of crowding effects over project expected mortality rates. The sources of project mortality are not only external to the firm, but also relate to bottlenecks in internal resources and the decision making process. Our study suggests that firms should carefully monitor the project mortality process, and single out the resource bottlenecks that can cause the death of projects with good market potential. In particular, interviews we made complementing the quantitative data analysis confirm that there are serious risks of resource misallocation due to crowding effects.

Second, managing patterns of evolution requires a careful tuning of the exploration/exploitation trade-off. The portfolio of projects should comprise at any time a balanced set of new traits, which present high risk but also higher development potential, and well-estabished traits that provide resources for supporting the cost and the risk of exploration and stability and reliability in the relationships with market niches. However, the key point is that organizations need to perform simultaneously more exploration of new solutions *and* more exploitation of the results of former explorations. Reconciling these needs implies governing the diffusion process of successful new variants in order to turn quickly new discoveries into profitable businesses. As we have seen, generating novelty doesn't warrant that novelty will succesfully diffuse within the population of projects. Furthermore, the capability to absorb novelty into the population seems to vary with time, and is subject to learning effects, as section 4 has shown.

This study seems to support the view that monitoring and managing the diffusion curves of new traits is the key for tuning the exploration/exploitation dilemma. This in turn requires to rethink traditional management tools such as team staffing and mobility, incentive policies, and information storage and retrieval (see for example Axelrod and Cohen, forthcoming), conceptualizing them as tools for setting the parameters of intra-firm dynamics.

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