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1. INTRODUCTION

This deliverable is presenting an articulated theoretical background grafting the tools and concepts of complex system dynamics in the analysis of the relationship between demand side policies and the generation and exploitation of technological change.

It is the product of the Work Package 3 "Development of an integrated analytical framework" (Months: 1-18), in which UNS acted as leader, and CCA, CSIC and UHOH as partners.

It synthesizes the work that has been done by the different partners in:
- Task 3.1 - Review of the existing theoretical and analytical contributions analyzing the relationships between demand and innovation, providing a taxonomy based on the kind of modeling approach they used and the main outcomes and implied policy suggestions
- Task 3.2. - Exploration of different possible avenues to develop an integrated model analyzing the role of demand-oriented policies on innovation in a framework shaped by complex systemic interactions
- Task 3.3. - Implementation of analytical models.

The deliverable is aiming at identifying the characteristics of the state of the art. It appears that most of the theoretical and empirical frameworks devoted to the analysis of innovation policies are dominated by a supply-side perspective, and that the main rationale for public intervention in the promotion of innovation activities is the occurrence of market failures and socially suboptimal investments. Despite the recent renewed interest in demand-driven innovation policies, there is no theoretical and empirical studies attempting to frame the role of public procurement within the complex set of interactions that constitute evolving innovation systems, and there is no systemic data about the implementation of this kind of policies. Quantitative assessment of the influence of direct and indirect public procurement on the systemic dynamics of technological change is also missing.

Based on this state of the art, the objectives of the deliverable are the following. It is aiming at developing and validating an integrated model for the assessment of the effects of demand-driven innovation policies on the complex set of organization and interactions involved in the generation, diffusion and exploitation of technological knowledge. It focuses on theoretical bases, while so far the need for demand-based innovation policies involved essentially stakeholders and policymakers. It is intended to promote an integrated framework able to provide the analytical and empirical foundations for the design of future public policies. It focuses on the rationale for demand-oriented innovation policies, distinct from broader demand-oriented policies.

In order to achieve these objectives, the research strategy implemented in the deliverable has been oriented towards:

- Improving the understanding of the effects of innovation policies from a theoretical and analytical viewpoint
- Grafting the recent advancements in the application of complexity theory to the analysis of innovation dynamics into a demand-oriented framework
- Providing a new interpretation able to give public procurement a long-run time horizon
- Considering new technological knowledge as an outcome of systemic dynamics

- Capturing the interactions between heterogeneous and creative agents
- Introducing intentional action in the theoretical and empirical reference frameworks
- Understanding how individual action and interaction shape and are shaped by the dynamics of the system

The structure of the deliverable is the following. In section 2, we provide a review of the state of the art. In section 3, we identify the progresses to be made beyond the state of the art. In section 4, we present a complexity based approach which is in line with the progresses that are required to provide an integrated analytical framework. In section 5, we develop some methodological implications driven by this integrated analytical framework.

2. STATE OF THE ART

2.1. General overview

Innovation and technological knowledge have long been regarded as the key factors enhancing the competitiveness of economic systems and boosting economic growth. A wide body of theoretical and empirical contributions has indeed provided robust foundations to this argument, within different strands of economic literature. The European Commission itself has emphasized the crucial role of knowledge and innovation, as witnessed by the **Lisbon agenda**, and the more recent claims about the need to increase innovation efforts to come out from the global crisis and to cope with the new challenges raised by the concerns about global warming.

Strangely enough, the **relationships between innovation and the ongoing global crisis** have not received the due attention by innovation scholars. Archibugi and Filippetti (2009) show that while innovation may help to cope with the economic downturn, the crisis is likely to **harm knowledge creation**, through the reduction of the private resources dedicated to innovation activities. Therefore, the policy dimension of innovation processes becomes once more of paramount importance.

Innovation policies have increasingly become the strategic lever aimed at rejuvenating the growth process in mature industries and at creating the conditions for the birth of new industries, as well as at providing the means by which less developed area could have reduced the gaps with advanced economies. **However, innovation policies have mainly been designed to work on the supply side of the knowledge production process**. The traditional approach to innovation policies places in the correction of ‘market failures’ the main rationale for public intervention. Based on the analysis by Kenneth Arrow (1962), knowledge is basically considered as information, and hence described as a public good characterized by non-rivalry, non-excludability and non-appropriability. In this direction, most innovation policies involved the dissemination of incentives and subsidies to compensate would-be innovators for the pretended non-appropriability of knowledge and hence remedy to ensuing market failures.

The **evolutionary perspective** on science and technology policy represents a clear step forward (Lundvall, 1992; Nelson; 1993; Edquist, 1997). First of all, the view of knowledge as a public good is abandoned to propose a more realistic view of knowledge as embodied in the idiosyncratic features of economic agents and of the networks within which they conduct their research. In this framework knowledge is essentially tacit, and much emphasis is put on learning dynamics and skills development, as well as on the interactive nature of the innovation process occurring within innovation systems defined at both national and regional level (Rosenberg, 1990; Pavitt, 1998). As Salter and Martin (2001) show, the evolutionary approach to technology policy allows for the appreciation of a wider set of economic and social benefits, that go well beyond the simplistic argument concerning market failures. They identify six classes of benefits that may accrue from innovation policies, which relate to i) the increase in the stock of available knowledge; ii) training of skilled graduates; iii) creating new scientific instrumentation and methodologies; iv) networks and social interactions; v) problem-solving; new firms' creation. Although grounded on a more advanced understanding of the innovation process, these policies are **still oriented on the supply side**. Moreover, they share with the evolutionary and the innovation system approaches a **pretty deterministic view on technologies**, which are supposed to follow defined stages of a lifecycle once introduced, and the **idea that systemic ties are given by nature and only wait to be fuelled**.

However, the analysis of the relationships between demand and innovation hardly is a radical new topic in economics. It can indeed be dated back as early as to the 1776 work by Adam Smith. His example of the pin-making factory stands as a brilliant representation of the principle by which the division of the labour is limited by the extent of the market. According to this, the increase in demand is likely to engender efforts to achieve increased productivity on the supply side. This view has been further elaborated by Allyn Young (1928) and Nicholas Kaldor (1972). Young emphasized that the fact that demand plays such a prominent role in fostering progress and growth implies that increasing returns are endogenous to the economic system, i.e. they are the result of intentional actions. This makes demand a powerful enabling device for innovation driven economic growth. Fifty years later, Kaldor stressed the implications of Young's analysis, by emphasizing its intrinsic dynamic flavour. Increasing demand in a specific market is likely to foster increasing returns on the supply side, so that a larger amount of goods are produced. An increased flow of income eventually follows as a result of increasing sales/profits, so that the workers and the entrepreneurs producing that specific good have more available income, which will be directed towards the demand for other goods. The demand in one market is therefore likely to engender the demand in other markets, feeding dynamic economies of scale and scope and sustained economic growth.

The demand side determinants of productivity performances have thus been stated by Kaldor (1966), building on the evidence provided by Verdoorn (1949). The argument is that the division of labour enhances workers' skills and know-how, induces the introduction of technological innovation and, through increased specialisation, changes the sectoral structure of the economy since new industries emerge leading to further specialization and productivity growth. In this way manufacturing industry is subject to increasing returns deriving from the exploitation of both static and dynamic scale economies. While a large empirical literature (see Bairam, 1987 and McCombie et al., 2002 for extensive reviews) has provided support for this argument, three main limitations have been pointed out. First, in estimating Verdoorn Law, Kaldor assumed demand as exogenous, while it can be argued that it is partially endogenous, due to income and price effects, leading to biased econometric results (Rowthorn, 1975). However, on the price effect, Fagerberg (2000) showed that productivity growth is not always translated into reduced prices, and therefore, especially in the short term, this source of endogeneity is of minor importance. This evidence is particularly important for studies at the industry level, where the price influence on demand is the crucial one. Moreover, when different solutions to the endogeneity problem were adopted, (Dixon & Thirlwall, 1975; McCombie, 1981; Leon-Ledesma, 2000), the significance of the Verdoorn coefficient and the validity of Kaldor`s argument, suggesting a causal link from the dynamics of demand to that of productivity, were largely confirmed independently from the estimation technique used. Secondly, the analysis of the relationship between demand and productivity has traditionally been conducted for manufacturing industries only. A few studies have found positive and significant Verdoorn coefficients also for service sectors, concluding for the existence of increasing returns to scale also in services (Leon-Ledesma, 2000; Seiter, 2005). Thirdly, in this context the treatment of technological change and its effects on productivity growth is far from being satisfactory, since the Verdoorn coefficient, at best, indistinctly accounts for induced embodied and disembodied technological change (Dixon and Thirlwall, 1975; Rowthorn, 1979).

These theoretical grounds have been empirically tested with the so-called "Kaldor-Verdoorn law", according to which the growth of labour productivity is a function of the growth of output. This literature has shown a rather constant relation between the increase of output and the increase of productivity, both across countries, across regions and across industries (McCombie, 1981). This relation is considered to be the main explanation for the presence of increasing returns and it considers spillovers, economies of scale and inter-industry specialization driven by the increase of production as the main reasons behind labour productivity growth. Anyway, this demand-driven interpretation of growth does not focus specifically on the technological side of the process, but rather on the changing structure of the organization of labour and on the possible positive inter-dependencies between economic actors.

On a different and yet complementary ground, Jacob Schmookler has explicitly brought technological change into the analysis of demand-driven economic growth, by analyzing the effects of demand on the levels of inventive activity. He carried out long-run empirical analyses, whereby the increase in the demand for a specific good was proxied by the increase in the use of the inputs necessary for its production, and the level of inventive activity was proxied by patent applications (Schmookler, 1954 and 1966). Schmookler's contribution has been eventually criticized by Nathan Rosenberg (1974), who disagreed with the excessive emphasis placed on demand-side effects. Indeed, while demand in no doubt represents a crucial factor boosting investments in technological activities, as it affects the perception of where one may find prospect for profits, the role of the relative advancement of the state of knowledge in different scientific disciplines and technological fields cannot be disregarded as well. In the same vein, Mowery and Rosenberg (1979) conducted an extensive review on the empirical studies emphasizing the effects of demand on innovation and on the policy implications that they suggested. They maintain that most of the reviewed studies share the complete neglect of supply-side considerations, while proposing demand as the main driver of innovation. On the contrary, even demand-oriented approaches to innovation policies should pay much attention to the systemic ties that characterize the dynamics of innovation.

2.2. The "classical" debate: demand pull and technology push

In the 1960s and 1970s the literature on the determinants of innovation has been dominated by the debate between two contrasting perspectives on innovation, the technology-push and demand-pull models. The first one emphasises the role of scientific and technological knowledge and of the opportunities for innovation in determining the rate and direction of technological change in industries (Rosenberg, 1974; Freeman, 1974, 1979; Dosi, 1988). The second approach emphasizes the importance of demand dynamics in influencing the investment in inventive activities and the direction of innovative efforts across products and industries (Schmookler, 1966). Schmookler's seminal contribution was an attempt to demonstrate the economic nature of technological change, in contrast to the neo-classical idea that technological change can be treated as a pure exogenous factor in the growth process (Solow, 1956). In particular, he claimed that demand conditions crucially influence the desirability and realization of inventions and that the existence of an expected profitability and the expansion of market demand represents the key stimulus to which inventive activities react1.

Schmookler and the advocates of the demand-pull hypothesis were criticized on both theoretical and empirical grounds (Rosenberg, 1974; Mowery and Rosenberg, 1979, Scherer, 1982a; Kleinknecht and Verspagen, 1990). The first critique was that the stock of scientific knowledge represents a basic determinant of the kinds of inventions that can actually be produced (Rosenberg, 1974). Secondly, it has been argued that the influence of demand factors on innovation was not demonstrated to be greater than the effect of other factors (Mowery and Rosenberg, 1979). Finally, it has been shown that the empirical evidence proposed by Schmookler was weaker than he claimed it to be (Scherer, 1982a; Kleinknecht and Verspagen, 1990).

The debate has been enriched by a large number of case studies (Walsh, 1984; Malerba, 1985; Howells, 1997; Ende and Dolfsma, 2005) or econometric analyses at the firm or aggregate levels (Wyatt, 1987; Parker, 1992; Geroski and Walters, 1995; Kleinknecht, 1996; Brouwer and Kleinknecht, 1999) and has greatly increased our comprehension of technological change by showing strengths and weaknesses of the two approaches. The conclusion of such a debate was that the influence of changes in the state-of-the-art in technological knowledge and capabilities, on the one hand, and demand factors, on the other hand, are both important sources of innovation.

2.3. Technological factors, supply conditions and evolutionary perspectives

Since the 1980s, the rapid growth of innovation studies with more extensive use of R&D and patent data and the rise of innovation surveys has led to a concentration of research on the sources, processes, nature and impact of technological advances in firms and industries. Major areas of study have included the nature of knowledge (tacit or codified) and competences used in innovation; the technological opportunities that are present in particular fields and industries; the property rights rules, incentives, investment decisions and organisational routines that contribute to innovative performances; the diffusion patterns of particular technologies; the importance of structural factors associated to the sectoral composition of the economy; the interaction between supply conditions, financial systems and institutional factors. Several streams of research have emerged (Fagerberg, Mowery and Nelson, 2005), shedding new light on important dimensions of the innovative process, including the role of technological regimes (Breschi et al., 2000); the operation of national and sectoral innovation systems (Lundvall, 1992; Nelson, 1993, Malerba, 2004a,b); and the broader evolutionary perspectives on technological and economic change (Nelson and Winter, 1982; Dosi et al., 1988).

The focus of such literature, however, has largely been a supply side story, rooted in micro-economic studies, firm level investigations and industrial dynamics, where demand constraints are assumed to be of minor relevance. More attention to demand has emerged in recent evolutionary work, such as Metcalfe (2001), Andersen (2001) and Saviotti (2001) that have proposed models where consumption is investigated in its effects on innovation, economic structures, and growth, bringing into considerations income and time constraints, behaviours and utilities, satiation and preferences for variety.

An original view of economic growth as an adaptive process has been proposed by Metcalfe, Foster and Ramlogan (2006). Here the interaction between the diversity in technical progress and the diversity in demand dynamics generate endogenous structural change and evolutionary growth. This highlights the importance of demand and consumption practices in relation to innovation and productivity growth and as factors shaping the process of structural change (see also Fatas-Villafranca and Saura-Bacaicoa, 2004).

A further development trying to link an evolutionary perspective with the process of structural change is the model by Saviotti and Pyka (2004), where the presence of potential, unmet demand spurs the search process that leads innovative firms to create new sectors of activity that sustain the growth of the economy. Their simulations suggest that growth in variety among firms and their activities is necessary for growth; productivity growth in existing activities and the generation of new sectors are complementary sources of development. Once potential demand is defined, no demand constraint for production is assumed until saturation occurs as sectors mature. This model points out the importance of technological strategies aiming at the creation of new products and sectors, and the importance of their ability to address potential unmet demand.

2.4. Innovation, productivity, demand and structural change

Efforts to reconcile the dynamics of innovation with demand have developed along different paths. In an early work with a neo-Schumpeterian perspective, Sylos Labini (1969) had combined technological factors with market structures and demand conditions. In oligopolistic and monopolistic markets – he argued – demand cannot be assumed to be infinitely elastic; rather, it may represent a constraint for growth and profits, in a similar way to the Keynesian approach in a macro context. It follows that in concentrated markets the rate and type of innovation and investment are driven by the expansion of demand.

The parallel dynamics of technology and demand have been put by Pasinetti (1981, 1993) at the root of the process of structural change, inspiring a stream of studies where most attention has been devoted to productivity growth (due also to the lack of detailed information on innovative activities). In connection to such an approach, a view of growth based on the works of Kaldor and of the French Régulation School, has led to address the mechanisms of cumulative growth and structural change, considering the interaction between technology-driven productivity growth and demand dynamics, often exploring the employment consequences (Petit, 1995; Vivarelli, 1995; Pini, 1995; Fagerberg and Verspagen, 1999; Fagerberg, 2000; Petit and Soete, 2001; Boyer, 2004). In particular, the model proposed by Cornwall - Cornwall (2002) explains productivity growth considering adoption of new technologies, changing output structure and demand conditions.

In such a perspective, an effort to bring together the Schumpeterian and evolutionary attention to the variety of innovation and the "structural" emphasis on the role of demand was developed in Pianta (2001), where the distinction is made between a strategy of technological competitiveness based on product innovation, and the search for cost competitiveness relying on process innovation; the demand conditions are shown to interact with the specific types of innovations introduced in firms and industries, leading to particular outcomes in terms of growth and employment. Several studies have then investigated the impact of such an interaction on jobs (Pianta, 2000; Antonucci and Pianta, 2002; Mastrostefano and Pianta, 2004) and on productivity growth (Pianta and Vaona, 2005). In such works, however, demand is considered in aggregate terms at the industry level, typically using sectoral value added as a proxy. An important improvement provided in this paper with respect to previous studies, is the break down of demand in its major components. This leads us to the insights of the input-output literature which provides the tools for identifying the roles of intermediate demand and different final uses for goods and services.

2.5. Input-output studies

Important insights can be obtained by matching the input-output approach and the analysis of technological change and innovation systems (Mohnen, 1997; Los and Verspagen, 2002). In particular, the original idea of studying the interrelations between different parts of an economy proposed by Leontief (1936) can be a powerful tool for the study of the interaction between producers and users of innovative or R&D intensive goods, helping to identify the sources of innovation and productivity growth. Studies in this direction include the pioneering work of Brown and Conrad (1967) and Terleckyj (1974, 1980), as well as Momigliano and Siniscalco (1984) and Marengo and Sterlacchini (1990).

While input-output analysis traditionally deals with the study of intersectoral flows of commodities, a different stream of research has mapped the flows of technological knowledge across sectors of the economy, aiming at developing an “innovation matrix” (Scherer, 1982b, 2003; DeBresson, 1996; Evenson and Johnson, 1997; Verspagen, 1997; Los, 2001). Different methods and data (including R&D and patents) have been used to build such matrices in order to identify sources and effects of inter-industry technology flows (Leoncini and Montresor, 2003). In particular, while the analysis of commodity flows can help to detect embodied technology flows between sectors, the use of R&D data makes it possible to estimate R&D spillovers by connecting performance measures such as total factor productivity growth in one sector to R&D performed in other sectors3 Moreover, the information contained in patent documents can be used to analyse disembodied technology flows (Verspagen, 1997) while data on scientific publications can help track scientific knowledge flows (Godin, 1995; Meyer, 2002).

3. PROGRESS BEYOND THE STATE OF THE ART

3.1. General overview

The existing policy-related literature provides a useful starting point to develop and articulated the analysis of the relationships between public demand and innovation dynamics. The Report for the European Commission “Innovation and Public Procurement: Review of Issues at Stake” provides the foundations to the elaboration of this new approach. It elaborates a taxonomy of public technology procurement along two dimensions, i.e. the societal needs and market conditions. It is also helpful in that it identifies some cases of demand-oriented innovation policies implemented across different European countries. In this direction, also the contributions by Edler (2007 and 2009) and Edler and Georghiou (2007) will provide basic guidance.

As for the economic analysis of the relationship between demand and innovation, it dates back to the studies conducted by Jackob Schmookler (1962), who showed the existence of a relationship between the increase in national income and the increase in inventive activity. Scholars in economics of innovation have however mostly focused on the supply side of innovation dynamics, **leaving the demand-side a pretty unexplored field of enquiry**. More recently, some empirical contributions have emphasized the role of public intervention in shaping the demand for technologies, like the analysis of the effects of federal procurement on the development of ICTs, or the analysis of the effects of environmental regulation on the trade of environmental-friendly technologies.

More than 30 years ago, Mowery and Rosenberg (1979) synthetized with greatest clarity the issue by stressing an important event. Increasing criticisms against Federal funding of basic research in America has led the NSF to establish its Research Applied To National Needs program in view of contributing more to the solution of pressing economic and social problems. The justification for these new policies emphasizing the decisive importance of "demand-pull" over "supply-push" aspects was based on the idea that market demand forces had to "govern" the innovation process, much more than what government or supply forces would do. For a better efficiency, innovations needed to be "called forth" or "triggered" in response to demands for the satisfaction of certain classes of "needs". The authors suggested that these new attitudes were motivated by some empirical studies, and showed that these reference studies were simply unable to lead to the conclusion that the governing influence upon the innovation process is that of market demand.

In 2011, the OECD Innovation Strategy stressed that governments have long fostered innovation in firms by focusing on supply-side factors such as the formation of human capital and public investment in R&D, while the role of demand and markets in inducing innovation was taken as a given. The question of demand is thus now receiving a renewal of interest, but with a slightly different justification. In Mowery and Rosenberg (1979), the outcome was not to deny that market demand plays an indispensable role in the development of successful innovations. Rather, the idea was to contend that the role of demand has been overextended and misrepresented, with possible consequences for the understanding of the innovative process and of appropriate government policy to foster innovation. In a sense, "(B)oth the underlying, evolving knowledge base of science and technology, as well the structure of market demand, play central roles in innovation in an interactive fashion, and neglect of either is bound to lead to faulty conclusions and policies" (OECD, 2011, p. 105). Today, the emphasis is put on the advances in ICT and the increased user participation in the innovation process that accelerates the interaction between the two, and also on the fact that the understanding of crucial role of demand is now much better. In what follows we will review the arguments supporting this new 'demand pull' OECD innovation strategy, where the basic idea will be to match supply-push with demand-pull forces (see graph below).

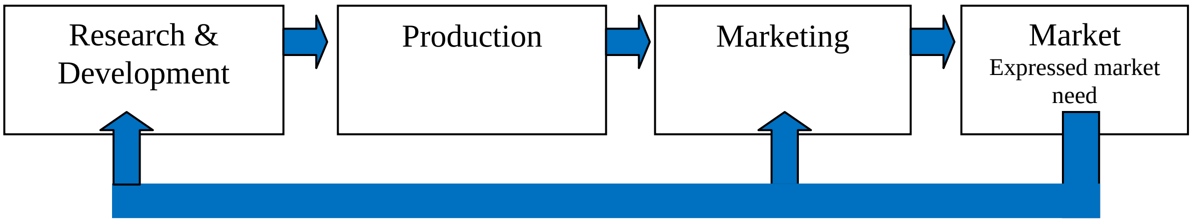


Fig. 1: Demand pull hypothesis in OECD innovation strategy

Source: OECD (2011), from Martin (1994)

For the OECD, demand-pull representations suggest that the ability to produce innovations is widespread and flexible, but often requires market opportunity, i.e. demand. This strategy focuses not on the beginning of the innovation chain but on its end, i.e. the market place. Demand is thus the force that directs resources and capabilities for innovation in a certain direction to meet societal or market needs. Therefore, a demand-side policy approach focuses on boosting demand and on encouraging suppliers to meet expressed user needs. It also aims at reducing barriers to innovation and stimulate the emergence or the redesign of markets. Of course, the effectiveness is dependent on several variables:

Price versus quality effects
As well known in standard economic theory, markets with strong competition between firms will tend to lower prices; and will increase consumers' access to innovative products or services. However, if prices are too low, both innovation and competition will be limited: firms will not invest in developing quality with new products or services if they cannot appropriate some of the rents from innovation. In addition, if low profits are expected for new entrants, this will tend to deter market entry.

Network effects
For goods with network effects a critical mass of users is necessary to make the good attractive, as the benefit for users grows with scale (e.g. the use of videophones or software such as electronic messaging services). In this case, price and access are of central importance for the diffusion of innovations. Low prices and competitive access to the network are needed to achieve the necessary critical number of users.

Switching costs
Though innovation may be launched at a lower price in the marketplace, it is possible to observe demand inertia due to switching costs, as consumers may voluntarily choose not to switch to another company or technology. These costs include cognitive (or psychological) costs, eventually the cost of replacing one's equipment, transaction costs such as the cost of collecting information about alternative offers, and contractual costs that customers often have to respect a subscription period (Krafft and Salies, 2008).

Sectors' characteristics
Malerba (2005) identifies a distinction between:
• sectors with quite homogeneous demand, more prone to be characterized as technology-push industries (like chemicals, pharmaceuticals) as the supply of novel or radical innovations often comes out of large in-house R&D programmes, or of R&D collaborative activities with universities and small.
• sectors with heterogeneous demand, like platform or standards-based industries (such as computer operating systems, automobiles, machine tools or telecommunications), where changing demand through incremental innovations is more frequent and, arguably, more desirable.

Beside these variables that favor or prevent demand for innovation to be taken into account, the different steps to be considered in the strategy are closely related to the categories of users: the early adopters, the mainstream consumers, and the laggards (OECD, 2011, based on Rogers, 1962). The basic idea here is that for the successful introduction of a radical innovation into the market, it must be commercially viable but also socially accepted. Early adopters are the first users, and play a decisive role in the adoption of the innovation by the market. Early users take the risk of testing an innovation that may not be fully optimised or functional in return for the possibility of solving a problem faster (e.g. high-technology lightweight materials were only used for mountain bikes many years after the introduction of the first models). This user population often bears higher costs as it assumes the learning costs of later users (Edler, 2007). Early users have a central role in two respects: i) they allay possible concerns about the perceived risk of adopting a new technology; ii) they provide the producer with early revenue and feedback which can lead to improvements. However, the real challenge for an innovation is to be taken up by mainstream consumers. The majority of users usually join in when innovations become more incremental and tend to embody a smaller degree of inventiveness, but also when price competition between suppliers starts and prices fall until the technology reaches a saturation point (Bower and Christensen, 1995).

Variables	Steps
Prices and quality	Early adopters
Network	Early majority of mainstream consumers
Switching	Majority of mainstream consumers
Sectors	Late majority of mainstream consumers
	Laggards

Table 1: Variables and steps in OECD (2011)

These elements are presented as important advances in the understanding of demand pull innovation, when economists usually devote little attention to the factors which influence the rate and direction of innovation. Much of the formal economic theory on technical change has been for a long time only concerned with the description of the consequences of technological innovation at a very high level of aggregation or abstraction. These demand pull representations focus at a less aggregated level on the specific innovative outputs of industries and firms when they launch there innovation on the market, with potentially the premise of explaining some differences among industries, firms, and nations. Serious empirical work on biases and inducements in the innovation process, at an industry or firm level of analysis, is on the way, based on a deeper investigation of the effects of these variables and steps may have.

But do we really go beyond what Mowery and Rosenberg (1979) already stressed? Using their own words, do we really sort out a stronger predictive theory of innovation, offering more than simply considering the motivations of individual firms to undertake research projects with the identification of these variables and steps? Do we succeed in dealing with the mechanism by which this motivation may be transmuted into an innovative response, one influenced heavily by such factors as the supply of applicable science and technology. Rather than simply referring to “variables” and “steps” in the process, a useful theory of innovation must try to explain the varied length and distribution of such delays in the response to “needs”. Such an analytic schema must explicitly consider institutional structures and dynamics, rather than the static analyses to which many theorists are wed; the analysis should also be applicable at a fairly high level of aggregation, allowing international, inter-industry, and intersectoral comparisons to be made.

To answer these questions, we have to move beyond the state of the art, by identifying basic hints towards the elaboration of an integrated framework. From the review provided in section 2, it appears that most of the theoretical and empirical frameworks are devoted to the analysis of innovation policies are dominated by a supply-side perspective, and that the main rationale for public intervention in the promotion of innovation activities is the occurrence of market failures and socially suboptimal investments. Thus, despite the recent renewed interest in demand-driven innovation policies, there is still only few theoretical and empirical studies attempting to frame the role of public procurement within the complex set of interactions that constitute evolving innovation systems. There is also poor systemic data about the implementation of this kind of policies, and the quantitative assessment of the influence of direct and indirect public procurement on the systemic dynamics of technological change is missing in general. On all these points we bring in new insights.

We are thus now able to summarize the limits of the state of the art in the following points:

- Innovation policies mainly informed by technological determinism and exogenous systems of innovation;

- Lack of an integrated analytical framework to the analysis of the effects of demand-driven innovation policies on growth and competitiveness;

- Difficulty to identify and quantify demand-oriented policy measures across different countries;

- Lack of empirical evidence on the processes through which demand-oriented policies may have an impact on innovation and on productivity growth at the national and regional level.

3.2. Early and more recent references calling for a systemic approach

Initial hints towards the elaboration of an integrated framework, with the ability to overcome the limits of the state of the art, can be found in several approaches calling for a systemic approach.

Evolutionary theory, in addition to interactive learning theory, is one of the theoretical perspectives that have strongly influenced the development of systemic approaches. Nelson and Winter (1982) have proposed an evolutionary theory of technical change, putting a special emphasis on the existence and reproduction of a certain setup of technologies and organizational forms in innovation studies. Some mechanisms introduce novelties in the system, i.e., create diversity, and they can include significant random elements or more predictable novelties. In the meantime, a selection process reduces diversity and the mechanisms operating can be either market selection or political-institutional selection as regards technical change. Together the selection mechanisms constitute a filtering system that functions in several stages and leads to a new setup of, for example, technologies and organizational forms. There might also be feedback from the selection to the generation of new innovations.

The framework originally built by Lundvall (1985) stressed processes of learning and user–producer interaction. The notion of interaction has paved the way for a systemic approach. The focus on interaction within national systems has also highlighted the importance of institutions and organizations beyond the market. Authors who have been working within the "interactive learning" tradition draw attention on how innovation processes, like most learning processes, are "influenced … by the institutional set-up of the economy".

But the more recent efforts to **apply the basic tools of complex system analysis** to social sciences and to implement an actual economics of complexity are more particularly helpful for the purposes of the project. This frame recognizes the central role of innovation, both as the key explanandum and the basic explanatory variable in the understanding of the social and economic dynamics of a system. It actually assumes explicitly that innovation is the basic engine of the dynamics of social and economic systems. **Innovation takes place in organized contexts characterized by qualified interactions among heterogeneous and creative agents** that are able to act intentionally to face the risks of decline. **The outcome of their interactions is determined by the structured contexts into which they are embedded**. At the same time however their actions and interactions do affect the structure of the system and hence ultimately the aggregate outcomes of the dynamics. In this approach **neither interactions nor the organized structures into which they take place are exogenous**, as they are determined internally by the dynamics of the system. The individual and intentional action of creative agents is central in the dynamics of the system, yet no individual agent can claim responsibility or even long-term sight on the eventual results of his or her action (Arthur et al,1997; Lane et al., 2009). By acknowledging the inherent complexity of innovation dynamics, this approach would provide the background for the development of an extended and integrated framework for the analysis, assessment and design of demand-driven innovation policies. Particular emphasis will be given to the concept of coalitions for innovations. According to this view, innovation takes place when effective coalitions based on the purposed convergence of the incentives, the structured complementarities of the competences of a variety and multiplicity of heterogeneous actors, and the aligned and mutual directedness of their interactions emerge so as to enhance the cohesion of the group and organize the inherent complexity of the system around a common goal and shared objectives (David and Keely, 2003). The case for an articulated and multi-layered demand-driven innovation policy then emerges. Most of the existing demand-oriented innovation policies has indeed exclusively focused on the identification of key industries or technologies able to address explicit or latent societal needs. However, **the** luckily ex-ante **identification of successful technologies is not a sufficient condition to foster innovation-driven competitiveness and growth**. Demand-driven innovation policies should aim at the creation of systems of innovations, or ‘market systems’, which should become the objective of intentional decision making at the policy level and of strategic action for corporations with the implementation of centred coalitions around **technological platforms** able to implement and guide the working of specific coalitions (Consoli and Patrucco, 2008) and **collective entities clustered in geographical and technological space** (Lane, 2002) (See in Appendix B, Annex B1, Annex B8 and Annex B9).

4. A COMPLEXITY BASED APPROACH

4.1. Aims and scope

Complexity is emerging as a new unifying theory to understand endogenous change and transformation across a variety of disciplines, ranging from mathematics and physics to biology. Complexity thinking is primarily a systemic and dynamic approach according to which the outcome of the behavior of each agent and of the system into which each agent is embedded, is intrinsically dynamic and can only be understood as the result of multiple interactions among heterogeneous agents embedded in evolving structures and between the micro and macro levels. Different attempts have been made to apply complexity to economics, ranging from computational complexity to econophysics, connectivity complexity and bounded rationality complexity. Too often these attempts have missed the basic feature of economics that consists in the analysis of the role of the intentional, rent-seeking conduct in the interpretation of the behavior of agents. Agents are portrayed as automata that are not able to implement the intentional pursuit of their interest (Rosser, 1999 and 2004).

This section presents a systematic attempt to show how, building upon the achievements of complexity theory, a substantial contribute to the economics of innovation can be implemented. At the same time it shows that an economic approach to complexity can be elaborated and fruitfully implemented. This section articulates the view that innovation is the emergent property of a system characterized by organized complexity. It implements an approach that enables to provide basic and simple economic foundations at the same time to analyzing the outcome of the intentional economic action of agents endowed with some levels of creativity, both at the micro and macro level, and to the notion of organized complexity. According to the theory of complexity, emergence is a phenomenon whereby aggregate behaviors that arise from the organized interactions of localized individual behaviors, provide both the system and the agents with new capabilities and functionalities. Innovation and organized complexity can be seen as emerging properties of a system stemming from the combined result of the action of individual and heterogeneous agents with the structural characteristics of an organized system that is able to qualify and amplify the results of their action. The analysis of innovation as an emergent property of a system enables to combine the individualistic analysis of innovation as the result of intentional decision making of agents with the holistic understanding of the properties of the system into which such innovative action takes place and actually makes it possible. For the same token, the analysis of an organized complexity as an emerging property enables to appreciate how the structural and architectural characteristics of a system are themselves the product of the interactions within the system and provide the context into which the individual reaction of agents can yield the introduction of innovations.

Here complexity theory enables a major progress in the economic analysis of innovation, especially if the latter is defined as a productivity-enhancing event. It is difficult, in fact, to understand how and why economic agents would not push innovative activities to the point where their marginal costs match their marginal revenue. The appreciation of the special features of the system into which the individual action takes place and of the specific processes by means of which the features of the system lead to the emergence of innovations, marks an important analytical progress.

Economics of innovation may help the theory of complexity, and especially its applications to economic analysis, in two ways. First, complexity theory often misses an economic analysis of the incentives and motivations of individual action. Economic agents are and remain rent-seeking individuals and it is necessary to understand why they may want to change and move in the multidimensional spaces that characterize economic systems. Here the economics of innovation may contribute the analysis with the understanding of the out-of-equilibrium determinants of the attempt of agents to try and introduce innovations. Second, in the complexity theory a major distinction is made between disorganized and organized complexity. In the former "the interactions of the local entities tend to smooth each other out" (Miller and Page, 2007:48). In the latter "interactions are not independent, feedback can enter the system. Feedback fundamentally alters the dynamics of a system. In a system with negative feedback, changes get quickly absorbed and the system gains stability. With positive feedback, changes get amplified leading to instability" (Miller and Page, 2007:50). Yet the theory of complexity does not provide an analysis of the endogenous determinants of the features of system. A basic question remains unresolved in much complexity thinking: how, when and why is a system characterized by organized or disorganized complexity? The basic distinction elaborated by Hayek between cosmos and taxis, e.g. spontaneous and designed order, provides basic guidance (Hayek, 1945 and 1973). The notion of organized complexity as an emerging property of an economic system enables to grasp the endogenous dynamics of the system. The reaction of firms that happens to be creative because of the feedbacks available, affect the structure of the system and can either implement its organization or open a degenerative process. Clearly the characteristics that qualify the levels of organization of the systems complexity are endogenous to the system itself.

It seems clear that all the effort made in the identification of innovation as an emergent property of a system as a mean to try and articulate its endogeneity would be spoiled if it eventually leads to accept the view that the organized complexity of a system is an exogenous and unpredictable characterization. Here the economics of innovation can provide important elements with its analysis of the endogenous formation of economic structures as the result of the recursive process of path dependent change. Our attempt to implement the merging of the theory of complexity with the economics of innovation provides a complementary path to recent attempts to apply the methodologies elaborated by complexity into economics, such as complex networks (see Cowan, Jonard, Zimmermann, 2006 and 2007), percolation (see Antonelli, 1997; Silverberg and Verspagen, 2005), and NK-modeling (see Frenken, 2006a and 2006b; Frenken and Nuvolari, 2004a), for it focuses attention upon the scope of application of the basic tools of the economics of innovation to embrace the full range of analytical perspectives brought by the analysis of innovation as an emerging property stemming from the endogenous result of both the intentional, rent-seeking conduct of individual and heterogeneous agents and the endogenous characteristics of economic systems qualified by organized complexity.

In this approach, agents are myopic: their rationality is bounded, as opposed to Olympian, because of the wide array of unexpected events, surprises and mistakes that characterize their decision making and the conduct of their business in a ever changing environment. Agents retain the typical characteristics of economic actors, including intentional choice and strategic conduct, augmented by the attribution of potential creativity. In this approach, however, economic agents may change both their production and their utility functions. Agents, in fact, are endowed with an extended procedural rationality that includes the capability to learn and to try and react to the changing conditions of their economic environment by means of the generation of new tastes as well as new technological knowledge and its exploitation by means of the introduction of technological innovations. In this approach agents do more than adjusting prices to quantities and vice versa: they can try and change their technologies and their preferences. Agents are intrinsically heterogeneous. Their basic characteristics differ in terms of original endowments such as learning capabilities, size, and location. Their variety is also endogenous as it keeps changing as a result of the dynamics of endogenous technological change (Albin, 1998).

The determinants and the effects of this potential creativity and the context into which it can be implemented, however, require careful investigation. The actual creativity of agents is not obvious, nor spontaneous, but induced and systemic.

To investigate the determinants of the actual creativity of agents three steps are necessary. First, the incentives to change must be identified and qualified. Agents are reluctant to change their production and utility functions and a specific motivation is necessary to induce them to try and change their routines. Second, the localized context of action and the web of knowledge interactions and externalities into which each agent is embedded are crucial to make their reaction actually creative, as opposed to adaptive, so as to shape the actual effects of their endogenous efforts to change their technologies and their preferences. Third, the sequential process of feedbacks that make the creative reaction a sustained process must be identified. The creative reaction of each agent in fact is not a punctual event that takes place isolated in time and space, but rather a historic process where the sequence of feedbacks plays a key role (Arthur, 1990).

The analysis of the effects must include, next to the introduction of innovations that increase the efficiency of the production process, the structural consequences upon the context of action. The successful introduction of new localized technologies, in fact, changes the structure of the system and hence the flows of knowledge externalities and interactions. This dynamic loop exhibits the characters of a recursive, non-ergodic and path dependent historic process. This approach enables to move away from the static, low-level complexity of general equilibrium that applies when both technologies and preferences are static, or the smooth and ubiquitous growth based upon learning processes and spontaneous spillover of the new growth theory. It makes it possible a significant progress also with respect to evolutionary thinking where the causal analysis of the determinants of the generation of innovations is reduced to the random walks of spontaneous variations. This approach provides the tools to grasp the dynamics of technological change as an endogenous and recurrent process that combines rent-seeking intentionality at the agent levels with the appreciation of the knowledge externalities and interactions that stem from the structural characters of the system.

4.2. The economics of innovation as an emerging property of an organized complexity

4.2.1. Definitions

Economics of innovation studies the determinants and the effects of the generation of new technological and organizational knowledge, the introduction of innovations in product, process, organization, mix of inputs and markets, their selection and eventual diffusion. Innovation takes place when it consists in actions that are able to engender an increase in the value of the output, adjusted for its qualitative content, that exceed their costs (Griliches, 1961).

Technological and organizational changes are defined as innovations only if and when the two overlapping features of novelty and increased efficiency coincide. Changes are innovations if they consist at the same time in the introduction of a novelty that is also able to yield an increase in the relationship between outputs and inputs. Total factor productivity can be considered a reliable indicator of the relationship between outputs and inputs of the production processes: novelties that are actually able to increase the ratio of inputs to output are true innovations. Either characteristic is necessary to identify an innovation. Only if we retain such a strict definition of innovation, as a productivity-enhancing novelty can we grasp its out-of-equilibrium characteristics.

It is clear in fact, on the one hand, that indeed total factor productivity may increase for a variety of other factors, especially if and when markets are not in equilibrium. On the other however it is also clear that often novelties do not last and are selected out in the market selection process with no actual economic effect. On a similar ground we see that minor changes in products may feed monopolistic competition and do not increase the efficiency of the production process at large. It is not surprising that much theorizing upon the new theories of growth never tackles the issue and prefers a more comfortable definition of innovation as a form of increase in the variety of products. Innovation is the result of a variety of activities. Learning processes of various kinds play a major role in the accumulation of the competence that is necessary to generate new technological knowledge and eventually to introduce innovations. The access to external knowledge is a crucial factor in the generation of new technological knowledge. The adoption of new capital and intermediary goods incorporating technological innovations is an essential component of the innovation process. Research and developments indicators are able to grasp only a fraction of such activities. Much R&D on the other hand is funded and performed to generate novelties that are not able to increase the efficiency of the production process. As it is well known only a fraction of the technological innovations being introduced is represented by patent statistics. Neither R&D nor patent statistics account for innovations in organization, input mix and markets. Innovation counts suffer the subjective character of the claims upon which they are based. Product innovations introduced by upstream producers are often considered process innovations by downstream users (Kleinknecht, van Montfort, Brouwer, 2002). The distinction between innovation, adoption and diffusion is more and more blurred by the increasing awareness of the amount of creative efforts that are necessary to adopt and imitate an innovation. Moreover, and most importantly, the economic analysis of innovation should take into account the time distribution of adoptions, rather than their punctual introduction. Total factor productivity indicators instead can grasp the full bundle of the economic effects of the introduction and diffusion of an innovation. Hence total factor productivity indicators are likely to provide an accurate measure of the actual amount and extent of the innovations being introduced (Crépon, Duguet, Mairesse, 1998).

In sum, new products, new processes, new organization methods, new inputs and new markets can be defined as innovations only if they yield an increase in total factor productivity. Hence the marginal product of innovation efforts exceeds its marginal costs. This is at the origin of a serious problem for textbook economics.

4.2.2. Departing from dead-ends

This new approach enables to overcome the limitations of two contending approaches: general equilibrium analysis and darwinistic evolutionary population thinking.

The merging of the theory of complexity and the economics of innovation provides a new way to integrate economic and complexity thinking and contributes to the building of an economic theory of complexity that puts the endogenous and systemic emergence of innovation at the core of the analysis. The continual introduction of new technologies and their selection is seen as the emerging and systemic property of an out-of-equilibrium dynamics characterized by path dependent non-ergodicity and interactions both among agents and between micro and macro levels. The organized complexity of the system that enables the emergence of innovations is itself the product of the recurrent and path dependent interaction of rent-seeking agents (Arthur, 1994 and 1999).

Organization thinking, as distinct from population thinking, plays a crucial role to grasping the causes and the consequences of the changing structure, composition and organization of the system (Lane, 1993a and b; Lane et. alii 2009).

Technological and structural change are the result of a sequential process of systemic change where agents are never able to anticipate ex-ante the outcome of their reactions to emerging surprises. The changing characters of their localized context of action in fact engender out-of-equilibrium conditions to which they react. When knowledge externalities and interactions engender positive feedbacks their reaction is creative. Firms are able to change both their technologies and the structure of the system: a recursive, historic and path-dependent process of change takes place. When the context of action does not provide knowledge externalities and interactions sufficient to engender positive feedbacks, the reaction of firms is adaptive and a single static attractor consolidates: general equilibrium analysis applies.

In general equilibrium economics the preferences and the technologies, of the representative agent and hence her production and utility functions, are allowed to change only as the result of exogenous shocks. As soon as the notion of endogenous change is introduced and heterogeneous agents are credited with the capability to change their production and utility functions in response to economic stimulations, the general equilibrium analysis appears a simplistic approach. The assumption of the necessary gravitation and convergence towards a single equilibrium point cannot be retained because of the changing centers of attraction. As soon as we acknowledge that both preferences and technologies are the result of the intentional decision-making of heterogeneous actors that are part of a system of interdependencies, the foundations of general equilibrium economics collapse, yet its powerful systemic approach should be retained and implemented.

Kenneth Arrow has provided key contributions to reconcile the evidence about growth with general equilibrium analysis both with the articulated notion of learning by doing, eventually implemented with learning by using, and with the path breaking analysis of the limitation of knowledge as an economic good (Arrow, 1962a, 1962b, 1969, 1974). Building upon his legacy, the new growth theory shares the view that knowledge is characterized by an array of idiosyncratic features such non-appropriability, non-divisibility, non-excludability, non-exhaustibility that are the cause of knowledge externalities and contribute the continual and homogeneous introduction of innovations. The new growth theory however has not been able to appreciate the endogenous, idiosyncratic and dynamic character of knowledge spillovers. Assuming that knowledge spillovers are given and evenly distributed in time and space, the new growth theory claims that technological change takes place evenly through time and space without discontinuities and leads to smooth dynamic processes (Romer, 1994).

The main limitation of new growth theory is the underlying assumption of an automatic, spontaneous and ubiquitous trickle down of the new technological knowledge inputs into every other kind of activity in the economic system. In Aghion and Howitt's model, downstream sectors make no particular efforts to identify, understand or use the new knowledge embodied in new intermediary inputs. Technology adoption and transfer take place in the absence of effort, interaction or dedicated activity. Although perhaps not like manna from heaven, new technological knowledge rains from upstream and wets whatever is below – be it sectors or regions (Aghion and Howitt, 1992, 1999; Aghion and Tirole, 1994).

These assumptions contrast sharply the rich evidence about the punctuated and discontinuous rates and directions of technological change and are not able to explain the wide variety across countries, regions, industries and firms in terms of rates of introduction and diffusion of innovations (Mokyr, 1990a, 1990b, 2002).

The second attempt to elaborate an evolutionary economics based upon darwinistic population thinking, implemented by Nelson and Winter (1982) since the late seventies of XX century, has much contributed to place innovation at the center stage of economic analysis. Evolutionary economics has built an outstanding corpus of knowledge about the characteristics of innovation and of technological knowledge with the identification of important taxonomies and significant sequences. The grafting of biological metaphors has focused on population thinking, as distinct from organization thinking, stressing the role of the natality, mortality, entry, exit and mobility of agents, while little attention has been paid to the causes and effects of the organization of economic systems. Agents are not credited with the intentional capability to change their technologies and their preferences.

Consistently with the general evolutionary frame of analysis, innovation is regarded as the product of random variations and accidental mutations, rather then the result of the intentional action of agents. The radical criticism raised by Edith Penrose against the first wave of attempts to integrate Social Darwinism into mainstream economics, based upon the well-known article by Armen Alchian (Alchian, 1950), apply very much to second wave as well: "to abandon [the] development [of firms] to the laws of nature diverts attention from the importance of human decisions and motives, and from problems of ethics and public policy, and surrounds the whole question of the growth of the firm of with an aura of 'naturalness' and even inevitability" (Penrose, 1952, p. 809; Penrose, 1953).

Evolutionary economics has focused much more the analysis of the selective diffusion of new technologies rather then the analysis of the actual determinants of the generation of new technological knowledge and the introduction of innovations (Metcalfe, 1994).

The causal analysis of the determinants of technological change, however, has been left at the margin of the exploration. This seems quite paradoxical. Evolutionary economics is not able to explain the determinants of the central mechanism of economic change (Hodgson, Knudsen, 2006).

4.2.3. Standing on giants' shoulders: Marshall and Schumpeter

In a complexity approach, innovation is not only the result of the intentional action of each individual agent, but it is the endogenous product of dynamics of the system. The individual action and the system conditions are crucial and complementary ingredients to explain the emergence of innovations. Innovation cannot be considered but the intentional result of the economic action of agents: it does not fall from heaven. Neither is it the result of random variations. Dedicated resources to knowledge governance are necessary to implement the competence accumulated by means of learning and to manage its exploitation. Agents succeed in their creative reactions when a number of contingent external conditions apply at the system level. Innovation is made possible by key systemic conditions: "innovation is a path dependent, collective process that takes place in a localized context, if, when and where a sufficient number of creative reactions are made in a coherent, complementary and consistent way. As such innovation is one of the key emergent properties of an economic system viewed as a dynamic complex system" (Antonelli, 2008a:I).

An innovation economics approach to complexity thinking makes it possible to overcome the limitations of both general equilibrium economics and evolutionary analysis into a complex dynamics approach. It builds upon the integration of Schumpeterian analysis of innovation as a form of reaction, to the changing conditions of product and factor markets, with the Marshallian partial equilibrium approach to localized increasing returns based upon circumscribed of externalities. This approach contrasts the general equilibrium analysis where economic agents are indeed embedded in a systemic analysis but are not supposed to be able to change purposely their technologies and their preferences. This effort can contribute a complex dynamics where technological change is the central engine of the evolving dynamics-viewed and it is the result of the creative response of intentional agents, embedded in the organized complexity of a system populated by interacting and reactive agents (Antonelli, 2007, 2008a and 2009).

The Marshallian approach provides the basic frame for a systemic understanding of the behavior of heterogeneous agents that are interdependent within a dynamic context characterized by localized increasing returns and increasing levels of division of labor engendered by specialization. The Marshallian partial equilibrium analysis provides a rich analytical apparatus that emphasizes the idiosyncratic variety of agents and markets that interact in a systemic context characterized by endogenous structural change. The Marshallian partial equilibrium enables the use of the foundations of microeconomics as they provide the analytical context into which the maximizing conduct of individual agents can be interpreted and yet makes room for understanding the interactive process of structural and technological change. The integration of partial equilibria, however, does not lead to general equilibrium.

As Young (1928) has shown, each change in a component of the system modifies its structural composition and organization and feeds in turn new ripples of technological change via new flows of externalities. Technological change and structural change are intertwined and necessary components of an aggregate and systemic dynamics (Foster, 2005; Metcalfe, Foster, Ramlogan, 2006).

For these reasons the Marshallian approach can be retained and integrated with the Schumpeterian and classical approaches that stress the role of the creative reaction of firms caught in out-of-equilibrium conditions into an economics of complexity that emphasizes the endogenous emergence of technological change and the continual transformation of the structure of the system (Schumpeter, 1941; Downie, 1958).

The aggregate dynamics of the system, in fact, is far from the assumptions of an even, smooth and homogenous pace. It is instead characterized by strong elements of contingent discontinuity as well as historic hysteresis (Anderson, Arrow, Pines, 1988). The understanding of the dynamics of the system requires the grasping of the causes and determinants of both individual action and the changing centers of gravitation of the system (Blume and Durlauf, 2005).

The appreciation of the systemic conditions that shape and make innovations possible, together with their individual causes lead to the identification of innovation as an emergent property of a system. This approach provides a solution to the conundrum of an intentional economic action whose rewards are large than its costs, only if the organized complexity that enables the mergence of innovations is explained as an endogenous and dynamic process engendered by the interactions of rent-seeking agents.

The reappraisal of a somewhat forgotten contribution by Joseph Schumpeter (1947) provides basic support in this endeavour. The direct quote with added italics of a key portion of this text seems most appropriate here: "What has not been adequately appreciated among theorists is the distinction between different kinds of reaction to changes in 'condition'. Whenever an economy or a sector of an economy adapts itself to a change in its data in the way that traditional theory describes, whenever, that is, an economy reacts to an increase in population by simply adding the new brains and hands to the working force in the existing employment, or an industry reacts to a protective duty by the expansion within its existing practice, we may speak of the development as an adaptive response. And whenever the economy or an industry or some firms in an industry do something else, something that is outside of the range of existing practice, we may speak of creative response.

Creative response has at least three essential characteristics. "First, from the standpoint of the observer who is in full possession of all relevant facts, it can always be understood ex post; but it can be practically never be understood ex ante; that is to say, it cannot be predicted by applying the ordinary rules of inference from the pre-existing facts." This is why the 'how' in what has been called the 'mechanisms' must be investigated in each case. "Secondly, creative response shapes the whole course of subsequent events and their 'long-run' outcome. It is not true that both types of responses dominate only what the economist loves to call 'transitions', leaving the ultimate outcome to be determined by the initial data. Creative response changes social and economic situations for good, or, to put it differently, it creates situations from which there is no bridge to those situations that might have emerged in the absence. This is why creative response is an essential element in the historical process; no deterministic credo avails against this. Thirdly, creative response –the frequency of its occurrence in a group, its intensity and success or failure- has obviously something, be that much or little, to do (a) with quality of the personnel available in a society, (b) with relative quality of personnel, that is, with quality available to a particular field of activity relative to the quality available, at the same time, to others, and (c) with individual decisions, actions, and patterns of behavior." (Schumpeter, 1947: 149-150).

4.2.4. Innovation and organized complexity as emergent properties of an economic system.

Innovation is an emergent property that takes place when complexity is organized, i.e. when a number of complementary conditions enables the creative reaction of agents and makes it possible to introduce innovations that actually increase their efficiency. The dynamics of complex systems is based upon the combination of the reactivity of agents, caught in out-of-equilibrium conditions, with the features of the system into which each agent is embedded in terms of externalities, interactions, positive feedbacks that enable the generation of localized technological knowledge, the introduction of localized technological change and lead to endogenous structural change. The process is characterized by path dependent non-ergodicity.

This approach builds upon five basic points:
- The distinction between ex-ante and ex-post is crucial. Bounded rationality limits the foresight of agents. Economic agents however are credited with the basic capability to react to unexpected changes in their economic environment by changing their technology. Agents try and change their technology when their performances are both below and above their expectations.
- The reaction of firms can be either adaptive or creative. Occasionally, when the context is favorable, their reaction becomes creative and they can innovate. When the organization and composition of the economic structure and the quality of the external conditions add to the characteristics of the individual firms to explain whether, when, how and why their reaction can be either adaptive or creative. The levels of knowledge externalities and the quality of the generative relations that take place in the context into which firms are localized, determine the actual chances that the reaction of firms leads to the actual introduction of innovations.
- Their reaction is localized by the irreversibility of their tangible and intangible inputs as well as by their competence based upon learning processes and rests upon the recombinant generation of knowledge that is both internal and external. Innovation emerges as the result of the fertile interaction between the knowledge characteristics of the context and the competence of the individuals.
- The introduction of innovations changes the structure of the economic system into which firms are embedded, including the availability of knowledge externalities and the quality of generative relations. These in turn affect the direction and the rate of the economic dynamics. Occasionally, loops of systemic positive feedbacks between structural and technological change lead to the emergence of organized complexity that feeds innovation cascades and Schumpeterian gales of innovations.
- The interaction between technological and structural change engenders dynamic processes that are non-ergodic because history exerts a strong effect in shaping their dynamics. History matters in influencing the dynamics of economic processes but innovations, introduced along the path, can alter it. History matters, yet small events can change it

Table 2. Dead ends and new prospects

	MICRO	MESO	MACRO
GENERAL EQUILIBRIUM	THE REPRESENTATIVE AGENT CAN ADAPT BUT CANNOT INNOVATE	MARKET TRANSACTIONS	LOW-LEVEL STATIC COMPLEXITY
MARSHALLIAN PARTIAL EQUILIBRIUM	INTRINSIC HETEROGENEITY AND VARIETY OF AGENTS AND LOCATIONS	LOCALIZED INCREASING RETURNS BASED UPON EXTERNALITIES	UNEVEN GROWTH

ARROVIAN LEGACY	LEARNING; KNOWLEDGE AS AN IMPERFECT ECONOMIC GOOD	KNOWLEDGE SPILLOVER	SPONTANEOUS, EVEN AND STEADY DYNAMIC EQUILIBRIUM
DARWINIAN EVOLUTIONISM	RANDOM VARIATIONS AND OCCASIONAL MUTATIONS	SELECTION BASED UPON REPLICATOR DYNAMICS; EMERGENCE OF DOMINANT DESIGNS	GROWTH&CHANGE BASED UPON SELECTIVE DIFFUSION OF INNOVATIONS
COMPLEXITY CUM INNOVATION	INNOVATION AS AN EMERGENT PROPERTY WHEN INDIVIDUAL REACTIONS BASED ON GENERATIVE RELATIONS MATCH ORGANIZED COMPLEXITY	KNOWLEDGE GOVERNANCE; NON-ERGODIC CHANGES IN THE ORGANIZATION OF STRUCTURES AND NETWORKS	GROWTH AND PATH DEPENDENT CHANGE BASED UPON INNOVATION WITHIN ORGANIZED COMPLEXITY

4.3.The determinants of the creative reaction

Consistently with the dominant view that technological change is exogenous or, at best, the automatic product of either spontaneous learning procedures within firms or uncontrolled leakage of knowledge externalities among firms, very little attention has been paid to the analysis of the determinants of innovation. This contrasts the size and the wealth of the large literature that has explored the effects of innovation on the increase of total factor productivity and hence on growth, profitability, performance, economic and industrial structures. Even evolutionary economics assumes that innovation is the spontaneous outcome of random mutations: agents introduce innovations occasionally without any specific motivation. In evolutionary economics there is no attempt to identify the historic, regional and institutional determinants of the decisions that lead to the generation of innovations. Much effort is made, instead, to explore the features of the selection, adoption and diffusion mechanisms of the 'spontaneous' flow of innovations. Much evolutionary economics, so far, elaborates a theory of selective diffusion of innovations, rather than a theory of innovation. As a result, the analysis of the determinants of the introduction of innovation, considered as the result of intentional decision-making, remains substantially under-investigated. This is not surprising as it is indeed difficult to provide a consistent and coherent explanation of decision-making procedures that lead to an increase of output that exceeds the increase of inputs and hence cannot be justified according to marginalistic procedures. Rational innovators in fact should stretch their innovative activities to the point where marginal costs match marginal revenues: no room for residuals should be left. In the classical economics of technological change three different frames have been identified to try and explain the endogenous introduction of innovations: a) the inducement approach elaborated along the lines of the early contributions of Karl Marx, b) the demand pull approach elaborated by the Post-Keynesian school; c) the Schumpeterian legacies.

The complexity approach impinges upon the late contribution of Joseph Schumpeter and focuses the role of the relations between profitability and innovation. The analysis of the causal relations between levels of profitability, as distinct from competition, enables to elaborate a consistent and coherent frame of analysis and integrate these different and yet complementary strands of literature that share the view that technological change is endogenous and that the decision to innovate is an intentional and relevant component of economic decision-making. The contribution of the behavioral theories of the firm provides substantial help in this effort. The decision to innovate, in fact, cannot be treated with the standard maximization procedures. The outcomes of innovations are hard to predict, and the actual chances of introduction of successful innovations are subject to radical uncertainty. The introduction of innovations is the result of a complex sequence of intentional decision-making that takes place when firms are found in out-of-equilibrium conditions. According to James March (March and Simon, 1958; Cyert and March, 1963), firms are not profit maximizers. Firms are able to rely upon procedural, as opposed to substantive, rationality: firms use satisfying procedures and identify satisfactory levels of performances. Firms are risk adverse and hence reluctant to change their routines, their production processes, their networks of suppliers, their products and their marketing activities. Firms can overcome their intrinsic inertia and resistance to change only when unexpected changes in their environment push them to take the risks associated with innovation (March and Shapira, 1987). Nelson and Winter (1982) make an important contribution along these lines: " In the orthodox formulation, the decision rules are assumed to be profit-maximizing, over a sharply defined opportunity set that is taken as a datum, the firms in the industry and the industry as a whole are assumed to be at equilibrium size, and innovation (if it is treated at all) is absorbed into the traditional framework rather mechanically. In evolutionary theory, decision rules are viewed as a legacy from the past and hence appropriate, at best, to the range of circumstances in which the firm customarily finds itself, and are viewed as unresponsive, or inappropriate, to novel situations or situations encountered irregularly. Firms are regarded as expanding or contracting in response to disequilibria, with no presumption that the industry is 'near' equilibrium. Innovation is treated as stochastic and as variable across firms" (Nelson and Winter, 1982: 165-166). The integration of these elements, into the single frame of the localized technological change approach, enables to overcome the limitations of the stochastic approach of evolutionary approaches and elaborate the hypothesis that firms try and innovate when they are found in out-of-equilibrium conditions, and more specifically when profits are either below or above the norm. When equilibrium conditions prevail and there are no extra-profits, firms are not induced to try and change their technologies, neither their organizations, markets and input mixes. According to this approach a non-linear relationship between profits and innovation is at work (See in Appendix B, Annex B10).

Let us first review the main hypothesis elaborated about the relations between out of equilibrium conditions and the inducement to innovate.

4.3.1. The Marxian legacies

Marx contributed the first elements of the theory of induced technological change. The introduction of new capital-intensive technologies is the result of the intentional process of augmented labour substitution. When wages increase, capitalists are induced to introduce new technologies that are embodied in capital goods. Hence technological change is introduced with the twin aim of substituting capital to labor so as to reduce the pressure of unions and increasing the total efficiency of the production process (Marx, 1867).

John Hicks (1932) and Fellner (1961) extracted from the analysis of Karl Marx the basic elements of the theory of the induced technological change: firms are induced to change their technology when wages increase. Technological change is considered an augmented form of substitution: technological change complements technical change. Binswanger and Ruttan (1978) eventually articulated a more general theory of induced technological change: firms introduce new technologies in order to save on the production factors that are relatively more expensive. Such production factors can be labor, as much as energy or even capital in specific circumstances. The induced technological change approach has been criticized by Salter (1966) according to whom firms should be equally eager to introduce any kind of technological change, either labour- or capital-intensive, provided it enables the reduction of production costs and the increase of efficiency. An important facet of the Marxian analysis is missing in the induced technological change approach. The analysis of the Marxian contribution by Rosenberg (1976) highlights the limitations of the induced technological change approach and helps to understand the key role of profitability. Firms try and contrast the decline in their profitability, stemming from the increase in wages, with the introduction of technological innovations. Starting from a common reference to Marx, Hicks paved the way to a tradition of analysis that focuses the role of the changes in the prices of production factors in inducing technological innovations. Rosenberg, instead, stresses the role of the decline in profitability as the focusing mechanism that pushes firm to undertake innovative activities. According to Rosenberg, firms innovate in order to restore the levels of profitability (that have been undermined by the raise in wages). According to Hicks firms react to the increase in wages (and the related decline in profitability). As Nathan Rosenberg (1969) argues Marx provides elements to build much a broader inducement hypothesis, one where the levels of profitability are a cause of endogenous technological change. This line of analysis has received much less attention in the economics of innovation, and yet it provides a clear replay to Salter's arguments.

4.3.2. The role of profitability in the demand pull hypothesis

The post-keynesian approach elaborated by Kaldor (1972 and 1981) stressed the key role of the demand in the explanation of the endogenous origin of technological change. To do so Kaldor had revisited the dynamic engine put in place by Adam Smith. According to Adam Smith the division of labour is determined by the extent of the market and is the cause of the increase of specialization. This leads to the accumulation of new technological knowledge, and eventually to the introduction of technological innovations. Technological innovations in turn lead to an increase in productivity. The increase in productivity leads to an increase in the demand and hence of the extent of the market. According to Adam Smith the relationship between division of labor, specialization, increase of competence, introduction of technological innovations, productivity growth, increase in demand and new division of labor consists in a recursive loop. Building on this interpretation Kaldor argued that an increase in the levels of the aggregate demand would engender an increase in the division of labor, hence of specialization, and eventually of the rate of introduction of technological innovations. The so-called 'demand-pull' hypothesis was borne. Schmookler (1966) provided empirical support to the hypothesis that demand growth pulls the increase of technological knowledge, hence of inventions and eventually technological innovations. Rosenberg and Mowery (1979) provide an outstanding account of the pervasive role of the demand-pull hypothesis within the post-Keynesian approach. Less attention has received a previous contribution by Schmookler (1954) according to which the increase in the demand leads to the generation of additional technological knowledge and the eventual introduction of technological innovations via the increase in the profitability of both inventors and innovators. Firms are pulled to generate new technological knowledge and to introduce technological innovations by the high levels of prices for the products that are the object of an increasing demand and by the high levels of rewards that are attached. Young scholars specialize in the fields were wages increase because of the demand for their competence. New firms enter with innovative ideas in the industries where profits are growing because of the increase of the demand. Incumbent firms are induced to innovate by the growth in the demand and the extraprofits that are attached. Following this line of analysis we can claim that excess demand engenders out-of-equilibrium conditions that lead to an increase in prices and in profitability. Out-of-equilibrium conditions here are determined by the un-expected increase in the demand: had the firm anticipated the high levels of the demand, current supply would have already accommodated it with no increase in prices and hence in profits. When the demand fetches un-expected levels, instead, prices increase and consequently profits. Then firms are pulled to accommodate the increased levels of the demand with an increase in supply. The increase in supply however can be obtained both via investments with a given technology and an increase in productivity of the given resources, via the introduction of technological innovations. The accumulation of competence and expertise based upon learning processes enables the generation of new technological knowledge. Extraprofits provide the opportunity to fund the generation of new technological knowledge and the introduction of technological innovations. Hence the increase in demand feeds the introduction of innovations by means of an increase of profits above the norm. In other words we can easily reconcile the demand-pull hypothesis with the argument that extra profits favor the introduction of additional innovations. The chain-loop elaborated by Kaldor after Smith can be integrated with a an additional ring: increase in demand, extraprofits, new division of labor, specialization, increase of competence, introduction of technological innovations, productivity growth (Scherer, 1982a,b). The increase in demand engenders an increase in profits that in turn provides both the incentives and the opportunities for the introduction of innovations. The incentives are the determined by the perspective to take advantage of the excess demand via the increase in supply by means of new productivity-enhancing technologies. The opportunities stem from the resources made available by extraprofits.

4.3.3. The Schumpeterian legacies

The third basic starting point to elaborate a theory of the endogenous decision-making of innovation is provided by the Neo-Schumpeterian literature that has debated and implemented the so-called Schumpeterian Hypothesis on the relations between forms of competition and incentives to innovate. The consensus was reached about the argument that the rate of innovation is higher when forms of oligopolistic rivalry characterize the market structure. When perfect competition prevails, firms cannot bear the burden of research activities. When the number of competitors is too small, close to monopolistic conditions, incentives to innovate are missing. Cutthroat competition risks to reduce the incentives to introduce technologies for the intrinsic non-appropriability of knowledge and the high risks of imitation and entry of new competitors that can take advantage of opportunistic behavior. Some intermediary levels of workable competition, comprised between the extremes of monopoly and perfect competition, among large firms might favor the rate of introduction of innovations. Oligopolistic market structures and the large size of firms are viewed as positive factors able to sustain the rates of introduction of innovations (Scherer, 1967; Dasgupta and Stiglitz, 1980; Link, 1980). The Neo-Schumpeterian school has been very selective in implementing the Schumpeterian legacy and has neglected two crucial contributions of the late Schumpeter. As a matter of fact the scope of the analysis elaborated by Schumpeter in 1947 with two path-breaking and yet almost forgotten articles published by the Journal of

Economic History provides ammunitions to elaborate much a more radical departure from equilibrium analysis. With the analysis of the role of creative reaction, Schumpeter (1947) fully elaborates the view that firms and agents at large are not passive adapters but can react to the changing conditions of both product and factor markets in a creative way, with the introduction of innovations, both in technologies and organizations and changing their products and processes. If firms are credited with the capability to innovate as a part of their business conduct, the notion of creative reaction becomes relevant. The conditions that qualify it warrant systematic investigation. Schumpeter makes a sharp distinction between adaptive and creative responses. Adaptive responses consist in standard price/quantity adjustments that are comprised within the range of existing practices. Creative responses are triggered by strategic interactions. The rivalry among firms able to introduce –purposely- new technologies is a major factor in fostering the rate of technological change (Scherer, 1967). Here, interactions take place in the market: the extent to which firms innovate is stirred by the change in behavior of other competing agents, namely the introduction of innovations, by neighbors in the product and output markets. Creative responses consist in innovative changes that can be rarely understood ex ante, shape the whole course of subsequent events and their 'long-run' outcome: their frequency, intensity and success is influenced by a variety of conditional factors that are both internal to each firm and external. For a given shock, firms can switch from an adaptive response to a creative response according to the quality of their internal learning processes, and the context into which they are embedded. Learning in fact is a necessary but not sufficient condition for the generation of new knowledge. The notion of creative response elaborated by Schumpeter can be considered the synthesis of a long process of elaboration. One extreme can be identified in Business Cycles (1939). Here the appreciation of the role of creative reaction in economic history is fully consistent with the Rosenberg-Marx line of analysis. Here Schumpeter suggests that the gales of innovations peak in the periods of decline of the rates of profitability and growth. After a sustained phase of expansion, the decline in the opportunities for further growth of output and profits induces firms to innovate. Hence the business cycle and the innovation cycle are specular. In periods of expansion the rates of introduction of innovations decline. When profitability and growth are high, firms exploit and refine the technological innovations introduced in the periods of crisis. Technological change is characterized by the introduction of minor and incremental innovations. On the opposite, major breakthroughs take place when the search for new technologies acquires a strong collective character. When the rates of growth are lower, and the profitability declines, in fact, many firms try and react by means of the systematic search for new ideas.

Following Schumpeter, Nelson and Winter elaborate the hypothesis of a relationship between negative profitability and innovation performances and implement formally the analysis of the relationship with a simulation model. According to Nelson and Winter when the profitability levels fall below average levels and enter into negative figures firms realize that business as usual is no longer viable and take into account the need for a change in routines and start the search for new technologies: "…we assume that if firms are sufficiently profitable they do no 'searching' at all. They simply attempt to preserve their existing routines, and are driven to consider alternatives only under the pressure of adversity ... In the simulations run here, only those firms that make a gross return on their capital less than the target level of 16 percent engage in search" (Nelson and Winter, 1982: 211). The formalization of the relationship between negative profitability and innovation articulated in Business Cycles by Schumpeter, establishes the notion of failure-induced innovation, well rooted in the Schumpeterian tradition (Antonelli, 1989). In Business Cycles Schumpeter implements also the basic notion of the complementarity between innovators in the introduction of the new gales of innovations. The new gales of innovation are in fact but the result of the convergent and complementary search activity of a variety of agents who search for new technologies that enable them to contrast the decline in profitability. The new gales can emerge only when a myriad of agents characterized by the variety of competences and localized knowledge is able to engage in a myriad of complementary actions of exploration and search. The generalized decline in profitability and the complementarity among individual search activities stemming from the intrinsic indivisibility of knowledge and favors the emergence of collective knowledge pools and hence the chances of introduction of radical innovations. The causal relationship between profitability and innovation acquires in Business Cycle an aggregate dimension.

In Capitalism socialism and democracy (1942), Schumpeter identifies the large corporation as the driving institution for the introduction of innovations. The corporation is itself an institutional innovation that favors the introduction of technological innovations for many reasons. As a large literature has stressed, the corporation can use the barriers to entry as a barrier to imitation. The risks of uncontrolled leakage of proprietary knowledge in fact are reduced when the innovator enjoys the benefits of economies of scale and absolute cost advantages so that new competitors might imitate but cannot actually enter the market place. Schumpeter is very clear in stressing the role of the corporation as a superior allocation and selection mechanism that reduces the inefficiency of financial markets in the provision of funds to innovative undertakings and increase the matching between competence and resources available to develop new technologies. Schumpeter regards the corporation as a hierarchical system that makes it possible the coordinated working of internal markets where financial resources matched with competence can be fueled towards risky but innovative undertakings.

Within the corporation the resources extracted by the extra-profits match the competences of skilled managers and the vision of potential entrepreneurs. The Schumpeterian corporation can reduce the intrinsic failure of competitive markets in the allocation of resources to research, in the identification of the proper level of rewards and hence incentives to the introduction of innovations. The corporation is an effective institution able to substitute the financial markets in the provision and allocation of funds to innovative activities because it combines financial resources and learning with entrepreneurial vision within competent hierarchies, provided that extra-profits can be earned and a consistent share is directed towards the generation and introduction of innovations (Penrose 1959).

It seems clear that the careful reading of the full range of contributions of Schumpeter suggests that the two articles published in 1947 do synthetize and frame the results of the long-term evolution of his thinking from the onset elaborated in The theory of economic development (1934). Building upon this Schumpeterian legacy we can try and articulate the hypothesis that firms try and innovate both when their profits fall below satisfying levels and when profitability provide the resources to use systematically innovation as a competitive tool. Here it is clear that the higher are the profits and the larger the opportunities to use a share to fund research activities and hence to increase the rates of introduction of new technologies.

The appreciation of the Schumpeterian notion of creative response and the identification of out-of-equilibrium conditions in: a) the reappraisal of the Marxian analysis of the role of the decline in profitability in pushing firms to innovate as a key component of the augmented induced technological change approach, b) the failure-induced approach elaborated by

Schumpeter in Business Cycles, c) the reconsideration of the Schumpeterian analysis of the extra-profits associated with the corporation as an institutional engine for continual introduction of innovations, d) the appreciation of the role of extra-profits in providing incentives and opportunities to firms to innovate in the demand pull hypothesis; provides the basic tools to articulate the hypothesis of a causal relationship between profits above and below the norm, interpreted as indicators of out-of-equilibrium conditions, and innovation. The focus on the relationship between profitability and innovation provides key elements to integrate into a single frame the different hypotheses articulated in the literature about the endogenous determinants of innovations. Table 2 summarizes the main results and shows that the hypothesis of a non-linear relationship can be considered the integrative device.

Table 3. Profitability and innovation: an integrative framework

	PROFITABILITY BELOW THE AVERAGE	PROFITABILITY ABOVE THE AVERAGE
CLASSICAL INDUCEMENT	The increase in factor costs engenders the fall in profitability that induces the introduction of innovations	
DEMAND PULL		The increase in demand engenders the increase in profitability that pulls the introduction of innovations
SCHUMPETER: 'BUSINESS CYCLES'	Recession engenders the generalized fall of profitability that induces the collective search for new technologies	
SCHUMPETER: 'CAPITALISM SOCIALISM AND DEMOCRACY'		Barriers to entry and to imitation favor the duration of extraprofits and provide large corporations with the opportunity to fund R&D activities

4.4. Localized technological knowledge and the emergence of innovation as a system property

The appreciation of the role of intentional decision-making in the generation of new knowledge and of the central role of learning processes and external knowledge qualifies the localized approach. Firms induced to innovate by irreversibility and disequilibrium in both product and factor markets search locally for new technologies. Procedural rationality, as opposed to Olympian rationality, and localized competence based upon learning processes, limit the global search of firms and constraint their search for new technologies in the proximity of the techniques already in use, upon which learning by doing and learning by using have increased the stock of competence and tacit knowledge. Both the rate and the direction of technological change are influenced by the search for new technologies that are complementary to existing ones. The quality of the context plays a key role in assessing the actual possibility that the reaction of firms is creative, rather than adaptive. In this approach the introduction of innovations and new technologies is the result of a local search, constrained by the limitations of firms to explore a wider range of technological options. This dynamics leads firms to remain in a region of techniques that are close to the original one and to continue to improve the technology in use. The generation of new technological knowledge is the result of an intentional activity based upon four distinct and complementary inputs such as learning, research and development, and the access to both tacit and codified external knowledge. Each of them can be substituted only to a limited extent. In order to generate new technological knowledge firms must rely upon each of them and act as a system integrator (Antonelli, 1999).

In the localized technological knowledge framework of analysis, learning is the primary and indispensable source of competence and tacit knowledge. As a consequence firms are rooted in a limited portion of the knowledge space defined by the context into which their learning processes have been taking place, both in doing, in using and in interacting. Consequently no firm can command the full range of knowledge items that are necessary to generate new knowledge. Consequently no firm can innovate in isolation (Antonelli, 2001).

External knowledge is an essential input into the generation of new knowledge. External knowledge can be substituted to internal sources of knowledge only to a limited extent: full-fledged substitutability between internal and external knowledge cannot apply. With proper access to external knowledge firms can complement their localized, internal competence and actually introduce new technologies. Only when a complementary set of knowledge fragments is brought together within a context of consistent interactions, successful innovations can be introduced and adopted: technological knowledge is the product of a collective activity. The access conditions to external knowledge are a key conditional factor in assessing the actual chances of generation of new knowledge. Firms that have no access to external knowledge and cannot take advantage of essential complementary knowledge inputs can generate very little, if no new knowledge at all, even if internal learning and research activities provide major contributions (Antonelli, 2003).

The reaction of firms localized in a poor context, unable to provide appropriate flows of pecuniary knowledge externalities will not be able to generate new productivity enhancing technologies and will just adaptive: firms will move in the existing map of isoquants or introduce small changes that enable the introduction of technical change based upon substitution. Innovation will emerge as a system property when the reaction of firms, supported by the access to collective knowledge, will become actually creative and consist of the introduction of productivity enhancing technological changes that reshape the map of isoquants when their internal knowledge matches the availability of appropriate sources of external knowledge and is the result of a process of knowledge recombination (See in Appendix B, Annex B2).

4.4.1. The recombinant generation of technological knowledge

Technological knowledge internal to each firm is localized in a limited portion of the knowledge space by the learning processes that are at the origin of its accumulation: the key role of learning and tacit knowledge roots and limits the span of command of the firm in the knowledge space. In order to generate new knowledge the firm must identify other bits of complementary knowledge and recombine them with the internal one. The notion of recombinant knowledge qualifies the nature of the knowledge production activity (Antonelli, 2008; Antonelli, Krafft, Quatraro, 2010).

The recombinant knowledge approach complements and integrates the analysis of external knowledge and localized technological knowledge. As Weitzman (1996: 209) recalls: "when research is applied, new ideas arise out of existing ideas in some kind of cumulative interactive process that intuitively has a different feel from prospecting for petroleum". As Arthur (2009:21) notes: " novel technologies arise by combination of existing technologies and …therefore existing technologies beget further technologies….". This insight leads to the recombinant growth approach which views new ideas as being generated through the recombination of existing ideas, under the constraint of diminishing returns to scale in the performance of the research and development (R&D) activities necessary to apply new ideas to economic activities (Weitzman, 1998).

A large literature on biological grafting has applied the so-called NK model in the economics of knowledge. According to Kauffman (1993) the success of a search process depends on the topography of a given knowledge landscape shaped by the complementary relations (K) among the different elements (N) of a given unit of knowledge. In the NK model, the features of the topological space within which the economic action that leads to the generation of new technological knowledge takes place, are not characterized from an economic viewpoint. Rather, the number of complementary relations and their distribution are given, as are the number of elements belonging to each unit of knowledge. As frequently occurs when biological metaphors are grafted onto economics, this is compounded by the fact that the number of components and their relations are exogenous and there is little economic analysis of their associated costs and revenues.

This approach can be implemented as soon as the characteristics of the knowledge space into which eventual recombination may take place are appreciated: some regions of the knowledge space are more fertile than others. Recombinations are seen as the products of a combinatorial engine where the location in knowledge space of each agent possessing the bits of complementary knowledge plays a key role in shaping the recombinatory process. In this view, recombination does not take place as if it were the product of a random process. On the opposite, recombination is guided by the intentional action of perspective agents seeking to solve the specific problem they are facing and is shaped by their distribution in knowledge space. Proximity in knowledge space matters as much as the actual intentionality of agents to try and change their own technologies and to participate into the recombination. Passive agents are not likely to join the recombinatory process. New technologies are the result of a recursive process of recombination of the bits of knowledge possessed by intentional agents distributed in a map that evolves together with the technology itself.

The new economics of knowledge suggests that the knowledge is a system that can be represented by means of a map where a variety of interrelated components or modules are connected by links of varying strength according to their cognitive distance. The map of the knowledge system shows that the knowledge space is rugged and is characterized by different levels of complementarity and interdependence among a variety of components. The relations among such components may be qualified in terms of fungibility, cumulability and compositeness according to the contribution that each body of knowledge is able to make in the recombinant generation of new technological knowledge. Radical technological change takes place when a variety of complementary bodies of knowledge come together to form a hub that provides knowledge externalities to the "peripheries", which in their turn provide new inputs and help the pursuit of further recombination stretching its core (Antonelli, 1999 and 2008a).

The generation of new knowledge by means of the recombination of pre-existing knowledge items does not yield the same results in all possible directions. Some recombination processes are likely to be more fertile than others. Some knowledge items happen to be central in the generation of new knowledge (Olsson, 2000; Olsson and Frey, 2002).

The empirical evidence provided by the new economics of knowledge suggests that the knowledge space is rugged and is characterized by a variety of landscapes. In some regions knowledge cores emerge and contribute to form a hub that provides knowledge externalities to the "peripheries", which in their turn are reliant on this knowledge from the core. In other regions however such dynamics does not take place. Some regions are potentially fertile and others are not able to support the reaction of firms. The generation of new technological knowledge and the eventual introduction of productivity enhancing new technologies depend upon the quality of the context into which firms are localized, as well as on their capability to accumulate competence and implement appropriate recombination processes: organized complexity matters in the recombinant generation of knowledge.

New technological knowledge can be generated whenever, wherever and if previous and parallel knowledge is available and accessible. Moreover, at each point in time, no agent possesses all the knowledge inputs required. External knowledge is an essential input into the recombinant generation of new knowledge. Knowledge communication, both internal and external to firms, among learning agents plays a central role in the generation of new knowledge. Agents search in the knowledge space for other knowledge item, create communication channels and activate knowledge flows. Moreover firms can move within the knowledge space and select their location so as to access the new knowledge that will be most usefully recombined with their existing competences. Agents identify other agents with whom cognitive interactions and transactions are most likely to yield positive outcomes so as to benefit from localized pecuniary knowledge externalities.

In this context knowledge, external to firms, is an essential input into the generation of new knowledge. Access to external knowledge generally requires investment to enable search, screening, interaction and understanding, all of which are necessary before the external units of knowledge can be recombined with firms' internal knowledge. In certain areas of the knowledge space, fertile knowledge is available and can be accessed at a cost. Recombination will only occur if it is expected to yield net revenues in terms of the flows of knowledge outputs that it will generate.

Knowledge recombination is the process by means of which new technological systems based upon webs of complementary technologies emerge. The process is characterized by clear sequences based on highly selective exploration. The emergence of a core of complementary technologies is the first aggregating step. This initial core of technologies is very productive and is characterized by low recombination costs and high revenues from the additional knowledge generated. This engenders a process of technological convergence. The emergence of new knowledge cores pushes firms already active in existing knowledge space to explore seemingly less complementary knowledge regions in an effort to take advantage of new, marginal opportunities for knowledge recombination. Eventually, the increasing variety of these recombinations will prove less and less effective and the diminishing returns to recombination will become apparent.

In sum, the generation of technological knowledge and the introduction of technological change are characterized by three assumptions: a) firms are rooted in a limited portion of the space of technology, knowledge and geography both by the irreversibility of their stock of tangible and intangible inputs and by the competence based upon learning processes; b) firms are characterized by bounded rationality, but their procedural rationality includes the possibility to react to un-expected events and generate intentionally new technological knowledge and introduce new technologies react; c) because external knowledge is an indispensable input into the generation of new knowledge and no firm or agent can command all available knowledge, the quality of the reaction of each firm, whether adaptive or creative, depends upon the amount of knowledge available in the proximity within the technological, regional and knowledge space into which each innovator is embedded.

4.4.2. Knowledge positive feedbacks and the emergence of innovation

The complexity analysis enables to put in context the notion of knowledge positive feedback. Knowledge positive feedbacks take place in well specific circumstances when and where the interplay between the recombinant generation of technological knowledge and the changing characteristics of the knowledge and regional space feed each other so as to support the reaction of firms and make it creative.

The notion of positive knowledge feedback has two important implications. First, recombinant knowledge and localized technological change do not provide unlimited opportunities, which are fertile at any time, and in any place. Knowledge recombination may occasionally yield positive returns in well-defined and circumscribed circumstances that take place in historic time, regional space and knowledge space, when a number of key conditions apply. In some cases, however, the returns from recombination may be less productive.

When the structure of the system is such that knowledge externalities are not available and the access to external knowledge is burdened by heavy transaction, search and communication costs, high levels of congestion and strong appropriability, and the architecture of interactions limits knowledge interactions, single innovations may occasionally take place, but remain isolated acts of a minority of individual firms with little systemic effects. When the competitive threat to established market position is weak and hence creative social reactions are not solicited, inferior technologies are likely to be resilient. Adaptive responses, as opposed to creative ex-adaptive ones, are likely to occur when firms have not access to knowledge social interactions and the generation of knowledge should rely only upon internal sources. Firms are not able to introduce new localized, productivity enhancing technologies and may prefer to switch, i.e. just to change their techniques within the existing maps of isoquants. When the access of firms to external knowledge is costly if not inhibited, and adaptive responses, as opposed to creative ones, prevail, no technological change takes place and hence the structures of the system do not change.

The conditions for the emergence of innovations are set when the mismatch between expectation and real market conditions stirs the reaction of myopic but reactive agents and the flows of pecuniary knowledge externalities are large and consistent with their knowledge base. When both conditions apply, agents discover that their reaction is actually creative and activates a process of centred recombination that may occasionally generate new radical technologies. The actual emergence of innovations in fact takes place when active users of pre-existing technologies access the knowledge spilling over from the innovative activities of other actors co-localized in the knowledge space and combine it with their core knowledge. The larger the number of reactive agents, able to mobilize their competence and tacit knowledge and intentionally searching for new technologies and the larger the actual chances that a chain reaction leading to the generation of new technological knowledge and the eventual introduction of new technologies is set forth.

When positive feedbacks qualify the individual reaction of a firm into a creative process, innovations emerge from a collective process of generation of new technological knowledge and can lead to actual innovation cascades. It is clear in fact that the larger is the number of innovations and the larger the mismatch between the plans of individual myopic firms and the actual conditions of product and factor markets, hence the number of firms that are induced to react creatively and the larger is the amount of technological knowledge that is generated in the system. In such conditions not only a larger number of firms is induced to try and change its technology, but also a larger amount of knowledge is being generated. The chances that the reaction of firms becomes actually creative and can actually lead to the introduction of successful technological innovations that increase the levels of total factor productivity in turn increase (Antonelli, 2007 and 2008a). The organization, composition and distribution of the knowledge base, i.e. the complementarity between the competence of reacting firms, the variety and coherence of their individual research efforts, play a key role in supporting the reaction of firms and helping the emergence of innovation. (Antonelli, Krafft, Quatraro, 2010).

In special circumstances the dynamics of positive feedbacks can activate self sustained chain-reactions that lead to broader innovation cascades or Schumpeterian gales of creative destruction. New technological systems emerge and articulate around core technologies that act as general purpose technologies, i.e. hubs in the collective process of knowledge generation in which all the parties involved act intentionally, within a well-identified rent-seeking perspective. Such exceptional outcomes of individual interactions are clearly influenced both by the population dynamics of the entries of more or less compatible agents with whom recombination can be practised, and the organization and composition of the knowledge base. New gales emerge from a sequential process of selective aggregation in the knowledge space of heterogeneous agents yet encompassing specific knowledge components with high levels of potential complementarity and coherence.

Schumpeterian gales of innovation can be better understood as a historical process of emergence of new technological systems based upon a selective and sequential overlapping among complementary technologies that takes place in well defined circumstances (Antonelli, 2001). Much progress can be done by merging the literature on localized technological change and recombinant knowledge with the General Purpose Technology (GPT) literature. The notion of GPT implements and elaborates the Schumpeterian notion of the gales of technological innovations. According to Schumpeter the gales of technological innovations occur when a radically new technology with a wide scope of applicability is introduced in the system. There is today a large body of empirical and theoretical work investigating the hypothesis that when a core body of new, radical knowledge with a wide scope of application emerges out of a generalized and collective process of search and exploration and may promote a wave of ripple effects that invest all the system (Bresnahan and Trajtenberg, 1995; Lypsey et al., 1998, 2005).

It becomes now clear that externalities are but endogenous. As it is well known, the notion of externalities has been first introduced by Alfred Marshall to identify the external causes of increasing returns at the firm level. Its meaning has been eventually stretched so as to consider more generally the effects that an array of factors, including knowledge spillovers, external to each firm, but internal to a regional system, have on their performances. The notion of externalities has progressively acquired dynamic implications so as to include the consequences on the individuals of the changing features of the system with the notion of localized increasing returns. At the same time, however, a growing confusion has been taking place about the origins of externalities.

At the system level externalities are not exogenous but rather endogenous. Externalities and specifically knowledge externalities are a specific and yet dynamic and changing attribute of the system that is produced by the interaction of the individual agents that belong to the system. This seems especially true when the generation and exploitation of knowledge matter: new knowledge is in fact at the same time, an output and an input and its generation requires the participation of a variety of agents because of its intrinsic characters of partial appropriability, non-exhaustibility and non-divisibility.

As soon as it is clear that externalities stem from the collective results of the behavior of the individuals, however, it becomes also clear that they cannot be exogenous, but rather endogenous to the system into which each firm is embedded. A recursive process takes place where structural change at the system level and technological change at the individual level are the two sides of the same coin. The performances of the firms and their interactions affect the structural characters of the system and these in turn affect the context of action of each individual firm with external effects (See in Appendix B, Annex B5, Annex B6 and Annex B7).

4.5. The emergence of the organized complexity of innovation systems: the recursive dynamics of structural and technological change

The recursive and systemic dynamics of technological change can now be explored in more detail. The actual capability of firms to react creatively to out-of-equilibrium conditions, and to change their own technologies depends upon the proper combination of internal knowledge and competence and the localized availability of knowledge externalities and interactions. At each point in time in fact the reaction of firms is qualified and constrained by their location and the consequent conditions of access to external knowledge. When external knowledge cannot be accessed properly, the reaction of firms is adaptive and consists in standard switching upon the existing maps of isoquants.

Their reaction can become creative as opposed to adaptive and engender the actual introduction of successful, productivity enhancing innovations, when and if the interactions and feedbacks shaped by the structure of the system provide the access to external knowledge and external learning conditions. The intensity and the effects of interactions are shaped by the structure of the system and specifically by the network topology of agents distributed in the multidimensional space, at each point in time: hence innovation as an emerging property of the system into which the dynamics takes place.

The creative reaction of firms however consists both in their innovative capability and in their strategic mobility in multidimensional space. Firms can change their location, enter and exit product and factor markets, create new links and communication channels, change their position in vertical inter-industrial linkages and in regional districts and do change their knowledge base, hence their complementarities with respect to other firms. Firms can introduce institutional innovations that help the emergence of new markets and new forms of organization of the system at large, such as in the case of venture capitalism. The distribution of agents in the multidimensional space is itself the endogenous result of the locational strategies of agents carried out in the past. Clearly knowledge externalities are internal to the system: they depend upon the specific combination of activities and channels of communication in place among them. Knowledge externalities depend upon the structure of the system. The organization and composition of the structure of the system into which firms are localized exerts a key role in shaping the dynamics both at the aggregate and the individual level. Hence the organization of the systemic complexity is it itself an emerging property. Here it is clear how important are the contributions of both organization and population thinking. The former enables to appreciate to what extent the introduction of innovation depends upon the organization of the system, while the latter enables to grasp how population dynamics, in terms of entry and exit, reshapes the organization of the system. The analysis of the structural composition of the system, its effects on the conduct of firms and its evolution initiated by Simon Kuznets (1930, 1955, 1966, 1971, 1973) can be retrieved and enriched by the appreciation of other structural characteristics. The systems of innovation approach has captured some aspects of the interplay between the structural characteristics of the system at each point in time and the actual capability of firms to react creatively and introduce productivity enhancing innovations (Nelson, 1993).

These structural characteristics of the system are the features of a rugged and evolving landscape into which firms are at the same time rooted and yet able to change as a result of their strategic conduct. The organization and composition of the structure of the system are neither static nor exogenous: they change through time, albeit at a slow rate, as a result of the dynamics of agents and of the aggregate. The meso-economic dynamics of the system act as a filter between the dynamics at the individual and the aggregate levels (Burt, 1992; Dopfer, 2005). Several structural dimensions matter: institutional structures, economic structures, industrial structures, regional structures and knowledge structures, all contribute to shaping and framing the actual and effective access of firms to external knowledge and hence their chances to introduce productivity enhancing innovations. The institutional organization of an economic system plays a crucial role in many aspects. Intellectual property right regimes qualify the exclusivity of proprietary knowledge and hence define the conditions for the use of external knowledge as an input into the generation of new knowledge. At the same time however they define the appropriability of the new knowledge generated. The interactions among users and producers of knowledge as well as the viability of the markets for knowledge are much influenced by the intellectual property right regimes. The institutional conditions for the interaction between firms and the academic and public research sector, whether based upon personal contacts or more organized transactions, are most relevant in favoring the bidirectional flows of knowledge so as to increase both the dissemination of existing knowledge and the active participation of the scientific undertaking in directions that are directly useful for the business community (Antonelli, Patrucco, Rossi, 2010; Antonelli, Ferraris, 2010). The analysis of the basic endowments is crucial to grasp the incentive structures for the direction of technological change. It is clear in fact that firms have a strong incentive to introduce technological innovations that make a more intensive usage of locally abundant inputs (Binswanger, Ruttan, 1978; Kennedy, 1964; Samuelson, 1965).

The distribution and organization of markets, both intermediary and final, is far from obvious and spontaneous. On the opposite the quality of markets vary across economic systems and affects their performances. The quality of the markets in terms of density of players on both the demand and the supply side, and thickness, recurrence, and distribution of transactions is a crucial structural attribute of an economic system and has powerful effects on its dynamics (Burt, 1992; Antonelli, Teubal, 2012). The composition of the economic system in terms of primary, manufacturing and tertiary sectors and specifically the active role of knowledge intensive business service industries has a pivotal role in framing the access of firms to external knowledge. The analysis of the vertical structure of industrial and economic systems has appreciated the role intersectoral linkages as vectors of input flows and identified the central role of key sectors in the dissemination, appropriation and exploitation of knowledge as both an input and output (Pavitt, 1984; Fransman, 2007). The spatial distribution of the industry plays a key role. Economic geography has explored successfully the central role of regional districts and clusters as forms of governance of economic activity, analyzed the effects of the spatial composition of industries and economic activities in supporting the introduction of innovations and assessed the role of spatial proximity in the dissemination of technological knowledge (Breschi, Lissoni, 2003; Boschma, 2005).

The analysis of the composition of the knowledge base of an economic system is a recent important area of fruitful investigation. Technological knowledge is far from being a homogeneous aggregate of knowledge items. Knowledge is itself a complex system of highly differentiated elements related by intricate webs of complementarity and interdependence. At the aggregate level it is more and more clear that the composition and the organization of the knowledge base in terms of variety, whether related or unrelated, coherence, specialization and concentration in specific knowledge fields has important implications for the recombinant generation of new knowledge fields (Saviotti, 1996; Frenken, 2006a,b; Frenken, van Oort, Verburg, 2007). At the meso level, the structure of knowledge networks and their governance are determinant to channel knowledge externalities (Nesta and Saviotti, 2005 and 2008).

According to Paul Krugman (1994) such rugged landscapes in geographical, technological, knowledge, market and product space are at the same time the consequence and the determinants of complex dynamics. The structure of the system acts as a vector of catalyzers of a self-sustained of positive feedback in supporting the creative reaction of firms. Yet it is the result of their action. This approach makes it possible to pay attention to the evolution of the organization and composition of the structural characteristics of the system in terms of the distribution of agents in the different space dimensions, and to appreciate the changing architecture of the relations of communication, interaction and competition that take place among agents in assessing the rate and direction of technological change. The structure of interactions and the flows of knowledge externalities depend upon the organization of the system in terms of the architecture of sectors and markets, the forms of competition that prevail in each of them and among them, the geographical distribution of firms, their density in regional and technological clusters, the forms of organization within and among firms, the shape and structure of knowledge networks, the vertical organization of industrial filieres, the governance mechanisms, the institutional context. All these structural elements are the meso-economic carriers of history and, as such, embody the memory of the system and, occasionally, at the same time the product of the creative reaction of firms.

It is clear that positive feedbacks take place only in specific circumstances: some structures are more conducive than others. In some circumstances structural change leads to forms of organized complexity where the reaction of firms become actually creative and leads to the introduction of innovations. These in turn however affect the organization, composition and architecture of the structure of the system. The organization of the structure has lead to the introduction of technological changes that in turn affect the organization of the system: the dynamics loop between structural and technological change is set.

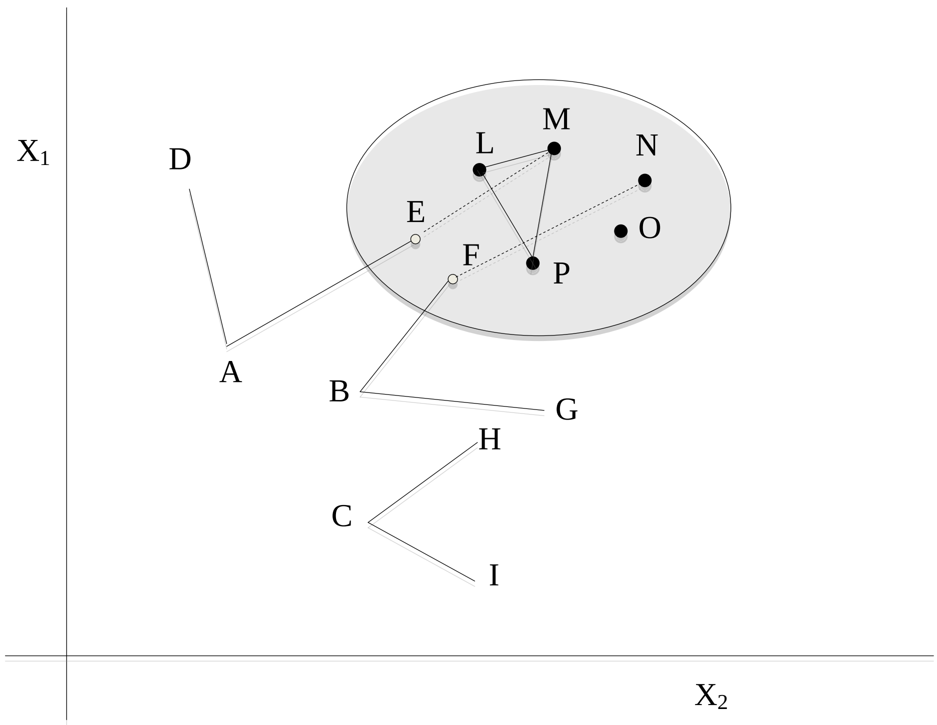
In special circumstances structural change leads to the emergence of strong innovation systems empowered by highly performing network structures that are the result of the collective dynamics of a myriad of agents in search of potential, vertical and horizontal-complementarities. The emergence of highly performing innovation systems leads to Schumpeterian gales of innovations. The successful accumulation and generation of new technological knowledge, the eventual introduction of new and more productive technologies and their fast diffusion are likely to take place in a self-propelling and spiralling process and at a faster pace within economic systems characterized by fast rates of growth where interaction, feedbacks and communication are swifter. In such special circumstances, the system can undergo a phase transition leading to the introduction of a new radical technological system (See in Appendix B, Annex B3 and Annex B4).

The changing structure of the system is endogenous to the system itself: the architecture of knowledge networks, as well as the industrial, sectoral, regional, knowledge and economic composition is heavily influenced by the strategies of firms seeking to improve their multidimensional location within systems of interactions. The national system of innovations approach framed by Nelson (1993) and widely used and implemented, contributed widely to appreciate the key role of the structural characteristics of economic systems in shaping their innovative capability, but clearly suffers from the basic assumption that the structure of the system is either given or exogenous. In this line of enquiry there is no effort to grasp the endogenous determinants of structural change (Patel, Pavitt, 1994).

The complexity approach makes it possible to focus the attention on the intertwined dynamics of knowledge externalities and interactions, localized technological changes and structural change. Our approach makes it possible to grasp that both the occurrence of creative reactions and the introduction of an innovation as well as its organized complexity are key emerging properties of an economic system. Knowledge interactions and externalities, and hence positive feedbacks, are not exogenous, the amount of knowledge externalities and interactions depends upon the structure of the system. The structure of the system is determined by the conduct of firm including both market strategies, the introduction of innovations and new communication and interaction networks. The activation of knowledge interactions is the result itself of intentional action. At each point in time, in fact, agents can change both their production and utility functions and their location. Agents are mobile, albeit in a limited range constrained by relevant switching costs, and they can change their production and utility functions, building upon their experience and competence based upon learning processes, hence in a limited span of techniques and preferences practiced in their past. Firms select their interacting partners, build communication channels, elaborate governance mechanisms: all actions that favor knowledge interactions. At each point in time the map of multidimensional space into which each firm is embedded is exposed to the changes brought by the changing location of firms. Firms are both creative with respect to their technologies, and mobile, with respect to their location in the space of knowledge, technologies, and reputation, hence they can change the structure of the system. The introduction of institutional changes adds on to the endogenous evolution of economic structures.

Innovation systems consolidate through time when the structural emergent properties leading to an organized complexity feed the introduction of innovations as emergent properties that in turn are able to feed further qualifications and improvements of the organized complexity of the system. As Figure 2 shows, each firm directs the generation of technological knowledge in a simple Lancastrian knowledge space with two characteristics (X1 and X2) depending on the opportunities to benefit from the locally available pecuniary knowledge externalities. At time 1 each firm moving respectively from point A, B, C, directs its technological strategy either towards D or E, F or G, H or I depending on the conditions of the external context. In turn, once rooted in either point, new possible directions can be chosen, within corridors defined by the firm's internal characteristics that include the preceding path. The technological path of each firm reflects the characteristics of both its own internal quasi-irreversibilities and learning processes and of the structure of the local context. The initial conditions play a key role in defining the context of action. The external context however, at each point in time, has powerful effects on the dynamics. According to the quality of knowledge interactions, some directions are favoured and others impeded. In Figure 2 the firm in A is induced to direct its innovation process towards E rather than D. The firm in B would move towards F rather than G. If other firms act as firms A and B the structure of the existing network LMMNOP will change. A new architecture of the network emerges. Its governance will change according to the ability of each new and old member respectively to enter and to participate to the new communication flows within the new architecture of the network.   By no means the new structure of the network is bound to be superior to the previous one. If the structural change increases the actual amount of knowledge externalities and interactions, a self-propelling process takes place. As long as additional changes reinforce this dynamics and consolidate the network each the process gains momentum.

Figure 2. The direction of technological knowledge



Positive feedback is likely to reinforce the process as the effort to increase the complementarity of each firm's research activity reinforces the local pools of knowledge that, in turn, increases the possibility to access external knowledge. At the same time increasing awareness of the opportunities for better knowledge exploitation provided by the intensive use of locally abundant and idiosyncratic production factors increases the intentional convergence of knowledge generation strategies towards a common direction shaped by the collective identification of the local idiosyncratic inputs. At the population level, the effects of individual convergence are reinforced by selection mechanisms. The success of the localized knowledge exploitation strategies acts as a powerful focusing mechanism that, through selection processes, favors the survival and growth of firms that have selected convergent paths of knowledge generation and exploitation (Antonelli, 2008b). Each firm engaged in generating new knowledge and appropriating its benefits in terms of extra-profits, discovers that the convergent alignment of its internal research activities with the complementary research activities of other firms, co-localized in both geographical and knowledge space, is a powerful factor of competitive strength. It is immediately clear in fact that the lower the unit costs of external knowledge are, the larger is both the amount of knowledge that the firm is able to generate and the larger is its localization in a specific context. A firm that is located in a conducive knowledge environment, and is able to identify and access the local pools of knowledge at low cost, is induced to take advantage of it and hence to base the generation of its new knowledge in the characteristics of its environment. This in turn is likely to affect the architecture of the local pools of knowledge and their governance.

Firms are able to try and change their environment and to influence its evolution by an array of actions ranging from the intentional mobility across regional and knowledge space, the creation of new communication links with other firms and institutions active in the generation of knowledge, the organization of networks and clubs, the introduction of better knowledge governance mechanisms. Here the notion of coalition for innovation, a term borrowed from political science, plays a key role. Firms and economic agents, at large, try and organize coalitions that are effective when they succeed to improve knowledge governance mechanisms by aligning and converging incentives and interactions based on their complementary competences. The aligned and mutual directedness of their interactions emerges, as the product of collective actions, aimed at increasing the quality of knowledge governance and enhance the cohesion of the group and to organize the inherent complexity of the system around shared objectives (Antonelli, 1997; David and Keely, 2003; Lane et al., 2009).

The dynamic coordination of creative agents emerges as a key issue. At the system level the creation of platforms that enable to implement the dynamic complementarities of firms helps the emergence of clusters and favors the intensification of knowledge interactions and hence the rates of introduction of localized technological changes. At the firm level the counterpart consists in the design and implementation of dedicated governance mechanisms to implement knowledge interactions such alliances, technology clubs, long term contracts (Consoli and Patrucco, 2008). Innovation systems emerge, through historic time, articulated in horizontal and vertical blocks of industrial sectors and filieres, technological districts, clusters, and networks when the generation of new technological knowledge is reinforced by the emerging structure of complementarities based on communication channels provided by the intentional research strategies of firms that discover new sources of complementarities and move within the knowledge space. The active role of the lead users and their fruitful interactions with their customers are encapsulated in these structures of the systems. The institutional features of the system complement the geographical and industrial ones and qualify the characterization of the mesoeconomic structure of the economic system.

The changing organization and architecture of the structure of networks within and among sectors, clusters and filieres is the result of a collective process. Each firm is able to move in such a knowledge space and generate new knowledge taking advantage of increased proximity and reinforced communication and interaction channels with other firms within knowledge coalitions clustering in nodes (the shaded region of Figure 2) where potential knowledge complementarities can be better understood. As a result, new systems of innovation, based upon coalitions and nodes of coherent knowledge complementarity, emerge (and others decay) while the direction of technological knowledge is shaped by the alignment towards a collective convergence of the research strategy of each firm. The levels of organization of the complexity of an economic system are endogenous and are themselves an emerging property (Antonelli, 1997 and 2010a).

Among the possible consequences, however, it is clear that, at the system level, the mix of activities that engender knowledge externalities and interactions may deteriorate over time: the entry of new members in the network as well the changes in the governance of the networks may cause congestion so as to lead to the actual decline of the amount of knowledge externalities and interactions available within the local system. Each agent is both myopic and localized in a limited region of the space, hence it is not able to make a global choice. Exit from an old location, be a product market, a network, an industrial sector, or a region and entry in a new one may improve its own individual chances to access external knowledge and yet it can engender a decline in the overall viability of the innovation system. The mobility of agents in multidimensional space affects the organization of the system. The latter in turn affect their chances to be creative and hence to introduce technological changes. Technological and structural changes are knitted in a close and dynamic interdependence. It becomes better clear how population dynamics affects the organization of the system and viceversa. Hence the need to rely both upon organization and population thinking (Lane et al., 2009).

The changes in the organization and architecture of the structure of the system have a direct bearing upon the amount and the quality of externalities interactions, and specifically upon the flows of knowledge externalities and knowledge interactions that make available, to each agent, external knowledge. The endogenous and dynamic character of externalities is set. New structures emerge and with them new architectures of externalities, communication and interactions. These in turn affect the dynamics of feedbacks and ultimately convert the chances that the creative reaction of firms leads to the actual introduction of productivity-enhancing innovations (Consoli Mina, 2009).

Within local and sectoral systems of innovation the organization and architecture of the communication channels that link each agent to other, the distribution of nodes can be seen as the result of an endogenous process of emergence that shares the complex dynamics of Internet network creation. The evolution of these networks, however, can exhibit both positive and negative features. Scale free networks, as opposed to random networks, based upon 'preferential attachments' may emerge and favor the access to external knowledge for a variety of actors. Some firms can emerge as the stars of the system as they are able to act as general switchboards of the communication flows (Barabàsi, and Albert, 1999; Barabàsi, Jeong, Neda, Ravasz, Schubert, and Vicsek, 2002; D'Ignazio and Giovannetti, 2006; Pastor–Satorras and Vespignani, 2004). The industrial structure of the system is changed by the emergence of new industries both upstream and downstream with important effects for the system at large. New markets become effective with new opportunities for supply and demand to interact and new possibilities for division of labor and specialization. New flows of intraindustrial externalities may be caused, while others may be hampered by the structural changes. The introduction of directed technological changes biased towards the intensive use of locally abundant production factors affect their prices and hence changes the structure of relative endowments. Antonelli (2009b) has shown that when firms are able to align their research strategies so as to take advantage of locally abundant knowledge, the amount of knowledge generated is larger. The amount of external knowledge that has been used in the knowledge generation process has a direct bearing not only upon the amount of knowledge being generated and hence on the efficiency shift engendered in the production process, but also on its characteristics. Firms that rely more upon external knowledge are more likely to produce complementary knowledge (Antonelli, 2010). Antonelli and Teubal (2008 and 2010) have shown how venture capitalism has changed the structure of interactions and transactions in financial markets with important effects upon the capability to fund, select and exploit new technological knowledge. Venture capitalism itself is a major institutional and organizational innovation that has activated a new mechanism for the governance of technological knowledge. Venture capitalism, as well, is the result of a systemic dynamics where a variety of complementary and localized innovations introduced by heterogeneous agents aligned and converged towards a collective platform. The new mechanism favors the creation of new science based start-up and has lead to the creation of new, dedicated financial markets. These new financial markets, specialized in the transactions of knowledge intensive property rights, combine the advantages of polyarchic decision-making in screening and sorting radical innovations with the direct participation to the profits of new outperforming science-based start-up typical of the corporate model.

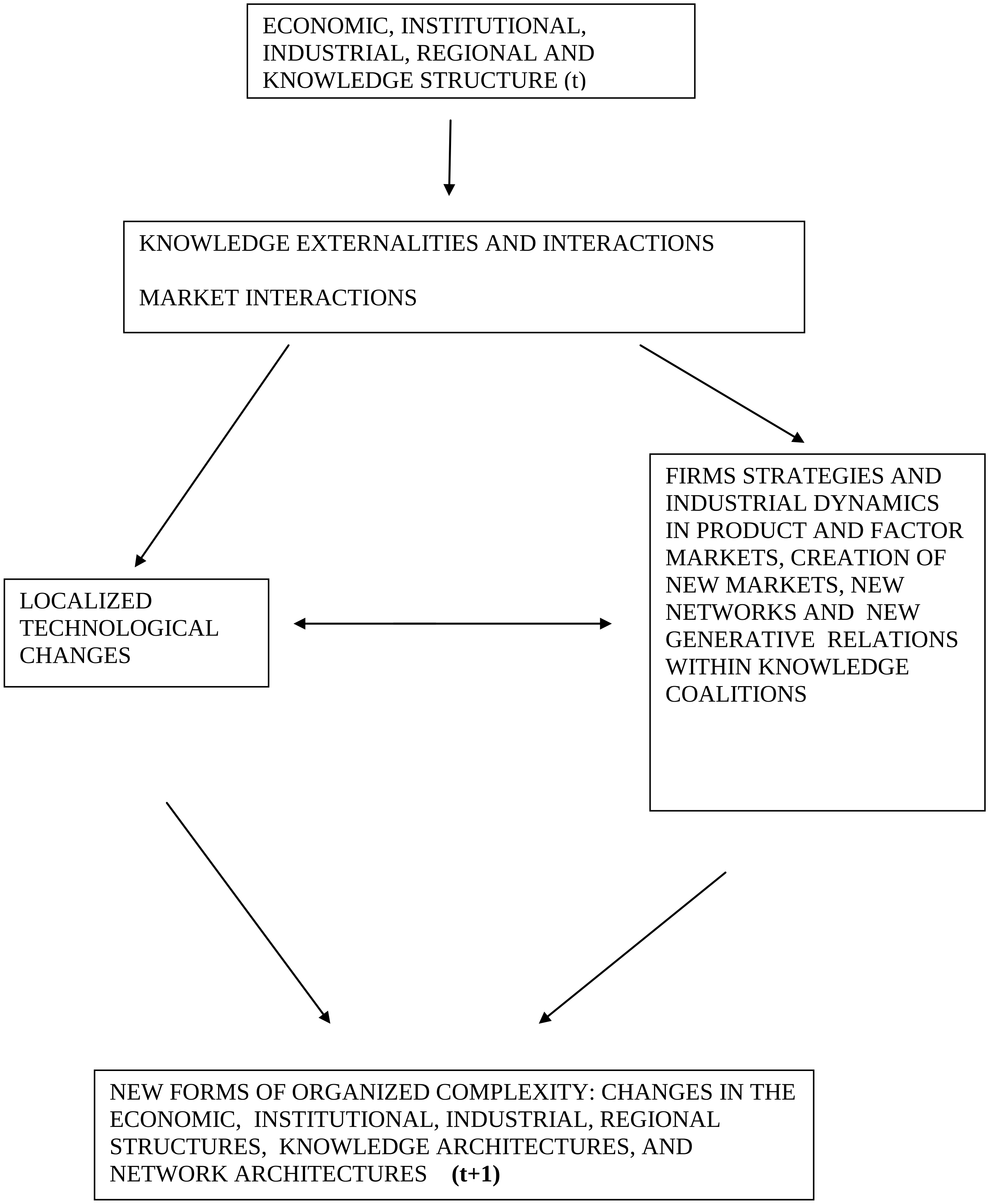
Agglomeration within clusters in the long run may engender negative effects. Knowledge governance costs may increase along with the number of firms accessing the same knowledge pools because of congestion effects in coordination. Eventually density may have negative effects in terms of reduced knowledge appropriability: the case of excess clustering can occur when proximity favors the uncontrolled leakage of proprietary knowledge within the local system (Antonelli, Patrucco, Quatraro, 2008 and 2010).

The convergence of the direction of technological change and the emergence of innovation systems in geographical and technological space occurs as long as the positive effects of knowledge interactions are larger than their negative effects. In specific contexts the interplay can lead to logistic processes of emergence with S-shaped dynamic processes that identify critical masses. At each point in time the emergence of new innovation systems may be blocked by a number of countervailing forces. The process is far from being past dependent: it is shaped, at each point in time by the ability of the actors to contrast the dissipation of pecuniary externalities. Both at the firm and the regional level these processes are likely to occur with a strong non-ergodic and sequential stratification (David, 1994). The path dependent dynamics stems from the interplay between past dependence and intentional action. The internal stock of knowledge acquired through learning by each firm together with the features of the local pools of knowledge and of the economic structure is the past dependent components as at each point in time they are the result of historic accumulation. The amount of knowledge being generated, the direction of technological change being introduced, the levels of knowledge governance costs and the price of locally idiosyncratic production factors are, at each point in time, the result of the intentional action of agents. Hence they provide the opportunities for intentional action to change the original path. At each point in time the intentional action of the embedded agents adds a new layer to the original structure: the original shape exerts an effect that the new layers can modify, depending on their thickness and density. Each firm in fact is able to interact with the system and to change it. This occurs at different levels: by introducing changes to the structural conditions and the topology of the system's communication channels, with the introduction of organizational innovations in knowledge governance mechanisms, and by changes in the factor markets due to innovations that change the supply of the idiosyncratic production factors. The emergence and decline of innovation systems is the result of continual feedback between the structure of the system and the innovative action of its agents.

When the negative effects of agglomeration exceed the positive effects, the mobility of firms in geographical and knowledge space is centripetal and leads to divergent path of exploration. Firms leave existing pools of knowledge and search for new possible agglomerations around new platforms and other sources of knowledge complementarity.

Externalities are endogenous and dynamic. Their dynamics is characterized by non-ergodicity. The past has a consequence on the future. Such non-ergodicity however cannot be characterized as sheer past-dependent. Structural and technological changes interact and shape at each point in time the new architecture of the structure into which firms are localized. The new structural conditions shape the creative reaction of firms as well as their strategies. These in turn change the structure of the system. The key determinants and characteristics of the systemic dynamics of technological change are set. Technological change and structural change are intertwined and mutually interdependent. The introduction of innovations is part of a more general and dynamic process of self-organization of the structure of the system. The actual introduction of technological and organizational innovations by each agent at each point in time is the result of a long term process of feedbacks that make possible their creative reaction at the system level via the continual changes in product and factor markets and the related strategic reactions of firms including research and development expenditures and the mobilization of internal tacit knowledge and competence, on the one hand, and the changes in the structure of knowledge interactions and externalities that provide and implement the access to external knowledge, on the other. Hence the conversion of adaptive responses into creative reactions is not a punctual and individual event that takes place isolated in time and space, but rather a collective process that finds its sustainability at the system level. Consistently the innovative capability of a system is an emergent property of the system, a fragile process that takes place when a number of complementary conditions and circumstances are set and their coherence is the result of constant implementation and maintenance over time. The dynamic coordination of structural and technological change appears necessary and yet extremely difficult because each element in the system is changing. Here the notion of path dependence plays a key role to grasp the dynamics of innovative systems (See in Appendix B, Annex B11 and Annex B12).

Figure 3. The evolving interaction between technological and structural change



5. METHODOLOGICAL IMPLICATIONS

5.1. Complexity-based approach and the analysis of demand-driven technological knowledge

A crucial dimension to think about complex dynamics in social systems is the agent/artefact space. The contributions by Arthur (2009) focus primarily on the artefact side, and propose a concept of technology as the outcome of a combinatorial process, according to which each technology is characterized by one or few key principles interacting with many other complementary technologies in defining the functionalities. As such technologies are characterized by an operational structure which organized the way the components are combined together. Such structures feature the components at each level of the nested hierarchy. New functionalities arise in the context of a process of exaptive bootstrapping. In other words, new artefacts, say a new products or new technologies, are designed to achieve some particular functionality. However, besides the expected functionality, the potentials of an artefact cab be fully grasped only as a function of use. In the course of utilization of artefacts new patterns of interactions emerge around them, which leads to the emergence of new functionalities that can represent the main functionalities driving the design of further new artefacts. This in turn generates again patterns of utilizations likely conducive to the discovery of new functionalities, engendering a self-propelling process. Once new artefacts are introduced, they enter 'in competition' with those already existing in the system, and therefore, since identity is relational, the attribution of a new identity to the new artefact involves also the renegotiation of identity for previously existing ones. These new attributions emerge out of interactions that are called 'generative relationships' (Lane, 2011).

In the agents/artefact space artefacts emerge as an outcome of the interactions among agents, who identify the functionalities to be implemented in the novel designs, and engage therefore in a combinatorial process. An important feature of complex systems is that the modification in one part of the structure is likely to be reflected on the other interconnected elements, as well as on the other structures linked through higher-level structural organizations. The implementation of a new functionality may require the modification of two or more attributions, what is called epistatic relationships. Moreover, one property of a system component is pleiotropy, i.e. the number of components that are likely to be changed as an effect of intentional changes on its role in the structure (this applies both to change of configuration and to substitution). The higher the pleiotropy of a particular component, the more risky is any action on it. Given a functioning design, the improvement of high-pleiotropy component may engender such a chain of adaptations in the structure that the net effect on the new design is a worsening of the whole performance.

Epistatic relationships and pleiotropy are features not only of the components of artefacts structure, but also of the 'organisations' which represent the interacting entities in the agents domain. People in a team, or firms in a joint research project, may be though as interacting elements of a complex system, which interact to the purpose of achieving a particular target which will come about as an emergent property. The metaphor of the network has been much used in the last decade to describe the structure of interactions of agents in complex socio-economic systems. A network is indeed composed by nodes, i.e. the elements of a complex systems, and by edges, i.e. the actual interactive relationships among nodes. The usefulness of the network (and also a methodological tool, as we will see later on) lies in the fact that some of its properties depends exclusively on its geometry, or the architecture of its structure, irrespective of the characteristics of the nodes. Obviously, it provides also the means to describe the single nodes, although in a relational way. A particular class of networks is largely used in the context of complex system dynamics, i.e. 'scale-free' networks (Barabasi et al., 1999; Barabasi et al., 2002), which is characterized by a highly asymmetric distribution of links about nodes. Letting the degree the number of link insisting on a node, scale-free networks are such that the degree distribution follows a power law. The existence of such distribution has been explained by adopting basically two mechanisms, i.e. fitness models and preferential attachment. The former mechanism is based on the idea that new nodes entering in a network choose the nodes with which establish a link on the basis of fitness values. In this direction, following a kind of 'supremacy of the fittest' principle, nodes showing higher levels of fitness degree are likely to attract a higher number of links. Barabasi and Albert (1999) have recently developed a model to model the growth of the World Wide Web based on this mechanism. The preferential attachment refers to a class of stochastic process in which some quantity is distributed among a number of individuals according to how much they already have. In other words, the flow is a function of the cumulated stock, such that the individuals showing the highest values of cumulated stock are interested by highest values of flow. According to this, the few nodes in the network showing high degree centrality are likely to increase their degree much more than the peripheral nodes.

The concept of network, and especially of scale-free networks, is particularly useful for social sciences, along with the properties allowing for their description. However, the discussion conducted so far proposes the existence of isomorphism between the structures in the agents and in the artefacts domain. The network metaphor can be used therefore to describe also the structure of 'organisations' in the artefact side, as well as the dynamics of their interactions.

An important brick in such building is, in our opinion, a contribution much neglected by scholars interested in grafting complex system dynamics onto economics, i.e. François Perroux' elaboration on the concept of economic space (Perroux, 1950). Perroux maintains that "we may distinguish in our discipline as many economic spaces as there are constituent structures of abstract relations which define each object of economic science" (Perroux, 1950: p. 91). What is interesting is the definition of space on the basis of structure relations. Moreover, the idea of a multiplicity of spaces points to a set of interconnected structure. The author distinguishes between geonomic space and economic spaces. The former, also called 'banal space', is defined by geonomic relations between points, lines and volumes. As an example, the characterization of firms on the basis of their geographical coordinates is based on their localization in a geonomic space. The same applies for two points in a Cartesian coordinate system. Economic spaces are instead "defined by the economic relations which exist between elements. These economic spaces conveniently reduce to three. (1) economic space as defined by a plan; (2) economic space as a field of forces; (3) economic space as a homogenous aggregate" (Perroux, 1950: p. 94). The former dimension refers to the set of relations among the units in the economic space. The second one refers to the existence of centres, or poles, from which centrifugal forces emanate and to which centripetal forces are attracted. The concept of attractor, very much related to phenomena of persistence and therefore dynamic preferential attachment, can be included in this perspective. Finally, "the relations of homogeneity which define economic space […] are relative to the units and to their structure, or relative to the relations between these units" (Perroux, 1950:p. 96).

Perroux' elaboration of the concept of economic spaces allows for the integration of socio-economic phenomena into a single framework susceptible to be modelled as a complex system of interacting elements. The articulation of socio-economic life in one single scheme is a pretty hard task which goes beyond the scope of this volume. An illustrative example is provided in Figure 1, where we have partitioned the agents and the artefacts dimensions, and depicted the relationships between the most relevant subsystems as well as a sketch of the structure of interactive elements which they consist of. The artefact space is instead populated by objects the creation of which stems from an emergence process at the agents levels. For the sake of clarity, we have omitted the exemplification of the complex structure that features each of these classes of artefact or lower-level subsystems in the agents space. Firms, for example, can be described as networks in which nodes are represented by tasks/agents and the links the transfers among the nodes.

There are some emergent properties that are not properly classifiable as artefacts, like knowledge or like human capital, which can be thought as the outcome of complex system dynamics of the agents acting in the education system as well as in families. There is also a sensible degree of overlapping among the subsystems: firms for example are both part of the innovation and the productive system. Human capital is a structured component informing the productive system, the innovation system, the institutional system and the education system itself. By looking at this quite simplified diagram, it clearly emerges how each sub-system can be seen as a component of a higher-order system. After all, Perroux himself emphasized the mutual dependence of different economic spaces. The organization of socio-economic systems seems therefore not to escape Gödel's theorem of incompleteness, according to which no system can be found able to be completely self-explaining.

The topology, or the structure, of relations occurring in such abstract spaces dominated by both between- and within-system complex interactions, exhibits an architecture which shapes both the pattern of linkages across the components and the quality of the components themselves. The architecture is therefore a key concept for the analysis of complex dynamics. Henderson and Clark (1990) introduced the concept of architectural change in the context of products design complexity. The isomorphism which we maintain to characterize both artefacts' and agents' structures allows for extending the idea of architectural change beyond the scope of product technologies. The architecture of systems of interacting innovating agents is important in that it influences the likelihood to capitalize knowledge externalities and generate new technologies. Cowan and Jonard (2003) shows that the way the structure of interactions is designed has a strong influence on the system performance. Moreover, interactions across components are not equally productive. There are some components that are better suited to interact with other specific components. Network theorists have labelled this property as 'homophily' of nodes (Skvoretz, 1991; Powell et al. 2005). According to this principle, elements in a network are more likely to interact with other elements that are similar. This principle has been proposed as an explanation o the patterns of development of nations by Hidalgo et al. (2007) and Hidalgo (2009), who proposed the concept of product space conceived as a network in which nodes are product classes and links are the interaction among them. They show that the development pattern of nations is such that they move in the product space by developing goods that are close to what they already produce. The same principle underlies the idea that social proximity shapes the interactions of collaborative networks for innovation to a larger extent than geographical proximity.

The architecture of the structure of interactions in complex systems is therefore characterized by the patterns of linkages among components, as well as by the features of the components themselves. This supports the idea that the complexity approach is able to synthesize individualism and holism. A much neglected aspect of architectures is its number of components. In Henderson and Clark (1990) architectural change only concerned the changes in the patterns of relationships among components. One property of scale-free networks is the growth of the network itself, which occurs by the entry of new elements in the system.

Architectural change can also happen in view of an addition of new components to the structure of relations. Altenberg's models of constructional selection, which extend Kauffman's N-K fitness landscape models, represent an interesting exception to the substantial neglect of endogenous change of architecture in the analysis of complex system dynamics.

To synthesize, the architecture of a complex system may well change over time, and so may the structure of epistatic relationships. This may occur either due to a change in the relative weight of some elements in the system, these elements switching from a non-influential to an influential position, or by means of introduction of new elements within the system. This is in turn likely to alter the existing structure of relationships. Within this context, the pleiotropy represents the number of elements in the system that are affected by the appearance of new elements. It is clear that the higher the pleiotropy, the greater the change in the architecture of the system that the inclusion of new elements may engender.

The viewpoint of endogenous complexity makes the analysis of knowledge dynamics particularly appealing and challenging. In view of the discussion conducted so far, knowledge can indeed be represented as an emergent property stemming from multi-layered complex dynamics. Knowledge is indeed the result of a collective effort of individuals who interact with one another, sharing their bits of knowledge by means of intentional acts of communication (Antonelli, 2008; Saviotti, 2007). In other words, the adoption of an endogenous complexity made possible by an augmented recombination approach allows for the combination of the view on technology as an artefact with the view of technology as an act, i.e. as the product of collective actions involving agents with converging incentives and aligned interests (Figure 2 provide a zoom in the dynamic interactions between these two systems) (Arthur, 2009; Lane et al., 2009).

The structure of the network of relationships amongst innovating agents represents therefore a crucial factor able to shape the ultimate outcome of knowledge production processes. Constructional selection matters, in that new institutions entering the network need first of all to choose with which incumbents they want to be linked with. The concept of preferential attachment applies to this situation. In a wide number of contexts, the new nodes in a network generally end up to link with those 'old' nodes already characterized by a large number of connections (Barabasi and Albert, 1999). As a consequence, the entrance of new actors in the network is likely to reshape the relative weight of nodes, and hence modify the structure and the balance of relationships.

Knowledge so produced stems from the combination of bits of knowledge dispersed among innovating agents. Creativity refers to the ability of agents to combining together these small bits of knowledge so as to produce an original piece of technological knowledge. This in turn may be thought about as a structure of bits of knowledge linked one another. The knowledge base itself, at whatever level, can be therefore imagined as a network in which the nodes are the small bits of knowledge and the links represent their actual combination in specific tokens. Knowledge in this sense turns out to be an emergent property of complex dynamics featuring the interdependent elements of the system, i.e. the bits of knowledge.

This is a quite unexplored consequence of the structural character of knowledge production, which provides further richness to its dynamics. Since such complex system may be represented as network, the knowledge base is characterized by a structure with its own architecture. This in turn may evolve over time, as an effect of the introduction of new small bits of knowledge and the consequent change in the relative weight of the nodes within the network, as well as due to the change in the patterns of linkages among bits of knowledge. Indeed, like in the networks of innovators, new nodes will be attached to some existing nodes, the centrality of which will be altered. Learning dynamics and absorptive capacity represent a channel through which the topology of knowledge structure affects search behaviour at the level of agents networks. Indeed, agents move across the technology landscape in regions that are quite close to the area of their actual competences (principle of homophily). Technological change is localized as an effect of the interactions between the complex dynamics at the knowledge and the agents' level. However the topology of knowledge structure is in turn shaped by the choices made by innovating agents as to which bits of knowledge combine together. A self-sustained process is likely to emerge, according to which the knowledge creation process tends more and more towards a local attractor in which they are locked in (Colombelli and von Tunzelmann, 2011).

This dynamics indeed makes preferential attachment work also at the knowledge level. Agents' search behaviour is indeed constrained by the topology of the knowledge structure. In this direction, those small bits of knowledge which have grown in importance are likely to exert a much stronger influence. This process is rooted in historical time, according to which the gradual sorting out of knowledge bits which have proved not to be so fertile, leaves the floor to few and more fertile bits. New bits of knowledge entering the knowledge base later on are likely to be linked to these few pillars.

Preferential attachment introduces a great deal of path dependence in system dynamics of technological knowledge. It amounts to articulate the concept of persistence beyond the rate of introduction of innovations, so as to apply it to the centrality of the specific smaller bits of knowledge which make the structure of the knowledge base.

Still, while this self-enforcing process is likely to trap the search process within a bounded area, the dynamics of technological communication at the agents' level as well as the capabilities to cope with search in areas that are far away from the competences of innovating agents are likely to introduce discontinuities in the evolutionary pattern. This amounts to introduce a wide variety of new bits of knowledge which are loosely related with those already existing in the knowledge base, so as to give rise to radically new combinations. The process of evolution, fed by learning dynamics and cumulativeness, leads to the gradual selection of the best combinations (principle of fitness), which grow in centrality and hence begin to constrain agents' search behaviour. Knowledge sharing and technological communication ensure therefore the emergence of new variety, which is more likely to occur in transition phases. At this stage a wide range of alternatives are viable, and multiple local attractors are likely to emerge from mutual influences between complex dynamics at the knowledge and the agents' layers.

Clearly, the patterns of change in the architecture are likely to bear important systemic effects. First of all, the impact of node substitution depends on the pleiotropy level. Changes affecting a high-pleiotropy node by definition will engender changes and adaptation in a large part of the system. The change of a high-pleiotropy node in the structure of knowledge is likely to generate a discontinuity of in the knowledge base. Interestingly enough, a node, a small units of knowledge, can be co-responsible of its own substitution. Knowledge bits are indeed combined so as to create new knowledge. This new knowledge can also germane the elimination or the improvement of one the bits used to generate it. Generative relationships matter in that each module in the knowledge structure is likely to interact to generate new modules.

The possibility to represent knowledge as a network provides an adequate conceptual foundation for the study of processes of knowledge generation and utilization in firms and industries. To identify all the variables and the connections present in the knowledge base of a firm at the lowest possible level of aggregation would be a prohibitively expensive task. An approximate version can then consist of identifying relatively 'small' units of knowledge and their connections. We identify these 'small' units within the traces of knowledge which have been used so far, such as patents and publications.

Whatever the level of analysis, the knowledge base (KB) can be defined as the collective knowledge that agents can use to achieve their productive objectives. The collective character comes from the interactions between individuals, research units and departments of the same firm or research organization. Such interactions are specific to each organization and can be expected to lead to a different knowledge time path even in the case in which the initial competencies of all the persons employed were the same. When we want to study the knowledge base of an industrial sector or of a field of science such collective character of course includes inter organizational interactions.

The KB can be mapped by identifying the units of knowledge composing it and by their connections or links. These units can be either technological classes or themes. Connections are determined by the joint utilization of the units in particular texts, be they patents, papers or something else. For example, if we use technological classes the connections are given by the co-occurrence of different classes in the patents used, and the frequency of co-occurrence can be interpreted as a measure of the strength of the link. In this way we can construct visual maps of the KB of a firm and follow the evolution of such KB in the course of time. These maps of the KB can be considered a representation of the brain of the firm.

In order for these maps not to be purely descriptive devices we need to identify some general properties of the knowledge base which can be measured and used both in empirical studies and in modeling, by exploiting both the network structure of knowledge and the statistical potentialities provided by the matrixes of technological co-occurrence.

5.1.1. The use of co-occurrence matrixes: coherence, cognitive distance and variety

The three properties of the KB which we will use in our analysis are its variety, related or unrelated, its coherence, and its cognitive distance.

The variety of a KB measures the extent of its diversification, with related variety measuring it at a lower level of aggregation and unrelated variety at a higher level of aggregation (Frenken et al, 2007). Technological variety can be measured by using the information entropy index. It was introduced by Shannon (1948) to measure the information content of messages, and can be used as a distribution function in a number of circumstances (Theil, 1967, Frenken 2006a,b). The use of information entropy to measure variety is based on the rise in the information content of systems as the number of their distinguishable components increases: a system with a large number of distinguishable components requires more information to be described than a system with a smaller number of distinguishable components.

The information entropy index has interesting features, like its decomposability into a between-group and within-group component, and the extension to multidimensional cases. According to the latter, one may calculate the variety of the actual combinations of technological classes in a given context (say a firm or a sector). The former property allows for the operationalization of the distinction between related and unrelated variety. One could say that related variety (within-group entropy) measures diversification at a local level, or within a technological class, while unrelated variety (between-group entropy) measures diversification at a more global level in a knowledge space. The important implication of this distinction is that while a growth in unrelated variety implies a rise in cognitive distance, a growth in related variety is compatible with a more incremental development and even a fall in cognitive distance.

The coherence of a KB measures the extent to which different types of knowledge can be combined. This is of a fundamental importance since the types of knowledge required by firms to create new products or services are not necessarily found within a discipline, but need to be combined to produce the desired output. The ability of firms to combine these different types of knowledge is not constant but can be expected to vary systematically during particular phases of the evolution of knowledge. For example, we can expect the ability of firms to combine different types of knowledge to fall as a completely new type of knowledge emerges at a discontinuity and to rise again as the new type of knowledge starts maturing. The coherence of the knowledge base can be calculated by modifying a procedure developed by Teece et al (1994) to measure the coherence in the output of a firm. The basic principle underlying the calculations is that the higher the frequency with which different technologies are used together by a firm the more coherent is its knowledge base. The calculation proceeds by first calculating the frequency of co-occurrence of each pair of technologies in the KB and then by averaging them over the whole firm, or sector in the present case (see Nesta Saviotti, 2005, 2006 and Krafft, Quatraro, Saviotti, 2009).

Cognitive distance measures the extent of discontinuity involved in the emergence of a new type of knowledge. It is the inverse of an index of similarity. This measure is of fundamental importance to be able to distinguish the effect of the emergence of a discontinuity from that of the subsequent period of normal or incremental development. There are many ways to calculate cognitive distances but we used the complement of the index of similarity proposed by Jaffe (1989).

From a technical viewpoint, such variables will be implemented as follows (See in Appendix B, Annex B5).

An overview upon calculations

Variety

Let us start by the variety indicator, which we decided to measure by using the information entropy index. Entropy measures the degree of disorder or randomness of the system, so that systems characterized by high entropy will also be characterized by a high degree of uncertainty (Saviotti, 1988). Differently from common measures of variety and concentration, the information entropy has some interesting properties (Frenken and Nuvolari, 2004a,b). An important feature of the entropy measure is its multidimensional extension. Consider a pair of events (Xl, Yj), and the probability of co-occurrence of both of them plj. A two dimensional total variety (TV) measure can be expressed as follows:

$$TV \equiv H(X,Y) = \sum_{l}\sum_{j} p_{lj} \log_2 \left(\frac{1}{p_{lj}} \right) \qquad (5.1)$$

If one considers plj to be the probability that two technological classes l and j co-occur within the same patent, then the measure of multidimensional entropy focuses on the variety of co-occurrences of technological classes within regional patents applications.

Moreover, the total index can be decomposed in a “within” and a “between” part anytime the events to be investigated can be aggregated into a smaller numbers of subsets. Within-entropy measures the average degree of disorder or variety within the subsets, while between-entropy focuses on the subsets measuring the variety across them. Frenken et al. (2007) refer to between- and within- group entropy respectively as unrelated and related variety.
It can be easily shown that the decomposition theorem holds also for the multidimensional case. Hence if one allows l□Sg and j□Sz (g = 1,…,G; z = 1,…, Z), we can rewrite H(X,Y) as follows:

$$TV = H_Q + \sum_{g=1}^{G}\sum_{z=1}^{Z} P_{gz} H_{gz} \qquad (5.2)$$

Where the first term of the right-hand-side is the between-entropy and the second term is the (weighted) within-entropy. In particular:

$$UTV \equiv H_Q = \sum_{g=1}^{G}\sum_{z=1}^{Z} P_{gz} \log_2 \frac{1}{P_{gz}} \qquad (5.3)$$

$$RTV \equiv \sum_{g=1}^{G}\sum_{z=1}^{Z} P_{gz} H_{gz} \qquad (5.4)$$

$$P_{gz} = \sum_{l \in S_g}\sum_{j \in S_Z} p_{lj}$$

$$H_{gz} = \sum_{l \in S_g}\sum_{j \in S_z} \frac{p_{lj}}{P_{gz}} \log_2 \left(\frac{1}{p_{lj}/P_{gz}} \right)$$

We can therefore refer to between- and within-entropy respectively as unrelated technological variety (UTV) and related technological variety (RTV), while total information entropy is referred to as general technological variety.

<u>Knowledge similarity and dissimilarity (cognitive distance)</u>

We need a measure of cognitive distance (Nooteboom, 2000) able to express the dissimilarities amongst different types of knowledge. A useful index of distance can be derived from the measure of technological proximity. Originally proposed by Jaffe (1986 and 1989), who investigated the proximity of firms’ technological portfolios. Subsequently Breschi et al. (2003) adapted the index in order to measure the proximity, or relatedness, between two technologies. The idea is that each firm is characterized by a vector V of the k technologies that occur in its patents. Knowledge similarity can first be calculated for a pair of technologies l and j as the angular separation or un-cented correlation of the vectors Vlk and Vjk. The similarity of technologies l and j can then be defined as follows:

$$S_{lj} = \frac{\sum_{k=1}^{n} V_{lk} V_{jk}}{\sqrt{\sum_{k=1}^{n} V_{lk}^2} \sqrt{\sum_{k=1}^{n} V_{jk}^2}} \quad (5.5)$$

The idea underlying the calculation of this index is that two technologies j and l are similar to the extent that they co-occur with a third technology k. The cognitive distance between j and l is the complement of their index of the similarity:

$$d_{lj} = 1 - S_{lj} \quad (5.6)$$

Once the index is calculated for all possible pairs, it needs to be aggregated at the industry level to obtain a synthetic index of technological distance. This can be done in two steps. First of all one can compute the weighted average distance of technology l, i.e. the average distance of l from all other technologies.

$$WAD_{lt} = \frac{\sum_{j \neq l} d_{lj} P_{jit}}{\sum_{j \neq l} P_{jit}} \quad (5.7)$$

Where Pj is the number of patents in which the technology j is observed. Now the average cognitive distance at time t is obtained as follows:

$$CD_t = \sum_l WAD_{lit} \times \frac{P_{lit}}{\sum_l P_{lit}} \quad (5.8)$$

Knowledge coherence

Cognitive distance measures the degree of dissimilarity among technologies. We expect it to provide us with an indication of the difficulty, or cost, a firm has to face to learn a new type of knowledge. Typically a firm needs to combine, or integrate, many different pieces of knowledge to produce a marketable output. Thus, in order to be competitive a firm not only needs to learn new 'external' knowledge but it needs to learn to combine it with other, new and old, pieces of knowledge. We can say that a knowledge base in which different pieces of knowledge are well combined, or integrated, is a coherent knowledge base. The technologies contained in the knowledge base are by definition complementary in that they are jointly required to obtain a given outcome. For this reason, we turned to calculate the coherence of the knowledge base, defined as the average relatedness of any technology randomly chosen within the sector with respect to any other technology (Nesta and Saviotti, 2005 and 2006; Nesta, 2008).

To yield the knowledge coherence index, a number of steps are required. In what follows we will describe how to obtain the index at whatever level of analysis i. First of all, one should calculate the weighted average relatedness WARj of technology j with respect to all other technologies present within the sector. Such a measure builds upon the measure of technological relatedness τjm (see below). Following Teece et al. (1994), WARj is defined as the degree to which technology j is related to all other technologies j≠m in the aggregate, weighted by patent count Pmt:

$$\mathrm{WAR}_{jit} = \frac{\sum_{m \neq j} \tau_{jm} P_{mit}}{\sum_{m \neq j} P_{mit}} \tag{5.9}$$

Finally the coherence of knowledge base within the aggregate i (be it a firm, a sector or a region) is defined as weighted average of the WARlt measure:

$$R_{it} = \sum_{j \neq m} \mathrm{WAR}_{jit} \times \frac{P_{jit}}{\sum_j P_{jit}} \tag{5.10}$$

It is worth stressing that such index implemented by analysing co-occurrences of technological classes within patent applications, measures the degree to which the services rendered by the co-occurring technologies are complementary to one another. The relatedness measure τ jm indicates indeed that the utilization of technology j implies that of technology m in order to perform specific functions that are not reducible to their independent use. This makes the coherence index appropriate for the purposes of this study.

In order to calculate the parameter τ, i.e. technological relatedness, we start by calculating the relatedness matrix (Nesta, 2008). The technological universe consists of k patent applications. Let Pjk = 1 if the patent k is assigned the technology j [j = 1, …, n], and 0 otherwise. The total number of patents assigned to technology j is $O_j = \sum_k P_{jk}$. Similarly, the total number of patents assigned to technology m is $O_m = \sum_k P_{mk}$. Since two technologies may occur within the same patent, $O_j \cap O_m \neq \varnothing$, and thus the observed the number of observed co-occurrences of technologies j and m is $J_{jm} = \sum_k P_{jk} P_{mk}$ .. Applying this relationship to all possible pairs, we yield a square matrix Ω (n × n) whose generic cell is the observed number of co-occurrences:

$$\Omega = \begin{bmatrix} J_{11} & & J_{j1} & & J_{n1} \\ \vdots & \ddots & & & \vdots \\ J_{1m} & & J_{jm} & & J_{nm} \\ \vdots & & & \ddots & \vdots \\ J_{1n} & \cdots & J_{jn} & \cdots & J_{nn} \end{bmatrix} \tag{5.11}$$

We assume that the number xjm of patents assigned to both technologies j and m is a hypergeometric random variable of mean and variance:

$$\mu_{jm} = E(X_{jm} = x) = \frac{O_j O_m}{K} \tag{5.11}$$

$$\sigma^2_{jm} = \mu_{jm} \left(\frac{K - O_j}{K} \right) \left(\frac{K - O_m}{K - 1} \right) \tag{5.12}$$

If the observed number of co-occurrences Jjm is larger than the expected number of random co-occurrences μjm, then the two technologies are closely related: the fact the two technologies occur together in the number of patents xjm is not casual. The measure of relatedness hence is given by the difference between the observed number and the expected number of co-occurrences, weighted by their standard deviation:

$$\tau_{jm} = \frac{J_{jm} - \mu_{jm}}{\sigma_{jm}} \quad (5.13)$$

It is worth noting that such relatedness measure ha so lower and upper bounds: $\tau_{jm} \in \left]-\infty;+\infty\right[$. Moreover, the index shows a distribution similar to a t-student, so that if $\tau_{jm} \in \left]-1.96;+1.96\right[$, one can safely accept the null hypothesis of non-relatedness of the two technologies j and m. The technological relatedness matrix Ω' may hence be thought about as a weighting scheme to evaluate the technological portfolio of regions.

The adoption of these variables marks an important step forward in the operational translation of knowledge creation processes. In particular, they allow for a better appreciation of the collective dimension of knowledge dynamics. Knowledge is indeed viewed as the outcome of a combinatorial activity in which intentional and unintentional exchange among innovating agents provides the access to external knowledge inputs (Fleming and et al., 2007). The network dynamics of innovating agents provide the basis for the emergence of new technological knowledge, which is in turn represented as an organic structure, characterized by elementary units and by the connections amongst them. The use of such variables implies therefore a mapping between technology as an act and technology as an artefact (Arthur, 2009; Lane et al., 2009; Krafft and Quatraro, 2011). Co-occurrences matrixes are very similar to design structure matrixes (DSM) (Baldwin and Clark, 2000; Murmann and Frenken, 2006; Baldwin, 2007), in that they can be thought as adjacency matrixes in which we are interested not only in the link between the elements, but also by the frequency with which such links are observed.

In other words these measures capture the design complexity of knowledge structure, and allow for featuring the innovation behaviour of firms, as well as its evolution, in relation with the changing architecture of such structure (Murmann and Frenken, 2006). In this perspective, an increase in knowledge coherence is likely to signal the adoption of an exploitation strategy, while a decrease is linked to exploration strategies. Increasing values of cognitive distance are instead related to random screening across the technology landscape, while decreasing cognitive distance is more likely to be linked to organized search behaviour. Knowledge variety is likely to increase in any case when new combinations are introduced in the system. However the balance between related and unrelated variety should be such that the related one is likely to dominate during exploitation phases, while the unrelated one gains more weight in the exploration strategies (Krafft, Quatraro, Saviotti, 2009).

5.1.2. Social Network Analysis

The representation of the knowledge structure as network, clearly lends itself to the utilization of the toolkit provided by social network analysis (cf. Scott, 2000; Wasserman and Faust, 2007). A network may be defined as a graph made of nodes that are tied each other by one or more types of interdependency. Relationships among nodes are expressed by arcs, which in turn may be directed or undirected. Two nodes that are connected by a line are said to be adjacent to one another. Adjacency is therefore the graphical expression of the fact that two nodes are directly related or connected to one another. The points to which a particular point is adjacent are termed its neighbourhood.

Points may be directly connected by a line, or they may be indirectly connected through a sequence of lines. It may be thought as a 'walk' in which each point and each line are distinct. This is called path. The length of path is measured by the number of lines that constitute it. The distance between two points is the shortest path (the geodesic) that connects them.
One of the most widely used measures to describe a network is the density. It describes the general level of linkage among the points in a graph. The density of a network is therefore defined as the total number of actual lines, expressed as a proportion of the maximum possible number of lines:

$$\Delta = \frac{l}{n(n-1)/2} \tag{5.14}$$

A network is complete when all the nodes are adjacent, and the measure of density attempts to summarize the overall distribution of lines in order to assess how far the network is from completion. Density depends upon two other important parameters of the network, i.e. the inclusiveness and the sum of the degree of its points. Inclusiveness can be defined as the share of network nodes that are not isolated, i.e. the share of nodes that are connected to at least another node. For example, in a network of 20 nodes with 5 isolated nodes the inclusiveness is 0.75. The more inclusive the graph, the more dense the network will be.
However some nodes will be more connected than other ones. The degree of a node is an important measure of centrality that refers to the total number of other points in its neighbourhood. Formally one can represent the degree by the following equation:

$$D(v) = \sum_{s \in V \neq v} x_{vs} \tag{5.15}$$

This measure is obviously biased by the network size. Therefore it is useful to use a standardized measure, which consists in dividing the degree measure by its maximum value as follows:

$$ND(v) = \frac{D(v)}{n-1} \tag{5.16}$$

The higher the degree of the connected points in the network, the higher will be the density. For this reason the calculation of density needs to take into account both measures. It should compare the actual number lines present in the graph with the total number of lines that the graph would show if it were complete.
While the density describes the network as a whole, the measures of centrality refer to the relevance of the nodes belonging to the network. A point is locally central if it has a large number of connections with other points in its immediate environments, i.e. other points in its neighbourhood. Global centrality refers instead to the prominence of the node with respect to the overall structure of the network. Measures of global and of local centrality have a different meaning.

Measures of global centrality are expressed in terms of the distance among various points. Two of these measures, i.e. closeness and betweenness, are particularly important. The simplest notion of closeness is that calculated from the 'sum distance', the sum of geodesic distances to all other points in the graph (Sabidussi, 1966). After having calculated the matrix of distances among the nodes of the network, the sum distance is the row of column marginal value. A point with a low sum distance is close to a large number of other points, and so closeness can be seen as the reciprocal of the sum distance. Formally it can be expressed as follows:

$$C(v) = \frac{1}{\sum_{t \in V \neq v} d_G(v,t)} \tag{5.17}$$

Where the denominator represents the sum of the geodesic distance of the vertex v to all other points.

The betweenness measures the extent to which a particular point lies ‘between’ the other points in the graph: a point with a relatively low degree may play an important intermediary role and so be very central to the network (Freeman, 1979). The betweenness of a node measures how much it can play the part of a broker or gatekeeper in the network. Freeman’s approach is built upon the concept of local dependency. A point is dependent upon another if the paths which connect it to the other points pass through this point. Formally, let G be a graph with n vertices, then the betweenness is calculated as follows:

$$B(v) = \sum_{\substack{s \neq v \neq t \in V \\ s \neq t}} \frac{\sigma_{st}(v)}{\sigma_{st}} \qquad (5.18)$$

Where σ_{st} is the number of shortest geodesic paths from s to t, and $\sigma_{st}(v)$ is the number of shortest geodesic paths from s to t passing through a vertex v.

The centrality measures discussed above, allow us to characterize each single network node. However, for the purposes of this paper it is worth calculating the sector averages for all of the three indexes. In this direction, one must consider that each node corresponds to a technological class observed with a specific relative frequency, which must be taken into account when averaging out the centrality measures. We can then propose weighted average centrality measures as follows. Let Z(v) be one of the three centrality measures referred to the generic node v, the weighted average centrality at time t is:

$$\overline{Z(v)} = Z(v) \times \frac{P_v}{\sum_v P_v} \qquad (5.19)$$

Where Pv is the number of patents in which the technology v is observed.
The huge potential of social network analysis lies in the possibility to map the yearly patterns of co-occurrences into network structures for the aggregate under scrutiny. This would allow to obtaining the dynamics of such indicators like density, connectivity or nodes centrality, so as to investigate the evolution of knowledge structure as well as the co-evolutionary patterns of other relevant structures in the hierarchy of nested sub-systems.

5.2. Demand, Innovation and Agent-Based simulations

The European Commission (2010) highlights in its Horizon 2020 strategy the goal for smart, sustainable and inclusive growth for Europe. Without doubt this goal includes a strong role for innovation. Simultaneously the policy agenda has clearly disbanded from the sequential view on innovation processes and displaced it by a network view in which the different phases of innovation and the different actors involved in innovation strongly interact. An increasing attention is placed now also on the role of the demand side, both as important determinant in the diffusion of innovation, e.g. public procurement (Edler 2007) as well as a source of knowledge and creativity (von Hippel 2005). Obviously, no innovation could have contributed to economic growth without consumers willing to purchase the innovation. In our study we take up this issue and focus on the complex interrelation between demand and supply in a numerical model compiled in a Neo-Schumpeterian fashion.

5.2.1. Agent-based Modelling in economics

Scope of Agent-based Modelling in Economics

Agent-Based-Modelling (ABM) still is considered to be a new modelling approach which so far is only occasionally used. However, ABM gains increasingly attention and is considered as a methodological approach which has the potential to get rid of the shortcomings of the optimization and equilibrium-oriented framework of standard economic tools, in particular in cases when complex and dynamic phenomena are investigated (Fagiolo and Pyka 2007). Besides of being new also the rich set of possibilities offered in principle by ABM approaches requests a thorough methodological discussion which so far is not yet finished. To some extent this methodological discussion is also reflected in the many different terms which are still used for ABMs in the literature: e.g. Agent-based simulation modelling (Polhill, Gotts et al. 2001), multi-agent simulation (Ferber 1995, Gilbert, Troitzsch 2005), multi-agent-based simulation (Edmonds 2001) and multi-agent systems (Bousquet, Le Page 2004).

The essential nature of this modelling approach is its bottom-up perspective (Axelrod 1997). Most of the studies and labels mentioned above refer to this perspective but the elegance is sometimes hard to grasp. In short, building the model from the bottom-up means: to model complex macroscopic regularities as an emergent property from actions and interactions of microscopic entities (Epstein and Axtell 1996, Axelrod 1997). A good example which illustrates this underlying principle is a small biological system such as a flock of birds. If our goal is to explain and predict the movement of the birds and the flock, one could treat the system of birds as one unit, the flock as such. Thereby we would concentrate our observations on the behaviour of the flock as a whole and then create a simple model of the flock. Clearly, this approach is elegant in its simplicity and allows for good insights of the flock´s behaviour. But is a model which neglects the main drivers of a system accurate enough to understand, explain and predict the behaviour of a system itself?

The agent-based modelling approach follows the idea to start with individual and autonomous agents who build the macroscopic system with their behaviour and interactions (Epstein and Axtell 1996, Axelrod 1997). So in reference to the flock of birds, we create the complex behaviour of a flock by disaggregating to the level of its smallest units, namely the birds (See in Appendix B, Annex B10).

If we now find adequate behaviour rules for the birds, such as:
Separation - avoid crowding neighbours (short range repulsion),
Alignment - steer toward average heading of neighbours and
Cohesion - steer toward average position of neighbours (long range attraction) (Reynolds 1987), we can create the model of a flock from a bottom-up way of thinking (Fig. 4).

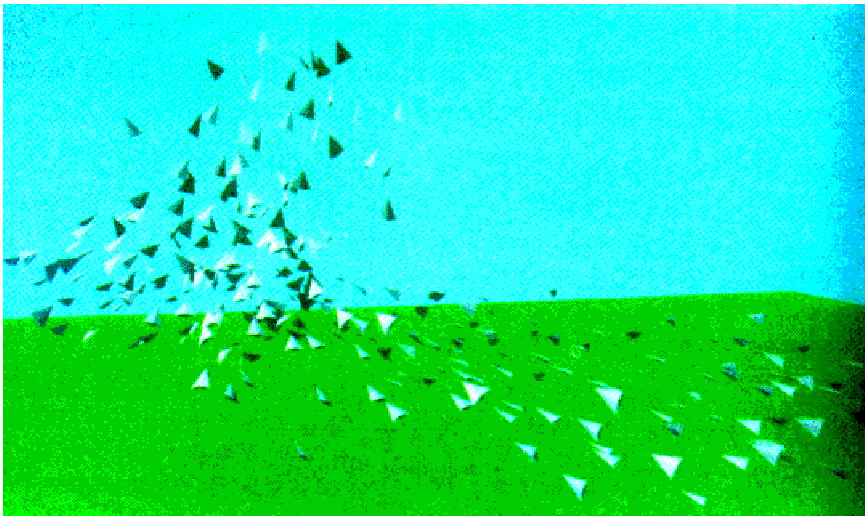


Fig. 4: Computer simulated Flock of Birds (Reynolds 1997)

Benefits and Pitfalls of Agent-Based Modelling:

Despite the disagreement concerning the right term there exist a broad consensus on the three key strengths of the Agent-Based modelling approach:
ABM captures emergent phenomena,
ABM provides a natural description of a system and
ABM is flexible (Bonabeau 2002).

In more detail, ABM focus on the actions and interaction of heterogeneous actors on a micro-level which are embedded in an environment of which they are a part of. The agents' interactions may lead to changes in the architecture on the meso-level, which were not intended by single actors nor built in their individual behavioural rules. So as a result, by using ABM we can grow the emerging macroscopic behaviour (Epstein 1999) by the actions and interactions of microscopic entities. Second, ABM does not need the restrictive assumptions of neoclassical models like perfect knowledge, homogeneity and equilibrium which are the methodological backbone of for example general equilibrium models. With the focus on individuals and their varying behavioural rules ABM explicitly takes into account heterogeneity and limited capabilities of the respective agents, hence the phenomena under analysis are described in a natural way. Finally, the simulation environment makes ABM flexible. It is possible to create computer aided simulation experiments where we systematically alter variables and analyse the outcome. This kind of numerical experiments complements experiments in natural science and are called "in-silicio" experiments (e.g. Ahrweiler et al. 2004, Triulzi and Pyka 2011)

As a consequence in our case, both the demand and supply sides of markets emerge from the behaviour of the relevant economic actors such as for example private and public customers as well as firms etc. From the actors' side our model therefore includes profit seeking firms producing heterogeneous products based on their individual knowledge stock which can be modified and displaced by innovation activities. The counterpart is a demand side composed of heterogeneous cunsumers, buying products based on their individual and limited information and knowledge about the supply side as well as their individual and changing preferences. With this, we can then test and analyze -in silicio- the complex interaction between demand and innovation.

From this follows that the ABM approach fits best for our attempt to create a model suitable for the analysis of versatile demand side effect on innovation and to derive important policy implications. With the agent-based computational modelling approach, we can avoid the simplicity of traditional models which fades out essential features of innovation processes which are, however, essential for a better understanding of the complex dynamics underlying this phenomenon. We explicitly take into account the heterogeneity and limited capabilities, such as bounded rationality and limited information, of both the consumers on the demand side as well as the firms on the supply side with the help of these ingredients the model will reach a level of so far unattained accuracy. In return, the possible policy implications will be much more specific and will address the relevant needs of economic actors. Through a flexible simulation environment it is possible to analyse the model behaviour intensively by performing wide sets of numerical experiments. Furthermore, the simulation environment will enable us to systematically adjust and customize our model to different industries and market conditions. Finally, scenario analysis will provide us with the qualitative and quantitative outcome of a broad set of different policies.

Naturally, a model aimed at analysing the effects of demand on innovation will have a level of complexity which is, as stated earlier, a strong pro. However, at the same time this level of complexity is a severe challenge. The handling of the complexity within the Agent-based model is still on debate and poses difficult methodological questions: The analysis of models is always a time consuming task even with the possibilities of computer aided simulation techniques. With increasing levels of complexity it becomes more and more challenging for the modeller to match the assumptions with the corresponding outcomes, or to put it another way, to understand the model and its behaviour. What are the causes and what are the effects of the observed outcomes of the model. The strong interaction of the variables, the high probability of non-linearities and the co-evolution dependencies among variables may lead to obscure interpretations. This difficulty has triggered a rich methodological discussion in which we find two distinct modelling strategies in the literature. First, following the KISS (Keep-it-simple-and-stupid) strategy one should start with a simple model which may be extended if necessary. In contrast, the KIDS (Keep-it-descriptive-stupid) strategy follows the idea to start with an descriptive model first which is then, if possible, simplified (Edmonds, Moos 2004). It is noteworthy that in general both strategies do not differ concerning the level of complexity. It is rather a question of how to get there.

An illustrative example for the KISS modelling strategy is Schelling´s model of segregation in North-American cities. In this model Schelling uses a simple grid for the representation of a city and to model neighbourhood relationships. He succeeds in identifying the mechanisms which lead to strong clustering patterns of ethnic groups, even if this was only mildly intended in the individual behaviour of Agents (Schelling 1971).

A good example for the KIDS strategy is the model of water demand by Edmonds and Moss 2004 which includes an extremely rich set of varying behaviour rules, preference systems, water consuming devices (power showers, water-saving washing machines etc.), pricing systems and policy options. With the help of this rich set of ingredients, backed by empirical observations, the authors intend to model water demand in a region close to the real water demand.

For our model of demand-side and supply-side interactions in innovation processes we will follow a modular strategy: The main feature of a model of innovative firms seeking for profits in a market with imperfect and heterogeneous customers has to be its representation of knowledge and technology as an emergent phenomenon driven by the research activities and knowledge exchange among agents. For this prupose we first have to define and analyse in detail the technological environment which allows us to display the dynamics involved.

5.2.2. Representing Knowledge as a Key Driver of the Innovation Process

A crucial prerequisite of this model of innovation and demand is a proper representation of (technological) knowledge. The knowledge representation is necessary to track changes in the preferences of consumers which then are targets of innovation activities of firms. When consumers are no longer represented by a representative household, but heterogeneity of wants and needs is accepted, then firms cannot longer offer one "optimal" product. Instead firms need to understand the needs and wants of consumers in order to innovatively adapt their diversified product portfolio. Furthermore, the changing product characteristics are influencing the preferences and needs of the demand side via their perception in the customers' knowledge bases. With the help of the consumers´ and producers' knowledge bases we intend to match demand and supply and additionally to take care on the pronounced heterogeneity on both market sides.

To model the firms´ key characteristic we make use of the so called kenes concept (Gilbert 1997) which has already been used in several models of Gilbert, Pyka and Ahrweiler, 2001, Gilbert, Ahrweiler and Pyka, 2007).

Drawing on the idea of genes in biology, the kene-concept represents the entire knowledge base K of a firm i by a number of single units of knowledge (Fig. 5). Each knowledge unit is described by the information about the general technological field (Capability C), the particular technological trajectory followed in that field (Ability A) and a corresponding expertise level (Expertise E) (Gilbert et al. 2001).

$$K_i = \begin{pmatrix} C_1 \\ A_1 \\ E_1 \end{pmatrix}, \begin{pmatrix} C_2 \\ A_2 \\ E_2 \end{pmatrix}, \begin{pmatrix} C_3 \\ A_3 \\ E_3 \end{pmatrix}, \dots, \begin{pmatrix} C_n \\ A_n \\ E_n \end{pmatrix}$$

Fig. 5: Knowledge Base of a Firm

Kenes and empirical Knowledge Representations

One way to portray the knowledge of our artificial agents and to validate our model in a way which allows comparison with empirical actors is the well-known International Patent Classification (IPC) of patent offices. The IPC provides a hierarchical system of language-independent symbols for the classification of patents according to the different areas of technology to which they apply. IPC Codes of patents allow the assignment of technological fields and competences with so-called concordance tables (cf. Schmoch et al. 2003) to identify industrial sectors. In this sense, the IPC Codes can be considered as coordinates of an empirical knowledge space and correspond approximately to the "units of knowledge" in the kenes of our model.

The kene´s capabilities C correspond to the 3-digit IPC Codes, which represent broad technological fields, e.g. the code C07 stands for organic chemistry. One level below, on the 4-digit level, we find the various occurrences within the capabilities domain, which correspond to the abilities A, e.g. the code C07K represents all technologies related to

processes of preparation of peptides. As every capability C has many (in principle infinite) occurrences (abilities A), each 3-digit IPC Code has several specifications on the 4-digit level, and these can be augmented if new, so far non-classified technologies become available.
Pyka and Hörlesberger (2004) use the IPC Codes of the patents of a firm to visualize its knowledge base. They assume that the expertise of a firm in a certain technological ability is high if the respective 4-digit IPC Code is found frequently in the patents of the firm. In the graphical representation shown in fig. 2, 4-digits IPC Codes are represented as circles whose size is dependent on this frequency, i.e. the more often the IPC Code can be found, the better developed are the respective abilities and the larger is the circle. This corresponds to the expertise level E of one unit of a kene. The positions of the abilities in the 2-dimensional knowledge map depend on the coordinates given by the IPC Codes. Additionally, technologically related technologies attract each other and therefore are moved together more closely in the knowledge map. Pyka and Hörlesberger (2004) consider the co-occurrences of IPC Codes to represent technological relatedness. The more often two IPC Codes are used together in a single patent, the better connected are the respective technologies. In the knowledge maps, these abilities are moved together and connected with a line.

As an example, Figure 6 describes the knowledge base of the French pharmaceutical company Rhone-Poulenc on the basis of all its 1266 patents filed at the European Patent Office (EPO) from 1995 to 1999. The largest circle in the centre (a61k), for example, stands for "preparations for medical purposes", which obviously is a core competence of a pharmaceutical company. The colour-shaded abilities belong to the domain c12, which is biochemistry. Accordingly, the knowledge map shows that in the mid 1990s Rhone-Poulenc started to integrate molecular biology into their core competences as these abilities are well connected to the traditional pharmaceutical technologies.

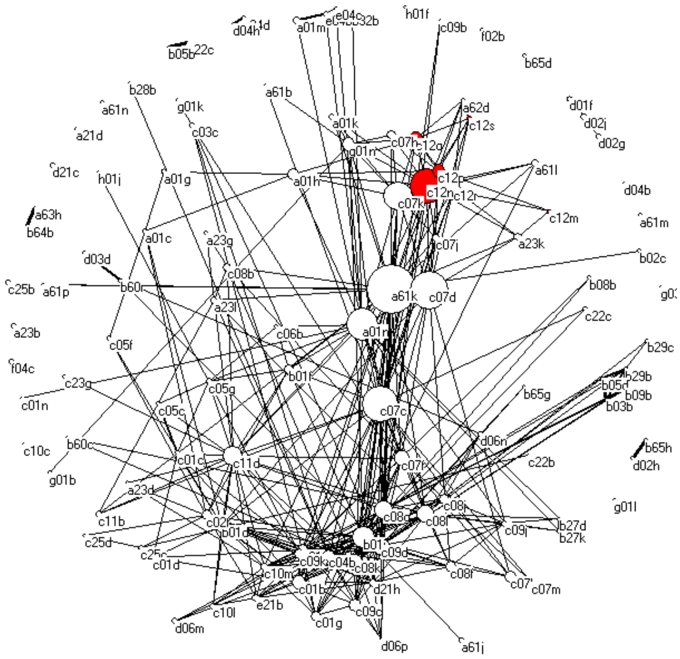


Fig. 6: Knowledge base of Rhone-Poulenc (1995-1999); source: EPO PATSTAT

The concept of kenes to model innovation processes

How are kenes used to model innovation processes and how is the link designed to match the knowledge of the firms with the products and services they offer to their customers?
It is assumed that the knowledge owned by a firm will not be entirely used for the production of a certain good. There are pieces of knowledge in the knowledge base which are well known to the firm, but are at a particular moment in time not necessary for production. Knowledge pieces which are used for the production of goods are part of a so called innovation-hypothesis (Fig. 4) (Gilbert et al. 2001, Ahrweiler et al. 2004).

Fig. 4: A firm´s knowledge and its Innovation-hypothesis

Based on their knowledge firms produce products that can differ in terms of product category as well as product quality. The product category (ID) is generated as

Where N Products is the total number of possible products. The product quality is generated in a similar way by using the abilities respective expertises levels:

In competition with other firms and to adapt to market conditions, the firms are equipped with three possibilities to change their knowledge base:
(1.) The first possibility can be referred to as learning by doing, i.e. a firm increases its expertise level by actually using its knowledge. Vice versa, forgetting by not doing, expresses a decreasing expertise level of knowledge and eventually the loss of the knowledge unit if it is not used.
(2.) The second possibility of changing knowledge results from own R&D efforts. R&D is modelled as a stochastically process which changes the Kene of a firm. A radical innovation is represented by the attempt of an actor to experimentally try a new capability. An incremental innovation is modelled by decreasing or increasing one of the abilities by one.
(3.) Finally, a firm may gain new knowledge by starting a cooperation with another actor and mutually exchange bits of knowledge.

Dynamics in the Knowledge Space

The dynamics created by this model of creation and using knowledge requires an in depth analysis. First of all, we can state that the model conceives knowledge in a recombinant way. Knowledge is displayed as single knowledge units, whereas firms have to find the right combination of units to successfully stay in the market in order to survive. In more detail, every combination of knowledge bits (which we call Triples constituted by a capability, an ability and an expertise level) defines a certain product and product quality. As a consequence there exist many different combinations which may lead to the same product. This reflects the observation of pronounced technological heterogeneity among firms even within a single industry. The creation or the discovery of new knowledge is driven by the market-oriented firms which try to improve their market shares with the help of innovation: the dynamics of knowledge creation is endogenous.

Confronted with our goal to model demand effects in the innovation processes, there are still a few shortcomings which have to be mentioned: First, the possible knowledge space is defined ex ante by the modeller. Every possible knowledge unit is created during the simulation initialisation and as a result firms only move through a fixed space of possibly knowledge units, searching for ex ante defined combinations, which lead to satisfying reward. Second, the only connection between the knowledge units is the mapping function which determines the respective product category. If a firm engages in R&D to innovate radically, it will acquire one of the units of the knowledge space. There exist no differences in terms of probability which unit the firm will learn in dependence to the already attained knowledge. If we look closer at the mapping function itself, another aspect becomes evident. If a firm innovates incrementally or radically, again, there is a more or less uniform distribution of probability which new product the firm will likely discover. This representation of research and development of firms as a random walk in a multidimensional knowledge space can be considered as a compromise between KISS and KIDS modelling strategies. On the one hand, real innovation processes are characterized by more path dependencies which might shape the search behaviour. On the other hand, however, such a detailed representation would also increase the computational intensity and thereby intensively also extend the time to perform experiments. As the focus of our model will be on the interactions between demand and supply side in innovation processes we decided to accept this level of simplification for the beginning.

The next question addresses the dynamics in terms of knowledge creation and the innovation process of firms depending on market conditions. Let´s say there are 20 firms competing on a market with a uniform distributed demand for 10 products. If we further assume that all firms are equipped with the same capabilities and abilities and a uniform distributed expertise level, all firms start with the same product but different product qualities. In the next period firms with a high product quality will not engage in R&D, firms with a medium level of quality will try to innovate incrementally and firms with a low product quality will engage in radical R&D. As a result, most of the firms will scan the knowledge space randomly in order to achieve sufficient rewards. In later periods, if the number of firms is high enough or the respective knowledge space and market small enough, the previously defined knowledge space will be completely discovered. In such a situation some firms will achieve satisfying profits and only adjust their expertises while some other firms will randomly scan the knowledge space unable to find profitable knowledge combinations.
A potential political intervention focusing on the demand side would lead to a modification of the reward landscape of the firms. The firms then have to restart their search processes in order to detect the new most promising i.e. rewarding knowledge combinations. From this follows that the representation of a fixed knowledge space and the search behaviour of firms lead to some limitations in cases of large firm populations and relatively small knowledge spaces. Depending on the experiments this limitation has to be taken into account e.g. by allowing for interdependencies among knowledge units and an endogenous mechanism to extend the knowledge space in cases a certain percentage of available knowledge already has been discovered.

Knowledge Landscape and Demand
The firms undertake their search processes in order to explore the multidimensional knowledge landscape on which potential rewards are defined by the needs and wants of the consumer population. Changes in the preferences and the consumption behaviour will lead to modifications of this reward landscape. The knowledge of firms represented by the kenes is used as coordinates of single rewards which are to be discovered. The needs and wants of the consumers will be used to determine the height of the rewards.

Conclusions and perspectives
In an agent-based model of innovation and demand we represent knowledge as an emergent property of individual and interacting firms, where the complexity of knowledge creation and

technology is endogenous. By taking into account the demand side the development of knowledge on the micro as well as the macro level will be determined by the needs and information of consumers as well as the innovation, learning and knowledge exchange processes on the supply side. The agent-based modelling approach will hereby allow us to overcome the so far needed simplicity of standard neoclassical models. In more detail, the model will entail heterogeneous actors autonomously acting and interacting in a knowledge driven environment.

Considering the inherent complexity of a model facing the rich dynamics involved, it becomes clear that a systematic course of actions is of vital importance. To begin with, an appropriate technological environment where firms can act and interact based on their profit oriented innovative behaviour is needed. The SKIN model is a good start but it still lacks some important aspects relevant in the case of the interaction of demand and supply side in innovation processes. To display the complex dynamics the representation of knowledge needs to be refined. In particular, further improvements have to be achieved on the mechanism which translates the needs and wants of consumers represented in their knowledge base into product attributes which can be targeted in the search process of the companies.

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