THE ROLE OF EXTERNAL KNOWLEDGE IN THE INTRODUCTION OF PRODUCT AND PROCESS INNOVATIONS[1]

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ABSTRACT

This paper contributes a novel approach to appreciating the role of external knowledge in the innovative process based upon the notion of knowledge generation function. In so doing this paper impinges upon the rich literature on spillovers and yet introduces a sharp discontinuity that highlights the role of external knowledge as a necessary and costly input into the generation of new technological knowledge. It attempts to identify the contribution of external knowledge directly to the generation of technological innovations and to explore the matching between kinds of technological innovations that are introduced according to its sources. This approach enables to avoid the systematic confusion between the effects of external knowledge upon knowledge exploitation and its effects on knowledge generation and is able to assess more directly and specifically the role of horizontal and vertical flows of external knowledge on both the rate and the direction of introduction of new technologies. The results of the empirical investigations confirm that external knowledge is a crucial input into the generation of new technological knowledge and in the eventual exploitation to introduce technological innovations. Moreover it shows that external knowledge generated by upstream suppliers and flowing vertically, embodied in capital goods, within interindustrial filieres, plays a strong and positive role on the introduction of process innovations, while external knowledge that flows horizontally from competitors has stronger effects on the introduction of product innovations.

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1. INTRODUCTION

This paper contributes the novel approach to appreciating the role of knowledge spillovers in the knowledge generation process as distinct from knowledge exploitation. It articulates the need to substitute the notion of technological spillovers with the notion of external knowledge and attempts to identify the contribution of external knowledge directly to the generation of technological innovations and to explore the matching between types of innovations and sources of spillovers. This approach enables to appreciate the effects of external knowledge upon the actual introduction of technological innovations disentangling them from the concurrent effects of the exploitation process. The latter is influenced by the conditions of product and factor markets.

This approach enables to better understand the types of bias that the sources of external knowledge exert on the composition and direction of technological change. In so doing it contributes the new line of analysis in the rich literature on spillovers that is able to assess more directly and specifically the role of technological spillovers in the introduction of new technologies.

So far most studies on the role of technological spillovers in the innovation process have implemented indirect approaches, as opposed to direct ones. We can group such indirect studies in two waves. The first, paved by the pathbreaking contributions of Zvi Griliches, explored and assessed empirically the contribution of technological knowledge spilling from third parties to the growth of the output of firms, industries, regions and countries. The second wave of contributions investigated the role of technological spillovers in the increase of labor and total factor productivity. All these papers try and identify the effects of external knowledge spilling from third parties, including other firms as well as research institutions and universities, on the economic performances of the firms able to take advantage of them, rather than on their innovative performances.

The focus on economic performances as distinct from innovation performances moreover could not take into account the specific effects of the knowledge exploitation conditions, as distinct from the knowledge generation conditions. This approach, moreover, was bound to assume the neutrality of spillovers effects upon the composition of technological changes introduced by firms that could rely upon them. The indirect approach inhibited the investigation of the bias exerted by spillovers upon the typology of innovations and the existence of a match between the different sources of technological spillovers and the typology of innovations whether product or process.

This paper focuses directly the generation of technological innovations as the result of a specific activity into which knowledge, external to each firm, spilling from other firms plays a central role. We claim that this focus of the analysis enables to better grasp the role of technological spillovers, as it provides a direct observation of the role of technological knowledge external to each firm without the interferences brought about by the contextual changes in product and factor markets that induced the introduction of technological innovations, Such interferences consist also in the changes in the organization of the production process and in the direction of technological change that are associated with the actual introduction of new technologies supported by external knowledge. This direct approach enables also to identify the role of external knowledge, articulated according to its different sources, in the introduction of technological innovations, articulated in product and process innovations, without the significant interferences of the conditions that affect the exploitation of technological innovations that rely upon external knowledge (March, 1991).

The rest of the paper is organized as it follows. Section 2 articulates a critique of the objects of analysis so far considered in the empirical endeavour of identification of the contribution of technological spillovers, presents the general theoretical framework on the role of external knowledge and elaborates the research strategy of the empirical analyses. Section 3 presents the analytical model and the methodology for the empirical investigation, including the data sources. Section 4 presents the results of the empirical analyses. The conclusions summarize the results and outline the main implications of the analysis.

2. THE THEORETICAL FRAME

2.1. THE LIMITATIONS OF THE EMPIRICAL EVIDENCE ON KNOWLEDGE SPILLOVERS.

The limitations of technological knowledge as an economic good in terms of non-appropriability, non-divisibility, cumulability and complementarity and the consequent incentives mismatch, market failure and ensuing undersupply, highlighted by Joseph Schumpeter and elegantly framed by Kenneth Arrow, have been for quite a long time a basic pillar in the economics of innovation. Zvi Griliches (1979, 1992) brought about a major discontinuity with the identification of the positive effects of non-appropriability, in terms of technological spillovers. Other firms can take advantage of the non-appropriability of technological knowledge.

The path-breaking contributions of Griliches pave the way to a new approach where technological knowledge spilling from one firm in the atmosphere contributes the technological advance of other firms. External technological knowledge has been viewed as an augmenting and facilitating factor in the introduction of technological innovations. Such a role has taken the form of a 'technological' externality, that is an unpaid production factor that enters freely into the production function of other firms.

Only in a second phase it has been understood that external technological knowledge does not spill freely in the atmosphere. Relevant search, absorption, and assimilation costs should be taken into account (Cohen and Levinthal, 1989 and 1990). This has led to the identification of a knowledge generation activity into which external technological knowledge becomes an indispensable input as well as the specific skills and competence of firms.

Technological spillovers have been the object of a rich and detailed array of empirical studies that confirm their pervasive role in favoring the economic performances of firms such as output, employment, labor productivity and total factor productivity. The literature has interpreted these empirical findings as a reliable clue to assessing the positive effects of technological spillovers upon the rate of introduction of technological changes by firms able to use external knowledge as an input in their own innovation process.

As a matter of fact the relationship that has been investigated is indirect rather than direct. Between the assessment of the effects of technological spillovers on the economic performances and the effects of technological spillovers on the actual innovative performances there is in fact an important filter that seems necessary to unveil and explore systematically. The exploration of the direct relationship between technological spillovers and innovation performance can help overcoming the second main limitation of indirect estimates that is the poor appreciation of the bias in the types of innovation being introduced with the support of external knowledge and the matching between types of spillovers according to their sources and types of innovation, whether product or process.

This literature has been often and sequentially reviewed by critical surveys that provide a masterly and systematic assessment of the many detailed empirical studies on the many facets, origins and destinations of the relationship between technological spillovers and the economic performances of the firms that confirms the depth and foresight of Zvi Griliches's intuitions and early empirical analyses (Mohnen, 1996; Feldman, 1999; Verspagen and De Loo, 1999; Breschi and Lissoni, 2001; Link and Siegel, 2007; Ozman, 2009).

We do not intend to review, again, this literature, but to highlight the shifting framework of analysis from: a) the original approaches based upon a standard production function that integrates explicitly the role of technology and specifically external technology as an externality augmenting the production of output of all the other goods, b) through the analyses of the efficiency effects of external knowledge still as an augmenting factor in the production of other goods based upon the notions of labor and total factor productivity. This two steps and the understanding of their limitations have opened the way to a third shift that is characterized by the passage from external knowledge as an externality to the production of goods to external knowledge as an indispensable input in a knowledge generation function into which external as well as internal knowledge are considered. In this third step the analysis of the effects of external knowledge are conducted directly upon the generation of technological innovations and knowledge.

Technological spillovers and output growth

As anticipated in the introduction, the original core of the first two waves of studies focuses the relationship between technological spillovers and the economic performances of the firms able to take advantage of them as a mean to assess indirectly the effects of technological spillovers on the actual introduction of innovation.

The first group of empirical studies attempts to identify the contribution of external knowledge spilling from one firm to another within the framework of the standard production function applied to the products of the firms. In this approach the efforts are directed to appreciating the contribution of external knowledge to the current output of the firm, as measured in terms of sales or value added. The empirical findings based upon this approach have indeed identified the positive effects of technological spillovers on the economic performances, yet their interpretation as a proper indicator of the effects of technological spillovers on the innovation performance suffers from a number of limitations (Jaffe, 1989; Audretsch, Feldman, 1996).

First and most important the studies based on the assessment of the output effects of technological spillovers are not able to take into account the context into which the introduction of new technologies takes place and their dynamics. As soon as we retain the Schumpeterian notion of innovation as a form of reaction to unexpected changes in product and factor markets, it becomes immediately evident that the actual effects of the introduction of innovation can be much larger than the growth of output. The introduction of innovations in fact enabled firms to contrast the reduction in output stemming from either the increase in factor costs or the entry of new competitors based in cheaper factor markets, or the introduction of technological innovations by new competitors and the combined effects of all such events. Empirical studies focusing the correlation between the access to external knowledge and the increase in output in other words are not able to account for the full array of positive consequences as they cannot appreciate the effects of the non-introduction of technological innovations. In a turbulent and changing market not having its output reduced might already be the positive outcome of a firm's innovative strategy.

Second, and more specifically, the empirical studies that use sales as a measure of output (O'Mahony and Vecchi, 2009) miss to appreciate the effects of the new technologies introduced with the support of technological spillovers on the vertical organization of the production process and hence on the changing role of value added. For the same token, the studies that rely upon employment as a measure of output (Hollanders and Ter Weel, 2002) fail to consider the direction of technological change being introduced in terms of bias towards more or less capital intensive techniques.

Thirdly and more importantly, these empirical studies mix up the effects of external knowledge upon knowledge generation with the consequences of external knowledge upon knowledge exploitation. These studies, in other words, fail to identify the (well-known) negative effects of technological spillovers on knowledge appropriability. Firms that do rely upon external knowledge spilling more or less freely in the atmosphere in their effort to introduce new technologies are quickly imitated and can appropriate the economic benefits of their innovation for much a shorter time span. Both the duration and the levels of the mark-ups associated with the introduction of the new technologies generated by taking advantage of quasi-public knowledge and the increase in output and market share are lower than in the case of new technologies generated in-house with a strong command of proprietary knowledge. In this latter case the generation of technological knowledge may be lower, but the exploitation much more successful.

Technological spillovers and productivity growth

The studies that focus on the relationship between technological spillovers and labor productivity are biased by the direction of technological changes being introduced. Minor capital intensive innovations risk to be appreciated more than many labor intensive ones. It is evident in fact that the introduction of capital intensive technologies has a strong and direct impact on labor productivity that is poorly related with the actual relevance of the flow of technological innovations. Once again, it seems clear that the use of results of the estimates of the relationship between technological spillovers and economic performances as an indirect way to assess their effects on the actual performances in terms of innovativeness are severely undermined by the array of concurring economic and technological factors that are associated with the inducement, the exploitation and the intrinsic characteristics of the innovation process.

These drawbacks affect quite systematically the empirical investigations that have used total factor productivity as the dependent variable in modelling the attempt to assess the contribution of technological spillovers. In a second wave of empirical enquiries about the role of technological spillovers in fact total factor productivity has been focused as the relevant object of analysis. Clearly the new approach enabled to exclude a number of spurious elements stemming from the dynamics of local growth and the related changes in factor and product markets that prevented the correct identification of the actual effects of technological spillovers (Cuneo and Mairesse, 1984).

Yet, these studies are not able to distinguish between the positive and the negative effects of the non-appropriability of technological knowledge that are associated with the use of technological spillovers in the generation of new technological knowledge. The negative effects of the low appropriability of technological knowledge in terms of reduced opportunities for the exploitation of the stream of benefits associated with the introduction of new technologies are well known since the early Schumpeterian writings. The entry of imitators squeezes and shortens the transient monopoly rents of innovators. The market prices of both new products and old products manufactured with new processes, new organization methods and new inputs, or delivered in new product markets, fall all the faster, the less proprietary is the knowledge it impinges upon. Once again these studies risk confusing the positive effects of technological spillovers upon the generation of technological knowledge with their negative effects upon its exploitation conditions. The reduction of transient monopoly rents impacts directly on the quantification of both output and total factor productivity measures (Antonelli, Patrucco, Quatraro, 2011).

It is not surprising that Crepon, Duguet and Mairesse (1998) can show the substantial coherence and consistency of these different approaches to assessing empirically the effects of technological spillovers upon the economic performances of their users: they are consistent because they rely upon the economic performances of the firms as a proxy of their innovative performances. The conditions for the exploitation of technological innovation are a source of major interferences and bias in the appreciation of their actual introduction.

The indirect research strategy on the role of technological spillovers suffers from a second source of limitations: the missing appreciation of the possible bias that external knowledge exerts upon the innovation activity and consequently the missing appreciation of the differentiated effects that different sources of external knowledge may exert on the different baskets of innovation being introduced.

The assessment of the effects of technological spillovers on the economic performances of the users of external knowledge as an indirect clue of their actual effects on the innovation performances has inhibited the exploration and identification of the specific kind of such effects.

It is time to integrate this literature with a direct analysis of the effects of external knowledge upon a knowledge generation function and hence upon the innovation performances of firms (Nelson, 1982; Acs, Audretsch and Feldman, 1992; Audretsch, Feldman, 1996).

2.2 THE GENERAL HYPOTHESES ON THE ROLE OF EXTERNAL KNOWLEDGE IN THE INNOVATION PROCESS

The identification of the knowledge generation function as a specific and dedicated economic activity into which knowledge is at the same time an output and an input enables a major shift in the appreciation of the role of external knowledge to assessing firms' innovation performances (Nelson, 1982; Adams, 1990; David, 1993; Weitzman, 1996 and 1998).

In the preceding stream of literature, based upon the notion of technological spillover, which ideally dates back to the marshallian concept of technological externalities, external knowledge is still conceived as an unpaid factor spilling freely in the atmosphere (Scitovsky, 1954). It is supposed to enter the production function of firms that share some degree of proximity, be of geographical, relational and cognitive nature. The access to such knowledge externalities does not require any interaction between the producers and the recipients of the external effects or dedicated and intentional efforts: technological spillovers are considered a characteristic of the 'atmosphere' of the districts, or industrial areas, into which firms are based into that benefit passive recipients. Moreover, external knowledge is not considered as a necessary and indispensable production factor, but rather as a supplementary input that helps increasing the output, but that can be dismissed.

The new approach, well operationalized by the open innovation paradigm, stresses the importance of external knowledge from quite a different perspective. In this approach the knowledge generation function is identified as a specific economic activity. External knowledge is a necessary and indispensable input into the generation of new technological knowledge. The users can access external knowledge only as a result of dedicated activities (Chesbrough, 2003; Chesbrough, Vanhaverbeke and West, 2006).

Here firms can exploit external knowledge only through the accurate planning of a strategy aimed at acquiring bits of knowledge that are complementary to their own competences. In this perspective external knowledge, as a necessary input into the generation of new technological knowledge is acquired at costs that include a variety of efforts and dedicated activities such as the screening, identification, interaction and purchase, and eventual absorption (Cohen and Levinthal, 1989 and 1990). When the characteristics of the system into which each firm is embedded are fertile, such costs happen to be below equilibrium levels and firms enjoy pecuniary knowledge externalities. In this approach the system-level and the firm-level characteristics are taken into account in a unique theoretical framework, in which the complex dimension of the system and the recombinant features of knowledge play a central role (Antonelli, 2008b).

The knowledge generation function qualifies and integrates the standard production function. Both are necessary to grasp the decision-making and the performances of the firm. Firms try and activate the knowledge production function when un-expected events take place in product and factor markets in order to face them by means of the introduction of technological and organizational innovations. The eventual reaction of firms to the changing condition of their economic environment can be either adaptive or creative, following Schumpeter[2] (1947). Reaction can be simply adaptive and consist just in traditional price/quantity technical (as opposed to technological) adjustments when firms are not able to generate appropriate amount of new technological knowledge and cannot actually innovate. For given levels of internal efforts, appropriate structural and institutional characteristics of the

[2] Schumpeter (1947) makes the point very clear: "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).

system qualify the reaction of firms and make it actually creative favouring the introduction of productivity enhancing innovations. Innovations are the result of the creative reaction of firms that emerge when external knowledge is actually available.

Many factors concur to the necessity by firms to introduce a coherent strategy in order to access external knowledge. First of all the nature of knowledge itself: knowledge is at the same time the output of a specific activity and an essential input into the generation of new knowledge. Because of knowledge indivisibility and, specifically, because of synchronic knowledge complementarity, the access to existing knowledge, at each point in time, is a condition necessary for the generation of new knowledge. The non-exhaustibility of knowledge favours repeated uses even beyond the original frame of application (Nelson, 1959). Technological knowledge is viewed as the product of recombination of existing ideas. The generation of new knowledge stems from the search and identification of elements of knowledge that had not been previously considered and their subsequent active inclusion and integration with the pre-existing components of the knowledge base of each firm (Fleming and Sorenson, 2001; Arthur, 2009).

The organization of the system plays a key role as it shapes the access to external knowledge. When the role of the external context is properly appreciated, it becomes clear that innovation is not only the result of the intentional action of each individual agent, but it is also the endogenous product of dynamics of the system. The organization of the system in terms of access conditions to the external pool of technological knowledge is the crucial and complementary ingredient, together with the quality and intensity of internal research efforts, that explain the emergence of innovations (Lane, 2009).

The notion of generative interactions plays a central role in this approach (Lane and Maxfield, 1997). The amount of knowledge externalities and interactions available to each firm influences their capability to generate new technological knowledge, hence the actual possibility to make their reaction adaptive as opposed to creative and able to introduce localized technological changes. When the access conditions to the local pools of knowledge make possible the actual generation of new technological knowledge and feed the introduction of innovations, actual gales of technological change may emerge. The wider is the access to the local pools of knowledge and the larger is the likelihood that firms are induced to react (Page, 2011). The larger the number of firms that react and the better the access conditions to external knowledge and the stronger are the chances that their reaction are creative: technological change becomes a generalized and collective process (Arthur, 1990, 1994 and 2009).

According to the structural conditions of the system into which firms are embedded the actual access to external knowledge differs: there are conducive contexts characterized by strong knowledge connectivity levels and high quality knowledge governance mechanisms and contexts into which the recollection and utilization of external technological knowledge is difficult because of poor knowledge governance mechanisms. The availability of external knowledge reflects the quality of the governance mechanisms and of the levels of knowledge connectivity of the system into which firms are localized (Nelson, 1993; Quatraro, 2009a and 2009b).

Agents succeed in their creative reactions when a number of contingent external conditions apply at the system level. Innovation is the result of the collective economic action of agents: "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).

More specifically, innovation is an emergent property that takes place when complexity is 'organized', i.e. when a number of complementary conditions enable 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 change and lead to endogenous structural change (Anderson, Arrow, Pines, 1988; Arthur, Durlauf, Lane, 1997; Lane, 2009).

In order to access the local pools of external knowledge, firms, cannot rely on automatic mechanisms. They must command specific competences within their own boundaries to actually access external knowledge. They need to invest dedicated resources on the establishment of specific channels of communication with the intentional purpose to access external knowledge external knowledge. Such capability of being "open" to external sources of knowledge, through the acquisition of external R&D, or through cooperation agreements with customers or suppliers, will create some sort of absorptive capacity (Cohen and Levinthal, 1989, 1990), which will alter the influence of the local pools of external knowledge on the innovative performances of firms.

A growing empirical evidence spanning from the economics of innovation to R&D management confirms that the interactions with users, suppliers, and institutions of various kind contribute substantially to the firms' innovative performances (Cassiman and Veugelers, 2006; Von Hippel, 1988), as well as the outsourcing of specific parts of R&D activity, or even the acquisition of firms, able to bring new specific knowledge within the firm's boundaries and to widen its competences (Howells, Andrew and Khaleel, 2003). According to the open innovation literature (Dahlander and Gann, 2010), firms that rely only on internal resources and in-house R&D, instead, miss important opportunities that fall outside "the organization's current business or will need to be combined with external technologies to unlock their potential" (Chesbrough, 2003; Von Hippel, 2005; Gassmann, 2006).

The analysis of the modularity and complementarity of knowledge, contributes to understanding the need to implement the firm's specific core-competences with bits of external knowledge able to contribute the introduction of innovations (Levin, Klevorick, Nelson and Winter, 1987). The evidence concerning the continuous evolution of the knowledge base of knowledge intensive industries, through the inclusion of different and complementary pieces of knowledge (Kraft, Quatraro, Saviotti, 2009; Quatraro, 2010), further confirms the need for firms to have access to specific –as opposed to generic- new pieces of knowledge. Also the increasing levels of specialisation, together with the shortening of the product cycle times and the growing disciplinary heterogeneity required to generate new knowledge, contribute the need for firms to establish dedicated channels of knowledge acquisition (Howells, James and Malik, 2003).

The empirical evidence at the aggregate level confirms the growing importance of external knowledge: in OECD countries the share of business expenditure on external R&D has increased since the 1980s (Vega-Jurado, Gutierrez-Gracia and Fernandez-de-Lucio, 2009) and so has the number of inter-firm partnerships and acquisitions (Desyllas and Hughes, 2010).

Building upon these underpinnings and following Nelson (1982) and Weitzman (1996 and 1998) we can specify a knowledge generation function. External knowledge is the qualifying input, together with internal knowledge obtained by means of research and development activities and the valorization of learning processes. External knowledge is a non-disposable input, for nobody can command all the knowledge available at any point in time. External knowledge has been generated in previous periods, it is available in the system, it can be accessed by means of knowledge interactions cum knowledge transactions and re-used as an input. Internal and external knowledge are complementary inputs that have to be combined in order to produce new technological knowledge.

In our case, the generation function of technological knowledge for each firm i can be written as follows:

(1) $KN_i = (IK^a , EK^b)$ with $a+b =1$

where KN represents the new technological knowledge that enables the firm i to introduce technological innovations generated with constant returns to scale by means of internal knowledge (IK) and external knowledge (EK).

Internal knowledge is the result of research and development activities as well as of all the efforts that are necessary to valorising the competence that relies upon learning processes. External knowledge does not spill freely in the atmosphere: its identification, access and use require dedicated activities. The recombination of external and internal knowledge in turn is a distinctive activity that impinges upon dedicated competence and capabilities that are specific and idiosyncratic to firms. The actual access to existing external knowledge stems from the intertwined combination of the idiosyncratic characteristics of each agent in terms of openness and receptivity and the structural characteristics of the system into which firms operate in terms of thickness and viability of knowledge communication flows. Firms differ in their ability and willingness to take advantage of existing external knowledge, as much economic systems into which firms are embedded in terms of the structure and viability of knowledge communications flows that make it possible to access the existing external knowledge.

This interpretative framework enables to substantiate the view that the generation of technological knowledge and the introduction of technological innovations is actually endogenous: it does not fall like manna, it is not the exclusive result of neither the heroic behavior of 'supermen' called entrepreneurs, nor the spontaneous given of 'lucky, atmospheric' conditions. It does not take place automatically and spontaneously at all times and in all locations. It is the emergent property of a complex system as it result of the interaction between individual action and systemic conditions as it impinges upon both the specific intentional activity of each agent characterized by its idiosyncratic characteristics, among which those that consent the access to external knowledge, and the characteristics of the system such as the architecture of knowledge interactions and transactions that shape the flows of external knowledge. The appreciation of both the individual and systemic characteristics are necessary to identify the actual chances of agents to implement their reactions, actually generate new technological knowledge, introduce innovations and implement a creative conduct, as opposed to adaptive (Blume, Durlauf, 2001 and 2005; Antonelli, 2011).

2.3 RESEARCH STRATEGY

Our theoretical framework stresses the central role of the availability and access conditions to external knowledge as key conditions to make the reaction of firm actually creative, as opposed to adaptive. Firms cannot generate new technological knowledge in isolation. Not only the amount and the relevance of the innovations being introduced at each point in time depend upon the access conditions to external knowledge, but also their characteristics. The rate and direction of innovations introduced by each firm is influenced by: i) its proximity to other innovators within the same industry that qualifies the chances to accessing and using their knowledge, and ii) by its position, into the vertical filieres that relate users to producers, that qualifies the access to external technological knowledge embodied in capital and intermediary goods.

The direct analysis of the role of external knowledge in the generation of new technological knowledge and in the introduction of technological innovations, not mediated by its exploitation conditions in product markets, is necessary to investigate these aspects. Our approach leads us to select a direct measure of the innovative activity of each firm as the key dependent variable in a modelling approach where, together with internal research efforts, external knowledge is a key independent variable.

Moreover a direct analysis of the role of external knowledge upon the innovative performances of firms, as distinct from their economic performances, enables to explore its effects on the direction of technological changes being introduced. This is an important aspect that has been left un-explored. It seems important to try and understand whether external knowledge favours the introduction of a specific kind of technological innovation according to its sources. This amounts to explore whether external knowledge exerts specific bias on the characters of technological innovations being introduced by firms that rely on it, according to its sources, whether horizontal among competitors or vertical within industrial filieres.

It seems relevant and useful to try and understand whether the reliance on external knowledge is neutral with respect to the kind of technological innovations being introduced or on the opposite the different sources of external knowledge have discriminatory effects on the typology of innovations. The distinction between vertical and horizontal flows of external knowledge seems most important.

Vertical flows of external knowledge stem from user-producers interactions along vertical interindustrial filières. Horizontal flows of external knowledge are found within the same industry and consist in the reciprocal borrowing and use of technological knowledge produced by each competitor able to imitate and implement the innovations introduced by the other firms engaged in the same innovation race. The external knowledge that flows vertically within upstream producers should mainly favour the introduction of process innovations as user-producer interactions are the main locus of the generation of technological knowledge. For the same token the horizontal flows of external knowledge among competitors within the same product markets would favour mainly the recombinant generation of product innovation.

TABLE 1. THE MATCHING BETWEEN SOURCES AND FLOWS OF EXTERNAL KNOWLEDGE AND TYPES OF INNOVATIONS

VERTICAL FLOWS OF EXTERNAL KNOWLEDGE	PROCESS INNOVATIONS	
HORIZONTAL FLOWS OF EXTERNAL KNOWLEDGE		PRODUCT INNOVATIONS

This hypothesis is quite important for its implications at the system level. If confirmed by the empirical evidence it would allow to understand the specific form of bias in favor of either process or product innovations that takes place at the system level, when firms innovation processes relies systematically upon the use of external knowledge as an input into the generation of new technological knowledge. In countries where the vertical flows of external knowledge are stronger than the horizontal ones we should in fact find a prevalence of process innovations and *viceversa* (Laursen and Salter, 2006).

3. EMPIRICAL INVESTIGATION

3.1. THE MODEL

We want to specify a knowledge generation function which takes into account the importance of the firm's own investments in R&D, the influence of the R&D performed by the companies active in the firm's own national sector and the contribution of suppliers, via the acquisition of machinery. We assume that each firm has a knowledge generation function of the following kind:

$$KN_i^s = R\&D_i{}^{\alpha}\ VERTICAL_i^{\beta}\ HORIZONTAL_j{}^{\gamma} \qquad (2)$$

Where $i = 1, \dots, N$ (num of observations)
and $s = PRODUCT\ INNO,\ PROCESS\ INNO,\ INNOVATION$

$PRODUCT\ INNO_i$ and $PROCESS\ INNO_i$ indicate the introduction of respectively product or process innovations by firm i, while $INNOVATION_i$ stands for the introduction of either one of the two or both of them. $R\&D$ stands for the flow of investments in R&D (either performed or bought) over total sales (R&D intensity). The variable $VERTICAL$ stands for the knowledge provided by the upstream producers, proxied by the share of firm's own expenditures in machinery and equipment on sales, it is hence firm-specific. The $HORIZONTAL$ variable instead measures the external knowledge coming from the industrial environment in which the firm is embedded, proxied by the sum of expenditures in in-house R&D of all the firms in its own sector, hence an industry-specific variable. More specifically:

$$HORIZONTAL_j = \sum_i INT\ R\&D_{ij}$$

and $j = sector\ of\ firm\ i$

Following Griffith et al. (Griffith, Harrison and Van Reenen, 2006) our assumption is that the degree of influence of the external stock of knowledge on firm i depends from the firm-specific degree of openness of the firm to external knowledge, which we indicate as O and which is proxied by the propensity to engage in extramural R&D expenditures (R&D bought from external partners).

$$\gamma_i = \pi\, O_i \qquad (3)$$

Taking logs in equation (2) we have that:

$$kn_i^s = \alpha\, r\&d\ int_i + \beta\ vertical_i + \gamma\ horizontal_j \qquad (4)$$

where lower case letters stay for logs. Hence, substituting (3) in (4) we obtain our equation to estimate:

$$kn_i^s = \alpha\, r\&d_i + b\ vertical_i + \pi\left(horizontal_j * O_i\right) + \delta x_i + u_i \qquad (5)$$

Equation (5) allows us to estimate the direct effect of the investments in R&D performed by the single firm on the generation of knowledge. It also highlights the importance of the link with upstream suppliers (proxied by ratio of expenditures in machinery on total sales) and finally gives a measure of the external knowledge coming horizontally from the industrial environment in which the firm is embedded. Our assumption is that the appropriation of the horizontal flows of external knowledge is filtered by the degree to which a firm is opened towards external knowledge. The measure of openness is proxied by the propensity to engage in extramural R&D expenditures. The x variables are usual controls for firm size and for sector and country effects, while u is an idiosyncratic error term.

3.2. DATA AND METHODOLOGY

Data

We use Eurostat's Harmonized Community Innovation Survey 4 data[3], which refer to the period 2002-2004; the great advantage of this harmonized database is the possibility to treat together firm data from the same wave of the CIS, but for different countries, something which was hardly possible until few years ago. We hence pooled in a unique database all the firms which answered the questionnaire from 6 countries and from all the manufacturing sectors. The countries are Belgium, Czech Republic, Germany, Italy, Norway and Spain

Furthermore the CIS database is suitable for our analysis since it allows to account both for the introduction by the firms of our chosen measures of innovation and for the expenditures in R&D. Each firm in fact must declare whether it has introduced at least one product or process innovation in the time-span covered by the survey. We hence have a dummy variable for the introduction of process innovation, another dummy for the introduction of product innovation and we are able to build a third dummy for the introduction of at least one of the two types of innovation. The R&D variable and the measures of both flows of external knowledge are taken from the expenditures in intramural and extramural R&D declared by the firms surveyed in the CIS4[4]. In order to build the proxy for the horizontal flows of external knowledge for each firm, we summed up all the expenditures in R&D for each national sector and obtained the overall

[3]The data have been released by Eurostat in micro-aggregated form, for confidentiality reasons. Further details on this procedure are provided in Appendix B.
[4]Since the cross sectional nature of our data does not allow us to build stocks, all our R&D variables are flows, they refer to the expenditures in R&D performed by each firm in 2004.

amount of R&D in the sector. Then, we also computed the average level of R&D for each sector by dividing the total sum of R&D by the number of firms in each sector. The measure of the vertical flows of external knowledge, which is firm-specific is instead proxied by the expenditures in machinery acquisition by each innovating firm.

Our database is hence composed of all the firms who answered the CIS4 survey in the 6 chosen countries. After some necessary cleaning procedures in order to eliminate outliers (see Appendix A) we ended up with 23,247 observations, which include both innovating and non-innovating firms. In Table (1) we present some descriptive statistics of the firms of our database.

INSERT TABLE 1 ABOUT HERE

Methodology

In order to estimate equation (4) our first problem consisted in the large number of firms who declare zero expenditures in R&D. This typical problem of censored distribution in R&D-based estimations is enhanced by the fact that in the CIS4 if a firm did not introduce any innovation in the reference period, it is not asked whether it had any expenditure in R&D. Furthermore we also hypothesize that it could be the case that innovative efforts are not always conducted through formalized R&D activity. We hence prefer to follow the strategy of Griffith et al. data (Griffith, Huergo, Mairesse and Peters, 2006) and focus rather on the innovative efforts of the firms. In such a way we will also be able to include in our analysis all firms of our database.

Our strategy is to introduce two decision equations: one for the intensity of internal R&D and another for the intensity of expenditures in extramural R&D. We want to identify the coefficients of the factors affecting this decision. In order to account for the large number of zeros in our R&D intensity equation, we adopt a Tobit type II estimation procedure, which means that we will implement two different equations: a selection equation for the decision whether to invest or not in R&D, in which the dependent variable is a dummy variable for the presence of continuous R&D activities

$$RD_i = \begin{cases} 1 \; if \quad rd_i^* = z_i^{'}\gamma + e_i > c \\ 0 \; if \quad rd_i^* = z_i^{'}\gamma + e_i \leq c \end{cases} \tag{6}$$

and an intensity equation in which the dependent variable (only observed when the selection equation is >0) is the (logarithm of the) intensity of the expenditures in R&D (R&D/total sales).

$$r_i = \begin{cases} r_i^* & if \; RD = 1 \\ 0 & if \; RD = 0 \end{cases} \quad \leftrightarrow r_i = \begin{cases} r_i^* = x_i^{'}\beta + \varepsilon_i & if \; RD = 1 \\ 0 & if \; RD = 0 \end{cases} \tag{7}$$

We assume that the error terms of the two equations are correlated. The adoption of the Tobit type II model allows introducing more independent variables in the intensity equation, for which we have more information.

After we estimated the coefficients of equation (7) we are able to predict the fitted values of the dependent variable. Hence we will have a value of the intensity of R&D for all the firms in our sample. As previously mentioned what we will be measuring will not be anymore the actual investments in R&D, but rather the intensity of the innovative effort. We will then introduce these predicted values into equation (5), where we check for the presence of flows of external knowledge[5].

Before going forward estimating equation (5) we still need to compute the degree of openness of each firm, that is its propensity to invest in external knowledge, proxied by the expenditures in extramural R&D (R&D bought by other partners). Again we follow a similar procedure as in equation (7). Since in the questionnaire firms are asked whether they have invested in external R&D only if they have innovated, if we took into consideration only declared expenditures we would risk to biasing our estimates. We hence prefer to introduce a specific equation to account for the decision whether to invest in external R&D or not. Hence O_i becomes a dummy variable equal to 1 if a firm invested in extramural R&D and equals zero otherwise.

$$O_i = \begin{cases} 1 \; if \quad O_i^* = m_i^{'}\delta + u_i > c \\ 0 \; if \quad O_i^* = m_i^{'}\delta + u_i \leq c \end{cases} \tag{8}$$

[5]The use of predicted values for R&D in the estimation of equation (5) will also avoid endogeneity problems, which are typically related to R&D variables. Indeed, especially in cross–sectional analysis, it is likely that R&D variables will be correlated with unobservable factors (such as the knowledge stock of a firm, or the quality of its labour units, or the efficiency of its management practices) which on their turn are correlated with the firms' ability to actually produce innovations. This would result in an upwards bias of the R&D variable, which, in our case, should be avoided.

We introduce a number of variables that are supposed to influence such a decision, then once we estimated our coefficients with a logit regression, we are able to use the predicted probabilities of investing in external R&D as proxies for the openness variable, thus obtaining a firm-specific variable. In such a way we overcome the problem of having data about external R&D only for innovative firms: we consider the predicted O_i as a general propensity to engage in external R&D.

Finally we are able to estimate equation (5) with three different proxies of knowledge creation: product innovation, process innovation or both of them. We estimate it with a logit model controlling for size, country and sectoral effects.

3.3. RESULTS

We first analyse the results of the Tobit II estimation of equation (7) in Table (2). Not surprisingly we find that the decision whether to invest continuously in R&D is positively related with the size of a firm, either this is measured in terms of sales or number of employees. We also find that issuing patents and competing in international markets positively affects such a decision, in line with previous studies on similar data (Griffith, Huergo, Mairesse and Peters, 2006). The results of the intensity equation, concerning the actual amount of expenditures in R&D confirms the importance of international competition and patenting activity and underlines also the importance of being part of a group: again this finding is quite in line with our expectations, since we assume that firms which are part of a group have greater financial means (Mohnen, Polder, Raymond and van Leeuwen, 2009) and can hence invest more in innovative inputs. As concerns the size we notice that the elasticity[6] of R&D to sales for the firms in our sample is about 0.72, which roughly means that to a one per cent increase in sales corresponds a 0.72 per cent increase in the firm's expenditures in R&D. Lastly we notice that firms who beneficiate from any

[6]The usual equation for the elasticity of sales to R&D is:
$\ln(R\&D_i) = \ln(sales_i)\beta + x_i^{'}\delta + \varepsilon_i$
where β is the elasticity of sales to R&D. Anyway in equation (6) R&D is measured as the ratio of R&D over sales. Thus we are actually estimating the following model:

$$\ln(R\&D_i/sales_i) = \ln(sales_i)(\beta - 1) + x_i^{'}\delta + \varepsilon_i$$

And hence in order to have β we need to add 1 to our estimated coefficient.

kind of fund for R&D activities tend to increase the intensity of their expenditures in innovation.

We then analyse the results of the logit estimation of equation (8), in which the dependent variable is the dummy variable indicating whether a firm has invested or not in R&D performed outside of the firm. Comparing these results with the previous estimation of equation (7), we notice that the size effect is weaker: once we account for size in terms of turnover, the employment dummies are not significant anymore. Competing in international markets and applying for patents are positively related with the purchase of R&D from external providers, but again the coefficients are substantially lower than in the case of the previous estimation. Conversely being part of a group is positive and significant also for the decision whether to invest in extramural R&D, while in equation (7) we found such variable to affect only the actual intensity of innovative expenditure and not the decision. In our estimation we included many of the variables of the survey for which we had information for all of the firms[7] (and not only from the innovators). Most of the variables used turned out to be significantly related with the investments in external R&D: the table with the total number of variables included is reported in Appendix A.

INSERT TABLE 2 ABOUT HERE

Having obtained the coefficients of equation (8) we are able to build a measure of the openness variable through the predicted values of the dependent variable: we hence obtain a useful weight, bounded between zero and one, which we multiply by the amount of R&D in the sector of belonging of each firm.

Finally we can introduce the measures of both flows of external knowledge in our main equation of interest, that is equation (4). In Table (3) we show the results obtained using both the overall sum and the average of intramural-R&D performed in a sector, as proxies of the stock of knowledge. In columns (1) and (2) the dependent variable is a dummy variable for the

[7] Indeed augmenting the number of regressors also allows us to increase the variability of the predicted values of the dependent variable, providing a thinner measure of each firm’s propensity to invest in exernal R&D.

introduction of at least one product and/or process innovation. The predicted R&D intensity is not surprisingly positive and significant, coherently with previous studies (Griffith, Huergo, Mairesse and Peters, 2006; Mairesse and Robin, 2009), the size effect, as measured by turnover, is also positive and significant, thus suggesting that larger companies tend to have a higher propensity to introduce product and process innovations. Also the purchase in the acquisition of machinery from upstream producers displays a positive and significant coefficient on the propensity to introduce innovation, thus highlighting the important role of vertical ties. The variable that proxies the horizontal flows of external knowledge, displays a positive and significant coefficient which confirms our hypothesis that the degree of openness positively influences the capability to access the knowledge stock in a sector. When we use the average level of R&D in a national sector as a proxy for the knowledge stock available the coefficient increases, thus providing confirmation of the role of the horizontal flows of external knowledge.

Our results become even more interesting when, in the following columns of Table (3), we distinguish between the introduction of product or process innovation. First of all comparing the two estimations we notice that the predicted intensity of R&D is more important for the introduction of product innovation and of lower relevance for the introduction of process innovations. Also the size effect is stronger for product innovation. Looking at the external knowledge variables, we notice that the external knowledge coming from the vertical/upstream linkages, proxied by the intensity of the expenditure in machinery, tend to favour process innovation, more than they do with product innovation. On the contrary we notice that the horizontal flows of external knowledge tend to increase product innovation, more than they favour process innovation. In both cases, anyway, the coefficient of horizontal flows of external knowledge is positive and significant.

INSERT TABLE 3 ABOUT HERE

Also when the horizontal flows of external knowledge are proxied by the average level of R&D in each sector (weighted by the degree of openness), rather than the simple sum, the results are robust to the new specification. The difference between product and process innovations becomes even more evident: indeed the coefficient displays a higher coefficient than in the previous specification in the product innovation knowledge equation, while in the case of process innovation the effect of the horizontal flows of external knowledge becomes smaller. The vertical flows of external knowledge coming through user-producer interactions are instead very robust to the use of the cumulated sum or the average levels of R&D and do not change the size and the significance of the coefficient, which remains higher in the case of process innovation.

4. CONCLUSIONS

The analysis of the knowledge generation process is taking the centre stage of the economics of innovation. Building upon the important acquisitions of the analysis of the characteristics of knowledge as an economic good, it is now possible to explore the economic activities that lead to its generation and eventual application with the introduction of technological innovations.

In this context the central role of external knowledge in the generation of new technological knowledge can be better appreciated and assessed. The notion of external knowledge can be considered as the result of a long process of analysis originated from the notion of limited knowledge appropriability, eventually implemented and elaborated into the notion of technological spillovers. External knowledge can be considered as a third step in this process: it differs sharply from the notion of technological spillovers. The latter refers to the supplementary role of knowledge spilling freely in the atmosphere. The latter appreciate its essential role as an indispensable input in the generation of new technological knowledge that firms need to access and use, at costs that may be lower than in equilibrium conditions in special and qualified systemic conditions qualified in terms of organized complexity.

Technological knowledge is the result of an economic activity characterized by strong systemic and processual elements. Technological knowledge, and consequently technological innovation, is an emergent property of the economic and institutional system into which innovators are embedded. As such it is the result of the interdependence between the action of individual agents and the structural characteristics of the system. It occurs when and if the structure of system into which firms are localized make knowledge interactions possible and provide access to the external knowledge that supports the reaction of myopic firms that try and cope with unexpected changes in product and factor markets. The access to external knowledge makes their reaction creative and enables the introduction of innovations. With poor knowledge interactions firms can cope with out-of-equilibrium conditions only by means of adaptive adjustments of prices and quantities.

No firm can generate the technological knowledge that is necessary to innovate, alone, in isolation. The access to external knowledge, knowledge generated and possessed by other firms and research institutions, is a necessary condition for the introduction of technological innovations. Each firm requires distinctive and specific competencies and capabilities to absorb the different kinds of external knowledge and recombine them with internal knowledge.

This approach calls for a direct assessment of the effects of external knowledge upon the innovation performances of firms, as distinct from their economic performances. The attempts to assess the effects of technological spillovers on such economic performances as the growth of output in sales, value added, employment, labor and total factor productivity offer only an indirect and biased clue of the role of external knowledge on sheer innovation performances as they are filtered by an array of complementary changes in labor and product markets as well as in the specific characteristics of innovating firms that rely upon external knowledge.

In this context it seems important to discriminate between sources of external knowledge, whether they flow vertically from upstream producers of capital and intermediary inputs to downstream users, or horizontally among competitors and to assess whether they favor respectively more process than product innovations.

Our empirical analyses have explored the direct effects of knowledge interactions and access conditions to external knowledge upon the actual amount of innovations introduced by European firms in 2004, as collected by the European Community Innovation Surveys. The dependent variable of our analysis has been the introduction of innovations, as well as, separately, the introduction of process and product innovations. In order to assess the role of the horizontal flows of external knowledge, as proxied by the flows of research and development activities performed by competitors, e.g. firms active in the same industry, have been filtered by the degree of openness to external knowledge as measured by the firm-specific propensity to invest in extramural R&D. Vertical flows of external knowledge have been appreciated taking into account the intensity of investment as a proxy of the amount of external knowledge flowing via user-producer interactions and embodied in the machinery purchased by downstream users.

The results confirm that external knowledge has a positive effect on the innovation performances of firms according to the degree of openness, as measured by the extent to which they are able to rely upon knowledge outsourcing. Moreover, the empirical evidence confirms that the intensity of investment of each firm, considered as a proxy of the vertical flows of external knowledge performed by upstream suppliers, embodied in capital goods and purchased by each downstream firm play a crucial role in determining the introduction of process innovation. External knowledge spilling horizontally from competitors instead has a stronger positive effect on the introduction of product innovations.

These results shed new light on the actual dynamics of knowledge externalities and stress the diversity of their effects whether they flow vertically along user-producers interactions associated with the adoption of new vintages of capital goods favoring the introduction of process innovations, or horizontally in innovation races enhancing the rates of introduction of product innovations. These results confirm the interest to go beyond the notion of technological spillovers and to explore more directly and more generally the role of external knowledge as a necessary input into the knowledge generation function that together with the production function qualifies the activity of each firm.

Table 1. Descriptive statistics

Variables	Mean (1)	Median (2)	St. dev. (3)
Firm level variables			
R&D intensity (logs)	-1.618	0	2.302
Predicted R&D intensity (logs)	-5.122	-5.164	0.833
Investment Intensity (logs)	-9.348	-11.51	3.381
Turnover in 2004 (logs)	15.59	15.36	1.793
Openness (predicted values)	0.176	0.099	0.196
Openness* sum of sectoral R&D (logs)	3.287	1.757	3.876
Openness* average sectoral R&D (logs)	2.260	1.173	2.775
size (employees): 50 -249	0.307	0	0.461
size (employees): >250	0.141	0	0.348
Cooperation	0.168	0	0.374
Patenting activity	0.146	0	0.353
size (employees): 50 -249	0.307	0	0.461
size (employees): >250	0.141	0	0.348
Local funding	0.121	0	0.326
National funding	0.124	0	0.330
European funding	0.055	0	0.308
Industry level variables			
Sum of sectoral R&D (logs)	17.97	17.72	1.693
Average sectoral R&D (logs)	12.00	11.43	1.632

Notes: The sample includes 23,247 firms. Data refer to the period 2002-2004. All the financial variables are in Euros

Table 2. Tobit and probit estimation of R&D

Dependent variable	Engagement in R&D	Intensity of R&D	Engagement in extra-mural R&D
	Tobit		Probit
	(1)	(2)	(3)
Turnover in 2004 (in logs)	0.052***	-0.282***	0.033***
	(0.003)	(0.018)	(0.002)
Belonging to a group	0.008	0.102***	0.034***
	(0.007)	(0.037)	(0.006)
International markets	0.121***	0.214***	0.036***
	(0.006)	(0.051)	(0.005)
Patenting activity	0.276***	0.630***	0.099***
	(0.010)	(0.042)	(0.009)
Size			
50 -249	0.042***	-0.115**	-0.002
	(0.008)	(0.047)	(0.006)
>250	0.061***	0.162**	-0.003
	(0.016)	(0.076)	(0.010)
Cooperation	-	0.207***	-
		(0.034)	
Local funding	-	0.204***	-
		(0.035)	
National funding	-	0.440***	-
		(0.035)	
European funding	-	0.180***	-
		(0.031)	
Constant	-	-0.792***	-
		(0.303)	
Observations	23,247	23,247	23,247
Wald test of indep. eqns. (rho = 0)	142.1	142.1	-
rho	0.472	0.472	-
Wald test - Chi-squared	3444	3444	4578
Log-likelihood	-18629	-18629	-7988
pseudo R^2	-	-	0.261

In column (1) the dependent variable is equal to one if a firm engaged continuously in R&D (whether bought or performed). The dependent variable in column (2) is equal to the logarithm of the ratio of total R&D expenditures over sales. In column instead (3) the dependent variable is equal to one if a firm engaged in extramural R&D (R&D bought from other partners) and zero otherwise. In column (1) and (3) coefficients display marginal effects computed at the sample mean. All models include industry and country dummies. The Tobit model also includes control variables concerning the importance of different sources of information. The probit model for extramural R&D includes control variables concerning the presence of organisational innovation and the use of measures of protection of innovation outcomes alternative to patenting. The model also controls for the factors hampering innovation activity. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table 3. Logit estimation of product and process innovation

Dependent variable	Product and/or Process Innovation		Product Innovation		Process Innovation	
	(1)	(2)	(3)	(4)	(5)	(6)
predicted R&D intensity	0.630***	0.642***	0.425***	0.436***	0.170***	0.186***
	(0.0201)	(0.020)	(0.015)	(0.015)	(0.011)	(0.011)
Turnover in 2004 (in logs)	0.158***	0.165***	0.104***	0.110***	0.048***	0.056***
	(0.006)	(0.006)	(0.005)	(0.005)	(0.004)	(0.004)
Openness* sum of sectoral R&D (in logs)	0.057***	-	0.050***	-	0.019***	-
	(0.003)		(0.003)		(0.002)	
Openness* average sectoral R&D (in logs)	-	0.0783***	-	0.069***	-	0.020***
		(0.005)		(0.004)		(0.002)
Investment Intensity	0.109***	0.109***	0.050***	0.050***	0.060***	0.060***
	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
Observations	23,247	23,247	23,247	23,247	23,247	23,247
Perc. correctly predicted	0.537	0.538	0.336	0.337	0.243	0.243
Log-likelihood	-8392	-8415	-9511	-9537	-10295	-10322
Wald test - Chi-squared	4578	4556	4774	4732	4908	4889
p-value	0.000	0.000	0.000	0.000	0.000	0.000
Pseudo R	0.477	0.475	0.374	0.372	0.276	0.274

The models include country and sectoral dummies. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Appendix A

<u>Cleaning procedure</u>

We followed a procedure similar to that implemented by Hall and Mairesse (1995): we removed any observations for which value added in 2002 or value added in 2004 was zero, we also eliminated any observations for which the growth rate of value added was less than minus 90 percent or greater than 300 percent. Finally we erased from the dataset firms for which the ratio between total R&D expenditures and value added was higher than 80%.

<u>Sectoral and national firms' distributions</u>

Table A1. Sectors included in the database

ISIC. REV. 3	Sector Name
C15T16	Food, Beverages and Tobacco
C17T18	Textiles and textile products
C19	Leather, leather products and footwear
C20T21	Pulp, paper and paper products
	Wood and products of wood and cork
C22	Printing and publishing
C23TC24	Chemicals and chemical products and coke
	Coke, refined petroleum products and nuclear fuel
C25	Rubber and plastics products
C26	Other non-metallic mineral products
C27	Basic metals
C28	Fabricated metal products, except machinery and equipment
C29	Machinery and equipment, n.e.c.
C30T33	Electrical and optical equipment
C34T35	Transport equipment
C36T37	Manufacturing n.e.c. and recycling

Table A2. Sectoral distribution by country and overall sectoral distribution

Countries		C15T16	C17T18	C19	C20TC21	C22	C23TC24	C25	C26	C27	C28	C29	C30T33	C34T35	C36T37	Total
Belgium	num.	182	93	5	75	101	108	59	74	34	172	105	106	66	71	1251
	perc.	14.55	7.43	0.40	6.00	8.07	8.63	4.72	5.92	2.72	13.75	8.39	8.47	5.28	5.68	100.00
Czech Rep	num.	224	224	82	235	124	130	152	148	118	254	225	418	240	205	2779
	perc.	8.06	8.06	2.95	8.46	4.46	4.68	5.47	5.33	4.25	9.14	8.10	15.04	8.64	7.38	100.00
Germany	num.	138	100	20	134	120	197	138	89	90	271	273	403	133	98	2204
	perc.	6.26	4.54	0.91	6.08	5.44	8.94	6.26	4.04	4.08	12.30	12.39	18.28	6.03	4.45	100.00
Italy	num.	629	802	181	516	308	421	314	493	288	991	564	616	347	321	6791
	perc.	9.26	11.81	2.67	7.60	4.54	6.20	4.62	7.26	4.24	14.59	8.31	9.07	5.11	4.73	100.00
Norway	num.	210	76	6	156	190	59	67	84	40	166	137	168	159	106	1624
	perc.	12.93	4.68	0.37	9.61	11.70	3.63	4.13	5.17	2.46	10.22	8.44	10.34	9.79	6.53	100.00
Spain	num.	1065	577	184	536	384	772	473	684	288	899	842	757	494	643	8598
	perc.	12.39	6.71	2.14	6.23	4.47	8.98	5.50	7.96	3.35	10.46	9.79	8.80	5.75	7.48	100.00
Total		2448	1872	478	1652	1227	1687	1203	1572	858	2753	2146	2468	1439	1444	23247
		10.53	8.05	2.06	7.10	5.27	7.28	5.17	6.76	3.70	11.84	9.23	10.66	6.19	6.21	100.00

Appendix B

"Micro-aggregation" is a procedure used in order to protect confidentiality. It consists in adding "error terms" to the raw micro-data, making it extremely difficult to break the anonymity of the individual firm surveyed, but still preserving "most" of the information useful for statistical analysis. In micro-aggregation methods, the error terms are not defined explicitly but included implicitly in the procedure (Dagenais, Mairesse, Mohnen, 2006). In the micro-aggregation process artificial units are created by replacing original values by the mean (only for quantitative variables) or in considering a cluster of 3 observations (in some cases 4 if the number of records is not a multiple of 3). Clusters are formed of individuals of 'maximum similarity', i.e. with the nearest value. The variables in the original dataset are micro-aggregated independently of each other, i.e. clusters are established separately for each specific variable. No single grouping of clusters exists for all variables. This means that three units which are part of the same cluster for a variable X often will be part of different clusters for another variable Y. Therefore the clusters consist of the most similar values. The clustering of the records is done throughout the whole population. For variables on innovators, the whole population of innovating enterprises within a country is used. For variables referring to both innovators and non-innovators, the creation of clusters is carried out on the entire dataset without any stratification. This implies that Nace divisions and size classes are not taken into account during the building of the clusters (Eurostat, 2010).

This amounts to adding to every (continuous) variable, for a given firm (i), an error term (ε_i) equal to the difference between the average value of the variable ($\overline{y_i}$) for the cluster of three firms (*i*, *j* and *k*) in which this firm is allocated and its individual value (y_i).

As Eurostat (1999) and Mairesse and Mohnen (2001) have shown such a procedure allows to work with error terms which do not behave in same way than random measurement errors. For large enough samples in fact they are not a source of bias in the estimation of linear regression models. Anyway as Mairesse and Mohnen (2001) have shown comparing results using raw data and micro-aggregated ones for the French CIS2 questionnaire, also non-linear models as the ones used in this paper were not sensitive to the micro-aggregation anonymisation.

In the data used in this paper the only variables which were micro-aggregated were:

- turnover (in 2002 and in 2004)
- expenditure in intramural RD;
- expenditure in extramural RD;
- expenditure in acquisition of machinery;
- expenditure in other external knowledge;
- total innovation expenditure.

Appendix C

Description of the variables used in the estimations:

Continuous R&D engagement: Dummy variable which takes the value 1 if the enterprise reports continuous engagement in intramural R&D activities during the period 2002–2004.

R&D intensity: (log of) share of R&D expenditures (external and internal) on the firms' turnover in 2004.

Investment Intensity: (log of) share of expenditures in the acquisition of machinery on the firms' turnover in 2004

Product innovation: Dummy variable which takes the value 1 if the enterprise has introduced at least one product during 2002-2004

Process innovation: Dummy variable which takes the value 1 if the enterprise has introduced new or significantly improved methods of production

Belonging to a group: Dummy variable which takes the value 1 if the enterprise is part of a group.

International markets: Dummy variable which takes the value 1 if the enterprise's most significant market is international.

Patenting activity: Dummy variable which takes the value 1 if the enterprise has applied for a patent in the period 2002-2004

Local funding: Dummy variable which takes the value 1 if the enterprise received local or regional funding for innovation projects during 2002–2004.

National funding: Dummy variable which takes the value 1 if the enterprise received central government funding for innovation projects during 2002–2004.

EU funding: Dummy variable which takes the value 1 if the enterprise received EU funding for innovation projects during 1998–2000.

Sources of information: Dummy variable which takes the value 1 if the enterprise considers the sources of information as highly important for the implementation of innovative activities.

Organizational innovation: Dummy variable which takes the value 1 if the enterprise has either introduced improved knowledge management system or change to work organization or a change in relations with other firms.

Factors hampering innovation: Dummy variable which takes the value 1 if the enterprise considers a factor as an important obstacle hampering innovative activity

Design: Dummy variable which takes the value 1 if the enterprise registered an industrial design in the period 2002-2004

Trademarks: Dummy variable which takes the value 1 if the enterprise registered a trademark in the period 2002-2004

Copyright: Dummy variable which takes the value 1 if the enterprise claimed copyright in the period 2002-2004

5. REFERENCES

Acs, Z., D. Audretsch and M. Feldman (1992), Real effects of academic research: comment, *American Economic Review*, 82, 363-367.

Adams, J. D, (1990), Fundamental stocks of knowledge and productivity growth, *Journal of Political Economy*, 98, 673-702.

Anderson, P.W., Arrow, K.J., Pines, D. (eds.) (1988), *The economy as an evolving complex system,* Addison Wesley, Redwood.

Antonelli, C. (2008a), *Localized technological change: Towards the economics of complexity,* Routledge, London.

Antonelli, C. (2008b), Pecuniary knowledge externalities: The convergence of directed technological change and the emergence of innovation systems, *Industrial and Corporate Change* 17, 1049-1070.

Antonelli, C. (ed.) (2011), *Handbook on the economic complexity of technological change*, Edward Elgar, Cheltenham.

Antonelli, C., Patrucco, P.P. and Quatraro, F. (2011) Productivity growth and pecuniary knowledge externalities: an empirical analysis of agglomeration economies in European regions, *Economic Geography*, 87, 23-50

Arthur, W.B. (1990) Positive feedbacks in the economy. *Scientific American* 262, 92.

Arthur, W.B. (1994*) Increasing returns and path dependence in the economy*. Michigan University Press, Ann Arbor.

Arthur, W.B. (2009), *The nature of technology,* The Free Press, New York.

Arthur, W. B., Durlauf, S.N. and Lane. D. A. (eds.) (1997) *The economy as an evolving complex system II.* Addison-Wesley, Redwood City, CA.

Audretsch, D.B., Feldman, M.P. (1996), R&D spillovers and the geography of innovation and production. *American Economic Review* 86, 630-640.

Blume, L.E., Durlauf, S.N. (2005), *The economy as an evolving complex system III*. Oxford University Press, Oxford.

Blume, L.E., Durlauf. S.N. (eds.) (2001), *Social dynamics*. MIT Press, Cambridge.

Breschi, S., Lissoni, F. (2001), Knowledge spillovers ad local innovation systems: A critical survey, *Industrial and Corporale Change* 10, 975-1005.

Cassiman, B. and R. Veugelers (2006), In search of complementarity in innovation strategy: internal R&D and external knowledge acquisition, *Management Science*, 52, 68–82.

Chesbrough, H. (2003), *Open innovation. The new imperative for creating and profiting from technology*, Harvard Business School Press, Boston.

Chesbrough, H., Vanhaverbeke, W. and West, J. (2006), *Open innovation: Researching a new paradigm*, Oxford University Press, Oxford.

Cohen, W.M., Levinthal, D.A. (1989), Innovation and learning: The two faces of R&D, *Economic Journal* 99, 569-596.

Cohen, W. M., Levinthal D.A. (1990), Absorptive capacity: A new perspective on learning and innovation, *Administrative Science Quarterly* 35, 128-152.

Crépon, B., Duguet, E., Mairesse, J. (1998), Research and development, innovation and productivity: An econometric analysis at the firm level, *Economics of Innovation and New Technology* 7, 115–158.

Cuneo, P., Mairesse, J. (1984), Productivity and R&D at the firm level in French manufacturing, in Griliches, Z. (ed.) *R&D, patents and productivity*, Chicago, The University of Chicago Press.

Dagenais, M., J. Mairesse and P. Mohnen, (2006), Innovativity: a comparison across seven european countries, NBER Working Paper N. 12280.

David, P.A. (1993), Knowledge property and the system dynamics of technological change, *Proceedings of the World Bank Annual Conference on Development Economics,* The World Bank, Washington.

Desyllas, P. and Hughes, A., (2010), Do high technology acquirers become more innovative?, *Research Policy*, 39, 1105–1121.

Dahlander, L., Gann, D.M. (2010), How open is innovation?, *Research Policy* 39, 699-709.

Eurostat (1999), *Annex II.9. Micro-Aggregation Process*, in "The Second Community Innovation Survey", Statistical Office of the European Communities, Luxembourg.

Eurostat (2010), "*Annex: Summary of the anonymisation method*", Statistical Office of the European Communities, Luxembourg.

Feldman, M. A. (1999), The new economics of innovation, spillovers and agglomeration: A review of empirical studies, *Economics of Innovation and New Technology* 8, 5-25.

Fleming, L., Sorenson, O. (2001), Technology as a complex adaptive system: Evidence from patent data. *Research Policy* 30, 1019-1039.

Gassmann, O. (2006), Opening up the innovation process: Towards an agenda, *R&D Management* 36, 223-228.

Griffith, R., Huergo, E., Mairesse, J., and B. Peters (2006), Innovation and productivity across four European countries, *Oxford Review of Economic Policy*, 22(4), 483-498.

Griffith, R., Harrison, R. and J. Van Reenen (2006) How special is the special relationship? Using the impact of U.S. R&D spillovers on U.K. firms as a test of technology sourcing, *American Economic Review*, 96, 1859-1875

Griliches, Z. (1979), Issues in assessing the contribution of research and development to productivity growth, *Bell Journal of Economics* 10, 92-116.

Griliches, Z. (1992), The search for R&D spillovers, *Scandinavian Journal of Economics* 94, Supplement: 29-47.

Hall, H.B. and J. Mairesse (1995), Exploring the relationship between R&D and productivity in French manufacturing firms, *Journal of Econometrics*, 65, 263-293.

Howells, J., Andrew, J., Khaleel, M. (2003), The sourcing of technological knowledge: Distribute innovation processes and dynamic change, *R&D Management* 33, 395-409.

Hollanders, H., Ter Weel, B. (2002), Technology, knowledge spillovers and changes in employment structure: Evidence from six OECD countries, *Labour Economics* 9, 579-599

Kraft, J., Quatraro, F. and Saviotti, P.P. (2009), The knowledge base evolution in biotechnology: a social network analysis, *Economics of Innovation and New Technology*

Jaffe, A. (1989), Real effects of academic research, *American Economic Review* 79, 957-970.

Lane, D. A., Maxfield R (1997), Foresight complexity and strategy. in Arthur W B, Durlauf S N, Lane D A (eds.), *The economy as an evolving complex system II,* Westview Press, Santa Fe, 169-198.

Lane, D. A. et al. (2009), *Complexity perspectives in innovation and social change*, Springer, Berlin.

Laursen, K., Salter, A. (2006), Open for innovation: The role of openness in explaining innovation performance among UK manufacturing firms, *Strategic Management Journal* 24, 131-150.

Levin, R.C., Klevorick, A. K., Nelson, R.R. and Winter, S.G. (1987), Appropriating the Returns from Industrial Research and Development, *Brookings Papers on Economic Activity*, *Economic Studies Program, The Brookings Institution*, 18, 783-832.

Link, A., Siegel, D. (2007*), Innovation, entrepreneurship, and technological change*, Oxford University Press, Oxford.

Mairesse, J. and P. Mohnen (2001), To be or not to be innovative: an exercise in measurement, NBER Working Paper No. 8644.

Mairesse, J. and S. Robin (2009) Innovation and productivity: a firm-level analysis for French Manufacturing and Services using CIS3 and CIS4 data, mimeo.

March, J. C. (1991), Exploration and exploitation in organizing learning. *Organization Science* 2, 71-87.

Mohnen, P. (1996), R&D externalities and productivity growth, *STI Review*, OECD 18, 39-66.

Mohnen, P., Polder, M., Raymond, W. and G. van Leeuwen (2009), Productivity effects of innovation modes, *MPRA Paper* n. 18893, November 2009.

Nelson, R.R. (1959), The simple economics of basic scientific research, *Journal of Political Economy* 67, 297-306.

Nelson, R.R. (1982), The role of knowledge in R&D efficiency, *Quarterly Journal of Economics* 97, 453-470.

Nelson, R.R. (ed.) (1993), *National systems of innovation*, Oxford University Press, Oxford.

O'Mahony, M., Vecchi, M. (2009), R&D, knowledge spillovers and company productivity performance, *Research Policy*, 38 (1), 35-44.

Ozman, M. (2009) Inter-firm networks and innovation: A survey of literature, *Economics of Innovation and New Technology* 18, 39-67.

Quatraro, F. (2009a) Innovation structural change and productivity growth: Evidence from Italian regions 1980-2003, *Cambridge Journal of Economics* 33, 1001-1022.

Quatraro, F. (2009b), Diffusion of regional innovation capabilities: Evidence from Italian patent data, *Regional Studies* 43, 1333-1348.

Quatraro, F. (2010), Knowledge coherence variety and productivity growth: Manufacturing evidence from Italian regions, *Research Policy* 39, 1289-1302.

Scitovsky, T. (1954), Two concepts of external economies, *Journal of Political Economy* 62, 143-151.

Schumpeter, J.A. (1947), The creative response in economic history. *Journal of Economic History* 7, 149-159.

Vega-Jurado, J., Gutierrez-Gracia, A. and Fernandez-de-Lucio, I. (2009) Does external knowledge sourcing matter for innovation? Evidence from the Spanish manufacturing industry, *Industrial and Corporate Change*, 18, 637–670.

Verspagen, B., De Loo, I. (1999),Technology spillovers between sectors and over time, *Technological Forecasting and Social Change* 60, 215–235

Von Hippel, E. (1988), *The sources of innovation*, Oxford University Press, Oxford.

Von Hippel, E. (2005), *Democratizing innovation*, The MIT Press, Cambridge.

Weitzman, M.L. (1996), Hybridizing growth theory, *American Economic Review* 86, 207-212.

Weitzman, M.L.(1998) Recombinant growth, *Quarterly Journal of Economics* 113, 331-360.