Via Po, 53 – 10124 Torino (Italy)
Tel. (+39) 011 6702704 - Fax (+39) 011 6702762
URL: http//www.de.unito.it

WORKING PAPER SERIES

COLLECTIVE KNOWLEDGE PRODUCTION, COSTS AND THE DYNAMICS OF TECHNOLOGICAL SYSTEMS

Pier Paolo Patrucco

Dipartimento di Economia "S. Cognetti de Martiis"

Laboratorio di Economia dell'Innovazione "Franco Momigliano"

Working paper No. 06/2005

Università di Torino

COLLECTIVE KNOWLEDGE PRODUCTION, COSTS AND THE DYNAMICS OF TECHNOLOGICAL SYSTEMS[1]

Pier Paolo Patrucco
Laboratorio di Economia dell'Innovazione "Franco Momigliano"
Dipartimento di Economia
Università di Torino
Via Po 53, 10124 Torino
Tel. +39 011 6702767
Fax. +39 011 6702762
Pierpaolo.patrucco@unito.it

ABSTRACT. Technological knowledge can be understood as a collective good only when its production requires the absorption and integration of external knowledge. Such external knowledge is the outcome of R&D investments that cannot be fully appropriated by firms and generate spillovers. The exploitation of such knowledge spillovers requires specific investments in knowledge communication and absorption, which brings about specific costs. These costs are affected by the structural and dynamic characteristics of technological systems in terms of the knowledge base, the variety of actors and the communication infrastructures and processes. This paper analyzes the costs of collective knowledge production and their implications for the way in which the firm chooses the mix of internal and external knowledge. This choice in turn shapes the evolution of technological systems.

1. INTRODUCTION

Technological knowledge can be analyzed as a collective good when it is the result of the integration between internal resources and the absorption of external knowledge. Internal resources amount to the portions of know-how and capabilities generated and accumulated within the firm through codified R&D activities and more tacit learning (e.g., routines). R&D and learning (hereafter, R&D&L) can be described as complementary processes allowing the generation

[1] I thank Cristiano Antonelli, Davide Consoli, Jacques Ravix, Laurel Smith-Doerr and the participants to the TELL project for their repeated suggestions and comments.

and accumulation of interdependent types of knowledge within the firm. When knowledge spillovers are available in the system because of knowledge indivisibilities, and when appropriability is not complete, external knowledge can augment internal resources as an input in technological knowledge production processes and increases the efficiency of such processes through technological communication. Internal and external knowledge are complementary rather than substitutable for increasing returns into the production and growth of knowledge to take place (Allen, 1983; Antonelli, 2001; Cowan and Jonard, 2003; Patrucco, 2004).

Access to existing external knowledge is the necessary condition improving both the amount of knowledge created and the efficiency of knowledge production. The exploitation of positive knowledge externalities enables the absorption of technological knowledge already stored but dispersed in a number of different but yet complementary artifacts, technologies and users (Cohen and Levinthal, 1989). However, since technological knowledge is industry- and region-specific, it is also very idiosyncratic and costly for use elsewhere, i.e. in other regions, other industries and other firms. Knowledge does not spill freely into the air. Specific investments in external learning and communication need to be implemented in order to take advantage of knowledge spillovers. Technological communication is the result of proactive and mutual efforts to exploit knowledge spillovers. Technological communication and external knowledge access, together with the exploitation of complementarities and spillovers have important cost implications.

Actors face specific costs for accessing portions of external knowledge and for internalizing the advantages of knowledge externalities. Since internal resources and external knowledge are complementary rather than substitutable for increasing returns to take place, the costs of accessing external knowledge add to the costs of internal R&D&L. These costs affect how firms choose the mix of internal and external knowledge as inputs that enter the knowledge production process. Such costs are affected by the structural and dynamic features of economic systems, defined as the number and variety of actors, their knowledge base and the opportunity to establish connections between them.

The aim of this paper is to analyze the interaction between the costs of internal knowledge production and the costs necessary to access external knowledge through technological communication. The analysis of the trade-off between internal knowledge production costs and external access costs paves the way for the understanding of how the firm can choose its mix of internal and external resources. Moreover, it also contributes to the understanding of those elements and processes that underpin the emergence and evolution of technological systems.

This paper is structured as follows. Section 2 presents a simple formal exposition of the characteristics of collective knowledge production, with a special emphasis on the costs of absorbing external knowledge and their implication for the firm's choice. Section 3 describes the implications of the relative cost of internal and external knowledge for the understanding of technological systems and the case for economic variety. Section 4 shows the way in which technological systems are path dependent outcome of the interaction between the costs of internal and the costs of external knowledge. Conclusions summarize the main results.

2. THE COSTS OF COLLECTIVE KNOWLEDGE: A SIMPLE FORMAL EXPOSITION

The conditions of access to external knowledge are a most important element to be taken into account when explaining the elements that characterize the dynamics of collective knowledge.

In particular, technological communication and the availability of external knowledge are necessary for the exploitation of the benefits of knowledge spillovers and the complementarity between internal and external knowledge (Patrucco, 2004)[2].

The appreciation of the costs involved in technological communication and their implications in terms of mix of internal resources and external knowledge in the firm's knowledge production process can now complete the full account of the dynamics of collective knowledge.

Access conditions to external knowledge determine how effective the acquisition and accumulation of technological knowledge is. It can be more or less efficient according to the quality and number of connections among agents, and the technological, industrial and institutional characteristics of the environment. In an economic space characterized by idiosyncratic and localized knowledge, firms

[2] Partial appropriability is necessary for the benefits of knowledge spillovers to be exploited through technological communication and increasing returns to take place. However, such inappropriability cannot exceed a given threshold beyond which standard decreasing returns to technological communication and knowledge distribution start to apply. In fact, if inappropriability is higher than the threshold, the firms' probability and opportunities to benefit from and appropriate the returns to their private investments in technological communication is decreasing and the profitability of being involved into collective processes of knowledge production and distribution starts to decrease as well.

face high costs for identifying and selecting the different technological opportunities, evaluating the portions of knowledge which are more appropriate and compatible with respect to their internal environment, and eventually integrating these with internal ones. In this perspective, the accessibility conditions that enhance the generation of technological knowledge and technological change can be defined in relation to the costs that must be incurred in order to access portions of knowledge and technology different from those actually used within the firm.

Access conditions are bounded by two factors. First, they are harmed by the costs agents must face to access, i.e. to search, evaluate, accumulate and assimilate the relevant bits of external idiosyncratic knowledge owned by different and complementary actors, that is, communication costs. Second, access conditions are also affected by the trade-off between internal knowledge production costs and external knowledge access costs. Here, internal knowledge production costs can be defined as the costs necessary to put in place internal learning and R&D efforts. External access costs can instead be defined as the costs necessary to implement formal and informal connections, communication and learning between the firm and the environment, in order to access external portions of knowledge, and can be specified into interaction costs and transaction costs (Antonelli, 1999 and 2001; Carter, 1989).

The relative costs of internal knowledge production and external knowledge access play a major role here. They affect the firm's choice between internal and external inputs, together with irreversibility and hence path-dependence. When standard factors substitutability applies, given a sufficient amount of knowledge spillovers, the higher is the relative cost of internal production, and the more convenient will be knowledge production processes relying upon external knowledge. And *vice versa*.

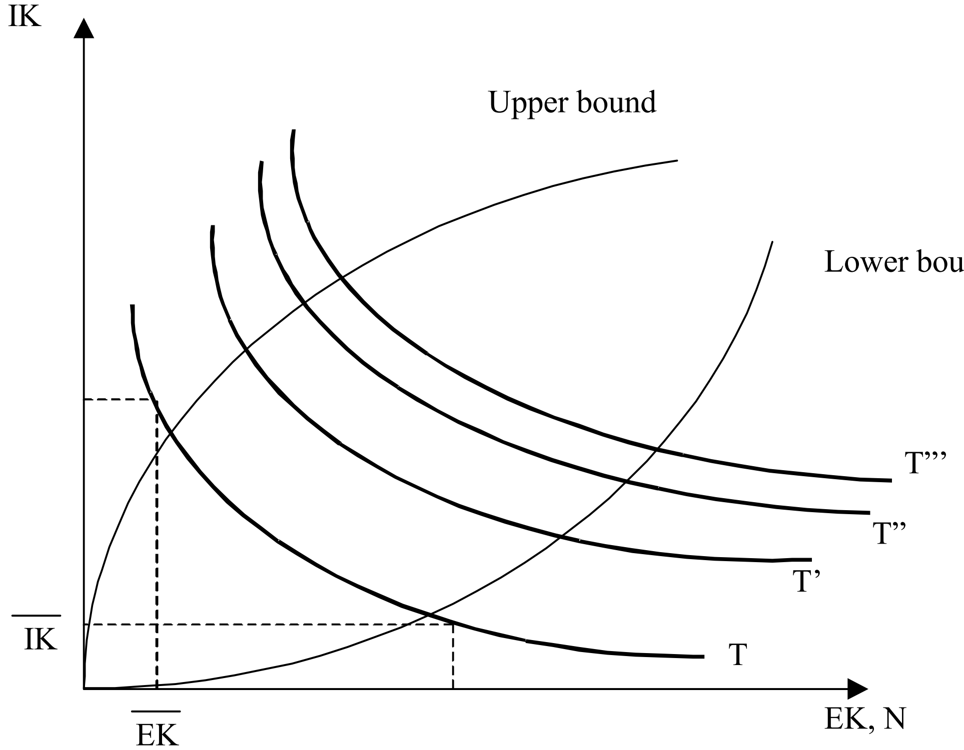
However, according to the collective understanding of technological knowledge, internal and external knowledge are not simply substitutable, but also complementary. For increasing returns to knowledge production both internal and external knowledge are necessary. Moreover, they must enter knowledge production with minimum amounts in both the inputs. Only with a minimum amount of investments in internal R&D&L, the firm can know how to use and integrate external knowledge into the internal innovative activity. The advantage of accessing external knowledge can be exploited only when a minimum amount of internal R&D&L is available. And *vice versa*.

Finally, factors endowment is not completely reversible. On the contrary, it can be very rigid according to the history of previous waves of investments. The more the firms and the system previously relied upon internal knowledge, the more difficult will be the shift to knowledge production relying upon external knowledge, even in presence of relatively more favorable costs conditions. And *vice versa*. Here, high and very costly new investments in learning and creative capabilities must be put in place in order to avoid possible lock-in. Factor substitutability and complementarity apply in a bounded economic space.

Figure 1 shows a map of isoquants for collective technological knowledge, where internal and external knowledge are the inputs. The vertical axis measures the amount of internal knowledge (IK) while the amount of external knowledge (EK) is on the horizontal one. A lower and an upper bound characterize the economic space depicted. Factor substitutability and complementarity is limited to the region between the lower and upper bound, and $\overline{IK}$ and $\overline{EK}$ measure the minimum amount of internal and external knowledge, respectively, necessary to produce a minimum level of technological knowledge T.

In order to cope with and react to irreversibility in endowment, firms need to exploit complementarity between internal and external knowledge allowing the effect of such complementarity to give place to increasing returns in knowledge production, and for such benefits to be higher than the costs of the inputs. The firm can change the mix of internal and external knowledge according to the relative costs of the inputs but only with given boundaries according to the complementarity effect, and cannot completely substitute one input with the other.

Figure 1. Internal and external knowledge and the boundaries of technological knowledge



The costs of such technological communication and access to external knowledge as an input in the production of technological knowledge need to be considered, together with the trade-off between internal and external costs, to appreciate the elements and the processes that affect the firm's choice in terms of the mix between internal and external resources.

Let us introduce a simple technological knowledge production function:

$$T_i = f\,(IK^{\gamma 1}, EK^{\gamma 2}) \qquad (1)$$

where *Ti* is the amount of technological knowledge produced by the firm *i,* EK is the amount of external knowledge that enters the knowledge production process as an input, IK is the amount of internal R&D&L devoted to the production of new knowledge, and γ_1 and γ_2 measure the efficiency through which internal and external knowledge are employed into the production process, respectively.

Moreover, $\gamma1 + \gamma2 > 1$, but $\gamma1, \gamma2 < 1$. Increasing returns in knowledge production are conditional to minimum amounts of both internal and external knowledge as inputs, according to the previous analysis.

The costs implied by the use of internal and external knowledge as inputs in such a production process are most important here and need now to be specified.

Equation (2) shows that the total costs C of collective knowledge production for a firm *i* is the sum of the costs of using given quantities of internal and external knowledge, and where *w* and *r* are the relative costs of the access to external knowledge and the investments in internal R&D&L, respectively:

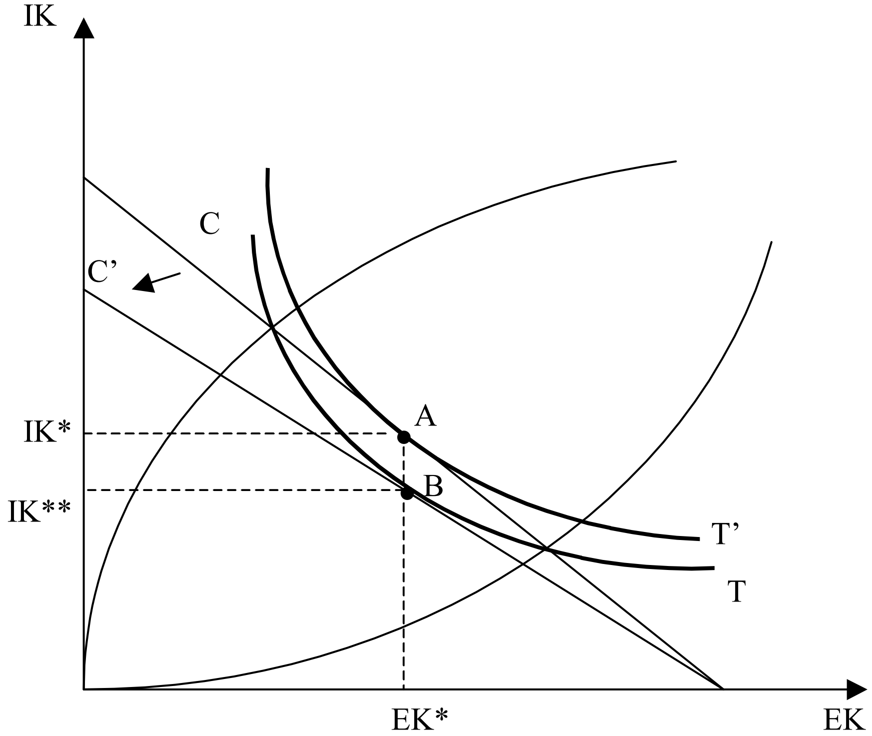
$$C_i = rIK + wEK \tag{2}$$

The access and absorption of external knowledge, now a crucial input in the production of technological knowledge, and its relative costs are affected by both the probability for those portions of knowledge that spill over to be diffused in the system and the specific investments in technological communication needed to exploit those spillovers internally. Moreover, technological distance is also important: the more different the knowledge base of a given firm is from the portions of external knowledge accessed, the more difficult and costly is the integration and implementation of those new portions into the existing ones. The more proximate are the internal competencies of the firm and the external portions of knowledge, the easier and cheaper will be the access and absorption of such portions of external knowledge. External knowledge will be efficiently absorbed and implemented in the internal R&D&L activities when internal and external knowledge are localized in the same technical space. Here, complementarity between internal resources and external knowledge can be efficiently exploited, with an increase in the efficiency of the process of knowledge production.

A simple geometrical exposition can clarify the implications of the relative cost of external knowledge for the technological knowledge production process of the firm and the firms' choice in terms of the mix of the production factors. Moreover, it can also show which are the implications of changes in the structural characteristics of economic systems for the relative cost of internal and external knowledge and the way in which firms can cope and react to such changes.

Given equation (2) we are now able to depict the trade-off between internal knowledge production costs and external knowledge access costs. The double dimension of collective knowledge production in terms of a trade-off between internal knowledge costs and external knowledge costs is depicted in Figure 2. The former dimension accounts for the costs implied by all those activities that are based on the implementation of mere internal knowledge production efforts (such as, internal R&D and learning). The latter accounts for the costs of knowledge production based on the viability of and access to external knowledge. Accordingly in the diagram I depict the internal costs (IK) and the external costs (EK) on the vertical and horizontal axis respectively. I represent a bounded economic space characterized by a lower bound and an upper bound between which factors are complementary and substitutable, together with a given isoquant T. In such a space I depict the locus of costs constraints given by the characteristics of economic systems and represented by equation (2), depicted as an isocost line C.

Figure 2. Input substitutability and the costs of collective technological knowledge



Clearly, at time *t* the firm selects *A* and *IK** and *EK** are the equilibrium levels of, respectively, internal knowledge production and external knowledge access that enter collective knowledge production. For a given change of the costs conditions and the related shift in the isocost within the region between the upper and lower bounds, the firms can substitute internal with external knowledge and *vice versa*. In fact, for a given change in the costs conditions represented by the new isocost C', firms can change their mix of productive conditions as represented by the new isoquant T'.

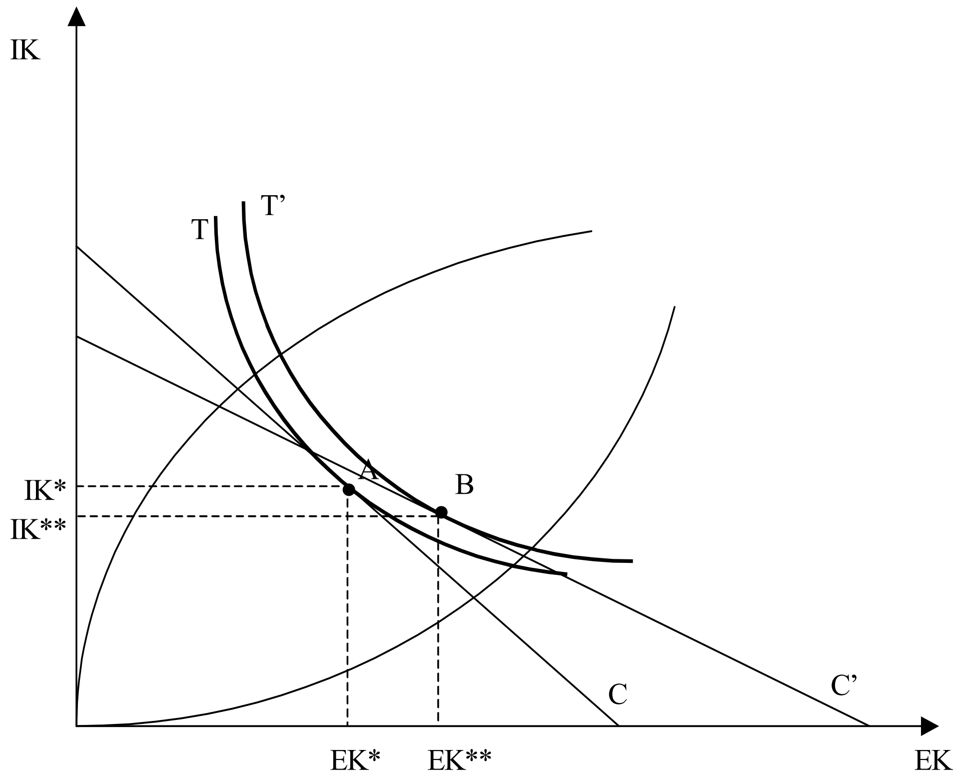
Assume a simple change, in time $t + 1$ in the characteristics of the economic system in terms of the relation between viability conditions and access to external knowledge on one hand, and internal production of knowledge on the other. Let us assume that internal production costs are higher than in time *t*, because R&D activity and internal learning are less effective and efficient, as represented by a new isocost *C'*, while access conditions to external knowledge are not affected by any change. This is, for instance, the case when R&D personnel are scarce and difficult to train internally. Internal costs can be high also because the technological, capital and organizational endowment of the firms is old and learning by doing and by using is based on obsolete technologies and thus less effective.

Clearly, a new context emerges; one with new structural conditions and one in which firms have to change their mix between internal knowledge production and external knowledge access. Internal knowledge production costs are now relatively higher than external knowledge access and firms will be engaged in relatively lower levels of internal knowledge production. The communication and access to external knowledge are instead relatively more important because more efficient, as depicted by the shift in the collective knowledge isocost from C to C'. The firm is now stable in *B*, and *IK*** and *EK** are the equilibrium levels of, respectively, internal knowledge production and the new portion of external knowledge access that enters collective knowledge production.

Let us now also assume a more complex change in the characteristics of the economic system. At time $t + 2$, both the costs of internal knowledge production and external knowledge access change, as depicted by the new isocost *C'* (Figure 3). While the costs of internal production of knowledge are higher than in the previous period, now the conditions for technological communication also change and are characterized by lower costs. For instance, information and communication technologies are updated to the new needs of either users or producers. Moreover, co-operation can be easier because new behaviors arise and firms are well aware of the benefits of collaboration. Finally, transaction costs can be lower because the risk of opportunistic behaviors is low or because the administrative and judicial costs of contracts decrease for external reasons.

Firms are now induced to change both the amounts of their input, decreasing the amount of the more expensive factor, namely internal R&D&L, and increasing the use of external knowledge entering the knowledge production process. It is clear that *A* is no longer a suitable solution because in A firms are still employing the same amounts of inputs they were using before the change in the relative costs of internal and external resources. This does not satisfy the standard tangency condition.

Figure 3. Collective knowledge and changes in both internal knowledge costs and external knowledge costs



In B the firm is facing the change in the relative costs of the inputs changing the mix and moving to the new isoquant T'. Moreover in B, the cheaper factor EK is used more intensively than the more expensive internal R&D&L, as represented by the new combinations of inputs, where IK** and EK** are the new optimal amounts of internal and external resources, respectively.

In sum, the amount of technological knowledge produced in a firm will depend on the composition effect that is at work with respect to the diachronic changes occurring between the employment of internal knowledge production and external knowledge access in relation to the changes in the characteristics of economic systems.

Collective technological knowledge can be more external knowledge intensive or rather internal R&D&L intensive according to the relative costs of internal and external resources and the capacity of the firm to react to changes in the relative costs of producing knowledge internally through investment in R&D and learning and of accessing knowledge externally through investments in technological communication.

Proactive firms are induced to change their processes of knowledge production in order to employ the more efficient technique or technology according to the changes in the relative costs of the inputs. A given change in the relative costs of the inputs induces firms to exploit complementarity between the cheaper and the more expensive factor changing their mix and using the less expensive resource intensively.

The efficient exploitation of such complementarities is bounded to the costs of accessing external knowledge, i.e. to 1) the extent to which external knowledge is diffused in the system, 2) the investments in technological communication, and 3) the technological distance between the new portions of knowledge externally accessed and the internal competencies of the firm.

These elements have major implications for the empirical understanding of the conditions under which technological knowledge can be produced and the effect that different characteristics of economic systems have on the process of knowledge production, resulting in different technological systems.

3. THE IMPLICATIONS FOR ECONOMIC VARIETY: FIRMS, MARKETS AND TECHNOLOGICAL SYSTEMS IN THE PRODUCTION OF KNOWLEDGE

The costs of collective production of knowledge are determined by the structural and dynamic characteristics of the economic system we eventually observe, in terms of the number of knowledge producers, and in terms of the number and quality of their interconnections.

According to the structural and dynamic characteristics of economic systems, firms can find internal generation of knowledge more convenient than external access, or vice versa. Firms can choose different combinations of internal resources and external knowledge according to the relative costs of internal and external inputs, in turn making the case for both technical and technological variety.

Sectoral, historical and institutional characteristics of technological systems, and more importantly the changes in such characteristics, affect the relative costs of internal and external knowledge and the shape and slope of the isocost, through many classes of factors.

In particular, the following characteristics seem most important: 1) the importance of scale and scope economies in R&D&L and the achievement of high level of efficiency in internal knowledge production through vertical integration; 2) the extent to which social capital is diffused and shared in the system; 3) the sectoral properties of the system in terms of knowledge base, connectivity between actors and institutions, and finally 4) the stage in which the system is playing with regard to the industry life cycle (Malerba, 2004).

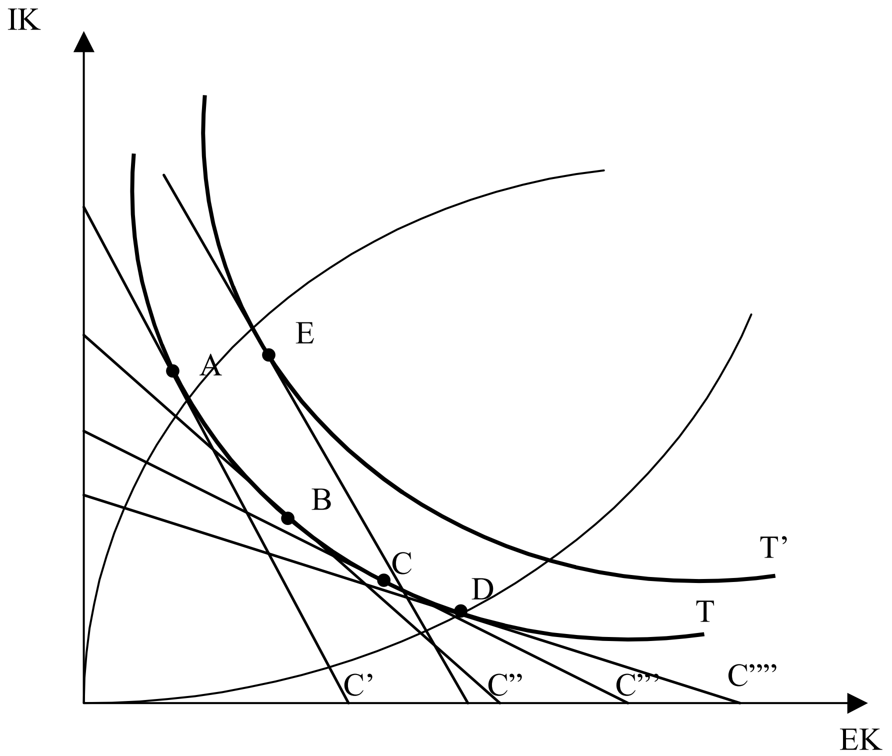
A range of empirical conditions is possible, according to the combinations of factors in terms of knowledge base, institutions for the diffusion, tradability and appropriability of knowledge, and the connectivity between actors. In such situations, external knowledge may be relatively more convenient than internal R&D&L, or *vice versa.*

Different modes of knowledge production can be identified as the effect of the different characteristics of economic systems, and of the changes in such characteristics, that induce firms to choose accordingly both the mix and the amount of internal and external knowledge. The case for both technical and technological variety applies.

Figure 4 shows the implications of different characteristics of economic systems in terms of the relative costs of internal and external knowledge. With a given technology (T) available in the system, different relative costs and costs structure imply that internal and external knowledge can be used in different proportions, the technological knowledge production process using more intensively the more convenient factor.

Technical variety and the possibility that different combinations of internal and external knowledge may generate the same amount of technological knowledge T is now the effect of changing characteristics of economic system. Standard substitution between internal resources and external knowledge takes place but within a bounded economic space. Technical change is here the induced effect of proportionate changes in factors costs.

Figure 4. Collective knowledge costs and technical variety



First, firms may find it easier to generate the greatest part of the knowledge they need to innovate (point A in figure 4). This is for instance the case when economic variety is very limited, a limited number of potential partners are available in the system and interaction is harmed by opportunistic behaviors, inappropriate communication channels or by the fact that players do not posses the competencies to understand external and different knowledge bases. In this case, the costs of external knowledge access are very high and the scope for the exploitation and appropriation of potential knowledge externalities very narrow. Technological systems are centered upon R&D-intensive large firms.

Large firms can achieve important scale and scope economies in R&D and economies of learning are most relevant. Here, internal R&D&L is more convenient than external access and new knowledge production uses internal resources more intensively (Chandler, 1990; Momigliano, 1975; Penrose, 1959).

Large firms and vertical integration are traditionally seen as the rational choice to a context in which high risk of opportunistic behaviors and thus high transaction costs make the use of the market and the recourse to external resources inefficient (Williamson, 1975 and 1985). However, according to the collective approach to technological knowledge, a minimal amount of external knowledge is necessary for increasing returns in knowledge production to take place. Here, economies of scale and scope in R&D are not only relevant in the direct production of internal knowledge but also in the recombination of different modules of knowledge. These can be originally developed in an external context and subsequently integrated because of high internal capabilities. The automobile industry can be a case in point. Car production requires the full understanding of the complementarities within a wide range of different technologies and the command of a very complex set of knowledge modules in engineering, electronics, chemistry, plastics technology, robotics, informatics and telecommunications. Knowledge is very complex, building upon the recombination of external and internal knowledge via the supply and demand of patents, components and process technologies, and via the accumulation of more tacit knowledge through user-producer interactions. Accumulation of internal knowledge and the recombination of different portions of knowledge can take place through mergers and acquisitions, corporate restructuring, services and intermediary research products delivered by third parties, and wider diversification in the patent portfolios of car markers. Car makers are in turn emerging as large R&D&L-performing firms. Knowledge diversification and knowledge economies of scope can be the strategic answer to increasing competition and entering into sectoral maturity. Such internal accumulation sustains technological diversification across technological and scientific fields, and shows the increasing complexity of the competencies that are necessary to introduce new products, technologies and processes in the car industry. The accumulation of such competencies is clearly benefiting from the advantages of size effects.

However, given an economic space characterized by bounded input complementarity and substitutability, the solution in A is not feasible because it takes place beyond the bounds of the system. The firm is induced to change technology, moving towards higher isoquants. Technological change (solution E on the new isoquant T') is here the response induced by the impossibility of technical change and technical variety.

Second, when the structural and dynamic characteristics of the system support wide horizontal interactions among a variety of complementary actors, and market and social institutions allow efficiency in knowledge transactions, then R&D efforts and recombination together with learning can play a major role in coordinating the creation and distribution of knowledge. Knowledge modules can be easily traded in the market place in both disembodied (i.e., patents and licenses) and embodied (i.e., basic inputs, components, process technologies) forms, and recomposed and recombined through market exchange. Knowledge can be characterized by higher levels of fungibility and horizontal complementarity, (formal) appropriability, and internal and external cumulability (Arora, Fosfuri and Gambardella, 2001; Guilhon, 2001).

The telecommunication system of innovation is a case in point. It emerges as a complex bundle of complementary portions of technological knowledge that is also characterized by high levels of fungibility. New information and communication technologies are the outcome of the recombination of a variety of knowledge modules in the electronics, telecommunications, physics, chemistry and plastics technologies. At the same time, new communication technologies can be in fact applied to a large variety of productive processes and service delivery in both new and emergent sectors. The markets for knowledge together with the intermediary role of knowledge-intensive business services play a very important role. They support the tradability of embodied and disembodied knowledge between large producers and large users, and between these and the academic and pure research system (Edquist, 2003).

When R&D activity and recombination are prevalent and transaction costs are low but in a very well limited technological space, external general knowledge is the main input in the generation of new portions of technological knowledge. Technological knowledge is now characterized by high levels of fungibility but low levels of complexity. University, public pure research and large firms R&D efforts are key elements in supporting the creation of the eventual module of technological knowledge and its diffusion. Knowledge can be easily traded in the marketplace through patents and licenses but within a well-defined community, bounded within a limited set of scientific and technological competencies. Knowledge co-ordination is limited as well, and does take place essentially through the working of the markets for knowledge and public provision. Biotechnology can provide clear evidence. Biotechnologies can be applied to a wide range of industries and activities such as pharmaceuticals, food and beverages, agricultural and chemical products. At the same time, advances in biotechnological knowledge benefit from the activity of a narrower scientific and technological community, in which recombination of external knowledge takes place almost exclusively through patenting and licensing (Carlsson, 2002).

Finally, external knowledge can be more convenient because of the effect of the sharing of social norms and the diffusion of social capital. Industrial, institutional and social networks are most relevant for the evolution of localized technological systems such as technological and industrial districts (Feldman and Massard, 2002). Here, economic systems are characterized by the presence of a variety of complementary partners. Moreover, vertical interactions among very specialized producers are very well rooted in the historical and social context of the system. In turn, firms may find easier access to external knowledge than producing internally most of the knowledge they need (point D in figure 4).

Where the structural and dynamic characteristics of the system cannot easily allow formalized co-ordination between small firms on the one hand, and University and science-based institutions (including large firms' R&D units) on the other, internal tacit learning and socialization can be dominant processes the co-ordination of the division of labor can be built upon. Geographical co-location and agglomeration favors the sharing of common social and cultural protocols that support tacit learning and the accumulation of a common pool of local and firm-based tacit knowledge with very low levels of fungibility and formal tradability. Industrial and technological district are characterized by relatively cheap access to external knowledge because of the role of shared social capital. Knowledge production increasingly relies on external knowledge. Here transaction costs, in principle, can be very high because of high levels of stickiness and inappropriability. However, these are eventually kept low by trust and common norms that counteract opportunism and eventually select and exclude free-riders from the network. Moreover, technological distance is low because of vertical interrelatedness among firms within the same industry and because of horizontal complementarity between firms in different industries. Embodied tradability via labor dynamics can be typical in such a context. Traditional industries such as the textile, furniture and mechanics sectors can be a clear example of technological systems where vertical linkages and user-producer relations co-ordinate the local division of labor. Knowledge is mainly tacit and embodied in workers and artifacts, and it can be exchanged and recombined by means of informal co-operation and interactions, and labor mobility (see for instance, Russo, 1985 and 2000; Belussi, Gottardi and Rullani, 2003).

It should be clear that the lower the cost of one factor and the more intensive the use of that factor, the less balanced will be the mix of internal and external knowledge. The technical solution adopted by the system will be closer to the bounds, and can be depicted as a corner solution (such as point D in Figure 4). Such corner solutions can be characterized by strong irreversibility and the risk of lock-in, in turn generating strong path-dependency in the dynamics of knowledge generation.

From the dynamic viewpoint this has important implications for the evolution of technological systems.

4. THE PATH-DEPENDENT EVOLUTION OF TECHNOLOGICAL SYSTEMS

In a dynamic context, the idiosyncratic initial endowment of economic factors, and particularly the accessibility conditions to external knowledge implies that the sequence of new knowledge generated and introduced in the system is itself constrained.

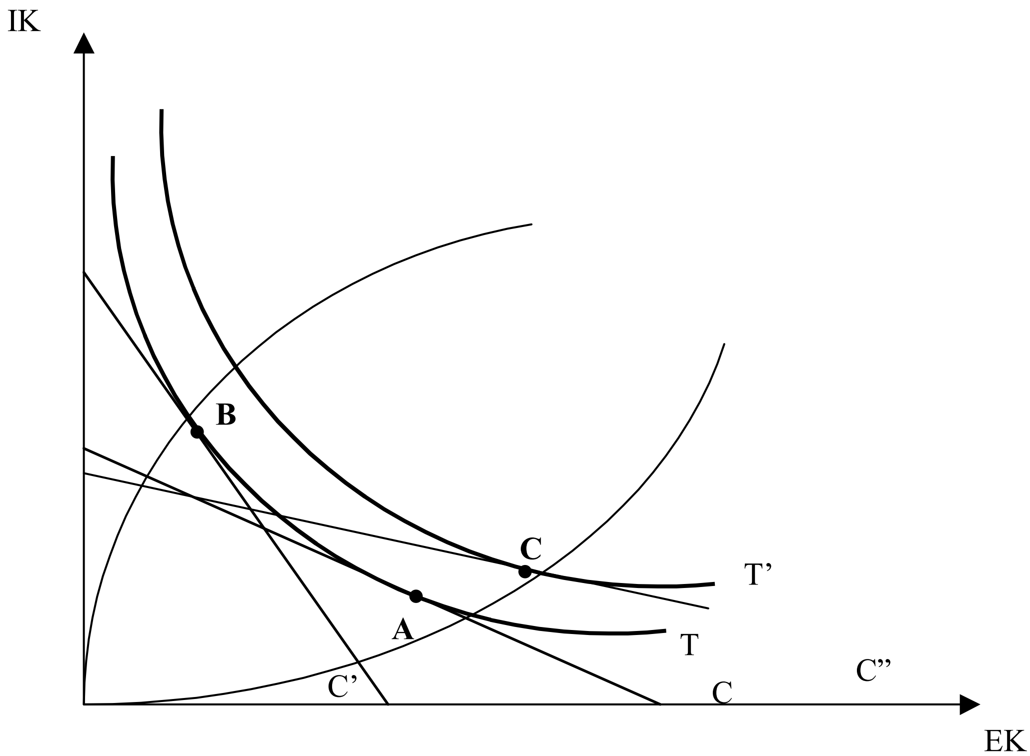
More precisely, the possibility of introducing changes in the way technological knowledge is produced is bounded by technical proximity. This can be defined with regard to the pool of technological knowledge and technology previously introduced and used, and with regard to the possibility to face relevant costs of learning, communication and access to external knowledge. New bodies of technological knowledge can be efficiently created in an economic space defined in terms of proximity to the pool of technological knowledge previously produced. Changes are possible only by incurring substantial costs that parallel the technical distance between the new pool of technological knowledge and the previous one. In this regard, human creativity and ingenuity are possible and knowledge production is not deterministically past-dependent. Nevertheless, ingenuity in the generation and introduction of new knowledge and technology is bounded. The production of new knowledge is characterized by path-dependent dynamics resulting from the interaction between internal learning and accumulation of external knowledge under specific constraints (Antonelli, 2003; David, 1975; Mokyr, 1990).

Strong elements of irreversibility characterize such process.

Let us assume a change in the relative costs of internal and external knowledge (Figure 5). With respect to the initial situation depicted by the solution in A on the isocost C and isoquant T, the solution in B would represent the standard situation in which changes in the relative costs of internal and external knowledge compensate each other and technical change would be the response to changes in relative costs. However, this would represent an inefficient solution. Irreversibility due to high initial endowment of external knowledge relatively to internal knowledge is at place. Changing the mix of resources from A to B would be extremely costly because of the higher technical distance between the two different mixes. Departures from the mix of resources used are possible only through an array of costly investments in learning that are proportional to the distance between the new pool of technological knowledge and the previous one. It should be clear that C represents a more appropriate and feasible when considering the initial mix of resources in A, because it represents a closer solution to the initial endowment of resources. Irreversibility induces technological change resulting in the upward shift to the isoquant T'.

In other words, economic actors are able to react to the changes in the characteristics of the systems. Precisely, they are able to lock-out and avoid lock-in introducing new technological knowledge, but only within specific boundaries.

Figure 5. Relative costs and technological change in technological systems



In such a situation, economic systems such as industrial and technological districts are induced to change technology rather than technique, taking advantage from the opportunity of achieving a decrease in the cost of external knowledge more than proportionate to the increase of the cost of internal knowledge. While technical variety is the result of proportionate changes in the relative cost of internal and external knowledge, on the contrary, when the reduction in the costs of one factor is more than proportionate to the increase in the cost of the other input, then technological variety is also possible as the result of the induced effect on output.

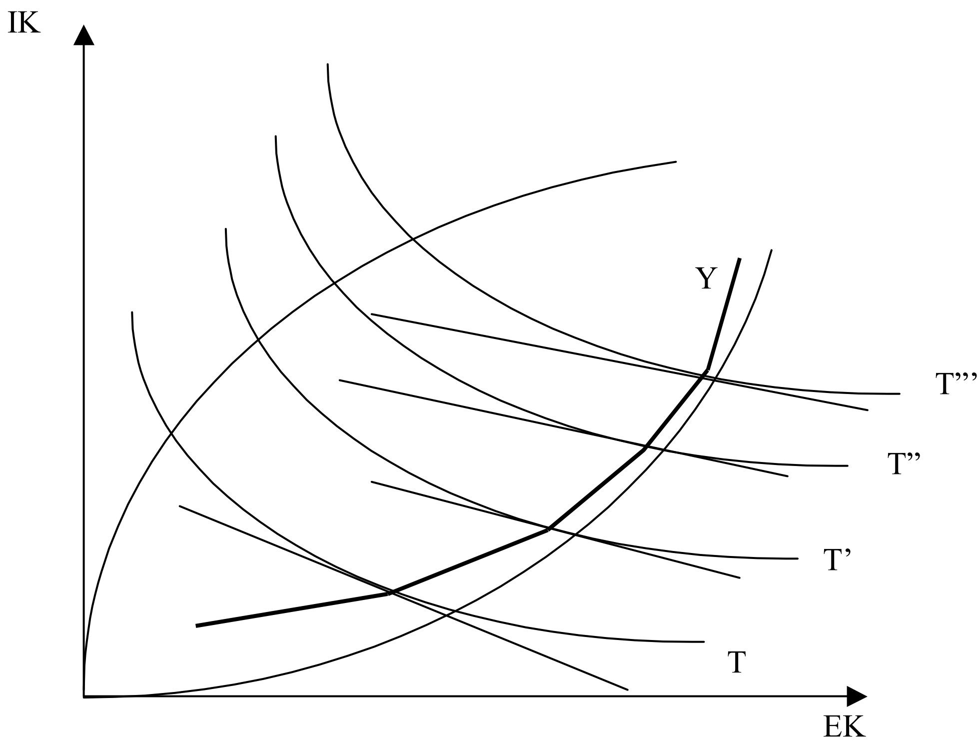
Technological and industrial districts can benefit from such an output effect, shifting from A to C, when the effect of social capital and the sharing of common norms and institutions make possible a reduction in the costs of external knowledge more than proportional to the relative increase in the cost of internal R&D&L. Knowledge is specific and highly tacit with potentially high costs both in access to a given pool of knowledge, and in integrating between different modules. Here technological communication is based on interpersonal interaction and tacit learning, which, together with industrial and institutional networks, favor more convenient access to external knowledge, resulting into higher amounts of technological knowledge. More complex localized technological systems can also combine the effect of social capital and the access to external and science-based knowledge through codification and access to 'blueprints'. Here, the costs to access and understand the code on which a given portion of knowledge is based, as well as the costs to replicate and integrate such a portion of knowledge in other contexts are also lower. The access and diffusion of knowledge is even easier because it combines the effect of social capital and codification, and technological communication can be also based on formal collaborations, ultimately with an even higher relative effect on output (Patrucco, 2003 and 2005).

When the traditional effect of agglomeration economies and geographical proximity can be combined with technological and institutional complementarities, the opportunities for knowledge spillovers can be exploited through a complex network of connections. Science-based, engineering-based, tacit and high-skills based modules of knowledge are provided by R&D departments of large firms and collective research centers, client firms, small producers and knowledge-intensive-business-services respectively. Those are recombined into a common local knowledge base by the systemic and systematic interactions between the different actors. Technological knowledge can be traded in both embodied and disembodied forms through user-producer interactions, the provision of knowledge services by means of consultants and technology centers, and triangular communication between these and University.

Within technological and industrial districts, changes in the technology used and implemented, together with changes in the level of knowledge produced, are also induced as the effect of the interaction between changes in the characteristics of the relative costs of resources and the irreversibility conditions that characterize the mix of resources because of the high endowment of external knowledge. Efficient channels of technological communication play a major role, creating the opportunity for cheaper access to external knowledge and favoring technological change based on the intensive use of external knowledge. In turn, such a technological change reinforces irreversibility itself, generating a new corner solution (C) and a new mix of resources in which external knowledge is used more intensively than in the previous mix (A).

At each time *t,* technological knowledge production is bounded with respect to the characteristics of economic systems in terms of the relative costs of inputs. In different periods *(t+1, t+2, ..., tn)*, technological knowledge production is affected and constrained by the changes in such relative costs and the irreversible mix of internal and external resources previously used. The overall process of knowledge growth and the evolution of technological systems based upon such knowledge production can now be represented as the evolution of a given technological knowledge production process (Y) at the same time constrained and supported by changes in the characteristics of the economic system (Figure 6).

Figure 6. The path dependent evolution of technological knowledge and technological systems



Changes in the relative costs of internal and external knowledge due to changes in the characteristics of economic systems affect the evolution of the growth of knowledge. More precisely, changes in the costs conditions shapes the direction of knowledge production and the related characteristics and evolution of technology systems. The evolution of technological systems is continuous and yet punctuated by changes. These are due to changes in the relative costs of internal and external knowledge and therefore in the relative mix of internal and external resources used in the knowledge production process.

5. CONCLUSIONS

Knowledge production, accumulation and evolution depend on very specific and irreversible conditions. These reflect the interactions between the structural and dynamic properties of economic systems in terms of different classes of factors: 1) the variety of receptive actors and connections between them; 2) the relative costs of internal knowledge production and external knowledge access; 3) the historical sequence of both the investments in knowledge production and the decision of organizing such investments whether internally or externally.

Viability conditions and learning mechanisms play a major role in the dynamics of collective technological knowledge and technological systems. Firms able to establish interconnections with a variety of actors can internalize complementarities between internal and external knowledge. Learning refers to both technologies and techniques that are already in place within the firm and to external knowledge. New amounts of knowledge and new technologies can be more easily introduced in those fields in which the firm has already accumulated competencies and know-how. Relevant elements of irreversibility now affect the process of learning and accumulation of technological knowledge, and the eventual generation of innovation. In other words, the introduction of new knowledge takes place in the space defined by the techniques used by the firm and the specific processes of external learning put in place by the firm. The dynamics of technological knowledge are the results of irreversible processes of accumulation and integration between internal and external kinds of knowledge that are distributed among a variety of actors with idiosyncratic features.

Technological systems can benefit to different extents from technological and geographical localization, according to the effect that structural and dynamic characteristics have on the interaction between internal production costs and external access costs. In turn, the production of knowledge can be specified into a variety of localized models that are affected by the specific composition of internal knowledge production costs and external access costs.

In sum, the production and diffusion of knowledge is affected by the interaction between internal knowledge production costs and external knowledge access costs. It takes place in different forms according to the structural and dynamic characteristics of economic systems. These determine actual costs conditions and affect the processes through which technological knowledge is generated and distributed.

Moreover, the appreciation of the implication of changes in the relative costs and the mix of internal and external knowledge is also important to understand the way in which different costs structures can promote technical and technological variety. When changes in the relative costs of internal and external resources occur and technical change is not possible because of the irreversibility of the mix of resources previously used, technological change is the response to the changes in the relative costs of inputs and to the impossibility of changing techniques. This contributes to the understanding of the variety of governance structures in the generation of collective technological knowledge and the emergence and evolution of technological systems.

The growth of knowledge might now be seen as relying upon a production process where the creation of new knowledge can build upon itself through the new recombination of existing portions of internal and external knowledge. Such recombination is affected by both the structural conditions of the system in which it takes place and the dynamic sequence of combinations of portions of knowledge. Structural conditions and the previous combinations of ideas sustain and at the same time constrain human creativity, in a cumulative, self-sustained and path-dependent production of new knowledge (Weitzman, 1996 and 1998). At the same time, such changes in the characteristics of economic systems and in the cost conditions shape the direction of the growth of knowledge and the evolution of the technological systems relying upon such knowledge dynamics.

REFERENCES

Allen, R. (1983). Collective invention. *Journal of Economic Behavior and Organization* 4, 1-24.

Antonelli, C. (1999). *The Mycrodynamics of Technological Change*. London: Routledge.

Antonelli, C. (2001). *The Microeconomics of Technological Systems*. Oxford: Oxford University Press.

Antonelli, C. (2003). *The Economics of Innovation, New Technologies and Structural Change*. London: Routledge.

Arora, A., Fosfuri, A. and Gambardella, A. (2001). *The Markets for Technology*. Cambridge, MA: The MIT Press.

Belussi, F., Gottardi, G., and Rullani, E. (eds.) (2003). *The Technological Evolution of Industrial Districts*. Boston: Kluwer Academic Publishers.

Carlsson, B. (ed.) (2002). *Technological Systems in the Bio Industries: An International Study*. Boston: Kluwer Academic Publishers.

Chandler, A. D. (1990). *Scale and Scope: The Dynamics of Industrial Capitalism*. Cambridge, MA.: Harvard Business Press.

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

Cowan, R. and Jonard, N. (2003). The dynamics of collective invention. *Journal of Economic Behavior and Organization* 52, 513 – 532.

David, P. A. (1975). *Technical Choice, Innovation and Economic Growth*. Cambridge: Cambridge University Press.

Edquist, C. (ed) (2003). *The Internet and Mobile Telecommunications Systems of Innovation*. Cheltenham: Edward Elgar.

Feldman, M. and Massard, N. (eds.) (2002). *Institutions and Systems in the Geography of Innovation.* Boston: Kluwer Academic Publishers.

Guilhon, B. (ed.) (2001). *Technology and Markets for Knowledge: Knowledge Creation, Diffusion and Exchange within a Growing Economy*. Boston: Kluwer Academic Publishers.

Malerba, F. (ed.) (2004). *Sectoral Sytems of Innovation*. Cambridge: Cambridge University Press.

Mokyr, J. (1990). *The Lever of Riches*: *Technological Creativity and Economic Progress*. Oxford: Oxford University Press.

Momigliano, F. (1975). *Economia Industriale e Teoria dell'Impresa*. Bologna: Il Mulino.

Patrucco, P.P. (2003). Institutional variety, networking and knowledge exchange: communication and innovation in the case of the Brianza technological district. *Regional Studies* 37 (2), 159-172.

Patrucco, P. P. (2004). The economics of collective knowledge and technological communication: a simple model, paper presented at the 2004 International Schumpeter Society Conference, Milano, 9-12 June, 2004.

Patrucco, P.P. (2005). The emergence of technology systems: knowledge production and distribution in the case of the Emilian plastics district. *Cambridge Journal of Economics*, 29 (1), 37 – 56.

Penrose, E. (1959/1995). *The Theory of the Growth of the Firm*. Oxford: Oxford University Press.

Russo, M. (1985). Technical change and the industrial district: the role of interfirms relations in the growth and transformation of the ceramic tile production in Italy. *Research Policy* 14, 329-343.

Russo, M. (2000). Complementary innovations and generative relationships: an ethnographic study. *Economics of Innovation and New Technology* 9, 517-557.

Weitzman, M. L. (1996). Hybridizing growth theory. *American Economic Review* 86 (2), 207-212.

Weitzman, M. L. (1998). Recombinant growth. *Quarterly Journal of Economics* 113, 2, 331-360.

Williamson, O. E. (1975). *Markets and Hierarchies. Analysis and Antitrust Implications.* New York: The Free Press.

Williamson, O. E. (1985). *The Economic Institutions of Capitalism*. New York: The Free Press.