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Dipartimento Economia e Statistica Cognetti de Martiis

Working Paper Series

13/17

DIGITAL KNOWLEDGE GENERATION AND THE APPROPRIABILITY TRADE-OFF

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brick Bureau of Research on Innovation, Complexity and Knowledge

UNIVERSITÀ DEGLI STUDI DI TORINO

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DIGITAL KNOWLEDGE GENERATION AND THE APPROPRIABILITY TRADE-OFF[1]

FORTHCOMING IN TELECOMMUNICATIONS POLICY

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ABSTRACT. The introduction of information and communication technologies (ICT) has changed in depth the organization of the generation of knowledge reducing significantly knowledge absorption cost and improving knowledge interactions. The digital generation of knowledge relies on the systematic access and use of the stock of quasi-public knowledge. ICT enable to reconsider the knowledge appropriability trade-off as it helps to better appreciate the positive role of knowledge spillovers in the recombinant generation of new knowledge, next to the well-known negative effects of the limited appropriability of knowledge on revenues and hence incentives to innovate. This new analytical framework calls for an augmented role of telecommunications policy that should take into account the positive effects of knowledge connectivity on the generation of knowledge.

KEY WORDS: KNOWLEDGE APPROPRIABILITY; KNOWLEDGE SPILLOVERS; KNOWLEDGE DERIVED DEMAND; DIGITAL KNOWLEDGE GENERATION; TELECOMMUNICATIONS POLICY, INFRASTRUCTURE, REGULATION.
JEL CODES: O31, O33

1. INTRODUCTION

New information and communication technologies (ICT) have been a radical innovation. As a general purpose technology their introduction has enabled an array of technological and organizational changes in a wide variety of activities (Bresnahan and Trajtenberg, 1995; David and Wright, 2003; Brynjolfsson and Saunders, 2010; Bauer and Latzer, 2016).

[1] I acknowledge the support of the research funds of the Collegio Carlo Alberto and the Università di Torino as well as the useful comments of Agnieszka Gehringer, Davide Consoli, the editor Erik Bohlin and two anonymous referees.

Their impact on the generation of knowledge is one of the most important. ICT have induced significant innovations in the knowledge generation process increasing its efficiency and changing in depth its organization and structure. These changes have in turn major effects on the role of knowledge spillovers and the cost of new knowledge. The new understanding of the actual role of knowledge appropriability on knowledge cost and revenue, brought about by the organizational innovations associated to the introduction of ICT, enables to reconsider the Arrovian market failure hypothesis, to reframe the appropriability trade-off and to suggest an augmented role of telecommunications policy.

The rest of the paper is structured as it follows. Section 2 recalls the analytical context of the knowledge appropriability trade-off. Section 3 reviews the main results of the different and yet complementary literatures ranging from knowledge management to economics of innovation and economics of knowledge that have explored the effects of the introduction of ICT on the organization of the knowledge generation process. Section 4 elaborates an integrated framework to assess their effects on the knowledge appropriability trade-off. Section 5 explores the implications of the results stressing the need for a new agenda for telecommunications policy. The conclusions summarize the analysis.

2. THE KNOWLEDGE APPROPRIABILITY TRADE-OFF

The understanding of the knowledge appropriability trade-off is the result of a long standing process started with the identification of the peculiar characteristics of knowledge as an economic good.

2.1 KNOWLEDGE APPROPRIABILITY AS A PROBLEM

Nelson (1959) opens the process with the identification and exploration of the consequences of the limited appropriability of knowledge and articulates the distinction between the social and private profit of knowledge: “The quantity of resources that a society should allocate to basic research is that quantity which maximizes social profit. Under which conditions will private-profit opportunities draw into basic research a quantity of resources that is socially desirable? If all sectors of the economy are perfectly competitive, if every business firm can collect from society through the market mechanism the full value of benefits it produces, and if social costs of each business are exclusively attached to the inputs it purchases, then the allocation of resources among alternatives uses generated by profit maximizing will be a socially optimal allocation of resources. But when the marginal value of a ‘good’ to society exceeds the marginal value of the good to the individual who pays for it, the allocation of resources that maximizes private profits will not be optimal" (Nelson, 1959: 298).

The comparative analysis of knowledge and standard economic good enabled Kenneth Arrow (1962) to generalize the intuition of Richard Nelson and to identify the peculiar and idiosyncratic characteristics of knowledge, such as limited appropriability, poor excludability and negligible reproduction costs. Because of the limited appropriability of knowledge 'inventors' can retain only a fraction of the economic benefits of the knowledge they generated.

The limited appropriability of knowledge exerts negative effects on the price of goods that include knowledge as an input in the production process. As a consequence, its derived demand is lower than the derived demand of a standard production input. In the Arrovian framework –because of the lower levels of the price of output - the equilibrium price of knowledge is below the competitive level. Because of the limited appropriability of knowledge and the divergence between its generation and reproduction costs, the market price of the product that embodies can actually be so low that it does not allow recovering the costs incurred to purchase - and use - knowledge.

In extreme Arrovian conditions, the use of knowledge with very low levels of appropriability, high generation costs and very low reproduction cost, in other words, can be at the origin not only of *lucrum cessans* (missing profitability) but also of *damnum emergens* (emerging losses*)*. In competitive markets, where both incumbents and entrants can imitate and use the knowledge generated by inventors, the market price would rapidly fall to levels below the marginal cost incurred by the inventor. These levels, in fact, would take into account all the other costs, incurred by every other firm, but the costs of knowledge that have been paid to inventors. Knowing his inability to appropriate knowledge, the inventor lacks incentive to innovate and the classical Arrovian market failure occurs.

The Arrovian analysis focused on the consequences of the properties of knowledge on the levels of knowledge produced and used by firms. Because of the reduction of the private rates of returns measured by the marginal productivity and profitability of knowledge -causedby its limited appropriability- firms generate and use –at the same time- a lower amount of knowledge than it would have happened had knowledge been a standard good (Arrow, 1962; 1969). This effect results in a negative incentive that lead to generate less knowledge than socially desirable.

This represents the Arrovian hypothesis of the “failure of the market” as the appropriate institutional setting for the allocation of resources to the generation of knowledge. The markets are unable to allocate and produce the correct amount of knowledge. Because of the idiosyncratic characteristics of knowledge as an economic good the market place is doomed to undersupply knowledge. The Arrovian framework has so far provided the foundations of an economic policy aimed at remedying the knowledge market failure (Antonelli and David, 2016).

The analysis of Arrow (1962) is a founding stone not only for its normative implications, but also as it makes an important methodological contribution as it relies the comparative analysis of ‘knowledge as a standard good’ with respect to ‘knowledge as a special good’. The comparative approach remains at the core of the economics of knowledge and enables to identify the full range of implications and consequences of the properties of knowledge both for economics and economic policy.

Recent contributions have further elaborated and developed the Arrovian analysis qualifying the context: the limited appropriability of knowledge exerts strong negative effects on the price of innovated goods mainly if not especially for the dynamics of imitation by competent rivals in the very same product markets. Rivals active in the very same product markets can easily take advantage of the novelties contained in each innovation and reproduce the knowledge on which they rely, at low cost (Akcigit and Howitt, 2015). The price of innovated goods falls and affects directly the position of the derived demand of knowledge. The negative effects of the limited appropriability of knowledge are much lower when the spillover of knowledge concerns unrelated agents active in other product markets for two reasons: i) the risks of imitative entry are much lower and hence the risks of missing revenue stemming from the spillover; ii) their capability to actual use it again as an input into their own knowledge generation processes is hindered by absorption costs that are larger the larger the distance in cognitive and product spaces.

2.2 KNOWLEDGE APPROPRIABILITY AS AN OPPORTUNITY

The Arrovian framework was questioned by the intuition of Zvi Griliches (1979 and 1992) that the limited appropriability of knowledge may have some beneficial consequences due to the occurrence of positive externality that favor the recipients of spillovers, rather than just negative ones due to the missing incentives and the consequent underproduction of knowledge. The knowledge that inventors cannot appropriate *spills* in the atmosphere and because of its non-exhaustibility contributes the stock of quasi-public knowledge that can be used by third parties at low costs.

Griliches provides the first definition of knowledge spillover: “The last major issue is that of "spillovers," the effect of "outside" knowledge capital-outside the firm or industry in question – on the within – industry productivity. The level of productivity achieved by one firm or industry depends not only on its own research efforts but also on the level of the pool of general knowledge accessible to it. Looking at a cross section of firms within a particular industry, one will not be able to distinguish such effects. If the pools of knowledge differ for different industries or areas, some of it could be deduced from inter-industry comparisons over time and space. Moreover, the productivity of own research may be affected by the size of the pool or pools it can draw upon. This would lead to the formulation of models allowing for an interaction between the size of individual and aggregate research and development effort.” (Griliches 1979:102).

With respect to standard goods, in fact, knowledge is characterized by a second set of characteristics such as indivisibility and hence complementarity, and non-exhaustibility and hence cumulability. As a consequence the portion of its marginal productivity that could not be appropriated by its producer adds to the stock of quasi-public knowledge and can be used –again- by third parties. This has positive consequences on the system as a whole. Because of knowledge non-exhaustibility, in fact, the same knowledge spillover can be used again and again at almost no cost. Knowledge non-exhaustibility augments the positive effects of knowledge spillover on the costs of new knowledge and on the scope for further generation of innovation. Specifically, the cost of knowledge stemming from the use of external knowledge, coming from third parties as an input in a further innovative process, is lower the weaker the appropriability provided by excludability based on secrecy, intellectual property and the larger its cumulability. This approach has been implemented by the notion of absorption costs introduced by Cohen and Levinthal (1989 and 1990) that have stressed the role of the tacit content of knowledge as a barrier to its secondary uses. External knowledge spills freely in the system because of its limited appropriability but its identification, selection, retrieval and actual use is not free. Firms need to implement dedicated and resource activities to actually access the stock of knowledge available in the system to use it as an input into the generation of new knowledge (Aghion and Jaravel, 2015).

2.3 THE KNOWLEDGE APPROPRIABILITY TRADE-OFF

The introduction by Zvi Griliches of the notion of knowledge spillovers revealed the positive role of the stock of knowledge that becomes available for further uses in the generation of new knowledge, more and more viewed as a process of recombination of existing knowledge items. Because of knowledge indivisibility, the stock of existing knowledge is an indispensable input for the generation of new knowledge that stems from its limited appropriability. This approach reveals the other side of the well-known problems raised by the analysis of the limited appropriability of knowledge in terms of missing incentives, undersupply and more generally market failure framed by Richard Nelson (1959) and Kenneth Arrow (1962). The knowledge appropriability trade-off is set. With respect to standard goods knowledge has peculiar characteristics that exert both positive and negative externalities.

The former consists in the fall of the price of innovated goods stemming from the ease of imitation in neck-to-neck competition with the consequent downward shift of the derived demand of knowledge and the reduction of the incentives to the generation of knowledge. The latter stem from the availability of a large stock of knowledge as a quasi-public good that (may) lead to the reduction of the cost of external knowledge and hence to compensate for the reduction of the demand for knowledge. The quality of the knowledge connectivity of the system here plays a crucial role: the better the knowledge connectivity, the lower knowledge absorption costs and hence the larger the actual positive externalities.

The new methodological advances of the economics of knowledge with the introduction of the technology production function (Griliches, 1979), the knowledge generation function (Griliches, 1979; Pakes and Griliches, 1984) eventually framed by the CDM (Crepon, Duguet, Mairesse, 1998) approach, the analysis of the derived demand of knowledge (Antonelli, 2017) and of the knowledge cost function (Antonelli and Colombelli, 2015b) enable to appreciate in an integrated and comprehensive framework the dual role of knowledge externalities.

3. ICT AND THE DIGITAL GENERATION OF KNOWLEDGE

The changes brought about by the introduction and diffusion of ICT in the organization of the generation of technological and scientific knowledge are most likely to affect the knowledge appropriability trade-off with important consequences in terms of firms strategy and economic policy.

Different economic literatures have contributed the exploration of the effects of the introduction of ICT in the knowledge generation process: the knowledge management literature, the economics of innovation and the economics of knowledge. The knowledge management literature has explored in depth the effects of ICT on the organization and structure of the knowledge generation process. It seems possible to identify two stages in this exploration. The first has concentrated its attention on the internal organization of the research process. The second has identified and appreciated the new role of external knowledge made possible by the systematic use of ICT. The economics of innovation and knowledge have analyzed in depth the consequences for the economic analysis of the results of the previous stages (Antonelli, 2009). Let us consider them in turn.

3.1 ICT: THE INTERNAL ORGANIZATION OF R&D ACTIVITIES.

In the first step the knowledge management literature has focused the analysis on the re-organization of research activities within corporations enabled by the introduction and intrafirm diffusion of an array of dedicated applications of ICT. Multinational corporations lead the adoption of ICT to increase the coordination and integration of their distributed activities (Antonelli, 1985 and 1986).

Zuboff (1988) and Davenport and Prusak (1998) synthetize the main achievements of this stage of analysis. ICT are regarded as a process innovation that enables to overcome the limits of the internal dissemination of information and data. According to Hendriks (1999) ICT lower temporal and spatial barriers between knowledge workers, and helps improving the motivation of workers to share information about knowledge. ICT augments the efficiency of the knowledge generation process increasing the internal interfaces among the different activities of the research laboratories and between them and the engineering, commercial, and financial functions of the firm. The improved quality of internal interactions favors the better use of internal information that was dispersed and higher quality alignment of research strategies with corporate strategies. The diffusion of ICT applications trickles down with their rapid adoption by smaller firms. According to Hempell and Zwick (2008) ICT increase the ability of workers to cooperate and take decentralized decisions within an integrated context.

Dodgson, Gann and Salter (2006) show how the introduction of ICT enabled the introduction of an array of ICT based innovations such as data mining, simulation, prototyping and visual representation. The increased efficiency of internal R&D activities coupled with the use of ICT applications widens the scope of the knowledge generation process and reduces the idiosyncratic advantages associated to the size of firms (Esposito and Mastroianni, 1998 and 2001). The use of ICT to perform R&D activities enables to overcome the classical limits that favored R&D activities conducted by corporations and allowed small firms to increase the efficiency of their internal R&D activities. The evidence provided by Morikawa (2004) confirms that Japanese SMEs using ICT in innovative activities were better able to perform R&D activities and introduce technological innovations than firms that had not adopted ICT and implemented their use in R&D activities.

The general consensus confirms that the adoption of ICT enables the introduction of major organizational innovations in the performance of internal research activities that enable to mobilize and integrate different sources of knowledge including the valorization of tacit knowledge and the interaction of different activities within the firm with the increase the efficiency of internal R&D activities and the ultimate reduction of knowledge costs (Debackere and Van Looy, 2003; D'Adderio, 2004).

3.2 ICT: KNOWLEDGE SPILLOVERS AND ABSORPTION COSTS

The second step of the literature is the result of a major shift in the focus of the analysis of the effects of ICT from the internal organization of R&D activities, to the appreciation and use of the large stock of external knowledge available in the system. ICT made it possible to improve drastically the economic value of the large stock of knowledge available in the system and to reduce its costs of absorption (Antonelli, Geuna, Steinmueller, 2000).

Cerchione Esposito and Spadaro (2015) document the wide range of specific computer applications that enable to widen the search in the stock of external knowledge available in the system. The use of the new ICT based techniques enables to overcome the classical separation of scientific and technological knowledge. The rich output of the scientific literature could be accessed and used only to a limited extent by competent and highly qualified experts. Only large corporations could take advantage of their skills. Much scientific literature could be not used to implement technological knowledge and consequently feed the introduction of innovations. The introduction of ICT based innovation reduces such barriers and favors the interaction between science and technology. Small firms especially benefit of the reduction of the barriers to the effective access to the stock of scientific knowledge to implement their own internal generation of new knowledge (Higon, 2011).

The systematic literature review by Pittaway et al. (2004) provides strong evidence on the effects of ICT based procedures on the access to the stock of external knowledge: “identification of key words; construction of search strings; initial search and identification of further key words; choosing the citation databases; review of the selected citation databases using the search strings; review of the citations identified based on inclusion and exclusion criteria; review of the citation abstracts and separation into different lists; encoding abstracts according to their content; reviewing significant articles; the addition of further articles, based on professional recommendation and references from reviewed articles.” (Cerchione, Esposito and Spadaro, 2015).

ICT applications enabled to make use of the huge amount of external knowledge that is available in the system. ICT enable to access much a larger quantity of information and data. ICT allow a drastic reduction of resources that are necessary to implement the search, gathering, storing, screening, access, absorption and finally use of the knowledge spilling in the atmosphere.

ICT enables to reduce the costs of distance in absorbing technological knowledge (Koellinger, 2008). Large evidence had documented the negative role of distance in geographic, product and cognitive space for the absorption of external knowledge. Proximity helps to access and use external knowledge. Geographical proximity helps personal interactions. Cognitive proximity reduces the costs of decodification and screening processes (Audretsch and Feldman, 2004). Product proximity helps the effective and timely imitation of both product and process innovations. The effects of distance reduced significantly the boundaries of the system into which the search for external knowledge could be performed (Boschma, 2005).

ICT based innovations reduce drastically the role of distance both in geographic and cognitive space: i) ICT based innovations such as Databases, Discussion lists, Notes databases improve the distribution of knowledge; ii) Knowledge delivery is made more effective by ICT based innovations such as Web, Networks, Intranets, E-mail; iii) The mobilization of tacit knowledge can take place by means of communication networks (Video conferencing) and especially the creation of communities of practice where digital infrastructure enables the effective interaction of practitioners specializing in a particular knowledge domain (Subashini Rita Vivek, 2012), the digitalization of heritage collections (Borowiecki and Navarrete, 2016), and, iv) most importantly, the sharing of protocols and procedures by means of such applications as groupware (Soto-Acosta, Colomo-Palacios, Popa, 2014; Hafeez-Baig and Gururajan, 2012); iv) agents active in product markets that are unrelated to the innovation can extract and access the knowledge that is relevant for their own innovation activities by means of digital un-coding procedures based upon digital content analysis.

ICT based applications enable to reduce the role of knowledge gatekeepers and to increase the number of agents that can interact directly with each other agent in the system. The access to existing knowledge, before the introduction of ICT based applications, was characterized by strong hierarchies that would give a pivotal role to gatekeepers able to centralize the search and processing of information on knowledge. The network representation of these systems would be characterized by centered networks where a central node interacts with a variety of isolated and disconnected agents unable to establish direct links with the other agents. The introduction of ICT based procedures of knowledge search and screening has reduced significantly the role of such gatekeepers favoring the reduction of the costs of access to external knowledge and increasing the scope of information flows (Whelan, 2007; Whelan, Teigland, Donnellan, Golden, 2010).

ICT based innovations in the knowledge generation process exert a powerful push towards the globalization of knowledge generation activities, both with respect to knowledge sourcing and to knowledge recombination. ICT allow to expand the scope of the effective search for external knowledge with the increase not only of the amount, but also of the variety of external knowledge that can be absorbed and used as an input (Rosenkopf and Nerkar, 2001). The use of ICT has in fact enabled to increase dramatically the geographic scope of the knowledge search, selection and absorption activities that are more and more conducted on global markets broadening the variety of possible knowledge suppliers and the opportunity to implement knowledge interactions nested with other transactions. The effects of ICT on the search capabilities of agents and their consequences in terms of the increased size of the choice set favor not only the global broadening of knowledge outsourcing, but also the increasing global offshoring with the selective localization of their knowledge intensive activities in knowledge intensive regions including in the recombinant generation of knowledge a variety of specialized based in remote sites (Abramovsky and Griffith, 2006; Rasel, 2017).

Loebbecke and Crowston (2012) identify knowledge portals a major organizational innovation introduced to synthesize widely dispersed knowledge and to interconnect individuals in order to favor the identification and access to the knowledge items of each organization. Loebbecke and Crowston define knowledge portals "as a type of portal that purposely supports and stimulates knowledge transfer, knowledge storage and retrieval, knowledge creation, knowledge integration, and knowledge application (i.e., the processes of knowledge management) by providing access to relevant knowledge artifacts. Repository-oriented components and functionalities of a KP include a knowledge organization system, repository access, search, and applications and services. In addition to the repository-oriented functionality of KPs, such a portal must also offer network-oriented components and functionalities. Some types of knowledge are most readily transferred through direct interaction between a knowledge seeker and another knowledgeable individual. To that end, a KP also provides functionalities to identify and connect users based on their expertise, such as collaboration and communication tools". Knowledge portals can be seen as the evolution from internal mechanisms of knowledge management introduced by corporations to improve the quality of internal knowledge flows to improve the quality of inter-organizational knowledge flows so as to improve the access and use of the stock of quasi-public knowledge.

ICT based applications enhance the opportunity to take advantage and valorize the user-producer knowledge interactions that parallel vertical market transactions. Digital applications enable to track the performance of capital goods and intermediary inputs at work in downstream production activities. The augmented storing capacity enables the accumulation of records and data about the strengths and weaknesses of the inputs at work. The augmented processing capabilities enable to process systematically the information gathered stirring the generation of knowledge based on empowered knowledge interactions between the two parties (von Hippel, 2001).

The use of ICT has major effects on the generation not only of technological knowledge but also of scientific knowledge (Heimeriks and Vasileiadou, 2008). The digital generation of scientific knowledge is characterized by higher levels of interaction within the scientific community and between the scientific community and the business sector. The integration of data mining and data management technologies for scholarly inquiries becomes a common practice with major effects in terms of increased role of team organization, augmented levels of co-authorship, distributed interactions and cooperation among scholars located in remote locations (Cobo and Naval, 2013). There is a strong consensus that the consequences are positive in terms of increased efficiency in the generation of scientific knowledge stemming from higher levels of division of labor and specialization (Hamermesh and Oster, 1998; Larson, R.R. et alii, 2014).

The digital generation of scientific knowledge, however, does not affect only knowledge costs, but also the organization and the architecture of scientific institutions. Agrawal and Goldfarb (2008) explore the consequences of the adoption of Bitnet in terms of increased cooperation between US universities showing their asymmetric effects on the structure of academic research that favored medium-ranked universities that could increase their interactions with top-ranked ones. According to Kim, Morse and Zingales (2009) elite universities are losing their competitive edge because of the enhanced opportunities for knowledge sharing and interactions among scholars based in peripheral universities. The creation of informal research cooperation mechanisms is favored by the use of ICT with the implementation of computer-mediated communication procedures that empowers distributed scientific work so that invisible colleges are being formed bringing together scholars based in a variety of research institutions (Walsh and Bayma, 1996). As Boppart and Staub (2016) note, the centrifugal effects at the institutional level take place together with centripetal effects on the visibility of academic stars. The easier access to the stock of scientific knowledge favors the concentration of citations and references to key authors increasing the typical power law of the Matthew effects.

van Schewick (2016) highlights the powerful effects of the architecture of Internet networks on the organization of the innovation process. The architecture of Internet influences “which actors can innovate, what incentives they have to do so and who controls whether an application can be developed, deployed and used” (van Schewick, 2016: 309). The introduction of ICT has increased significantly the knowledge connectivity of the system increasing the size and composition of the stock of quasi-public knowledge that can be accessed at low absorption costs.

3.3 ICT: THE RECOMBINANT GENERATION OF KNOWLEDGE AND OPEN INNOVATION

The reduction in the levels of absorption costs of external knowledge has in turn major implications for the organization of the knowledge generation activities. The appreciation of the recombinant character of the knowledge generation process and the introduction of the open innovation organizational methods can be regarded as a direct consequence of the new role of the stock of external knowledge made possible by the introduction of ICT.

According to Weitzman (1996) new knowledge is generated by means of the recombinants of existing knowledge items. As Brian Arthur puts it: “I realized that new technologies were not ‘inventions’ that came from nowhere. All the examples I was looking at were created-constructed, put together, assembled-from previously existing technologies. Technologies in other words consisted of other technologies, that arose as combinations of other technologies” (Arthur, 2009:2). The increased variety of external knowledge that can be accessed at low absorption costs by means of ICT based dedicated applications enables to expand significantly the combinations of the recombinant process and hence the opportunities for the effective generation of new knowledge (Harada, 2003).

The appreciation of the recombinant character of the knowledge generation process and the identification of the strict complementarity between external and internal knowledge (Antonelli and Colombelli, 2015a), leads to the introduction of the Open Innovation business model. Open Innovation can be regarded itself as a major organizational innovation in the knowledge generation process. In the Open Innovation business model, external knowledge is regarded as a necessary and indispensable input into the generation of new knowledge. Knowledge is more and more generated by means of the assembling of an array of knowledge items that have been outsourced. Firms keep funding R&D activities but perform intramuros only a fraction of the total amount of research activities. The firm acts a knowledge integrator that combines diverse knowledge items. The access to the stock of external knowledge is no longer regarded as an additional input, but as a necessary complementary input (Gehringer, 2011). Not only the amount of knowledge generated and its costs depend upon the access to external knowledge that can be accessed, but also the type of innovations that can be generated. The strategic selection of external knowledge inputs becomes necessary (Chesbrough, 2003; Chesbrough, Vanhaverbeke and West, 2006, Dodgson, Gann, Salter, 2006; Enkel, Gassmann, Chesbrough, 2009; Shearmur and Doloreux, 2013).

The use of digital technologies affects the generation of scientific and technological knowledge at three complementary levels: i) reduces the costs of accessing the stock of quasi-public knowledge; ii) makes knowledge interactions more effective and iii) favors the modularization of knowledge. The use of digital technologies enables the identification of modules of technological and scientific knowledge that can be better accessed and recombined.

The mutual interaction between the protocols of the generation of software and the procedures applied in the generation of knowledge characterizes the evolution towards the digital generation of knowledge. The generation of new software consists in the recombination of existing software modules that are retrieved and applied as inputs. Free and open source practices have shown the advantages of the collective generation of new software packages based upon the cumulative contribution of a myriad of independent experts able to contribute the enrichment and exploitation of an ever increasing stock of public knowledge. The methodologies elaborated to implement the recombinant generation of new software packages are themselves the result of the application of the procedures and protocols of the generation of new scientific an technological knowledge. Their evolution, however, has in turn reinforced the use of recombinatory procedures based upon the systematic use of existing modules of knowledge- properly framed- to generate new scientific and technological knowledge (David and Rullani, 2008).

Knowledge interactions supported by ICT enable to share and access the strong tacit component of all knowledge items. Even the most codified knowledge items such as scientific publications include irreducible tacit components that can be shared only by means of personal interactions (Cowan, David, Foray, 2000). The digital generation of technological knowledge magnifies the role of the systematic interactions between knowledge holders and agents at large not only within and among firms in the business sector, but also between the members and the institutions of the scientific community and the business sector, as the key mechanism for increasing knowledge output.

The effects of ICT based innovations change the organization of the knowledge generation process at the firm level with three different and yet complementary processes: i) the digital generation of technological knowledge is characterized by lower levels of vertical integration of research activities. The large intramuros research laboratories are squeezed and progressively integrated by the purchase of research inputs supplied by ii) knowledge intensive business service (KIBS) that progressively become specialized suppliers able to substitute intramuros corporate research laboratories, and the iii) the implementation of inter-firm coordination based on ICT based platforms that help the organized cooperation of a variety of actors that are endowed with complementary capabilities and competences (Antonelli and Patrucco, 2016).

Once again digital technologies provide the essential infrastructural backbone that supports the search of available information on existing knowledge and its active inclusion as an input in the knowledge generation process based upon the systematic sharing and integration of the modules of existing knowledge. The interactive use of large data bases is key to make the management of knowledge outsourcing and its eventual integration possible and effective. Digital technologies, such a broadband based procedures such as IoT, big data, cloud computing play a crucial role to make knowledge outsourcing and integration possible as they allow the effective organization of research platforms guided by a corporation for a dedicated task and a myriad of academic institutions and knowledge intensive business service suppliers that contribute specialized inputs (Consoli and Patrucco, 2008 and 2011).

Corporations keep funding research activities but rely more and more on the supply of research services both by public research infrastructure and firms specializing in knowledge generation and application (KIBS) to conduct research activities on a contractual basis. The borders between private and public research institutions are more and more blurred as the latter are more and more involved in the global markets for knowledge with an active role as specialized suppliers of knowledge services outsourced by corporations.

This process does not only favor the division of labor, the specialization of research units and the selection of the best research capabilities, but makes the interaction between knowledge holders, dispersed in the system, and the repeated use of the existing knowledge items more and more effective. The use of ICT enables to better take advantage of: i) the indivisibility of knowledge and hence the intrinsic complementarity of its components; ii) its substantial non-exhaustibility and hence cumulability, and iii) its irreducible tacit content so as to make the digital generation of knowledge much more effective than the traditional corporate model.

The digital generation of knowledge seems a major organizational and institutional innovation that enables to extract and better valorize the opportunities and the positive aspects of the limited appropriability and exhaustibility of knowledge.

These advances in the exploration of new business models for the generation of new knowledge parallel the advances in the economics of innovation about the economic characteristics of the knowledge generation function. In the knowledge generation function, in fact, external knowledge enters as a necessary input, strictly complementary to internal R&D activities. The recombinant character of the knowledge generation function and the strict complementarity of external knowledge to internal one stress the crucial role of external knowledge. Without external knowledge, the generation of new knowledge is actually impossible. Internal knowledge, in fact, can substitute external knowledge only to a limited extent. If external knowledge is not available, the generation of new knowledge cannot take actually place (Antonelli and Colombelli, 2015a).

The access to external knowledge, made possible by the introduction of ICT, with low absorption costs has three distinct and powerful effects: i) it enables firms to generate new technological knowledge making an intensive use of external knowledge; ii) it reduces drastically the costs of new knowledge as an output (Antonelli, Colombelli, 2015b); iii) it is associated with significant increase of the performance and productivity of firms able to rely systematically on external knowledge (Tambe, Hitt, Brynjolfsson, 2012).

4. THE DIGITAL GENERATION OF KNOWLEDGE AND THE APPROPRIABILITY TRADE-OFF: CAN KNOWLEDGE SPILLOVERS COMPENSATE FOR THE MARKET FAILURE?

The notion of derived demand of knowledge implemented by Antonelli (2017) as an extension and enrichment of the CDM model enables to articulate and operationalize the analysis of the knowledge appropriability trade-off and provides an effective framework to assess the effects of ICT.

The analytical framework includes, in a single system, 4 equations: i) a knowledge generation function, ii) a technology production function, iii) a knowledge derived demand equation, and iv) a knowledge cost equation. In the knowledge generation function, knowledge is the output of an intentional and dedicated activity based on two strictly complementary inputs: internal research and learning activities and external knowledge. The costs of external knowledge is influenced by the size and access conditions of the stock of external quasi-public knowledge that stems from the limited appropriability of proprietary knowledge generated by all the agents in the system. In the technology production function the output is the result of traditional inputs including technological knowledge supplied by the upstream knowledge generation function. The price of the goods produced using technological knowledge will be lower the lower is the appropriability. With low levels of appropriability, in fact, imitators can enter easily the market place shifting to the right the supply curve and hence engendering the fall of the price of the innovated products. Innovative incumbents may actually experience a fall of the price of the innovated product below their unit costs that include knowledge costs. Imitators bear much lower knowledge costs as they can take advantage of its limited appropriability. The level of the price in the downstream product markets has a direct and evident effect on position of the derived demand of knowledge. The derived demand of any input is nothing else but the value of its marginal product. The position of the derived demand for knowledge consequently measures the negative effects of the limited appropriability of knowledge. The lower is the appropriability of knowledge and the lower is the position of the derived demand for knowledge. Finally, the knowledge cost equation defines the position and the slope of the knowledge supply schedule. The lower is the appropriability of knowledge and the larger is the flow of knowledge spillovers, and the lower is the costs of external knowledge as an input into the knowledge generation function. Consequently the lower is the appropriability, and the lower is the position of knowledge supply. The lower is the position of the knowledge supply and the larger are the positive effects of knowledge spillovers.

Let us now explore the consequences of the introduction of ICT and the spreading of the digital generation of knowledge on the framework elaborated so far to assess the knowledge appropriability trade-off. According to the results of the literature review elaborated in section 3 it seems possible to claim that:

1) ICT have little effects on the negative externalities of knowledge appropriability. Imitation of innovations by competent rivals engaged in a neck-to-neck competition is poorly affected by ICT. Knowledge appropriability is already very low because of the proximity in product and cognitive space. The introduction of ICT is not likely to yield further downward shifts of the derived demand for knowledge.

2) ICT instead reduce drastically the cost of external, tacit and distant knowledge, and favor its use in the knowledge generation process. The introduction of ICT is

most likely to favor the downward shift of the knowledge supply schedule. Because of the lower costs of external knowledge as an input in the knowledge generation, knowledge as the output has in turn lower costs.

On these bases it seems possible to argue that the Arrovian market failure does not hold in the specific conditions that take place after the introduction of ICT in the knowledge generation process when the use of knowledge spillovers helps reducing knowledge costs below the levels of knowledge as if it was a standard good and favors a significant downward shift of the knowledge costs and supply curve.

Firms experience a negative externality stemming from limited knowledge appropriability and consisting in a reduction of the expected revenue of their innovation activities that can be compensated by the positive externalities stemming from limited knowledge appropriability and consisting in the knowledge cost-reducing effects of knowledge spillovers. If the positive externalities augmented by the effects of the introduction of ICT based innovations are able to compensate the negative externalities, the market place is actually able to produce and use the same amount of knowledge that would be generated if knowledge were a perfect economic good in competitive markets. In these circumstances the lack of incentives, the market failure and the underproduction of knowledge would not actually occur and, moreover, the lower cost of knowledge would have strong positive effects on the supply of knowledge and on total factor productivity levels. After the introduction of ICT in the digital generation of knowledge, the market place enriched by effective transactions-cum-knowledge interactions might actually generate a larger amount of knowledge at lower costs.

The introduction of ICT with its powerful effects in terms of increase of the knowledge connectivity of the system and the reduction of absorption cost favors the reduction of the cost of external knowledge. The introduction of ICT in the knowledge generation process magnifies the positive side of the appropriability coin.

The reduction of the absorption costs brought about by the introduction of ICT has direct effects on the cost of external and tacit knowledge that in turn reduces the cost of knowledge and hence engenders a downward shift of the supply curve of knowledge. If the fall of knowledge costs will be large and consequently the shift of the supply of knowledge also large, the equilibrium demand for knowledge in the system will be actually larger than expected in the Arrovian framework with positive effects both in terms of the equilibrium quantity and price of knowledge.

Figure 1 enables to compare the derived demand of and supply knowledge in these two different contexts.

INSERT FIGURE 1 ABOUT HERE

FIGURE 1. DEMAND AND SUPPLY OF KNOWLEDGE WITH SPILLOVERS AND KNOWLEDGE COSTS

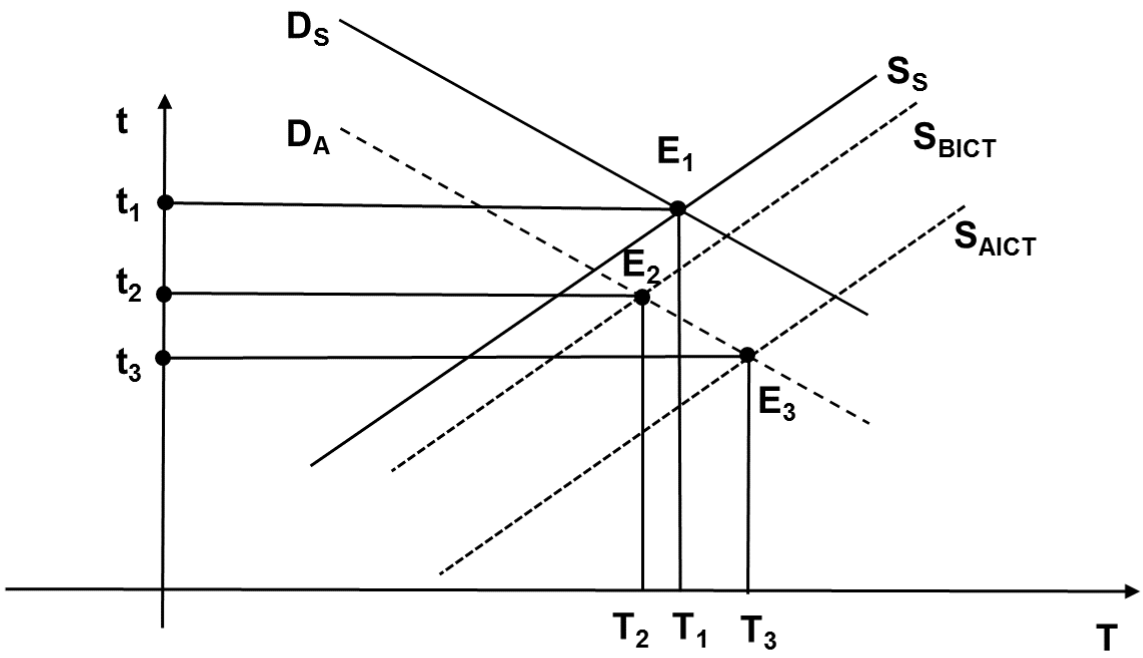

Figure 1[2] presents the effects of knowledge appropriability before and after the introduction of ICT on the derived demand of knowledge and its supply. The derived demand of knowledge as a standard good D_S lies above the derived demand of knowledge with its Arrovian properties D_A. The derived demand of knowledge with its Arrovian properties, in fact, reflects the low price of the good -that has been produced using knowledge as an input- that is well below the levels where it would have been were knowledge a standard good. Figure 1 exhibits three knowledge supply curves: i) S_S represents the position of the supply of knowledge were it a standard good; S_{BICT} represents the position of supply of knowledge with its Arrovian

[2] The geometric exposition relies on the stylized facts presented and the hypothesis outlined in the essay. Only dedicated empirical investigations can confirm whether it is consistent with the actual facts.

properties before the introduction of ICT; iii) finally S_{AICT} represents the position of the knowledge supply curve after the introduction of ICT.

We can now portray geometrically the effects of the introduction of ICT on the knowledge appropriability trade-off. The Arrovian properties of knowledge yield both positive and negative externalities. The position of the derived demand of knowledge is lower than it would have been. The positive externalities consist in the downward shift of the knowledge supply curve. The introduction of ICT empowers the positive externalities because of the reduction of knowledge absorption costs.

Figure 1 enables to compare the two cases. Knowledge limited appropriability is the cause of the shift of derived demand of knowledge from D_s to D_A and the parallel shift of the knowledge supply curve from S_S to S_{BICT}. Equilibrium shifts from E_1 to E_2. The equilibrium quantity of knowledge T decreases from T_1 to T_2. The Arrovian hypothesis is confirmed: the market place is unable to allocate the appropriate quantity of resources to the generation of knowledge with the well-known consequences in terms of undersupply.

Note that the Arrovian hypothesis holds even when the positive effects of knowledge spillovers are taken into account. The E_2 equilibrium solution is found at the intersection of the derived demand of knowledge after taking into account the negative effects of the reduction of the price of the goods that have been produced using knowledge as an input, and the supply curve (S_{BICT}) as determined by the positive effects of external knowledge.

After the introduction of ICT, however, the knowledge supply shifts to S_{AICT}. The new equilibrium is found in E_3 . The equilibrium quantity of knowledge T increases from T_2 to T_3. Where it is actually larger than it should have been in the benchmark condition that would have taken place if knowledge were a standard economic good.

The equilibrium quantity of knowledge that the market is able to allocate is much larger than the amount of knowledge that the market would have allocated were knowledge a standard good. The introduction of ICT makes the equilibrium supply of knowledge even larger and its costs actually lower. The Arrovian hypothesis of the lack of incentives to generate knowledge and hence its undersupply does not hold[3].

[3] If we regard the demand curve as a pecking order, the reduction - from t_1 to t_2 - of the price of knowledge may exert negative consequences in terms of exclusion of high quality research projects (Antonelli, 2017).

The knowledge market failure hypothesis could be tentatively questioned before the introduction of ICT. It must be questioned after the introduction of ICT. Moreover, the market price for knowledge (t) is lower: it shifts from t_2 to t_3 because of the downward shift of the supply curve[4]. The low costs of knowledge, below competitive equilibrium levels, account for total factor productivity growth (Antonelli, 2013)[5].

The appropriability trade-off can now be revisited. The value of knowledge that cannot be appropriated by the 'inventor' spills, but does not disappear. The introduction of ICT enables other firms to use it to generate new technological knowledge in turn. After the introduction of ICT the generation of knowledge can now rely on external knowledge as an input that complements internal knowledge. The access and use of external knowledge is cheap(er) because the introduction of ICT favors knowledge interactions and consequently the access to the stock of quasi-public and quasi-tacit knowledge and reduces its absorption costs.

It is clear that the actual effects of the introduction of ICT on the knowledge interactions and the access and use of knowledge spillovers on knowledge costs become the crucial issue. These effects are likely to be strongly affected by the properties of the system into which the process takes place. The structure and the organization of the system play a major role in terms of knowledge connectivity. Some systems provide higher levels of interaction, communication and coordination in the use of knowledge than others. This in turn depends upon: i) the variety and ii) complementarity of knowledge(s) that are available in the system; iii) the regional, industrial knowledge structure of the system; iv) by the quality and quantity of the communication channels among the units of system; v) the organization of networks of knowledge interactions; vi) the interactions that parallel and complement market transactions; and vii) the strength of interactions between the academic and research community and the business system. The quality of the telecommunications infrastructure, both in terms of its physical infrastructure and of the regulatory environment that shapes its access and use conditions, plays clearly a central role in this context.

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4 This price reduction is fully positive as it depends only from the shift of the supply curve.

5 The simultaneous solution of the model enables to take into account the feedbacks of the reduction of the cost of knowledge on the supply of the goods that use it as an input and hence a reduction of its costs with the consequent additional downward shift of the derived demand of knowledge. This secondary effect is not taken into account in Figure 1.

The quality of the telecommunications infrastructure is the key factor in assessing the levels of knowledge connectivity of a system. The higher is the knowledge connectivity of the system and the larger its knowledge output. With high levels of connectivity knowledge spillovers can be used again and again and accessed at low costs because of the quality of communication that improves the quality of knowledge interactions, so as to support the generation of new knowledge at low costs because of the complementarity between external and internal knowledge.

The new framework enables to appreciate the out-of-equilibrium conditions of the generation and use of knowledge and the levels of knowledge costs below equilibrium levels. It contrasts and yet complements the Arrovian framework, permitting us to formulate an improved framework of economic policy where telecommunication policy has much a wider and relevant role.

5. THE AUGMENTED ROLE OF TELECOMMUNICATION POLICY

The Arrovian framework has provided the foundations for the economic policy practiced for almost half a century. The failure of the markets for knowledge leads to the undersupply of knowledge. Public interventions are necessary to remedy the market failure. This approach has been implemented with four basic tools: i) public subsidies to R&D expenditures incurred by private firms to reduce the costs and related risks of firms, so as to favor a downward shift of the supply curve of knowledge (Hall, Van Reenen, 2000; David, Hall, Toole, 2000; Hall, Mairesse, 2006); ii) the public supply of knowledge by means of a public research infrastructure so as to provide free access to basic knowledge and, again, reduce the final costs of knowledge and augment the downward shift of the supply curve for knowledge; iii) the public procurement of knowledge intensive goods so as to reduce the risks of limited appropriability and favor the upward shift of the derived demand for knowledge (Edquist, Vonortas, Zabala-Iturriagagoitia, Edler, 2015); iv) the establishment of the intellectual property rights protection to increase knowledge appropriability and, again, reduce the risks of limited appropriability and favor the downward shift of the supply of knowledge (Antonelli, 2013).

The framework elaborated in this essay enables to focus the effects of knowledge spillovers, empowered by the introduction of ICT, on the reduction of knowledge absorption cost and of knowledge costs and regards it as a major goal of a new alternative knowledge policy. This new analytical framework provides the foundations of a new augmented agenda for a telecommunications policy aimed at increasing the knowledge connectivity of the system and hence the effects of spillovers on the reduction of knowledge costs. Dedicated interventions should be implemented in order to increase the reduction of knowledge absorption costs and the costs of knowledge as an output stemming from the use of external knowledge - spilling from ‘inventors’- as a key complementary input in the generation of new knowledge.

The effects of knowledge spillovers on the reduction of knowledge costs are limited by the costs of the activities that are necessary to absorb knowledge that is not appropriated by inventors.

The quality and coverage of the digital infrastructure has direct and powerful effects on the levels of knowledge connectivity of the system that favor the effective use of knowledge spillovers and empowers knowledge interactions. The digital divide has strong negative effects as it limits the connectivity of the system. It excludes a part of the system from the low-cost access to the stock of external knowledge. It engenders the loss of the increasing returns stemming from network externalities. Network externalities exert, in fact, their powerful effects also in the access to the stock of knowledge. The productivity of the network increases at a more than proportionate rate as the inclusion of each additional agent into the digital network has the twin effect of increasing the access to the general stock of knowledge and its actual size. The working of network externalities finds a new powerful dimension of application and understanding.

The layer methodology articulated by Martin Fransman to study the evolution of the ICT system contributes the understanding of the evolution of the knowledge generation process. The quality of the digital infrastructure, in fact, enables to add a new layer to the generation of technological knowledge: the systematic access and valorization of the stock of external knowledge available in the system as a source of knowledge items that can enter the knowledge generation process (Fransman, 2002).

The quality of the telecommunication infrastructure and of the communication regulation, as measured by its capillarity and inclusivity, becomes a crucial factor to increasing the knowledge connectivity of a system and hence its rate of generation of new knowledge and introduction of innovations. The inclusive coverage of the digital infrastructure is a basic tool for a research policy aimed at increasing the knowledge connectivity of the system and consequently the size and variety of the stock of knowledge that firms can access and use to generate additional knowledge at low absorption costs (Fransman, 2006).

Economic systems endowed with a high quality telecommunications network are likely to support faster rates of generation of technological and scientific knowledge and hence a larger pace of increase of total factor productivity. The architecture of Internet and its regulation play a major role in this context. Limitations to and deviations from end-to-end arguments may affect the use of Internet as a radical innovation in accessing and using the stock of existing knowledge to generate new knowledge (Bauer, 2014).

Net neutrality is likely to play an important role in this context. The set of rules that defines the interactions between internet service providers, content providers and customers can affect in depth the working of the digital generation of knowledge and the expected fall of the costs of accessing and using the stock of quasi-public external knowledge. Following Greenstein, Peitz and Valletti (2016) the enforcement of net neutrality seems important to prohibit both one-sided pricing practices i.e. payments from content providers to internet service providers and prioritization of traffic with or without compensation. In both cases in fact the access to the stock of quasi-public knowledge upon which the digital generation of knowledge rests risks to suffer the consequences of discrimination and segmentation with the consequent increase of knowledge absorption costs.

The support to the introduction of mobile broadband and to the adoption of mobile phones that provide high speed internet services seems to provide major opportunities for the diffusion of a new generation of digital modes of knowledge generation based upon the IoT, big data and cloud computing that are most likely to further enhance the access to the stock of quasi-public knowledge so as to further reduce the costs of external knowledge and consequently the costs of new knowledge at large increasing the extent to which the positive effects of knowledge spillovers are expected to overcome the negative effects of the limited appropriability of knowledge. Mobile broadband seems most important to reduce the digital divide that limits the diffusion of the digital generation of knowledge excluding rural areas and small firms from its beneficial applications (Briglauer, Gugler and Bohlin, 2013; Kongaut and Bohlin, 2016).

A good telecommunications policy aimed at reducing the digital divide and protecting the openness and neutrality of the Internet becomes a key but not exclusive component of a new research policy agenda aimed at increasing knowledge connectivity. Knowledge connectivity can be increased favoring the knowledge interactions that occur in the system. Knowledge interactions may be enhanced by means of: i) Non-exclusive intellectual property rights. The remuneration of intellectual property rights is necessary to increase the incentives to the generation of knowledge. At the same time it becomes more and more evident that patents block sequential innovation and reduce the rate of technological change (Galasso, Schankerman, 2015). Non-exclusive intellectual property rights built upon fair levels of royalties associated with the non- discriminatory use of proprietary knowledge can increase the use of existing knowledge to generate new knowledge (Antonelli, 2015). ii) The support to the mobility of scientists and inventors within firms, among firms and between firms and public research institutions. Tacit knowledge is embedded in human beings. Their mobility is the most effective mean to favor the repeated use of existing knowledge and hence the effective use of knowledge spillovers to generate new technological knowledge (Moen, 2005; Song, Almeida, Wu, 2003). iii) Knowledge outsourcing. The increasing reliance of firms on knowledge outsourcing is worth the public support as it is likely to favor the repeated use of existing knowledge as an input into the generation of new knowledge (Shearmur, Doloreux, 2013; Chesbrough, 2003; Chesbrough, Vanhaverbeke, West, 2006). The provision of subsidies to the purchase of knowledge rather than to its generation might have positive effects in terms of increased division of knowledge labor and reduction of duplications and repetitions. These positive effects would be especially strong when the provision of subsidies focuses knowledge transactions that take place between university and industry. The specialization of public research institutions and knowledge-intensive-business-service firms in the performance of research activities funded and purchased by firms specializing in the their recombination to generate new knowledge can help increasing the rates of accumulation of the stock of quasi-public knowledge (Arora, Fosfuri, Gambardella, 2001). vi) Knowledge alliances. The creation of alliances between firms and among firms and public research institutions finalized to the generation of knowledge, rather than its exploitation, can augment the connectivity of the system and hence favor the use of existing knowledge in a larger variety of applications (Link and Antonelli, 2016).

The quality of the telecommunications infrastructure and of the regulatory framework of a country and a region becomes an important factor in assessing the division of labor in the globalizing digital generation of knowledge. The better the quality of the telecommunications infrastructure and regulation and the higher the chances: i) to attract the destination of global offshoring with the localization of knowledge intensive activities; ii) to favor the global reach of knowledge outsourcing for domestic firms; iii) to favor the participation of domestic research centers to the global knowledge markets. Finally, the quality of the telecommunications infrastructure and regulation of a country is key to secure the localization of headquarters and central R&D laboratories of global corporations.

6. CONCLUSIONS

New information and communication technologies are the pillar of the knowledge economy. Their introduction and diffusion enabled the mobilization and effective use of the large stock of quasi-public knowledge embedded in the economy of advanced countries. The systematic use of new information and communication technologies enabled to increase the knowledge connectivity of the system reducing drastically knowledge absorption costs and hence the repeated use of knowledge as an input into the generation of new knowledge. New information and communication technologies enabled the industrialization of the recombinant generation of new knowledge favoring the division of knowledge labor, the specialization and the participation of an increasing variety of agents embodied with different and yet complementary knowledge items to its generation, the opportunities for more effective knowledge transactions and interactions in emerging knowledge markets and along user-producer interactions, with the eventual sharp increase in the efficiency of knowledge generation (Goldfarb, Greenstein, Tucker, 2015).

The appreciation of the positive role of ICT on the knowledge connectivity of an economic system enables to reconsider the knowledge appropriability trade-off. The positive effects of the limited appropriability of knowledge in terms of knowledge spillovers combined and augmented by ICT applications to the recombinant generation of knowledge help reducing the levels of knowledge costs below equilibrium conditions. When and where such effects apply, the Arrovian framework and its implications for knowledge policy need to be reconsidered.

A new agenda for telecommunications policy, that includes and highlights its economic, aimed at increasing the knowledge connectivity of the system and the reduction of absorption of knowledge not entirely appropriated by inventors and spilling in the system, should be implemented. The larger the connectivity of the system is, the stronger the positive effects of knowledge spillovers on knowledge costs are likely to be. The lower the actual knowledge costs and the larger are the rates of increase of total factor productivity. The traditional framework for knowledge policy based upon the Arrovian analysis of knowledge market failure applies when and where knowledge spillovers cannot be used effectively to generate new technological knowledge at costs below equilibrium levels. The two agendas for knowledge policy can complement each other.

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