ISSN (print): 2421-6798
ISSN (on line): 2421-7158

Consiglio Nazionale delle Ricerche

IRCrES

ISTITUTO DI RICERCA SULLA CRESCITA ECONOMICA SOSTENIBILE
RESEARCH INSTITUTE ON SUSTAINABLE ECONOMIC GROWTH

# Working Paper

Numero 2/2017

# A technological model of the R&D process and its implications with scientific research and socio-economic activities

*Angelo Bonomi*

WORKING PAPER CNR-IRCRES
Anno 3, Numero 2, Febbraio 2017

*Direttore Responsabile*
Secondo Rolfo

*Direzione e Redazione*
CNR-IRCRES
*Istituto di Ricerca sulla crescita economica sostenibile*
Via Real Collegio 30, 10024 Moncalieri (Torino), Italy
Tel. +39 011 6824.911
Fax +39 011 6824.966
segreteria@ircres.cnr.it
www.ircres.cnr.it

*Sede di Roma*
Via dei Taurini 19, 00185 Roma, Italy
Tel: 06 49937809
Fax: 06 49937808

*Sede di Milano*
Via Bassini 15, 20121 Milano, Italy
Tel: 02 23699501
Fax: 02 23699530

*Sede di Genova*
Università di Ge Via Balbi, 6 - 16126 Genova
Tel: 010-2465.459
Fax: 010-2099.826

*Segreteria di redazione*
Enrico Viarisio
enrico.viarisio@ircres.cnr.it

Working Paper IRCrES 2/2017

# A technological model of the R&D process and its implications with scientific research and socio-economic activities

ANGELO BONOMI [a]

[a] Research Associate CNR-IRCRES, National Research Council, Research Institute on Sustainable Economic Growth, via Real Collegio 30, Moncalieri (TO) – Italy

Mail: abonomi@bluewin.ch

ABSTRACT

This work describes a model of the R&D process derived by technology management and experience in carrying out this type of activity. The model gives a comprehensive description of the numerous processes of technological nature involving innovations from science to business. The model sees R&D as an organizing activity of fluxes of knowledge and capitals with a dynamics that is determined by R&D projects and their implementing rather than by R&D investments. The model recognizes the existence of a general knowledge generated by R&D activities, formed either by successful or abandoned projects, not necessarily linked to the objectives of the projects, and diffusing among the various actors making R&D in the distributed innovation system existing in conditions of open innovation. Such general knowledge has a role of driving force in developing innovative ideas and saving R&D costs. The model separates neatly the R&D process from scientific research considering existence of an intertwining process between research and R&D. About relation with socio-economic factors determining the effects of new technologies, the model presents different views about relation of R&D investments and economic growth. In fact it considers the inexistence of limits to generation of new technologies, when unlimited financing of R&D is available, and highlights the importance of the specific innovative system of a country in determining the contribution of R&D investments to its economic growth. Concluding the model considers that economic growth does not depend actually on R&D investments, that should be considered rather a means, but on the intensity of generation of innovative ideas, that depends on the efficiency of the territorial innovative system, and on adopted strategies and availability of capitals financing their development joined with an effective industrial organization.

KEYWORDS

research & development, R&D model, R&D management, technology innovation, knowledge spillover, socio-economic growth

JEL CODES:

O30, O31, O32, O47

DOI:

http://dx.doi.org/10.23760/2421-7158.2017.002

CONTENTS

# A technological model of the R&D process and its implications with scientific research and socio-economic activities

ANGELO BONOMI

## 1 INTRODUCTION

There is a vast literature on study of R&D activities in relation with scientific research and even more on R&D effects on economic growth. However, while science and technology research, sources of funding, performances, incentives and motivations for R&D are reasonably well understood by academics and policy makers, the quite complex process by which a technical idea of possible commercial value is converted through R&D into a new successful technology, is poorly documented and little studied (Auerswald, Branscombe 2003). In fact R&D is a complex activity in strict relation with knowledge originated by scientific research, and at the same time in relation with flux of capitals concerning either the sustenance of this activity or generation of return of investments. The organizational factors that concern either knowledge or capitals are then important in the development of a model of the process of R&D. A way to simplify the complexity of R&D activity is in limiting modelling only to its technological aspects in relation with definitions and concepts derived by a previous model of technology (Bonomi, Marchisio 2016), not considering in the study the search of any direct quantitative relation between R&D investments and economic results. In this way the model in fact describes only processes occurring in the R&D activity independent from scientific research or socio-economic factors that are present as externalities at the interfaces of the model. Although the model does not enter in discussions about the way scientific research is carried out, or about socio-economic factors determining the effects of new technologies entering in use, it may raise observations about how scientific research is used in the development of new technologies, and about assumptions or explanations advanced in studying the relations of the R&D process with the various economic factors.

The technological model of R&D proposed in this study takes its origin from the field of technology management and in particular from models used in R&D management (Dumbleton 1986). This author developed a model presenting the complex input and output of R&D activity based on the domain idea (Thompson 1967), however without giving any indication of the processes going on into the R&D domain. This domain model of R&D has been elaborated for the R&D process of a single firm and considers two separate fluxes of input/output, one internal and the other external to the firm. The internal flux concerns outputs including reports, products, processes etc. and inputs including marketing, manufacturing and corporate strategies. The external flux concerns outputs including presentations, publications, patents, etc. and inputs including state of the art, general knowledge, environmental aspects, etc. As we may see this domain model of R&D is essentially based on knowledge, part flowing internally and part externally to the firm. However, for our technological model, differently from the domain model, we consider a description of the R&D process, not only for a single firm, but also for entire territories or countries. Furthermore a technological model should enter in the description of processes internal to the R&D domain and including not only knowledge but also capital fluxes. Such model shall then be seen as a description of R&D as an organizing activity concerning both fluxes of knowledge and capitals. It is also important to be aware how the proposed model considers technology in the frame of the socio-economic system, and how it considers technology innovation in the frame of the industrial evolution. From the socio-economic point of view the model sees the effect of new technologies, originated by R&D activities, as a disruptive factor modifying continuously the routines used by industry, maintaining an economic system far from equilibrium, and contributing in large part to the economic changes (Nelson, Winter 1982). For the aspects of industrial evolution the model considers evident the contributions of universities, public and private research organizations, the military, other public actors and financial organizations, such as venture capital, in the generation and diffusion of technological advance in industry (Malerba 2007). Another consideration at the base of the model is that studying innovation and evolution of industries, there are good reasons that a study of the R&D process should be interdisciplinary, and the full understanding of topics such as innovation, as it is carried out by R&D, and evolution of industries requires the integration of economics, history, sociology, technology, management and organization disciplines (Malerba 2007), and the model takes account of some of them.

After this introduction, in a second section we give a brief description of the historical evolution of the R&D activity until the present situation. In the third section we describe the technological model of the R&D process in term of an organization of fluxes of knowledge and capitals and its dynamics in term of R&D projects. In a fourth section we give a description of the various phases of flux of knowledge including the generation of innovative idea, their use for preparation of R&D project proposals and their financing for R&D projects. In a fifth section we discuss the role and influence of knowledge generated by the R&D process as driving force for further innovations. In the sixth section we discuss the relations between scientific research and R&D, and in the seventh section the relation of R&D activity with various aspect concerning endogenous vs. imported technologies, private vs. public R&D investments and socio-economic growth. In the last section we present conclusions summarizing the main results of the model and final considerations.

## 2 HISTORICAL EVOLUTION OF R&D ACTIVITIES

Despite of the large number of studies carried out on R&D activity and its relation with growth, little is reported about its historical development and evolution toward the present situation. The difference between R&D activity and that of single inventors characterizing technology innovation in the past centuries is the presence of research laboratories and a certain number of researchers looking for possible technological innovations and not simply realization of a single inventive idea. The first R&D laboratories were probably created in Germany since 1870 by dye manufacturers and research consisted in the synthesis of new molecules suitable for dyes (Basalla 1988). In the same period another industrial R&D laboratory was created in Germany by Carl Zeiss in 1876 for optical applications. At the same time in 1876 it was created by Thomas Edison the famous research laboratory at Menlo Park (New Jersey) with about twenty researchers. It should be noted that at the beginning of R&D activities scientific knowledge was not necessarily fully exploited basing the research often only on large number of trials. This was the case of Edison laboratory that for example tested more than thousand materials before finding the suitable one for electric lamps. At the beginning of XX century there was a certain number of industrial R&D laboratories in the more developed countries. In USA we had for example the Bell Telephone Laboratories of the American Telephone & Telegraph Company and the research laboratory of General Electric. Within the first twenty years of the XX century there was the creation in USA of 526 facilities for R&D (Basalla 1988). Relations with universities were not particularly intense and limited mostly to consultancy. In the same period in USA we had the birth of a new activity consisting in supplying R&D services to industry with the creation of contract research laboratories. That was the case of Arthur D. Little founded in 1909 as profit organization for contracting professional services including research, or the Mellon Institute which started to sponsor industrial fellowship on a non profit basis at the University of Pittsburgh in 1913 and becoming an independent industrial research group in 1927 (Bohem, Groner 1972). In 1929 the Battelle Memorial Institute created a contract research laboratory at Columbus (Ohio) with twenty researchers as a non profit organization. Battelle had a great expansion in the post 2nd war period with the creation of two major laboratories in Europe at Frankfurt and Geneva (Bohem, Groner 1972). During the 2nd world war in USA were created by the government three main R&D laboratories at Los Alamos, Hanford and Oak Ridge for the development of nuclear weapons (Rhodes 1986). Such development, carried out between 1942 and 1946, corresponds to what it is probably the greatest R&D project never done, called with the name of Manhattan Project, and involving about a total of 130.000 people at the cost of about 26 billion $ at the present value of dollar. These laboratories continued their activity after the war also exploiting nuclear research results for civil applications and two further new national laboratories were created at Argonne (Chicago) and Brookhaven (New York). The US government, around year 2000, contracted management of Oak Ridge and Brookhaven National Laboratories, as well as some minor national laboratories, to Battelle that became probably one of the largest research organization in the world with 22,000 employees with a budget over six billions dollars. After 2nd world war there was a great expansion of industrial R&D laboratories in USA, Europe, and even in Japan, while universities opened activities of contract research with industry and creation of R&D laboratories. For example the Stanford University created in 1945 the Stanford Research Institute, charging Battelle for its organization (Bohem, Groner 1972). Such laboratory contributed later to the development of the Silicon Valley (Feldman, Francis 2002). Until the 2nd world war contract research practically did not exist in Europe but it developed rapidly. A study carried out by the European Commission in 1989 counted about 140 European contract research organizations with a turnover of about one billion euro at the present value (Berreur, Guillot, Lesrel 1989). Until the eighties of the past century industrial R&D was the main activity for technology innovation carried out in condition of competition and secrecy of development by the various industries. After these years many other than industrial actors became important for the R&D activity determining technical advances in industry (Malerba 2007). On the other side industrial companies limited R&D mainly on their core business considering for more radical innovations the buying of technologies developed by start up or carrying out R&D projects in cooperation with other industries and research laboratories in a situation that was further called distributed innovation (Haour 2004). Such change of conditions in R&D activity was well described in a workshop organized in April 2000 by the Advanced Technology Program of the US Department of Commerce (Bransomb, Morse, Roberts, Boville 2000). Practically making industrial R&D means today establishing a strategy that does not include research carried out only in its own R&D laboratories, but it is extended to many other possibilities such as contract research, start up acquisition, corporate venturing funding, co-development with other companies and laboratories, selling or buying of licences or competences associated to the development of new business models in what it has been called the regime of open innovation (Chesbrough 2003).

## 3 THE TECHNOLOGICAL MODEL OF THE R&D PROCESS

The technological model considers R&D as an organizing activity of a double flux respectively of knowledge and capitals. The inputs for the R&D process are financed R&D projects selected among the various R&D project proposals. Such projects may belong to the R&D internal activity of an industry or external to industry in contract research activities. Furthermore there are also R&D projects carried out not necessarily for economic purposes but contributing in a certain way to the overall R&D activity. The outputs of the R&D process are new technologies and a general knowledge generated by either successful or abandoned development projects. Such general knowledge, combined with external knowledge based on scientific, technical, economic, market, environmental, etc. information makes possible the generation of new innovative ideas and preparation of R&D project proposals for financing. The produced new technologies and possibly imported technologies constitute the technology input in the socio-economic system and may be seen as a flux of capitals in term respectively of cost (investment) of development or acquisition of the technologies. New or imported technologies require capitals for their industrial use and possibly generate returns of investment. The socio-economic system makes then available private and public investments for financing new R&D projects. It should be noted that public financing does not include only aid to industrial R&D but also governmental financing of R&D projects not necessarily carried out for economic purposes but for example for military purposes. A schematic view of the fluxes of knowledge and capitals described by the model is reported in Fig. 1. The process concerning the flux of knowledge at the right side of Fig. 1 may be studied profitably by a technological approach, on the contrary, capital needs and investment returns deriving from the use of new or imported technologies, as well as availability of R&D investments, determining the flux of capitals in the left side of Fig. 1, is the typical field of socio-economic studies based on statistics and econometric models.

### 3.1 Dynamics of the R&D process

The model considers R&D activity, not as an investment, but composed by a combination of various projects, or activities that may be assimilated to projects, each defined, following the rules of project management, as a single, non repetitive enterprise undertaken to achieve planned results within a time and budget limits. The projects activity, and not investment, is considered determinant for the R&D dynamics from the technological point if view. However it is important to consider the relations existing between projects costs and R&D investments in a territory as well as total cost of development of a new technology. Cost of projects activity and R&D investments made in a territory in a certain period of time are represented by the following equation:

$$I_{R\&D} = \sum_{i=1}^{N} p_i \quad (1)$$

$I_{R\&D}$ represents the total investments in R&D occurred in a certain period of time in a territory, while p represents the cost (investment) of each project of the N projects that have been carried out in the same period in the territory. From the point of view of the R&D activity, the costs of projects considered in equation (1) may be present in various situations such as:

- Cost of projects terminated in the period but started in previous periods
- Cost of projects started and terminated in the same period
- Cost of projects started in the period but terminated in successive periods
- Cost of projects started in previous periods and terminated in successive periods

Another important aspect of projects dynamics concerns the cost (or investment) for the development of a new technology. In fact this development implies normally a sequence of projects covering the various phases of the innovation process until the moment in which the new technology enters in use or its development is abandoned. That means the cost (investment) of development $I_{NT}$ may be expressed as:

$$I_{NT} = \sum_{i=1}^{n} p_i \quad (2)$$

$p_i$ representing the cost (investment) of each project of the n projects carried out for the development. Such sequence of n projects is in most cases extended through various periods of time (years) considered for R&D investments. However, in the reality of R&D activity, only a minor part of projects are carried out in a complete sequence developing a new technology, many projects sequences are discontinued abandoning the development of a specific new technology. In fact, considering a particular period of time and territory we have for the project dynamics the following situations:

- Projects that are abandoned stopping the development of the new technology
- Projects that continue beyond the considered period of time
- Projects that are terminated generating new technologies entering in use

In the first case discontinued projects generate, from the financial point of view, a loss involving not only costs of these projects but also of previous projects of the sequence. In the second case return of investment and growth appear only after the sequence of projects will be completed in a further period of time. Only in the third case the completed projects might trigger the generation of economic returns through the use of the new technology. However, projects that are terminated successfully in the period may generate return of investments and growth only in successive periods, and are related to investments done in previous periods. In conclusion it does not exist actually any direct relation between the R&D investments and growth of a territory registered in the same period, but a time lag between R&D investment and the moment a new technology may enter in use, and a second time lag between this moment and the periods in which the new technology generates return of investment and growth. Such time lags shall be taken account when studying the relation between R&D investments and growth. For example, in a study on relation between R&D investments and GNP of European countries, Japan and USA, it has been considered an average of R&D investment values for the period 1996-1997 and resulting GNP as average values of the period 1998-2001 assuming values of time lags in the range of 2 – 4 years (Coccia 2008).

## 4 Flux Of Knowledge And Capitals In The Model

The model describes the flux of knowledge that includes: the generation of innovative idea by combining R&D knowledge and external knowledge (scientific, technical, etc.), forming proposals for R&D projects and confronting proposals with available investments for R&D. Furthermore the financed R&D projects are carried out through a certain number of phases characterizing the innovation process. As previously cited, the technological model of R&D cannot discuss either the various aspects of flux of capitals, or the socio-economic factors that may favour or inhibit the process of generation of new ideas and R&D proposals. Neither it could define criteria for selection of proposals for R&D projects, establish objectives, performances, economy of the developing technology, and finally decide the continuation or discontinuation of the development or entering in use of the new technology.

### 4.1 Generation of innovative ideas

The model considers generation of innovative ideas as the result of a combinatory process involving knowledge generated by R&D and knowledge of scientific and technical nature as well as other knowledge that may be of economic, market, environmental, etc. nature. A new developed technology may be also considered as a combination of pre-existing technical components or technologies able to exploit new phenomena discovered by science (Arthur 2009), however important technologies may be obtained also by combination of pre-existing technologies without exploitation of new or already known but never exploited phenomena for technological purpose (Bonomi, Marchisio 2016). Examples showing this difference are photocopy, exploiting photoconductivity of materials, and Apple 1, personal computer based only on a successful combination of commercially available components (Bonomi, Marchisio 2016). The combinatory process depends on individual creativity.  Individual creativity was found an important aspect in R&D management concerning typically industrial R&D laboratories (Dumbleton 1986). It is composed by complex stages and found encouraged by favorable organization attitudes such as high trust, free flow of communication and allowed self determination and assessment. Generative relations are another important way in the emergence of new ideas for potential technologies. Such process has been studied and modeled as a convergence of different views during relations among various agents toward a common idea for an innovation (Lane, Maxfield 1995). Typically generative relations occur in R&D activity during discussions among researchers or among researchers and industrial partners. Generative relations have been found important especially in the case of cooperation among SMEs about R&D activities (Rolfo, Bonomi 2014). A particular type of generation of R&D projects and new technologies is observed with the appearance of a new radical technology. That may be at the origin of an explosion of new incremental technologies depending on or alternative to the radical technology (Bonomi, Marchisio 2016). Such effect has been observed indirectly looking to growth of number of patents with time for example in the case of computer tomography in the period 1973 – 2004 (Valverde, Solé, Bedau, Packard 2007). By consequence the observed economic growth generated by radical innovations depends not only by initial research activities, but also in large measure by researchers and technicians that expand the possible applications of the initial innovation and, by consequence, the importance in having also a good intermediate scientific and technical education for such purpose. In fact the importance of education in promoting R&D efforts and fostering economic growth has been found as one of the more important determinant in respect to patents right protection or income growth rates (Wang 2010).

### 4.2 Elaboration of R&D projects proposals

In order to start the development of the innovative ideas it is necessary the elaboration of R&D projects proposals that establish, objectives, research programs, timing and budgets necessary for projects submitted for financing. Rate of transformation of innovative ideas in R&D proposals, in a territorial innovative system, depends in a certain way on the efficiency of actors making R&D and on an effective exploitation of knowledge. Important it is also the free flow of knowledge existing internally and externally to the system. Such transformation of innovative ideas may be strongly motivated by various factors such as availability of financing or inhibited by an unfavorable climate for innovation developments. Another aspect for R&D proposals is the importance of preliminary studies concerning economy, market and even pre-feasibility studies on the innovative idea that may improve the research program of the proposal and, in the case of contract research, make the proposed R&D project more interesting for industrial financing.

### 4.3 Financing R&D projects

The model cannot enter in discussion either about availability of R&D financing, or in selection criteria for the choice of proposals that should be supported. It limits the discussion on the level of available financing compared with the required budgets of the R&D proposals specifying the possible situations as follows:

- Limits due to the availability of investments for R&D in respect to overall budget proposals for R&D projects. It is the most common case. Availability of R&D investments and selection criteria are not necessarily in relation with proposed R&D projects budgets but depends on various socio-economic factors.
- Limits due to scarcity of proposals in respect to available R&D investments (typically public aids) observed for example in low developed or in industrially declining territories.
- Full availability of R&D investments in covering all valid proposals that may lead to an exponential growth of financed R&D. This case, much less frequent, may be present in periods of war and in certain regions and phases of development of new technological sectors. A great example of full availability of R&D investments is represented by the Silicon Valley in which donations and venture capitals make available investments for almost all valid research proposals. Such situation maybe existed also in the field of nano-

technologies, for example in the period between 1987 and 1991, and in some other sectors between 1990 and 1998 showing exponential evolution of number of patents and publications (Hullmann, Meyer 2003).

It should be noted that, following the model, the exponential growth of innovative ideas, and then R&D projects, when enough financing is available, is essentially the consequence of the combinatory nature of generation of new ideas based on increase of R&D knowledge due previous R&D activity in a typical autocatalytic process of increasing returns of innovative ideas.

4.4 Implementation of the R&D activity.

Following the model, the R&D process may be considered as a part of an innovation process and composed by a sequence of projects carried out for the development of new technologies. A view of technology innovation as a process appeared in the seventies of the past century (Freeman 1974). The innovation process was explained as a sequence of three phases constituted by basic (oriented) research, applied (industrial) research and industrial development seen also as precompetitive development. This view of the process, with the name of Frascati Model, has been later accepted as standard reference for surveys on research and experimental development (OECD 2002), and it is currently used for socio-economic studies. However, in technology management, such view is considered too simplified to be useful in management of R&D activity that, as previously cited, it is composed by a sequence of projects that may be included in various phases. Actually R&D is separated by scientific research, and normally started by generation of R&D project proposals followed by a feasibility study that gives a preliminary view on the possibility to achieve the wanted application. In fact the sequence of R&D projects that leads to a new technology may be summarized in a sequence of three phases that includes: the feasibility phase, the development phase and the industrialization phase. To complete the innovation process we may add initially, as described previously, the phase of generation of the innovative idea that may include pre-feasibility activities, and a fifth final phase, concerning the use of the new technology, considering that in this last phase, the activity of learning by doing is also a source of incremental innovations apt to improve the technology (Bonomi, Marchisio 2016). The complete sequence of phases characterizing the innovation process is reported schematically in Fig. 2 and the various phases described as follows:

*Generation of innovative ideas*

Such phase is an essential starting step for any innovation process leading to R&D activities. Such generation is of combinatory nature including scientific, technical, economic, social and environmental knowledge leading to proposal for R&D projects. As discussed previously an innovative idea may include exploitation of new phenomena but also consisting in a combinatory work using new design and already existing technologies. Innovative ideas may emerge by creativity of single researcher of by generative relations as discussed previously. This phase may include also prefeasibility testing and preliminary studies useful to obtain financing and to enter in a full feasibility phase.

*Feasibility phase*

Such phase concerns the feasibility of the innovative idea and involves typically an R&D activity. Scientific and technological factors are of major importance in determining the continuation or not of the innovation process after this phase.

*Development phase*

This phase concerns mainly improvement of level of performance and specification compliances of innovation that are important for evaluation of its economy. Operation of pilot plants or construction of prototypes is a typical activity of such phase. Combinatory generation of new technologies may also start in such phase. Socio-economic externalities have the major impact for the future of the innovation and survival of R&D projects that in this phase is lower than in the feasibility phase.

*Industrialization phase*

This phase includes final development work and planning for the industrialization of the innovation. It should be noted that the level of projects survival in this phase is far higher than in the feasibility and especially in the development phase.

*Technology use*

With the industrialization phase normally the technology innovation process is considered terminated. However, the use of a technology may be also a source of technological innovations through learning by doing that is largely present in particular at the beginning of use of a new technology and decreases after until technology becomes obsolete and it is substituted by a new more efficient alternative technology (Bonomi, Marchisio 2016).

An important aspect of the R&D process is represented by risk of failure and how such risk changes during the various phases of the process. When discussing about innovation processes we shall separate the concept of risk from that of uncertainty (Knight 1921). Actually uncertainty represents the impossibility to evaluate a risk that it is seen as the estimation of probability of success or failure of an innovation development. In fact the R&D activity transforms uncertainty into risk making possible decisions to continue or not the innovation development. There are various types of risks or uncertainty accompanying the phases of the innovation process that concern technology, performance, economy and market. Technical uncertainty decreases principally in the feasibility phase. Performance uncertainty decreases principally in the development phase before economic uncertainty. Market uncertainty is the most difficult to eliminate and it may be substantially reduced only in the industrialization phase and during the use of the new technology (Scherer 1999).

The various projects for development of a new technology carried out during R&D activities have a specific dynamics when seen in the frame of the double flux model. As previously noted, at the end of a project there are three possible exits:

- a new technology is available for entering in use terminating the sequence of projects for its development
- the technology development is abandoned, the sequence of projects is terminated and only the R&D knowledge generated by the project sequence remains available
- the project is terminated but it is decided to continue the development of the technology with further projects and new projects proposals are prepared on the base of knowledge developed in the previous projects.

In every case all projects may be a source of general knowledge that combined possibly with further scientific, technical or other knowledge, may be used for development also of other types of technologies.

## 5 Role Of The General Knowledge Generated By The R&D Process

Following the model, the R&D process generates, beside possible new technologies, also a general R&D knowledge (GRDK) that has an important role as driving force for the development of new R&D activities. Such knowledge is generated by either successful or abandoned projects and not necessarily related to technologies object of these projects. GRDK does not include only technical, scientific or other information but also specific know how formed in the various research fields because of the technological nature of R&D activity. As technological innovations are the results of combinatory processes (Bonomi, Marchisio 2016), possibly exploiting scientific results (Arthur 2009), the GRDK may be considered a knowledge used in the combinatory process with pre-existing technologies generating a new technological idea. GRDK itself is not patentable differently from derived technologies. It should be noted that GRDK is subject with time to fading effects and then a loss of knowledge. This loss may be higher in the case of industry when part of generated GRDK might not meet the interest in evolving technological strategies of the firm. GRDK does not correspond to knowledge spillover, used in many economic studies on R&D, defined as an externality of R&D of a firm impacting technology innovation of other firms (Griliches 1992), and found effective in boosting growth in industrial and developing countries (Bayoumi, Helpmann 1996). Such defined knowledge spillover does not take account of knowledge generated outside firms activities, not necessarily with economic purposes, and by other R&D actors, existing beside firms (universities, public and private laboratories, contract research organizations and start up), in a distributed innovation systems (Haour 2004), and in the frame of an open innovation environment (Chesbrough 2003). GDRK, in fact, includes such defined knowledge spillover and it may include also for example knowledge generated in the frame of policies of leadership-driven innovation and called General-Purpose Technologies (Coccia 2014) that in fact have the nature of a knowledge originating technologies with their specific purpose.

The process with which the GRDK is diffused, exchanged and exploited for generation of new technologies in a territory is quite complex and varied. We would give an idea of that by presenting a certain number of real cases. The first one concerning the way with which GRDK is generated and exploited successfully in the Silicon Valley. In a second case we treat the generation of GRDK in a large R&D project for military purposes such as the Manhattan Project. The third case covers the diffusion of GRDK among firms such as Xerox, Apple and Microsoft for graphical interface for screen bitmapping, and it might be considered a case of knowledge spillover. The fourth case treats a technology developed for pharmaceutical purposes in a contract research laboratory and after used for metallurgical applications through a spin off and creation of a start up. Finally the last case concerns a technological operation developed for nuclear energy production migrating in various other technologies in sectors such as surface hardening, iron and steel refining and production of nanoparticles, the last two cases being a direct experience of the author.

The Silicon Valley innovative system and role of GRDK has been described following a study tour made recently in this territory by the author of this paper:

In Silicon Valley initial ideas for new technologies are generated in manifold ways and considered more a trigger of innovations than potential patentable inventions. They are freely discussed and improved constituting what it may be considered an informal exchange of GRDK. On the other side GRDK formed internally to firms is continually exchanged in the fame of their activities in form of projects for new products through development cooperation, dismissing or hiring following the need of the projects supported by the existence of a local market of competences. In this case a person may be dismissed or hired several time, taking account of his competence, and independently by the fact he has worked in the meantime for a concurrent firm, favouring in this way GRDK exchanges. It should be noted that such type of GRDK does not necessarily arise patents conflicts as it represents often a knowledge originated by projects, but not necessarily linked to the objectives of the projects in which it is born. The fact that useful innovations may be generated by projects carried out for other purposes, justifies the existence for example of specific budgets in contract research organizations available for development of such collateral ideas. These budgets exist also in universities with strong links with industry such as Berkeley and Stanford. It should be noted that Silicon Valley found a great support by military research during the war of Korea and cold war, developing in particular integrated circuits and mini-computers technologies, and winning the competition with electronic industry of Route 128 near Boston. That has been attributed also by a better exchange and exploitation of GRDK among firms against closure existing in electronic industries of the Boston area (Saxenian 1994). Civil applications derived by this R&D activity were considered only after some détente of cold war and oil price shock at beginning of seventies (Feldman, Francis 2002)), and boosted with the arrival of PC followed by an enormous development of Information and Telecommunication Technologies (ITC).

The Manhattan Project for development of nuclear weapons has been described in detail in a book on the history of making the atomic bomb (Rhodes 1986):

In order to develop the nuclear bomb technology the American government created in 1942 three main research laboratories at Los Alamos, Oak Ridge and Hanford. However only the Los Alamos laboratories charged to build up the bomb was operated directly by the army, the other laboratories, Oak Ridge for the production of uranium and Hanford for the production of plutonium, were given for operative management to two main US chemical industries respectively Union Carbide and Du Pont with the purpose to exploit their technological knowhow useful for the project but also to exploit research results by these industries for future civil applications with economic returns. At the end of the project Du Pont ceded management of Hanford to General Electric, however this company was interested, for production of energy, to develop pressurized or boiling water nuclear reactors instead of graphite reactors used in Hanford for plutonium production, and the Pacific Northwest National laboratory, built near the Hanford site for civil nuclear applications, was finally ceded in 1964 to Battelle, while Hanford site remained under the control of the Atomic Energy Commission. Union Carbide operated Oak Ridge longer until its disappearance after the Bhopal disaster occurred in 1984 and Oak Ridge operation was finally ceded by government with other national laboratories in 2000 to Battelle. Nuclear research carried out during the war generated a great number of civil technologies from nuclear reactors for production of energy to fluorinated plastics such as Teflon® used for example for frying pans with an anti-adherent surface for cooking.

The case of GRDK diffusion from Xerox to Apple and Microsoft concerning user interface by screen bitmapping, a milestone in PC development and used presently also in tablets and smart phones, is sometimes described as the biggest heist in the chronicles of industry and has been described in detail in the official biography of Steve Jobs (Isaacson 2011).

The idea of to develop a graphic user interface using screen bitmapping was born at Palo Alto Research Centre (PARC) of Xerox company in the second half of seventies. In1979 Xerox's venture capital was interested to invest in Apple and Steve Jobs agreed to the buying of 100,000 shares at a convenient price of 10 $ if Xerox opened information about R&D activity at PARC. Xerox accepted and during a series of meetings PARC presented three interesting features of its research concerning: networking of computers, object-oriented programming and graphic interface for screen bitmapping. This last feature, used at PARC for the moment only in computer prototypes, was found of great interest by Steve Jobs that started R&D at Apple on this subject. Apple's engineers in fact significantly improved the graphical interface that was applied for the first time to the successful PC model Macintosh, launched in 1983. Xerox tried also to launch in 1981, well before the Macintosh, the Xerox Star computer using a graphic interface, but it was expensive and less performing than the Macintosh and it was a commercial failure after that Xerox abandoned this line of products. Later the graphic interface developed by Apple interested Microsoft for its software development taking advantage of acquired knowledge in the collaboration with Apple on this topic. In fact Microsoft had an agreement with Apple that it will not create graphic interface for anyone other than Apple until a year after Macintosh commercialization. Unfortunately for Apple the agreement did not provide that commercialization of Macintosh would be delayed for a year. In this situation Bill Gates thought that was his right to reveal that Microsoft planned to develop a new operating system, based on knowledge obtained during collaboration with Apple, called Windows, for IBM PCs featuring a graphical interface. Of course Steve Jobs was furious because of this announcement but legal actions were unsuccessful, and Bill Gates commented litigation with Steve Jobs in this way "It is more like we both had this rich neighbour named Xerox and I broke into his house to steal the TV set and found out that you had already stolen it".

A fourth case concern a spin off exploiting GRDK generated in a great contract research laboratory and concerning a technology applied successfully in fields completely different to that of the original project and shows how contract research organizations may induce exploitation of GRDK more efficiently than industry:

In the middle of seventies an important Swiss pharmaceutical company contracted with the Battelle Research Centre in Geneva a R&D project on development of a granulation technology based on exploitation of effect of ultrasound vibrations on a laminar jet of liquid. Through a suitable tuning there is the appearance of vibrated nodes in the jet that, after solidification, form spherical and identical granules. In this way it is possible to dissolve a pharmaceutical principle in a fusible bulking agent obtaining a drug in form of granules of identical dimension and composition. Although good technical results, after few years, this project was discontinued in favor of other granulation technologies. However, a discussion internally to the research centre between a micro-granulation expert and a metallurgist made the birth of an innovative idea to use the same technology to granulate special metals that cannot be grinded because too soft, in particular calcium metal that had at that time growing applications in form of granules with the same dimension. These two researchers made a spin off in 1982 creating a company in France at Annemasse, a city near Geneva, with own capital and public aid proving the feasibility of granulation of calcium metal and finding French venture capital to terminate development and to build up an industrial production plant entering in function few years later. After calcium granules production the technology was extended to granulated tin soldering alloys used in printed circuits for electronic applications. Presently this company is still active employing about 30 people. Considering the case the pharmaceutical company would have made granulation research in its own laboratories, after discontinuation of the project, researchers, not aware of metallurgical art, would be assigned probably to other tasks and GRDK of this research lost. Now supposing a metallurgist that has the idea to use ultrasound in the same way to form metallic granules, he would probably succeed but without availability of previous R&D results this development would take more time and have higher costs.

A last case shows as a technological operation developed for a specific technology in nuclear energy production has been transferred to a series of completely different technologies showing how GRDK may diffuse in the interconnected network of the technology ecosystem:

At the beginning of seventies of the past century Battelle Research Centre in Geneva was developing a new product for hardening steel based on calcium carbide dissolved in molten salts as alternative to toxic and polluting molten cyanides currently used. The team faced a problem how to industrially discharge the molten product from the dissolution reactor. Pouring operation, largely used for molten metals, was not suitable because of destruction of contained calcium carbide in contact with air at high temperature. On the other side a mechanical valve operating around 800°C was not considered technically feasible. The team was in contact with many researchers involved in scientific research and technical use of molten salts and had the occasion to obtain a report on component systems of the molten salt fast breeder nuclear reactor, developed and later abandoned, at the Oak Ridge National Laboratory (Scott, Grindell 1967). The nuclear reactor operated with a fuel based on uranium hexafluoride dissolved in molten salts and had the necessity to evacuate rapidly the melt from the reactor. For this purpose it was developed a freeze valve constituted simply by an open tube at the bottom of the reactor in which the molten salt solidify forming a solid plug for containment of the melt. For evacuation an auxiliary furnace at the level of the plug melted the salt leaving a rapid flow down of the melt. This freeze valve was applied successfully to discharge of molten product for steel hardening, and even applied in other similar productions of dissolved calcium carbide in molten salts for pig iron refining and dissolved calcium metal for steel refining. The same freeze valve was also used by a start up, originated by a Battelle spin off, for production of advanced ceramics, composed by sub-micronic (nano) particles of titanium carbide, synthesized in a molten salt reactor. All these technologies were developed at the stage of small industrial production plants but later abandoned because not competitive.

All these real examples show well the great variety of processes assuring diffusion of GRDK for the generation of technology innovations, as well the importance on R&D carried out not necessarily for economic purposes, and the possible higher efficiency in exploitation of GRDK outside industrial R&D laboratories.

## 6 INTERFACE BETWEEN THE R&D MODEL AND SCIENTIFIC RESEARCH

Scientific research is an important source of exploitable phenomena for applications in new technologies (Arthur 2009) and it is also recognized as source of information useful in technical search in improving existing technologies (Fleming, Sorenson 2004). It is commonly considered that scientific research is at the origin and then preceding the R&D process, however, in certain cases, R&D needs for its purposes specific scientific knowledge, not already available, inducing the carrying out of scientific research to obtain such knowledge. The relation between science and technology is made quite complex because of induction of scientific activities by the technology innovation process. In developing R&D activities, especially in new fields, there is often an intertwining between R&D and supporting scientific research during the innovation process making difficult the separation about what it is done for scientific or applied purposes. Such intertwining between scientific research and R&D existed since the beginning of R&D activities in the XIX century. Search of new dyes in the first R&D laboratories involved synthesis of new molecules, a typical scientific activity, and verification of their interest as dyes, a typical R&D activity. The model suggests to distinguish clearly scientific research as activity improving knowledge of nature that might be potentially object of scientific publications, from R&D projects activities, verifying the use of phenomena for technological purposes that might be potentially object of patents. Relation between scientific research and R&D is often studied taking in considerations scientific publications and patents, relation not deprived of limits of interpretation when considering the R&D process. While scientific research activity is relatively well known through publications, books, conferences, etc. R&D activity has only available information concerning patents, technical publications, presentation, global investments, etc. that are far to be a complete view of R&D activity that includes also information on birth, conditions of development, history and destiny of R&D projects. Very little is known especially about abandoned developments that are a large part of R&D activity, not normally accompanied by patents, and not necessarily object of publications. Although scientific research publications should forerun patents publication, intertwining between research and R&D activities and protection of industrial rights may cause that patents publication may precede, even for certain number of years, scientific publications making possibly complex the study of their relations. The priority given to patents is a well known practice in running R&D projects and might explain for example the appearing of a wave of patents before of a wave of scientific publications observed at the beginning of development of nanotechnologies (Hullmann, Meyer 2003). Another difficulty concerns the fact that not all patents correspond to real applications and not necessarily derive from R&D activities. Furthermore it should be considered that a patent is a legal document using a technical language with the double objective to protect the invention and at the same time revealing the minimum information about the involved technology. Consequently, it is sometimes a poorly reliable source of information. Finally it should be considered that the process by which scientific results may be exploited for new technologies depends greatly by an existent entrepreneurial view of the research activity. This fact is at the origin of a gap of efficiency in exploiting scientific results between Europe and USA characterized by a more cultural view of scientific research in Europe while in USA the entrepreneurial view is historically prevalent (Ben-David 1968). Such entrepreneurial gap existing in Europe has been also presently confirmed by studies carried out for example in Italy (Bonomi 2014) and in a certain measure in United Kingdom (Lam 2011).

## 7 INTERFACE BETWEEN THE R&D MODEL AND SOCIO-ECONOMIC ACTIVITIES

The interface between the R&D model and the socio-economic effects of entering in use of new technologies is of great importance. The study of the model considers three main interactions that are: endogenous vs. imported technologies, private vs. public R&D investments and relation of the R&D process with economic growth. In this last case the various results of the model are confronted with some assumptions and discussions made in studies relating R&D investments and gross domestic product of a country.

### 7.1 Endogenous vs. imported technologies

The role of imported vs. endogenous new technologies is particularly important in emerging countries supporting their industrialization by policies concerning either R&D activities or import of technologies. The effects of such policies have been studied confronting economies based essentially on import of technologies as in the case of GCC countries, namely Saudi Arabia, and BRIC countries based on R&D, such as China, showing that an innovation-based economy actually is not dependent on total expenditure on R&D, but rather relies on the efficient allocation of investments and the rigorous implementation of innovation strategy (Gackstatter, Kotzemir, Meissner 2012). For our R&D model there are important differences in these two strategies concerning generated GRDK that it is nearly absent in the case of imported technologies. By consequence this policy limits sensibly the future possibility of endogenous generation of new technologies, especially those with a high radical degree and then competitive.

### 7.2 Private vs. public R&D investments

The difference of efficiency between private vs. public R&D investments has been studied by many authors (Becker 2013) finding in most cases higher returns to R&D in countries in which the ratio between private and public financing is high. It has been sometime observed that public investments in industrialized countries substitute part of private investments and vice versa with negative consequences on GDP when public investments are prevalent (Coccia 2007). Many explanations have been advanced for the major efficiency of private vs. public R&D investments, including the fact that public investments concern generally R&D projects with higher uncertainty and greater risks of failure and that industry has more experience and knowledge in carrying out R&D projects (Bilbao-Osorio, Rodriguez-Pose 2004). The R&D model cannot enter in such discussions but offers another point of view indicating two critical points in the innovation process in which uncertainty and need of R&D investments are both high and merit consideration for public aids. A first point concerns the phase of generation of innovative ideas and R&D proposals that would be better accompanied by economic, market and even prefeasibility studies as previously cited. The second point is in the final part of the development in which high R&D investments are necessary, for example in construction of pilot plants or prototypes, but still in conditions of high uncertainty of success. Actually most of public aids in R&D are often made available to firms in what it is also called precompetitive research for projects located typically at the end of the feasibility to the beginning of the development phase that are not in fact critical points. It should be argued whether direct public aid to industry for R&D is an effective way to support a growth. For example Switzerland does not supply any direct aid to industry for R&D, nevertheless it is considered one of the industrialized countries with the best results in technology transfer (Haour, Miéville 2011). In fact in Switzerland, differently than in many European countries, public aids for R&D are given to polytechnics and technical universities in support of search and implementation of industrial research contracts, and to firms for industrialization projects. As shown by the model, aids to polytechnics and technical universities would be particularly effective by improving exploitation of GRDK generated during contract research with industry for future projects developments.

### 7.3 R&D investments and economic growth

The relation between R&D investments and country or regional economic growth is a major subject of statistical and econometric studies. The results of the R&D model raise a certain number of observations about assumptions and discussion of results of certain of these studies. There are two aspects of the model questioning the relation existing between R&D investments and economic growth. The first one concerns the fact that the model does not consider any decrease to generation rate of new technologies, and then of growth, when there are enough available investments for valid R&D projects, contrarily to many results of econometric studies. The second aspect concerns the importance given by the model to the variety of innovative systems of countries and territories depending on presence in the system of distributed and open innovation activities. In fact, different availability of GRDK due to existence of R&D not related only to economic purposes, and differences in exploitation efficiency of scientific results as discussed previously comparing USA and Europe vision of scientific research, may lead to differences in results of R&D investments.

Concerning relation between R&D investments and growth, econometric and statistical studies have often found an inverted U curve about effect of various determinants on R&D (Becker 2013). An inverted U curve (quadratic function) has been also found for industrialized countries in a study of dependence of Gross Domestic Product (GDP) per capita, in the period 1998-2001, on Gross Domestic R&D Expenditure (GERD), expressed as percentage of GDP, in the period 1996-1997, then assuming a time lag between R&D investments and resulting GDP of about 2-4 years (Coccia 2008). This study shows also that a level of GERD percent equal to 2.7 maximises the GDP per capita, value close to the suggested objective of GERD of 3% for the European countries by the Lisbon strategy of EU (Room 2005). This study shows also that values of GDP of various industrialized countries, following the quadratic curve obtained by the econometric model, tends to increase less than proportionally increasing GERD and even decreasing as in the case of Sweden. Such behaviour, as cited previously, cannot be explained by the R&D model that on the contrary foresees an exponential increase of new technologies, and then of growth with the increase of availability of R&D investments. Such inverted U behaviour of GDP as a function of GERD has been attributed to diminishing returns to research investments that play a similar role to diminishing returns to capital accumulation into standard neoclassical growth model (Coccia 2008). However, the pertinence of the standard neoclassical growth model as explanation might be doubtful considering that technology is not a true economic good (Bonomi, Marchisio 2016), and that the neoclassical model would not be valid in studying effects of new technologies on the economic change (Nelson, Winter 1982). Following the previous considerations it seems that the observed inverted U behavior does not have actually a satisfying explanation. A striking example of inexistence of limits to technologic development associated to an economic growth is represented by the Silicon Valley. Its innovative system has been studied in the frame of the winning competition with electronic industry of Route 128, a region near Boston (Saxenian 1994), and following a study tour carried out recently in this territory by the author cited previously. In this territory firms strategies are based on a continuous development of innovations, organizing activities in term of projects and subcontracting production, indifferent to cannibalization of its owns products, sure that this strategy will necessarily generate economic growth. Innovation activity in the Silicon Valley is not seen in term of R&D investments but as general capital investments including industrialization and commercialization of products, and venture capital finances start up indiscriminately for R&D and business model developments. In fact Silicon Valley with its long term technical and economic success of its innovative system appears as an important challenge to traditional economic views on relation between investments in R&D and growth.

Another important aspect on relation between investments in R&D and growth concerns the effective role of territorial or country innovative system. Difference in dimension of population, innovation policies, etc. may influence the efficiency of the innovative system of the various countries that might transform differently the same R&D investments in contributions to the gross domestic products. This fact might raise questions about the validity of comparison of effects of GERD on GDP among the various countries. Such differences might be observed as deviations of growth values for a given R&D investments in respect to typical inverted U curves obtained by econometric models. We may consider for example the study on dependence of GDP of GERD cited previously (Coccia 2008) that used World Bank data of various countries. About agreement of data by the obtained curve we observe quite scattered positions for countries with low GERD, a good agreement in the case of France, Germany, UK and Sweden, but sensible deviations in the case of Italy, USA and Japan, The first two deviations with a value of GDP much higher and the last one much lower in respect to the curve. The dispersed data for GDP for low GERD value may be easily explained by the importance of other factors in the building of GDP in respect to investments in R&D activity in such type of countries. This fact has been already observed for example in the case of countries exporter of oil or not (Gackstatter, Kotzemir, Meissner 2012) cited previously. For the important deviations observed for USA and Italy we might advance an explanation considering the difference of the innovative system of these countries in respect to the other European countries. In fact USA innovative system is characterized by a large availability of GRDK mainly through military R&D, improving birth of new technologies and reducing cost of R&D for their development as previously discussed. On the contrary in Italy the deviation might be explained by a real value of GERD much higher than the recorded one due to an innovative system linked to existence of large number of SMEs, often organized in industrial districts. These firms do not necessarily take account of cost of their innovation activity in term of R&D investment, as already observed in previous studies (Hall, Lotti, Mairesse 2009). Another question about this study is that in fact the curve represents a nearly static situation, and it does not represent a dynamics of GDP showing effects of large changes in GERD. In fact large changes of GERD values for single industrialized countries are absent in the last decades of the XX century. For example in the case of Italy this country should double its GERD value to reach suggested values by the Lisbon strategy, but prior examples demonstrating the effect of such important increase on GDP in industrialized countries are not available. Actually there is an interesting example of an important economic growth with at the same time an important growth of R&D investments in the case of South Korea.

In the sixties South Korea was a underdeveloped country got out of a war with R&D investments lower than 0.5% of its GDP. In 1965 president Park negotiated with USA a loan of 150 million $ with scientific and technical assistance to develop scientific research and R&D in the country. The aid included the realization of two main research centres: the Korean Advanced Institute of Science (KAIS) with the help of Frederik Terman, the godfather of the Silicon Valley, and the Korean Institute for Science and Technology (KIST) for contract research organized by Battelle, later merged with KAIS becoming the Korean Advanced Institute of Science and Technology (KAIST). Such investments, accompanied by suitable policies, were successful generating an important economic growth and R&D investments reaching values around 3% of GDP in the nineties. However examination in detail of the followed policies it appears that success of South Korea cannot be attributed only to technological innovation efforts, based on model existing in USA, but also by adopting Japanese industrial organization (Stuart, Leslie, Kargon 1996).

The fact that a model of research and technical education and suitable industrial organization has been so successful in a developing country suggests that the South Korean experience may hold important lessons for both the developed and developing worlds (Stuart, Leslie, Kargon 1996).

## 8 Conclusions

This work presents a model considering R&D as an organized activity of fluxes of knowledge and capitals and based dynamically on R&D projects. These projects are the origin of a general knowledge that, when combined with scientific and technical results and other information, forms proposals for the development of new technologies. Such general knowledge is not limited to a knowledge spillover among firms but it rises from other actors in R&D as well from R&D activities carried out beside economic purposes in the frame of a distributed innovation system in a situation of open innovation. The model sees the interface of R&D with science as an intertwining process of scientific research and R&D activities in which scientific research is potentially suitable for publications and R&D potentially a source for patents. Concerning the interface of R&D with the socio-economic system the model raises questions about relations between GERD and GDP from econometric models considering that the type of innovative system of a specific country may influence this relation and proposes explanations of deviation of countries such as Italy and USA from results obtained by econometric models. On the other side the model disagrees with interpretation of obtained inversed U curves in relation between GERD in term of standard neoclassic model of diminishing returns considering the inexistence of limits to development of new technologies, with their positive impact, when enough financing of new innovative ideas is available. Concluding the R&D model might suggest, considering the Silicon Valley and the South Korean experience, that economic growth in industrialized countries does not depend actually by R&D investments, that might be considered rather a means, but by the intensity of generation of innovative ideas, that depends on the efficiency of the innovative system, and strategies and availability of capitals financing their development joined with an effective industrial organization.

That means also a simple increase of availability of R&D investments or public aids might be much less successful than expected if improvement of the efficiency of the innovative system of a territory is not combined with such investments increase.

## 9 BIBLIOGRAPHY

Arthur B. 2009. The Nature of Technology Free Press, New York.

Auerswald P.E., Branscomb L.M. 2003. "Valley of Death and Darwinian Seas: financing the Invention to Innovation Transition in the United States", *Journal of Technology Transfer*, 28, pp. 227-239.

Basalla G. 1988. The Evolution of Technology, Cambridge University Press.

Bayoumi T., Helpman E., Coe D.T. 1996. "R&D Spillover and Global Growth", *NBER Working Paper 5628.*

Becker B. 2013. "The Determinants of R&D Investment: A survey of the Empirical Research, Economics Discussion Paper Series", *School of Business Economics*, University of Loughborough UK.

Ben-David J. 1968. La recherche fondamentale et les universités. Réflexions sur les disparités internationales, OCDE, Paris.

Berreur L., Guillot P., Lesrel O. 1989. "Les Organismes de Recherche sous Contrat dans la CEE", *Commission of the European Communities*, EUR 12112 FR-EN.

Bilbao-Osorio B., Rodriguez-Pose A. 2004. "From R&D to Innovation and Economic Growth in the EU", *Growth and Change*, 35, 4, pp. 434-455.

Boehm G., Groner A. 1972. Science in the Service of Mankind, Lexington Books.

Bonomi A. 2014. "Bridging Organizations between University and Industry: from Science to Contract Research", *Working Paper Cnr-Ceris*, 15/2014.

Bonomi A., Marchisio M. 2016. "Technology Modelling and Technology Innovation: how a technology model may be useful in studying the innovation process", *IRCrES Working Paper,* 3/2016.

Branscombe L., Morse K., Roberts M., Boville D., 2000. "Managing Technical Risk: Understanding Private Sector Decision Making on Early Stage Technology-based Projects", *NIST GCR 00-787*, US Department of Commerce.

Chesbrough H.W. 2003. Open Innovation: The New Imperative for Creating and Profiting from Technology, Harvard Business School Press.

Coccia M. 2007. "Il finanziamento pubblico alla ricerca spiazza l'investimento provato in ricerca ? Analisi ed implicazioni per la crescita economica dei paesi", *Working Paper Ceris-Cnr*, 4/2007.

Coccia M. 2008. "Science, funding and economic growth: analysis and science policy implications", *World Review of Science*, Technology and Sustainable Development, 5, 1 pp. 1-27.

Coccia M. 2014. "Leadership-driven innovation & evolution of societies", *UNU-MERIT Working Paper Series*, 2014-087.

Dumbleton J.H. 1986. Management of High Technology Research and Development, Elsevier Science Publisher.

Feldman M.P., Francis J. 2002. The Entrepreneurial Spark: Individual Agents and the Formation of Innovative Clusters, in Complexity and Industrial Cluster, Quadrio Curzio A. and Fortis M. Editors, Physica-Verlag, Heidelberg.

Fleming L., Sorenson O. 2004. “Science as a map in technological search”, *Strategic Management Journal*, 25, 909-928.
Freeman C. 1974. The Economics of Industrial Innovation, Penguin, Harmondsworth (OECD Report: The Measurement of Scientific and Technical Activity).
Gackstatter S., Kotzemir M., Meissner D. 2012. “Building an innovation-driven economy – the case of BRIC and GCC countries, Basic Research Program at the National Research University”, *Higher School of Economics*, Moscow, Russian Federation.
Griliches Z. 1992. “The Search for R&D Spillovers”, *Scandinavian Journal of Economics*, 94 (Supplement) 29-47.
Hall B.H., Lotti F., Mairesse J. 2009. “Innovation and productivity in SMEs: empirical evidence for Italy”, *Small Business Economy*, 33, 13-33.
Haour G. 2004. Resolving the Innovation Paradox: Enhancing Growth in Technology Company, Palgrave Macmillan.
Haour G., Miéville L. 2011. From Science to Business: How Firms Create Value by Partnering with Universities, Palgrave Macmillan.
Hullmann A., Meyer M. 2003. “Publications and patents in nanotechnology. An overview of previous studies and the state of the art”, *Scientometrics*, 58 (3) pp. 507-527.
Knight F. H. 1921. Risk, uncertainty and profit, Hart Schaffner & Marx, Houghton Mifflin Co.
Isaacson W. 2011. Steve Jobs, Simon & Schuster.
Lane D., Maxfield R., 1995. “Foresight, Complexity and Strategy”, *Santa Fe Institute Working Paper*, 95-12-106.
Lam A. 2011. “What motivates academic scientists to engage in research commercialization: “Gold”, “Ribbon” or “Puzzle””, *Research Policy*, 40, (10) pp. 1354-1368.
Malerba F. 2007. Innovation and the evolution of industries, in Innovation, industrial Dynamics and Structural Transformation, edited by U. Cantner and F. Malerba, Springer Verlag, Berlin.
Nelson R.R., Winter S.G. 1982. An Evolutionary Theory of Economic Change, Cambridge MA & London: Belknap Press of Harvard University Press.
OECD 2002. Frascati Manual: Proposed Standard Practice for Surveys on Research and Experimental Development. Paris, France: OECD.
Rhodes R. 1986. The Making of the Atomic Bomb, Simon & Schuster, New York.
Rolfo S., Bonomi A. 2014. “Coopération pour l’innovation au niveau local: un exemple italien de succès”, *Innovations*, 44, pp. 57- 77.
Room G. 2005. “The European Challenge: Innovation, Policy Learning and Social Cohesion in the New Knowledge Economy”, *The Policy Press*, Bristol.
Saxenian A. 1994. Regional Advantage, Harvard University Press.
Scherer F.M. 1999. New Perspectives on Economic Growth and Technological Innovation, Brookings Institution Press, Washington, DC p. 66.
Scott D., Grindell A.G. 1967. Components and systems development for molten-salt breeder reactors, ORNL – TM – 1855.
Stuart W., Leslie S.W., Kargon R. 1996. “Selling Silicon Valley: Frederick Terman's Model for Regional Advantage”, The Business History Review, Vol. 70, No. 4 (Winter, 1996), pp. 435-472.
Thompson J.D. 1968. Organizations in action, McGraw-Hill, New York.
Valverde S., Solé R., Bedau M., Packard N. 2007. Topology and Evolution of Technology Innovation Networks, Phys. Int. Rev. E 76, 032767.
Wang E.C. 2010. “Determinants of R&D investment: The Extreme Bound-Analysis approach applied to 26 OECD countries”, *Research Policy*, 39, 103-116.

## 10 FIGURES

**Figure 1.** Double flux model of the R&D process

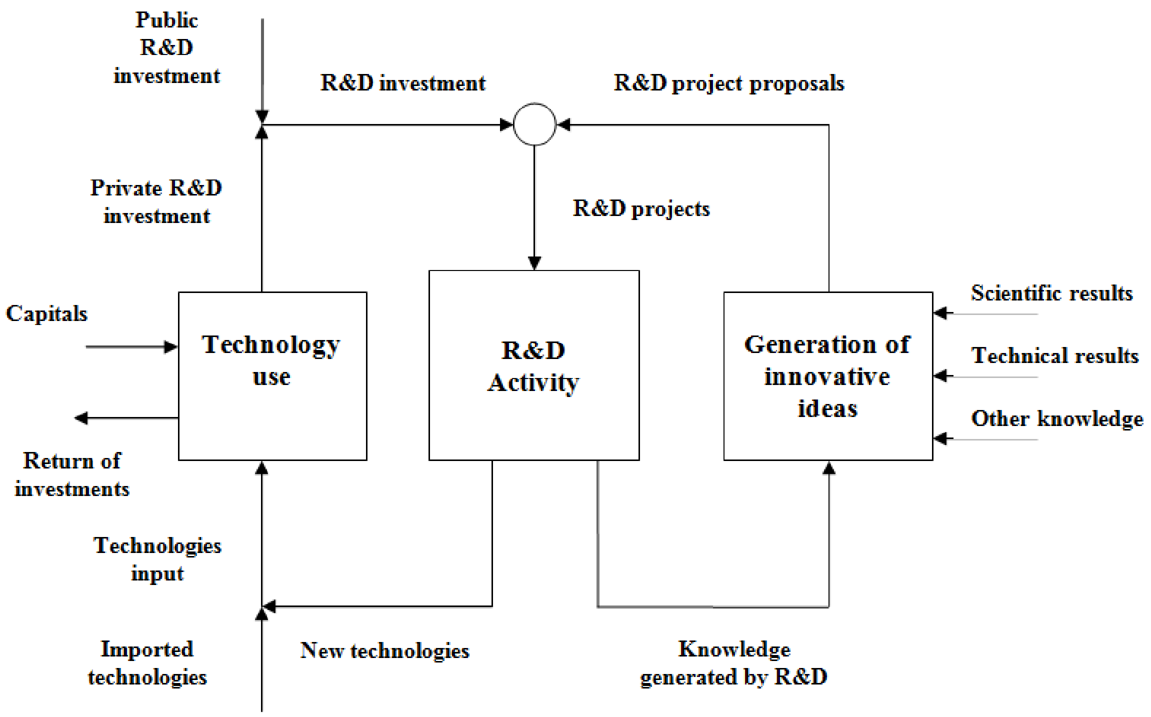

**Figure 2**. Phases sequence of the innovation process