Technology Modelling and Technology Innovation

How a technology model may explain the technology innovation paradox in SMEs

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1. INDRODUCTION

Technology innovation is a highly complex process. While science and technology research, sources of funding, performance as well as corporate motivations, governance, finance, strategy are reasonably studied and understood by academics and policy makers, the process by which an innovative technical idea can be developed to a successful new technology is poorly documented and little studied (Auerswald, Branscombe 2003). In fact technology innovation is largely studied by two point of views: the first one concerns science and technology developments in specific areas such as nanotechnologies, biotechnologies, etc. the second one concerns social and economic aspects of the process considering technology in most cases as an externality of the socio-economic system. However, technology may be also seen from a pure technological point of view, independently of specific nature of technology, and considering the social and economic aspects as an externality of the innovation process. This third point of view, although poorly considered, is however important in understanding the dynamic of the innovation process and generation of good practices for its management as well as explaining paradox of existence of technologically competitive innovators and market leaders with marginal activities in research & development (R&D) as observed in many sectors of Italian small and medium enterprises (SMEs) organized in local industrial clusters. For the establishment of a technology point of view it is useful the development of a general model of technology. There are two possible approaches: one considers a technology as an artifact composed by an ensemble of components. For example automobile technology may be seen as a car with its various components such as motor, brakes, wheels, etc. (Frenken 2001), the other one considers technology as a process described by a structured ensemble of technological operations in a temporal sequence making a product (Auerswald, Kauffman, Lobo, Shell,1998). For example a heat treatment technology may be seen as composed by three technological operations of heating, maintaining in temperature and cooling a material in a temporal sequence. For our purpose we will see technology as a process modelled in term of technological operations. The study of structure and relations among operations may be developed in a mathematical model using basically a previous work modelling a technology in term of production recipes (Auerswald, Kauffman, Lobo, Shell, 1998) and applied to learning by doing (LbyD). We have further extended such model to the entire innovation process including research & development (R&D) and a view of technologies either in term of graphs or matrices. Actually real technologies are normally too complex to be treated exhaustively by a mathematical model and its use is limited to theoretical studies such as learning by doing (Auerswald, Kauffman, Lobo, Shell, 1998), search of optimal technological recipes (Kauffman, Lobo, Macready 1998) or in experimental planning in order to reduce the number of experiments in the search of optimal recipes (Bonomi, Marchisio, Riu, 2007). However, many defined concepts and relations emerging from the mathematical model are useful in understanding dynamics of the innovation process and are the object of discussion in this paper.

This article is composed by four chapters. After the introduction, in a second chapter we present the model of technology. The mathematical aspects of such model allows the defining of various concepts such as the technological space, the space of technologies with the measure of the radical degree of a technology, the efficiency of technologies, the technological landscapes and the intranality and externality effects, that are useful in explaining the innovation process. However, we have chosen for simplicity of discussion to present the model in this chapter in a qualitative way defining: what is a technology, its structure, and the other important definitions derived by the model while the mathematical aspects are presented in an annex to this paper. In a third chapter we discuss the innovation process with paragraphs presenting the use of the model in explaining in a new way the innovation process. Technological innovation is presented as sequential process characterized by various phases, and how the model may suggest the existence of three main types of activities for innovation in term of R&D, combinatory development and learning by doing. Afterwards, it is discussed the role of the radical degree of a technology on its competitiveness, the role of externality and intranality effects in the innovation process, and links existing between patents and technological landscapes. The conclusions of the paper are reported in the fourth chapter.

2. THE MODEL OF TECHNOLOGY

2.1. Definition of technology

A technology may be defined in general term as an activity satisfying a human purpose (Arthur 2009). From the scientific point of view a technology is seen as an application of research results and from the technological point of view simply as an activity making a product. Such activity may be described in term of a mathematical model and in this chapter we present a qualitative description of the model.

2.2. Structure of the model and the technological space

The model sees a technology as a structured ensemble of technological operations (Auerswald, Kauffman, Lobo, Shell,1998). For example, a heat treatment technology may be seen as an ensemble of heating, maintaining at a certain temperature, and cooling operations. Such description, however, is not rigidly established and in modelling a technology we may use a more or less detailed set of operations giving a gross or fine description depending on the purpose of use of the model. That is possible because technological operations have themselves the nature of a technology. For example, in the production of faucets the technology is composed by a structure of operations such as casting, machining, finishing and chroming the products (Rolfo, Bonomi 2014). Each of these operations may be detailed and, for example, chroming operation is in fact composed by sub-operations such as degreasing, deposition of nickel followed by deposition of chrome and finally cleaning of the treated part. As operations are carried out in a certain sequence, the description of a technology as an operations ensemble may be improved by considering a graph structure in which nodes are represented by events of starting and/or ending of operations, and arcs oriented with time representing the various operations of a technology. This representation is analogous to what is used in the PERT method for project management in which the events represented by nodes are connected through oriented arcs constituting the tasks of the project. Definition of the operational structure of a technology is however not sufficient for the model, and we have to consider that for any operation it is necessary to give instructions setting the operational parameters that are characterized by particular values or choices. The whole set of parameters values constitutes a *technological recipe* for the use of a technology (Auerswald, Kauffman, Lobo, Shell 1998). Such parameters may be for example final temperature, heating velocity, maintaining time and cooling velocity as in the case of the cited heat treatment technology. Specific choice of parameters values for each operation constitute then a configuration or recipe of the technology and, if we consider that parameters may assume an ensemble of discrete values in a certain range, by a combinatory calculation we can obtain the whole number of configurations or possible recipes existing for the modelled technology. All the configurations of a modelled technology may be represented mathematically in a multidimensional discrete space in which each point represents a specific configuration or recipe of the technology that may be called *technological space*. In such space it is possible to measure mathematically the similarity of recipes by measuring the Hamming distance between two points, or recipes, of the space. Higher is the Hamming distance, lower is the similarity of the recipes. The definition of a technological space is important because the search of optimal conditions in operating a technology may be seen as an exploration activity in this space.

2.3. Space of technologies

Technological space is useful to describe a single technology with a defined operations structure. However, when discussing of various technologies, for example studying technological competition and evolution, it may be useful to have a representation space for all technologies. This representation can be obtained by the definition of technology as an activity able to fulfil a specific human purpose (Arthur 2009). By consequence we can consider the existence of an ensemble of technologies able to fulfil *the same* human purpose. It will be of interest to present this ensemble of technologies in term of a space in which it is possible to describe technology evolutions and evaluations of differences between technologies that are in competition for the same purpose. Technologies cannot be described by a simple combination of operations because they have a specific time-oriented structure that can be represented by a graph. From the mathematical point of view a graph may be considered also in term of a matrix. This leads to the possibility to define a technology as a matrix, and use it to define a space similar to the technological space, in which each point represents a technology with its specific structure of operations, and called *space of technologies*. Alike the technological space it is possible to measure a Hamming distance between two technologies that increases with the difference between the two. Such distance may be defined also as a measure of the *radical degree* of a new technology compared to a pre-existent technology. Such radical degree can play an important role in studying competition among technologies in the innovation process. Space of technologies and technological space are important because a technology innovation process may be described as an exploration of such spaces looking for an optimal structure of operations and of their parameter values constituting innovation activities such as R&D or learning by doing.

2.4. Efficiency of technologies

Technology efficiency is a complex concept that is difficult to define quantitatively in univocal terms. From the practical point of view there are many types of efficiency that may be considered. For example, it is possible to consider energy efficiency of a technology in terms of production of energy but also on the contrary in terms of minimization of consumption. It is also possible to define an environmental efficiency of a technology in terms, for example, of level of abated pollutants as well as in terms of level of purity, accuracy etc. One of the most important efficiency of a technology concerns its economy and may be expressed in terms of minimal cost of production. From the point of view of the model it is possible to define an overall efficiency of a specific recipe of a technology but also an efficiency of particular operations with specific values for their parameters. For practical use of the model it is useful to choose a mode of calculation of efficiency in such a way that the overall efficiency results of the sum of the efficiency of the various operations. For example, in a technology of production of energy there are operations that have a positive efficiency generating energy and operations with negative efficiency consuming energy and the overall efficiency corresponds to the sum of positive and negative values of efficiency of the various operations. In the case of economic efficiency we should express efficiency in terms of costs that should be minimized and overall cost of a technology will be in fact the sum of costs of the various operations.

2.5. Technological landscape

From the point of view of the model the efficiency depends on the considered technological recipe. As the whole ensemble of technology recipes are resulting by a simple combinatory calculation, certain recipes will have null or negative efficiency and others positive efficiency. Considering that all recipes may be represented by points in the technological space, we may associate to each point or recipe a scalar value of efficiency obtaining, by mapping this space, a fitness landscape that is called *technological landscape*. Such landscape is characteristic of the specific structure of operations characterizing the modelled technology and the defined type of efficiency. Exploring a technological landscape, we may find regions with recipes with nearly null efficiency and other regions with recipes with high values up to optimum values of efficiency. The landscape may present in certain cases only an optimum of efficiency at the top of a single "hill" of the landscape or have cluster of "peaks" of efficiency or even a rugged structure of high number of "peaks" with roughly the same efficiency. In a technological landscape the innovative process may be seen as an exploration searching an optimal "peak" of efficiency for the technology.

2.6. Intranality and externality of a technology

It should be noted that in practice the efficiency of an operation may be influenced not only by its specific instructions but also by changing instructions of other operations of the recipe. This fact is defined as the *intranality* of a technology. Such effect is important in optimization of a technology innovation that it is achieved by a tuning work of the various parameters in the search of an optimal recipe. Existence of intranality effects does not allow an independent optimization of efficiency of single operations in improving the overall efficiency of the technology. From the mathematical point of view it is possible to show that a single optimal "peak" in a technological landscape is possible only in absence of intranality effects. In presence of intranality effects the landscape tends to have clusters of peaks and, when these effects are very numerous, the landscape assumes a rugged aspect with a high number of "peaks" with roughly the same efficiency (Kauffman, Lobo, Macready, 1998). Operations efficiency as well as technology efficiency can be also influenced by external factors or variables that constitute the *externality* of the technology. External variables may be for example: raw materials characteristics, differences in type or composition of used products, various requirements in quality or types of certifications that production should satisfy, etc. As in the case of operations, the externality of a technology may be seen as an ensemble of factors each characterized by a certain number of parameters assuming a discrete number of values or choices in a certain range. Modelling of externalities, as in the case of technological operations, generates a certain number of configurations useful in searching an optimum in function of both recipes (intranality effect) and the external configurations that influence the efficiency of recipes (externality effect). In fact, each external configuration corresponds to a specific technological landscape.

3. THE TECHNOLOGY INNOVATION PROCESS

3. 1. Technology innovation

In the previous description of the model we have described a certain number of aspects of technology in terms of operational structure, technological space, space of technologies, radical degree of a technology, technological landscape. Such aspects derived by the model may explain in a new way the innovation process. Furthermore, the dynamic of the innovation process may be seen through the model as an exploration of the space of technologies and technological landscapes in searching optimal conditions for the choice of operations, their structure, and optimal instructions for a new technology. In fact the model presents in this way a common view of all types of technology innovation activities such as R&D or LbyD.

3.2. A sequential view of the technology innovation process

The use of the model in explaining the innovation process necessitates a description of the innovation process from a technological point of view. Such description should be independent of socio-economic factors as well as mode of financing or type of structure in which the process is carried out, and may be presented in a sequential form, composed by various phases of activity, as reported schematically in Fig. 1. Our sequential schema of the process is not substantially different from the schema given by previous authors (Aueswald, Branscomb, 2003), although in our case we have named the various phases in a different way following our technological point of view. In schema of Fig. 1 we have also reported the presence of the two main activities of R&D and LbyD in the various phase of the innovation process described as follows:

Generation of innovative ideas

Such phase is an essential starting step for any innovation process and it is typical of R&D activities. A new technology is considered the result of combination of already existing technology operations or components that is able to exploit new observed phenomena (Arthur 2009) as well as previously observed phenomena never exploited for the considered specific purpose. This fact represents the main link existing between science and technology and an example is laser, equipment that is composed by already existing electronic components but arranged in such way to make possible the exploitation of phenomena of emission of coherent light (Arthur 2009). In fact the generation of innovative ideas is strongly dependent by past experience such as successful or abandoned R&D projects in combination of economic, market or environmental factors that justify the socio-economic interest of innovation. Individual creativity has been always considered important and environmental working conditions favoring creativity have been described in handbooks for R&D management (Dumbleton 1986). However new ideas may also emerge from generative relations among people during formal or informal discussions, and a model for such generative process has been developed studying for example the case of introduction of computer capabilities in a traditional phone apparatus (Lane, Maxfield 1985). Innovative ideas may be generated not only exploiting new phenomena as in R&D but also by a simple combinatory work and this fact will be discussed later.

Feasibility phase

Such phase represents the beginning of the innovation process and concerns the feasibility of the innovative idea and involves typically an R&D activity. In this phase it appears another important link between the innovation process and scientific knowledge represented by use of such knowledge in delimitation of regions of space of technologies and technological landscapes in searching by exploration new valid technologies (Fleming, Sorenson 2004). Such use of scientific knowledge is of course not limited to the feasibility phase but exists also in all the other phases of the innovation process. Scientific and technological factors are of major importance in determining the continuation or not of the innovation process in this phase.

Development phase

This phase concerns mainly improvement of level of performance and specification compliances of innovation and evaluation of its economy. Operation of pilot plants or construction of prototypes is a typical activity of such phase and the new technology in this phase assumes its first operational structure. Socio-economic externalities have the major impact for the future of the innovation and uncertainty linked to performance and specifications compliance is relieved before the economic aspects of innovation. This phase is known to be the most selective for developing technologies and it has been called metaphorically the “Valley of Death” of innovation projects (Auerswald, Bransomb 2003).

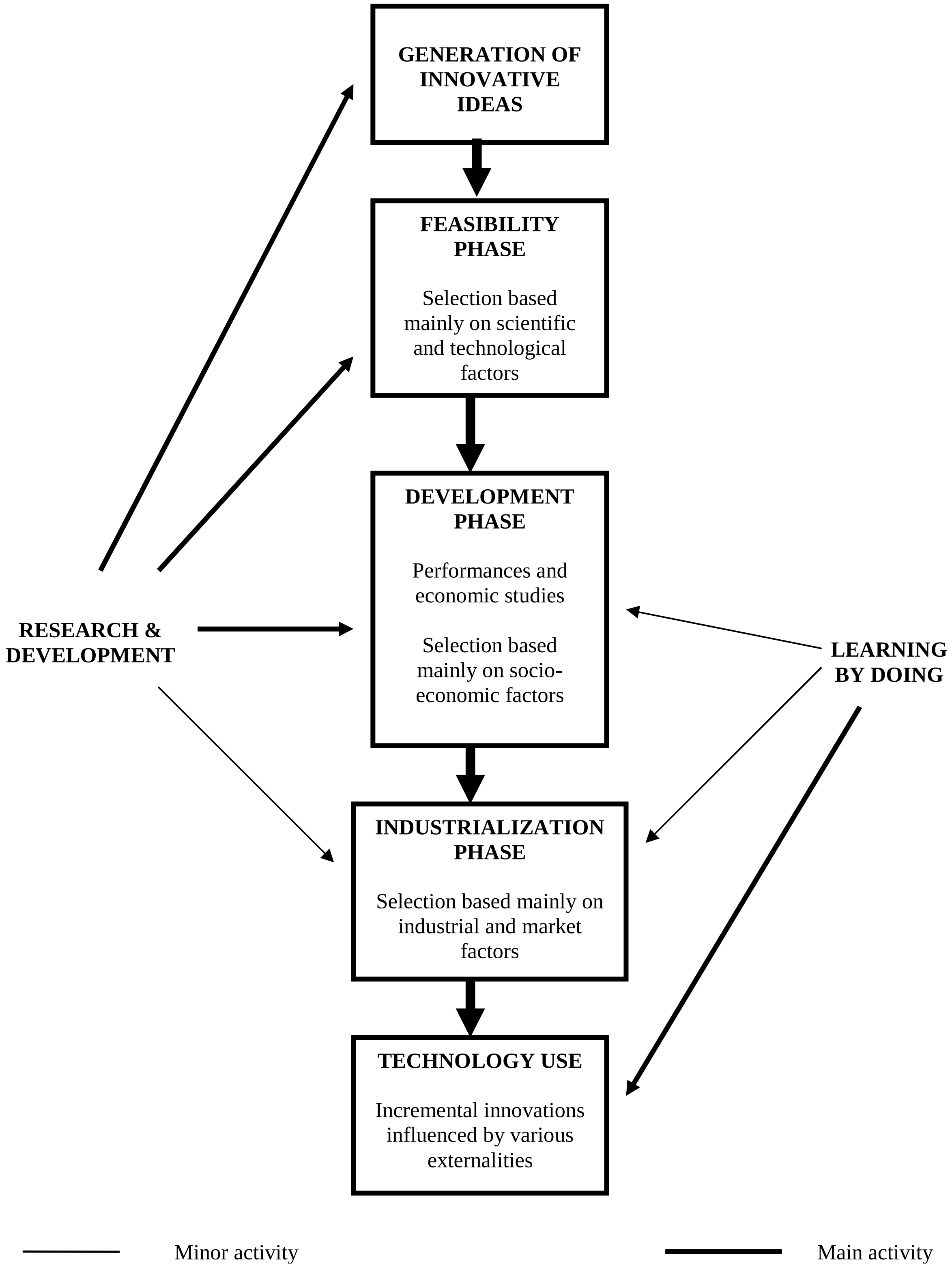

Fig. 1. Schematic view of phases of the technology innovation process

Industrialization phase
This phase includes final development work and planning of industrialization of the innovation and possibly construction of production plants. It should be noted that statistically 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, in our model the innovation process goes on also during the use of the technology, and technological recipes and operational structure of the technology is continuously modified by searching new optimal conditions and by responding to externality factors influencing the efficiency of the technology. Such improvements are typically the result of LbyD and only marginally of R&D. The life of a technology terminates when it becomes obsolete and it is substituted by a new more efficient alternative technology.

Concluding, the technology innovation process, from the point of view of the types of activity, is characterized at the beginning essentially by R&D while LbyD influences essentially the phase of use of a new technology

3.3. Technology model and the activities for innovation

We have seen that technology innovation may be seen by the model as a change in operations and recipes referred to a pre-existing technology. Such change may involve simply a modification of values of parameters searching optimal conditions in the technological landscape, but also minor or major changes in operations and/or in their structure. R&D and LbyD have the same nature as both are involved, from the point of view of the model, in a changing process of a technology. Differences may be noted only considering the extension of changes resulting by the innovation activity. In fact, LbyD involves generally changes in values of operational parameters and possibly minor changes in operations, while R&D is able to change also in a radical way the nature and structure of operations of a technology. For this reason LbyD is normally at the origin of incremental innovations while R&D may develop more radical innovations. As radical innovations have often a high degree of competitiveness and success, this explains the importance given to R&D in the development of innovations. However, there are not fundamental obstacles to LbyD in making radical modifications of the technology structure generating competitive innovations, and that has occurred often in the past history of technology. The difference between R&D and LbyD may be more clearly appreciated considering the relations existing between science and technology and how scientific discovery of new phenomena may be exploited for new technologies normally through R&D activities. However, new radical technologies may appear also in absence of exploitation of new or never used phenomena, but simply by valid new radical combinations of existing technologies fulfilling a specific human purpose. We may well understand such differences in the innovation process considering two important examples of radical technology developments such as the invention of photocopy, based on exploitation of photoelectric properties of matter, and the case of invention of personal computer resulting only by a new radical combination of commercialized components without any direct exploitation of new phenomena.

Photocopy was invented by Chester Carlson in the thirties of the past century (Bohem, Groner, 1972). His central idea was to exploit the photoelectric phenomena existing in certain materials, in form of photoconductive film, exposed to light in such a manner to reproduce, for difference of charges, an image attiring fine carbon powders that may be used to print a paper page. He made experiments in his own kitchen with good results sufficient to obtain a valid patent in 1937. After a period of interruption because of the war, in 1944 Carlson signed an agreement with the Battelle Development Corporation, a division of the Battelle Memorial Institute, for the development of the invention in Battelle Columbus Laboratories. At the end of 1946 Battelle was in measure to make an agreement with Haloid, a medium sized company in the field of photographic paper, for the development and industrialization of the invention. At the end of the fifties Haloid succeeded in offering an automated model with a strong market development and becoming the present Xerox company. The genesis of PC is more complex than that of photocopy as it results of efforts of many peoples and companies. It is usual to cite in this case the history of Apple with its founder Steve Wozniak in 1976, joined after a short time by Steve Jobs that may be considered the person that understood fully the potentiality of Wozniak machine. Looking at the generation of the innovative ideas of Wozniak and Jobs, we do not find any exploitation of new phenomena but a radical combinatory work using pre-existing technologies to develop a new technology for new human purposes. The successful combinatorial generation of Apple was based essentially on use of available commercial components. These ones were arranged following a functioning structure called Von Neumann architecture, known since 1944, obtaining a valid product functioning as a PC. Exploitation of new phenomena had been present only in used components, such as for example the use of transistor effect discovered in 1925 and the possibility to use silicon as solid transistor discovered in 1948.

Innovation activities based on radical new combinations of existent technologies are doubtfully classifiable as true R&D as they concern essentially the development phase of the innovation process involving directly for example the construction of prototypes, as done in the case of PC, but not the feasibility phase in which the possibility of exploitation of new phenomena is verified. On the other side such innovation activity does not correspond to the original definition of learning by doing (Arrow 1962) consisting in a shop floor work, increasing manufacturing experience, leading to a positive macroeconomic production externality independently of bringing additional capital or work and even R&D investments. Actually technology innovation, beside R&D work, is not limited to shop floor work but it may include also introduction of new existing technologies, adaptation of technologies existing in other industrial sectors, testing and analytical work in external laboratories, and even support by experiments in research laboratories, carried out during the phase of use of a technology. Such activity may need investments that sometimes are considered for R&D, sometimes for production or just for maintenance. In fact, considering both combinatory and operational aspects of a technology, it will be possible to define a third type of innovation activity, beside R&D and LbyD, consisting in a radical combination of existing technologies, but not exploitation of new phenomena, and affecting the development phase of the innovation process that we may call *combinatory development*. In such a way these three types of activities for innovation can be differentiated by the model in this way:

Research & development: an activity of technology innovation based on exploitation of new or never exploited phenomena for satisfaction of a human purpose. It is characterized by radical changes related to pre-existing technologies in terms of nature of operations and operation structures.

Combinatory development: an activity of technology innovation based on a combinatory process of existing technologies for satisfaction of a human purpose. It is characterized by radical changes related to pre-existing technologies in terms of nature of operations and operation structures.

Learning by doing: an activity of technology innovation for improving a technology and facing externalities affecting the efficiency of the technology. It is characterized by search of optimal conditions for parameter values of the various operations and possibly minor changes in the nature and/or structure of the technological operations.

From the point of view of the model these three types of activity involve the same process of changing operations and parameters values related to a pre-existent technology. However, if R&D is carried out typically in research laboratories, and learning by doing typically on shop floor, combinatory development has not typical structures for its activity and it may be carried out in laboratories or even in technical offices but not necessarily in structures such as university research laboratories or industrial plants. What it is notable is that combinatory development is able to generate new technologies with relatively high radical degree, and then very competitive, without appealing to scientific research and typical R&D work. This fact explains in a certain way the observed paradox cited in the introduction and existing in industrial territories able to have a global technological and market leadership for conventional products with very little investments in R&D

as it is observed, for example, in the case of small medium enterprises (SMEs) of some Italian industrial districts.

3. 4. Radical degree of innovations and their competitiveness

We have seen the possibility with the model to measure the radical degree of an innovation as a Hamming distance in the space of technologies between the new and a pre-existent technology in competition. In practice the radical degree is linked to the number of modifications in term of operations and their structure. The increase of technology competitiveness observed with the increase of the radical degrees of technologies, is essentially linked technologically to questions of competences, know-how and patents. We may explain that by considering a common situation existing in industrial districts involving two concurrent firms making the same product and using a similar production technology. If one firm improves its technology by LbyD simply by optimizing parameter values or minor changes in operations, the obtained incremental innovation remains probably also in the field of competences of the other firm and this firm would not have major difficulties to also improve its technology eliminating in this way the formed technological gap. Furthermore an incremental innovation may be not necessarily patentable or it may result probably in a weak patent that may be easily countered by the concurrent firm. As incremental innovations are generated continuously in the activity of firms, this leads to a situation called *Red Queen Regime* in which the technologies are continuously improved assuring simply survival but not development of firms. Red Queen Regime is a term used originally in description of genetic competition between preys and predators (Van Valen 1973) and the Red Queen is a character of Lewis Carroll’s “Through the looking glass” that tells to Alice “In this place it takes all the running you can do, to keep in the same place". On the contrary if one of the two firms develops a radical innovation with important modifications in the operations of the technology, it will be very probable that one or more operations will be so different to be extraneous to the existing competences of the other firms. Such firms would be forced to lose time and make efforts in acquiring new competences and know how to become again competitive. Furthermore it will be probable that a new radical technology can be protected by strong patents that will add further important difficulties in recovering competitiveness by the other firm. A conclusion derived by such discussion is that an industrial strategy based only on LbyD is not free from danger in the case of appearance of a new radical technology destroying competitiveness of per-existing technologies. A remarkable example of such situation was the case of Swiss watch industry in the middle of the seventies of the last century threatened by an emergent Japanese watch industry based on piezoelectric properties if quartz and liquid crystal technology instead of the traditional mechanical technology.

Swiss watch industry was composed in the seventies by a great number of SMEs, organized as an industrial district in the north west of the country, and using mechanical technologies for watches production. Innovations were essentially incremental and, although the use of quartz piezoelectricity was known, it was applied only to a few number of luxury models as considered expensive. Japanese watches industry oriented technical developments in a radical direction using quartz piezoelectric oscillations instead of traditional mechanisms, a digital indication of hours using liquid crystals, a material that change its luminosity as a function of applied voltage, and introducing a small battery supplying energy to the watch. This product had a relatively low price and reached a great success in the market putting in great difficulties the traditional Swiss watch industry and, at the end of the seventies, about 40% of Swiss watch firms disappeared. Survival and restarting of Swiss watch industry was due essentially to the action of Nicholas Hayek that organized the merging of many watch firms in the SMH holding, and developed a new watch concept, the SWATCH®, based technologically on a low cost quartz system with a technology industrialization that lasted about four years. Swiss watch industry did not have any liquid crystal technology and practically never used digital indications of hours in its models.

The history of survival and new expansion of Swiss watch industry shows how it was important to have available, although practically not used, a new technology based on quartz, and how was important the development of a new product concept combining both indication of hours and use of watch as an ornamental accessory. However, it should be noted that radical innovations in conventional technology field are relatively rare and a firm, using technology innovation for development, may also consider as complement a strategy of continuous and fast development of incremental innovations conserving continuously the technological gap and competitiveness. This strategy of continuous incremental innovation is, nevertheless, statistically less effective when a technology approaches obsolescence in conformity to the so called Wright law (Wright 1936).

3. 5. Externalities and intranalities in the innovation process

The presence of externalities and intranalities in a technology influences in various ways the innovation process. When a new technology is developed internally by a firm controlling the entire production process such effects are relatively easily well controlled. The situation is quite different when some technological operations of production are subcontracted in a complex network of firms as it is observed for example in industrial districts producing the same type of products. In this case there is often an extended subcontracting activity characterized by firms commercializing the final products that use specialized firms in various steps, i.e. technological operations, of their production while specialized firms have normally numerous final producers and not a single client. A situation of this type is current in Italian industrial districts and an example has been described in a previous work studying a case of cooperation for innovation in the field of tap and valve production (Rolfo, Bonomi 2014). In such case the knowledge of the operational structure of the technology is essential in studies on identification of the most important innovations needed by this sector, as well as in organizing cooperation in R&D projects in which all the necessary competences, spread among the various firms, shall be available for the project, and intranality effects are easily faced in the development of an innovation through cooperation. However, in certain cases, intranality effects in industrial districts may limit the technological development. This is the case of a firm that develops an innovation requiring modifications and/or investments in an operation carried out by a subcontractor. This one may not agree about the investment or in doing changes in its technology that may affect relations with others of his clients hindering in this way the possible use of the new developed technology. This effect has been observed in the Italian ceramic tile district in Sassuolo (Russo 2003).

3. 6. Technological landscapes and patents

Patents are legal documents, written with a technical language, delivered by an administration and establishing a real right about an invention. For such reason patents are necessary linked to a description of a technology and, from the point of view of the model, patent coverage will correspond to a particular region of a technological space and space of technologies. Claims and examples reported in a patent delimit in a certain way the regions of such spaces by establishing a range of variability of parameter values for the operations described in the examples of the patent. The similarity between patents and technologies leads to the existence of a radical degree also for a patent related to previous patents. In this way patents may have a high radical degree and strong patent position or cover only an incremental invention with a lower protection. Another aspect concerns the fact that radical patents, as radical technologies, may be at the origin of the growth of a great number of dependent patents, in analogy with the case of a radical new technology that, in fact, may generate a great number of further incremental innovations. A case of this type has been studied for example considering the original patent covering the invention of computed tomography (Valverde, Solé, Bedau, Packard 2006). The possible representation of patents as regions of the technological space or the space of technologies, and the fact that technology innovation represents an exploration of such spaces, makes of great importance patent intelligence studies, not only determining space regions already covered by existing patents, but also free regions of interest and generation of new innovative ideas. The lack of such type of studies in the development of technologies is a source of cases of failure in R&D activity carried out for example between universities and SMEs (Bonomi 2013).

4. CONCLUSIONS

The model of technology presented in this paper has allowed the definition of a certain number of concepts as technological recipe, technological space with the correspondent technological landscape, space of technologies with a measure of radical degree, and intranality and externality effects of technologies. Such definitions have been shown useful in explaining new aspects of the technology innovation process. In particular, the operational structure given by the model allows a view of the innovation process as a change in the operational structure of a previous technology in term of an exploration of the space of technologies and the technological landscape searching optimal conditions of functioning of the new technology. That means the various types of activities concerning technology innovation such as R&D or LbyD or the new defined activity of combinatory development are of the same nature for the model in terms of changes. These innovation activities may be differentiated only by the extension of such changes and whether or not they exploit new or never exploited scientific discoveries. The definition of the radical degree of a technology in relation to a pre-existent technology allows a new definition for incremental or radical innovation (Nelson, Winter, 1977) and allows the description of a path in the space of technologies for the evolutive trajectory of a technology (Dosi,1982). The operational structure of the model underlines the importance of operations composing a technology. The nature of operations determining the competitiveness of a technology in terms of competences, know how and patents. It is shown how in presence of only incremental innovations, competitiveness among firms reaches a situation of continuous innovation but absence of development in what it is called a Red Queen Regime. Intranality and externality effects, defined by the model, become especially evident in the case of cooperation of firms on specific innovation projects (Rolfo, Bonomi 2014) and it is shown how intranality can, in networks of subcontracted productions, be in certain cases an obstacle to new technology development (Russo 2003). Finally, the model highlights the relations existing between technologies and patents and how a patent corresponds to a region of the space of technologies and technological landscape.

ANNEX

MATHEMATICAL MODEL OF TECHNOLOGY

A1. Technology

This mathematical model is derived by a previous model (Auerswald, Kauffman, Lobo, Shell,1998) employing a variant of the NK model originally designed for analysing asexual biologic evolution (Kauffman, Levin 1987 and Kauffman 1993). This model considers a technology as a structured ensemble of technological operations. Each operation is characterized by a certain number of instructions or parameters and each parameter may assume a discrete number of values or choices in a certain range of variability. For example, a heat treatment technology may be composed by three operations: heating, maintaining in temperature, and cooling. Heating is characterized by parameters such as heating velocity and temperature that should be reached, maintaining characterized by maintaining time and maintaining temperature and cooling by cooling velocity. Each parameter may assume a certain number of values within a certain range. The operational structure of a technology may be represented by an oriented graph in which nodes represent the starting/ending points of an operation and arcs the operations. This graph is similar to representation of tasks used by the PERT method in project management. In Fig. 2 we have presented a simple example of oriented graph structure for the heating technology constituted by three arcs in sequence and their associated parameters.

Following the model a technology may be defined by a set O composed by N operations:

$$O = \{o_i, i = 1, ..., N\} \quad (1)$$

Each operation o_i is characterised by a set M_i of M_i specific instructions:

$$Mi = \{p_{ij}, i = 1, ..., N ; j = 1, \dots, Mi\} \quad (2)$$

In which p_{ij} represents the jth instruction associated with the ith operation o_i. The total number P of instructions characterising a technology is given by:

$$P = \sum_{i=1}^{N} M_i \quad (3)$$

The instruction p_{ij} may assume a set S_{ij} of different values or choices:

$$S_{ij} = \{s_{jik}, i = 1, ..., N ; j = 1, \dots, Mi ; k = 1, \dots, S_{ij}\} \quad (4)$$

in which S_{ij} indicates the cardinality of the set S_{ij}.

The N operations cannot be considered simply a set as in fact they have normally a specific temporal sequence that may be represented by an oriented graph. Indicating with E the set of events determining the start or/and ending of the operations and, as previously, with O the set of the operations we can build up a graph τ that we can call graph of the operations of the technology:

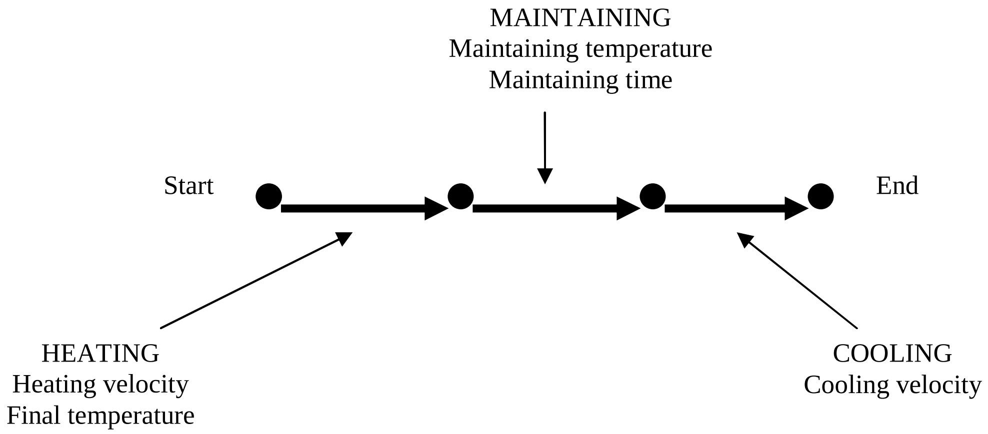

Fig. 2. A representation of a heat treatment technology as a graph

$$\tau = (E, O) \qquad (5)$$

In which ***E*** represents nodes and ***O*** the oriented arcs of the graph. Differently from the previous model of production recipes (Auerswald, Kauffman, Lobo, Shell, 1998), in our model we take into account that each operation can be associated to more than one instruction as in equation (2). For example, an operation such as heating in a heat treatment can be associated to an instruction as the final temperature but also to a specific velocity of heating. Being from equation (1) N the number of operations and from equation (3) P the total number of instructions we have:

$$P \geq N \qquad (6)$$

When $N = P$ each operation is characterised by only one instruction.

A2. Technological recipes and technological space

Considering a specific technology with a set of N operations corresponding to a total of P instructions, we can define as *technological recipe* the specific configuration ω obtained attributing a specific value or choice to each of the P instructions. The set Ω of all the possible configurations of a technology is given by:

$$\Omega = S_{11} \times S_{12} \times \ldots \times S_{1M1} \times \ldots \times S_{NMN} \qquad (7)$$

In other terms we have:

$$\Omega = \{\omega_l, l = 1, \ldots, \prod_{i=1}^{N} \prod_{j=1}^{M_i} S_{ij}\} \qquad (8)$$

The number of configurations $|\Omega|$ is given by:

$$|\Omega| = \prod_{i=1}^{N} \prod_{j=1}^{M_i} S_{ij} \qquad (9)$$

Should be $S_{ij} = S$, $i = 1, \ldots, N$ and $j = 1, \ldots, M_i$ we have:

$$|\Omega| = S^P \qquad (10)$$

We may note that the number of configurations varies exponentially along with the number of values or choices for the instructions and even with a small number of instructions the number of technological recipes is very high.

In order to better explain the previous equations we may illustrate a simple example considering a technology with the number of operations $N = 2$ and then:

$$O = \{o_1 , o_2\}$$

Should for example operation o_1 a heating and operation o_2 a cooling we have:

$$M_1 = \{p_{11} , p_{12}\}$$

Where the operation of heating is associated to $M_1 = 2$ instructions such as p_{11} as the final temperature and p_{12} as the velocity of heating. At the same for the operation o_2 of cooling we may have:

$$M_2 = \{p_{21}\}$$

Corresponding to a free cooling to a final temperature indicated by instruction p_{21}. Now considering there are two possible heating temperatures and only one value of velocity of heating we have:

$$S_{11} = \{s_{111} , s_{112}\} \; ; \; S_{11} = 2$$

$$S_{12} = \{s_{121}\} \; ; \; S_{12} = 1$$

At the same time should be two the final cooling temperatures we have
:

$$S_{21} = \{s_{211} , s_{212}\} \; ; \; S_{21} = 2$$

The number of configurations ω present in the set Ω will be four:

$$|\Omega| = S_{11}.S_{12}.S_{21} = 2.1.2 = 4$$

These configurations or technological recipes may be represented as:

$$\omega_1 = (s_{111}\ s_{121}\ s_{211})$$
$$\omega_2 = (s_{111}\ s_{121}\ s_{212})$$
$$\omega_3 = (s_{112}\ s_{121}\ s_{211})$$
$$\omega_4 = (s_{112}\ s_{121}\ s_{212})$$

We may also define a Hamming distance d among the recipes as the minimum number of substitutions to be made to transform a recipe ω into ω'. This operation is symmetric and we have:

$$d(\omega, \omega') = d(\omega', \omega) \quad (8)$$

In the same manner we may define the set N_δ of neighbours of a recipes $\omega \in \Omega$ defined as the number of configurations ω' existing at distance δ from ω as follows:

$$N_\delta(\omega) = \{\omega' \in \Omega \mid d(\omega, \omega') = \delta\} \quad (9)$$

The space in which it is possible to represent all the technological recipes through the reciprocal Hamming distance can be called *technological space*. The dimensionality of this space is given by number of neighbours $|N_\delta|$ for distance $\delta = 1$. Considering that each of the P instructions is characterised by S_{ij} values or choices the dimensionality of the technological space will be:

$$|N_{\delta}=1| = \sum_{i=1}^{N} \sum_{j=1}^{Mi} (S_{ij} - 1) \quad (10)$$

Should the instructions have all the same number S of values or choices the dimensionality of the technological space will become:

$$|N_{\delta}=1| = (S - 1)P \quad (11)$$

In this case the geometrical representation of the technological space becomes a hypercube of dimension $|N_{\delta=1}|$

A3. Space of technologies

Technological space is useful to describe a single technology with a defined operations structure representing all the configurations or recipes that this technology can assume following its model. When discussing of various technologies, for example studying technological competition and evolution, it may be useful to have a representation space for all technologies. This representation can be obtained considering a family of technologies defined as able to fulfil the same specific human purpose (Arthur 2009). In order to describe a space of a family of technologies it is necessary to define a distance among the various technologies taken into consideration. Technologies cannot be described by a simple combination of operations because they also have a time-oriented structure that can be represented by a graph, and a graph can be mathematically represented in form of a matrix. Distances among technologies can be then defined in terms of distances among matrices.

Let us consider a set (family) of technologies T involved for the same human purpose, for example writing, transportation, etc. Each technology belonging to T is characterised by M operations chosen from a set O of N different operations. It means that the same operations may be in certain cases repeated in the graph structure of a technology. Furthermore, some of the N operations can be also performed “in parallel” i.e. at the same time. Every technology $\tau \in T$ can be, hence, associated with a $M \times N$ matrix T whose elements, T_{ij}, can assume either the value 1 or 0. More precisely, $T_{ij} = 1$ if the jth operations is present in the M position on the graph g related to τ, otherwise $T_{ij} = 0$. At this point it is possible to establish a Hamming distance between any pair of technologies τ and τ' in T as the “difference” between their matrices T and T':

$$d(\tau, \tau') = \sum_{i=1}^{M} \sum_{j=1}^{N} |T_{ij}-T'_{ij}| \quad (12)$$

By knowing all distances among the technologies of the family T we may build up, as in the case of technological recipes, a space that we may name *space of technologies*. Furthermore, it is possible to define a set N_{δ} of the neighbouring technologies of the set T that are between the distance δ as:

$$N_{\delta}(\tau) = \{ \tau' \in T \mid d(\tau, \tau') = \delta \} \quad (13)$$

The number of all the technologies τ present in a given family T is not univocally determined because it depends both on the type and on the “parallel” compatibility of the N operations. If, for instance, none of the N operations could be performed at the same time as another one in O, the cardinality of T would be simply given by N^{M}.

In the space of technologies the Hamming distance between two technologies may be used as definition of the *radical degree* of a new technology as a measure of the difference between a new technology and a pre-existing technology in competition. In other words new technologies that are at a short Hamming distance may be considered as result of evolutive or incremental innovations while new technologies that are at a long distance in this space may be considered as drastic or radical innovations (Nelson, Winter, 1977) in the frame of the trajectory evolution of a technology (Dosi, 1982). Such trajectory, in the technology space defined by our model, may be seen as a path at short Hamming distances in periods of incremental innovations and transitions at high Hamming distance in presence of a radical innovation of a technology. In our model technological space and space of technologies represent the exploration spaces for the development of a technology innovation, considering that exploration in LbyD is mainly carried out in the technological space (Auerswald, Kauffman, Lobo, Shell, 1998), while R&D involves also exploration in the space of technologies.

A 4. Efficiency of technologies and technology landscape

Technology efficiency is a complex concept that is difficult to define quantitatively in univocal terms. Technology efficiency for example in term of energy, abated pollutants, etc. can be measured quantitatively only defining its specific aspects. An important type of technology efficiency is the economical efficiency that can be measured for example as the inverse of unitary cost of production. Relations between two types of efficiency may be established and particularly important are relations between the various types of efficiency with economic efficiency. The efficiency of a technology is strictly dependent on the particular used recipe. Certain recipes may have practically zero or negative efficiency but other recipes may have high efficiency and constitute an optimum. As previously reported (Kauffmam, Lobo, Macready, 1998), associating to all recipes of the technological space the corresponding value of efficiency we obtain the mapping of this space. Indicating with Θ the corresponding value of efficiency to a specific recipe ω of set Ω:

$$\Theta : \omega \in \Omega -> R^{+} \quad (14)$$

This mapped space is called *technology landscape* and it is characteristic of the specific structure of operations and instructions constituting a technology and depending of course of the used definition of efficiency. Exploring a technological landscape we will find regions with recipes with nearly zero efficiency and other regions with recipes with high values up to optimum values of efficiency.

The efficiency of a specific recipe is in general a function of the efficiency of the various operations constituting the technology. In our model we consider convenient to define operation efficiency or inefficiency in such a manner that the sum of single operation efficiency or inefficiency constitutes respectively the global efficiency or inefficiency of the recipe. Considering for example the efficiency θ_i of operation o_i, it will depend on values or choices s_{ijk} of its instructions p_{ij} but possibly also on values or choices of instructions of other operations o_l, $l \neq i$. The total efficiency $\Theta(\omega)$ of the technology with configuration ω composed by N operations is given by:

$$\Theta(\omega) = \sum_{i=1}^{N} \theta_i (o_i, o_l) \qquad (15)$$

This manner in calculating total efficiency of a recipe as sum of efficiency values of single operations is easy made in the case of technical efficiency such as energy, purity, pollution abatement, etc. In the case of economic efficiency if we define it as the inverse of cost of each operation the equation (15) is not valid as the sum of the inverse of operational costs does not give the total economic efficiency. In such case it is preferable to use directly the cost of operations the sum constituting the total cost of a recipe and optimal conditions in the technology landscape constituted by a minimum of costs. In such case the total economic efficiency $\Theta(\omega)$ of the technology with configuration ω composed by N operations will be given by:

$$\Theta(\omega) = 1 / \sum_{i=1}^{N} c_i (o_i, o_l) \quad (16)$$

The total cost C of the recipe by:

$$C(\omega) = \sum_{i=1}^{N} c_i (o_i, o_l) \quad (17)$$

It should be noted that in the cited former model (Kauffman, Lobo, Macready, 1989) there is a different definition of efficiency of a recipe as average of the sum of efficiency of the single operations.

A5. Intranality and externality of a technology

We have seen previously that the efficiency of an operation may be a function of the values or choices made for the instructions characteristic of the operation but possibly also by instructions of other operations existing in the recipe. That means if we modify values of parameters of an operation o_i, the efficiency θ_i of operation o_i will depend on values or choices s_{ijk} of its instructions p_{ij} but possibly also on values or choices of instructions of other operations o_l, $l \neq i$. This fact is defined as *intranality* of a technology. Such interaction has been already considered in technology landscapes of former models (Kauffman, Lobo, Macready, 1998) and defined using mathematically the NK model of interactions. In our model, differently of the former one, we consider the possibility to have more than one instruction for each operation corresponding to a more generalised NK model (Altenberg 1996). Considering the limited purposes of our model we have not developed a mathematical definition of intranality based on a more generalized NK model.

Operations efficiency as well as technology efficiency can be also influenced by external factors or variables that constitute in our model the *externality* of the technology and that should be taken account in our model. External variables may be constituted for example by raw materials characteristics, differences in type or composition of used products, various requirements in quality or types of certifications that production should satisfy, etc. As it has been previously done in the case of values or choices for instructions we may take in considerations various parameters for external variables forming specific external configurations in which the technology should operate. Consider the set V composed by B external variables v_i :

$$V = \{v_i, i = 1, ..., B\} \quad (18)$$

Each external variable v_i is characterised by a set R_i of R_i specific parameters:

$$\mathit{R}_i = \{q_{ij}, i = 1, .., B ; j = 1, \ldots, R_i\} \quad (19)$$

Where q_{ij} represents the jth parameter associated with the ith external variable v_i. The total number Q of parameters characterising an externality is given by:

B

$$Q = \sum_{i=1} R_i \quad (20)$$

The parameter q_{ij} may assume a set F_{ij} of values or choices:

$$F_{ij} = \{f_{jik}, i = 1, ..., B ; j = 1, \dots, R_i ; k = 1, \dots, F_{ij}\} \quad (21)$$

In which F_{ij} indicates the cardinality of the set F_{ij}.

Considering a specific externality with a set of B variables corresponding to a total of Q parameters, we can define as specific externality the specific configuration γ obtained attributing a specific value or choice to each of the Q parameters. The set Γ of all the possible configurations of an externality are given by:

$$\Gamma = F_{11} \times F_{12} \times ... \times F_{1R1} \times ... \times F_{BRB} \quad (22)$$

In other terms we have:

$$\Gamma = \{ \gamma_{l}, l = 1, ..., \prod_{i=1}^{B} \prod_{j=1}^{R_i} F_{ij}\} \ (23)$$

the number of configurations $|\Gamma|$ will be given by:

$$|\Gamma| = \prod_{i=1}^{B} \prod_{j=1}^{R_i} F_{ij} \quad (24)$$

Should be $F_{ij} = F$, i = 1, …, B et j = 1, …, R_i we have:

$$|\Gamma| = F^R \quad (25)$$

We may note that the number of configurations of external variables also corresponds to the number of technology landscapes existing for the technology operating under the influence of a defined configuration of external variables. Finally it is important to consider the value G resulting by:

$$G = |\Gamma|^*|\Omega| \quad (26)$$

$|\Omega|$ represents the number of possible recipes existing in the technology landscape and $|\Gamma|$ the number of externality configurations generated by external variables. Then G represents all the possible global configurations of a technology that takes into account both of the number of possible recipes and of the number of configurations of external variables that influence the efficiency of technology. We may easily represent the intranality and externality of a technology by building up a matrix constituted by columns representing all the operations o_j, I = 1 to N of a technology and rows representing all the instructions p_{ijk} i = 1, …, N and j = 1, …, M_i of the technology and all considered external parameters q_{ij}, i = 1, .., B and j = 1, …, R_i then assuming for each position a value of 1 whether influence of the specific instruction or external variable on the efficiency of the specific operation exists or 0 otherwise:

o_1 o_2 …… o_N
p_{11} ……………….
p_{12} ……………….
……………….
p_{NMN} ……………….
q_{11} ……………….
q_{12} ……………….
……………….
q_{BRB} ……………….

This matrix corresponds to a simplified adjacent matrix of a tri-parted graph constituted by the subset of instructions, the subset of external parameters and the subset of operations with arcs that are oriented exclusively from instructions and external parameters nodes to operations nodes. This graph represents the global interactions existing for a technology. Graph may appear completely connected or in form of clusters playing an important role in modelling a technology and designing exploration of correspondent technology landscapes. Such graphs find for example application in experimental planning for reduction of number of necessary experiments (Bonomi, Marchisio, Riu, 2007).

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