Modelling Technologies for Experimental Planning

Angelo Bonomi (*), Andrea Riu, Mario Marchisio
La Storia nel Futuro (§)

Abstract
This work presents a new approach to modelling technologies for experimental planning. Technology is described as a graph structured time oriented set of operations, each characterised by instructions determining a specific configuration or technological recipe. Such recipes can be represented by using a suitable definition of Hamming distance in a technological space. Considering efficiency of each recipes it is possible to map the technological space forming a technological landscape. Various technologies fulfilling a specific human purpose but different in terms of used operations may be also represented through a matrix structure and characterized by a suitable Hamming distance in a technology space. The distance between two technologies in this space is a measure of the degree of radicality of the innovation existing in passing from one technology to another one. Technology innovation process may be seen as an exploration of technology space, mainly in R&D activity, and in specific technology landscapes, mainly by learning by doing activities throughout the life of a technology in searching optimal technological recipes. Scientific research is seen as a helpful mapping of the spaces to make easier the search of optimal recipes. An example of application of such modelling is given considering the planning of experiments in the search of optimal recipes for a technology of leaching brass to avoid lead contamination of drinking water.

1. Introduction

Modelling of technologies represents a field in full development, mainly in economic sciences in order to understand the complex relations existing between technological development and economic development. Differently from typical models of technology developed in economic science, our approach on modelling considers technology as a complex of physical and chemical phenomena occurring during a specific technological activity. Economic, social, strategic factors and so on, influencing for example competition and evolution of technology, are considered as externalities. Such technical and scientific approach may have useful applications in experimental planning, for example to reduce the number of experiments necessary to characterize and find optimal recipes to operate a technology.

From the scientific and technical point of view a technology may be modelled as a complex system in term of an artefact or as a process. Considering technology as an artefact, this is considered as composed by a certain number of elements, each with various possible characteristics determining its functioning. Such type of modelling of technology has been developed to interpret for example technology evolution (Frenken, 2001) based on the NK model (Kauffman and Levin, 1987) in its generalized form (Altenberg, 1996). In our approach technology is instead considered as a process composed by a certain number of operations each characterized by various possible instructions. Our model may be considered an extension of previous work on modelling technology using a production recipe approach (Auerswald, Kauffman, Lobo and Shell, 1998) and use of technology landscapes for optimal search (Kauffman, Lobo and Mcready, 1998).

(*) Corresponding author abonomi@bluewin.ch
(§) La Storia nel Futuro, www.storianelfuturo.org , is an Italian cultural association for promotion of entrepreneurial initiatives in industrial districts that has sponsored such work.

As operations in a technology have a time sequence we have considered their representation as a graph defining, as in the production recipe approach, a technological space and a technology landscape. Furthermore, we have also defined a technology space representing a particular sets of incremental or radical technologies responding to the same human purpose (Arthur, 2005) and characterizing the degree of radicality of a technology. Finally we present, among the various possible applications of the model the case of an experimental planning to carry out an in depth knowledge of a new technology for quality assurance purposes.

2. Technology

Consider a technology as an activity composed of a great number of physical and chemical processes, linked each other, and exchanging matter and energy. In principle, should we know all the occurring processes, with their corresponding physical and chemical parameters, we would be able to calculate, using the knowledge of laws of physics and chemistry, the various possible behaviours and the optimal conditions of functioning. Of course we actually know that technology processes cannot be optimised by simple calculations, even if by hypothesis we will know all the physical and chemical processes occurring, their enormous number will not enable us to make calculations in reasonable times or even in this case it will be practically impossible to know all the necessary parameters to make the calculations. The enormous number of physical and chemical processes and the enormous number of their parameters existing, even in case of relatively simple technologies, constitute the basic complexity of technology and trials and experience are always necessary to start up and operate a technology.

Although it is impossible to describe in very details a technological activity, it is however possible to describe it in term of operations each including part of the numerous occurring physical and chemical processes. In this way a technology may be described as set of operations occurring in sequence, or at the same time, to fulfil its purpose. A technology could be more or less detailed following the chosen operations for the description. For example, should we consider an operation such as heat treatment, this operation may be further detailed in various steps, or sub-operations, such as heating, maintaining and cooling at various temperatures. The details in which are chosen the operations describing a technology define the grain structure of the technology model and we believe, from our experience, that such type of technology modelling, with a suitable level of fine grain structure of operations, may be useful in managing the development and the operation of a technology.

Putting a technology at work, a list of operations that should be done would not be sufficient and instructions in term of values or choices should be given to operations to enable the functioning of technology. In Table 1 we have reported some examples of technological operations and instructions useful to define a technology. The number of possible operations available for definition of technologies are very numerous and cannot be specified definitely as they depend on the chosen level of grain description of the technology.

Coming back to our model a technology can be defined composed 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:

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

Table 1. Examples of technological operations and instructions

OPERATIONS	INSTRUCTIONS
Heating	Temperature
Maintaining at a certain temperature	Time
Cooling	Velocity of displacing
Treating in a bath	Velocity of heating
Pouring	Distance of displacement
Drilling	Force
Charge an electrical capacitor	Values of electrical resistance
Use an electrical resistance	Values of electrical capacity
Transportation	Pressure
Crushing	Chemical composition
Compressing	Concentration

Where 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 $\mathcal{S}_{ij}$ of different values or choices :

$$\mathcal{S}_{ij} = \{s_{jik},\ i = 1, ..., N\ ;\ j = 1, \ldots, M_i\ ;\ k = 1, \ldots, S_{ij}\} \quad (4)$$

where S_{ij} indicates the cardinality of the set $\mathcal{S}_{ij}$.

The N operations cannot be considered simply a set as in fact they have normally a specific time sequence. Operations can be represented by a graph constituted by nodes, corresponding to the 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 described in the PERT method used for project management. In this case the events constituted by nodes are connected through oriented arcs constituting the tasks of the project. Indicating as ***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:

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

in which ***E*** represents nodes and ***O*** the oriented arcs of the graph. Differently from the model of Auerswald, Kauffman, Lobo and 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 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:

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

Where N = P when each operation is characterised by only one instruction.

2.1. 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:

$$\Omega = S_{11} \times S_{12} \times ... \times S_{1M_1} \times ... \times S_{NM_N} \quad (7)$$

In other terms we have:

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

The number of configurations $|\Omega|$ will be given by:

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

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

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

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 remains 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:

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

characterized by 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 $\omega \in \boldsymbol{\Omega}$ 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:

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

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 an hypercube of dimension $|N_{\delta=1}|$.

2.2. Space of technologies

Technological space is useful to describe a single technology with 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 of technologies. This representation can be obtained considering a family of technologies defined as able to fulfil a specific human purpose. In order to describe a space of a family of technologies it is necessary to define a distance among the various technologies taken in consideration. Technologies cannot be described by a simple combination of operations because they also have a time-oriented structure that can be represented in a graph. Because of the fact that there is a strict correlations between graphs and matrices, each technology has his own matrix representation. That leads to define distances among technologies in terms of distances among matrices.

Let us consider a set (family) of technologies *T* involved to fulfil a 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':

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

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 could name space of technologies. Furthermore, it is possible to define a set N_δ of 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 $\boldsymbol{\tau}$ 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 such defined space of technologies the Hamming distance between two technologies defines the degree of radicality characterizing the difference between the two technologies. In other words technologies that are at a short Hamming distance may be considered, in the time sequence of their entering in use, as evolutive or incremental innovations while technologies that are at a long distance in this space may be considered as drastic or radical innovations using the definitions of innovation proposed by previous authors such as Nelson and Winter (1977) and Dosi (1982). The path in this space that starts form an initial technology and continues through incremental and eventually radical technologies is a representation of the evolution of the initial technology.

2.3. Efficiency of technologies and technology landscape

Technology efficiency is a complex concept that is difficult to define quantitatively in univocal terms. Technology efficiency can be measured quantitatively only defining one of its specific aspects. For example one of the most important types of technology efficiency is related to economy efficiency that can be measured as the inverse of unitary cost of production, but it is possible to consider many other types of measurable technology efficiencies such as energy efficiency, accuracy, chemical purity, amount of abated pollutants for environmental efficiency. Quite important are the relations existing among the various types of efficiency and in particular between economic and technical efficiencies such as energy efficiency, accuracy, chemical purity, etc. Not always this relation is easily established, for example relation between economic efficiency and environmental efficiencies may be quite hard to define as it is difficult to evaluate the economic impact of pollutions in the environment. It is evident that the efficiency of a technology depends on the considered technological recipe. Certain recipes may have practically zero efficiency but other recipes may have high efficiency and constitute an optimum. As previously reported by Kauffmam, Lobo and 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_l of set Ω we have:

$$\Theta : \omega \in \Omega \rightarrow R^+ \quad (14)$$

This mapped space is called technology landscape and it is characteristic of the specific structure of operations and instructions constituting a technology. 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. Moreover 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. 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 will be given by:

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

This manner to calculate total efficiency of a recipe as sum of efficiency values of single operation is easy made in the case of technical efficiency such as energy, purity, pollution abatement, etc. It should be noted that technical efficiency of operations may also be negative. For example in energy efficiency of a technology it may be only one operation producing energy and many others consuming energy and then with negative energy efficiency corresponding to autoconsumption of an energy production plant. However, considering economic efficiency of operations, it is more convenient to calculate cost (inefficiency) of the various operations so that the economic efficiency of a recipe may be calculated as the inverse of the sum of the cost of the operations representing, in fact the total cost of the recipe. Considering for example the cost (inefficiency) c_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 economic efficiency $\Theta(\omega)$ of the technology with configuration ω composed by N operations will be given by:

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

and the total cost C of the recipe:

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

It should be noted that Kauffman, Lobo and Macready (1989) in their technology model adopt a different definition of efficiency of a recipe as average of the sum of efficiency of the single operations according their use of an NK model.

2.4. Intranality and externality of a technology

In the previous paragraph we have seen that efficiency of an operation may be influenced not only by specific instructions of the operation but also by instruction of other operations of the recipe.

This fact is defined as intranality of a technology. Such interaction has been already considered in technology landscapes by Auerswald, Kauffman, Lobo and Shell (1998) and Kauffman, Lobo and Macready (1998) and studied using a NK model of interactions. However in our model, differently of model described by Auerswald, Kauffman, Lobo and Shell, we consider the possibility to have more than one instruction for each operation and when studying intranality in our model we should use a generalised NK model as developed by Altenberg (1996).

Operations efficiency as well as technology efficiency can be also influenced by external factors or variables that constitute 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:

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

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:

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

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

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

where 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 is given by:

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

In other terms we have:

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

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 $F_{ij} = F$, $i = 1, \ldots, B$ et $j = 1, \ldots, R_i$ 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:

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

where $|\Omega|$ represents the number of possible recipes existing in a 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} $i = 1, \ldots, N$ and $j = 1, \ldots, M_i$ of the technology and all considered external parameters q_{ij}, $i = 1, .., B$ and $j = 1, \ldots, R_i$ 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.

3. Technology innovation

It is quite common to consider research & development activities (R&D) in technology innovation in term of research phases consisting in basic oriented research generating new ideas for technology innovation, followed by applied research, normally at a laboratory stage, and, in the case of successful results in an industrial development stage normally working on pilot plants or testing prototypes that finally make the innovation possibly suitable for industrial application. This view of research & development and technology innovation has been proposed by OCDE (Freeman 1974) and is generally accepted but its linear description of the process is a quite simplified way to consider the complex process of R&D. Furthermore, the role of scientific contributions is not limited to the initial phase of the process but in the reality these contributions may exist at any phase of the development of the innovation. Finally we should consider that R&D activities are not alone in the process of technology innovation but learning by doing and adaptation of other existing technologies may play an important role in the process.

Our model suggests a completely different approach to explain the technology innovation process using concepts such as the space of technologies and the technology landscape. In fact the activity of development of an innovation may be considered an exploration of a space of technologies and technology landscape to the research for optimal conditions to establish and operate the new technology. The innovation process may be considered mainly composed by two types of activities: at the beginning research & development consisting prevalently in exploration of technology space to the search for optimal operations structure followed by learning by doing on the industrial application consisting prevalently in searching for optimal instructions in the landscape of the technology. In fact this approach does not limit to description of the innovation process from research & development to the industrialisation phase but, through the learning by doing activity, considers the continuation of the innovative process along the entire life of a technology until reaching an obsolete stage in which the technology is abandoned in favour of more efficient technologies. In other words, our model suggests to describe, through the activity of exploration of the spaces of technologies and technology landscapes, the entire life of a technology from the beginning phase of its generation to the final stage of obsolete abandoned technology. Another important aspect of the innovation process is the role of scientific knowledge and oriented scientific research that may be useful not only at the initial stage of generation of the innovation. On the other side the process of innovation is generally also deeply influenced by information coming from other R&D projects and existing technologies. A schematic view of this process of technology innovation in the frame of the evolution of a technology is reported on Fig. 1.

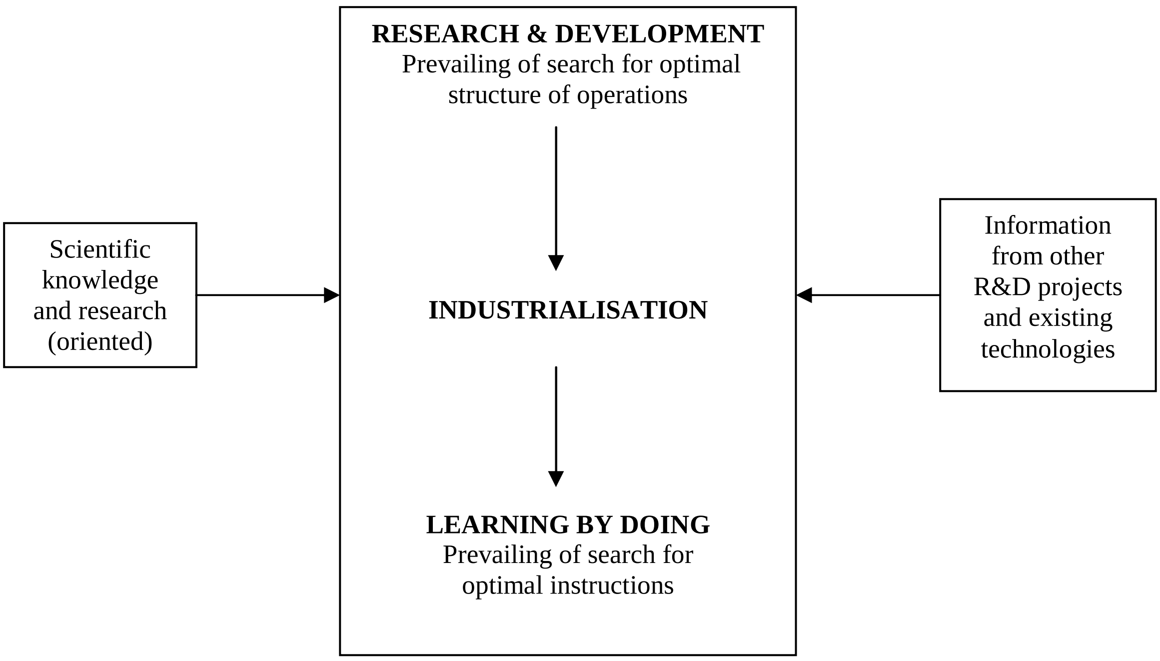

Figure 1. The technology innovation process in the frame of life of a technology

As cited previously technology innovation may be seen as an exploration of the technology space and technology landscapes. Such exploration may be done in different way randomly or based on specific algorithms suggested for example by previous experiences or learning by doing but a specific role is assumed by scientific knowledge and research as concerned mainly by the R&D process existing in the technology innovation process. According to Fleming and Sorenson (2004) and their empirical analysis of patent data the role of science in technology space or technological landscapes is of mapping of landscapes allowing a more efficient research of optimal technologies and recipes.

4. Applications of the model

Our model may be taken in consideration for various types of applications in the field of technology innovation and R&D management. The structure of operations of a modelized technology should be taken in consideration when planning cooperative R&D projects in industrial districts which use the same basic technology for their productions. Past knowledge of various aspect of operations existing in a new technology and their possible intranalities may help to anticipate problems and solutions in developing such new technology. Technology landscapes may be used to represent the scope of a patent on the base of its reported examples and claims and such knowledge may be used to develop alternative inventions not covered by such patent. We report here what may be considered one the most interesting application of the model i.e. the design of experiments in R&D activities.

4.1. Design of experiments in research & development

RUVECO® technology was developed and patented (Bonomi, Carrera and Franzosi, 2001) in the late nineties by Ruvaris, a company born of a joint venture of six Italian manufacturers of valves and faucets, with the aim of providing a method for the elimination of lead contamination from drinking water originated by valves and faucets made with brass containing lead. This metal can be eliminated by the surface of products by a selective dissolution and RUVECO® technology consists in a process of leaching lead by suitable bath composition. It is important for this process to eliminate lead from the surface efficiently in order to reduce contamination of water under specific levels complying the various regulations existing on the market. Treated brass components may have various forms and alloy composition and optimal conditions of treatment should be found for every specific case. In view to implement a quality assurance program it has been taken under consideration to carry out a set of experiments suitable to have a view of the optimal conditions of treatment as a function of the externality of the technology constituted essentially by the alloy composition, type of metal working used in the production of the part, form of the part under treatment as well as limits of contamination to comply for certification standards. Cost of the treatment is a function of treatment time and consumption of bath, that is essentially related to the concentration of the deleading agent, and consumption of degreasing and neutralising agents that should be used in the treatment. Optimum conditions are then defined as the minor cost of treatment necessary to reduce lead contamination to a level complying with certification standards. Considering the range of working parameters for the process it is possible to build up a technological space of recipes and define two types of correlated technological landscapes using respectively economic efficiency (cost) and deleading efficiency. This technical efficiency is represented by the loss of lead on the treated samples measured as increase of lead concentration in the bath. Further, the treated samples should be tested to verify the respect of level of contamination by norms of certification determining a set of recipes whose samples comply with standards. Recipes complying with standards that have a minimum cost constitute the optimal recipes for the technology.

4.2. Modelling of RUVECO® technology

RUVECO® technology consists in a simplified view of three main operations in sequence in three different treatment baths indicated as follows:

Operation A: degreasing of parts by a suitable agent
Operation B: selective deleading of parts surface by suitable agent
Operation C: neutralisation by sweeping off residual deleading bath from the parts

In the Table 2 we have reported the various instructions related to the three operations of the technology

Table 2. Operations and instructions implied by RUVECO® technology

Operations	Instructions	Instruction symbol
Degreasing	Temperature	A-1
	Time	A-2
	Degreasing agent concentration	A-3
Deleading	Temperature	B-4
	Time	B-5
	Deleading agent concentration	B-6
	Bath stirring	B-7
	Positioning of components	B-8
Neutralisation	Time	C-9

In Table 3 we have reported the selected values for instructions implied in the operations calculating s as the number of values or choices for each instruction:

Table 3. Number s of values or choices for instructions

Instructions	Values or choices	s
A-1	2 temperatures (40° and 50°C)	2
A-2	2 times (5 and 10 minutes)	2
A-3	2 degreasing agent concentrations (high and low)	2
B-4	2 temperatures (40° and 50°C)	2
B-5	5 times (5, 10, 15, 20, 30 minutes)	5
B-6	2 deleading agent concentrations (high and low)	2
B-7	2 levels of bath stirring (strong and medium)	2
B-8	2 possible positioning of components	2
C-9	2 duration of neutralisation (long and short)	2

The number of recipes of the technological space corresponding to the chosen range of instructions may be easily calculated using equation (9) reported in the Part 1 of this article:

$$| \Omega | = 2*2*2*2*5*2*2*2*2 = 2^8*5 = 1280 \quad (27)$$

It is also interesting to consider the intranality of the technology that is represented in Table 4 in which the existing interactions between instructions and operations efficiency are indicated by a cross.

Table 4. Intranality of RUVECO® technology

Instruction	Operations		
	Degreasing (A)	Deleading (B)	Neutralisation (C)
A-1	X	X	
A-2	X	X	X
A-3	X	X	X
B-1		X	X
B-2		X	X
B-3		X	X
B4		X	X
B-5		X	X
B-6		X	X
B-7		X	X
B-8		X	X
C-9			X

In addition to intranality we should also consider externality of the technology that may be composed by four external variables, each characterized in our case by only one parameter, that may influence the process:

Variable V-1: Brass composition
Variable V-2: Fabrication (wrought or cast component)
Variable V-3: Form of the component
Variable V-4: Certification (maximum admitted lead contamination)

Choices made for external variables are reported in Table 5 indicating with f the number of values or choices.

Table 5. Values or choices of external variables

External variable	Values or choices	f
V-1	3 alloy compositions	3
V-2	2 types of fabrications (wrought or cast component)	2
V-3	2 types of geometry (simple or complex)	2
V-4	2 types of certifications (easy or difficult)	2

The number of external configurations may be easily calculated by use of equation (24) reported in Part 1 of this article and data of Table 6:

$$|\Gamma| = 3*2*2*2 = 24 \quad (28)$$

There are 24 external configurations corresponding to 24 possible technological landscapes for each type of efficiency under consideration. The various external configurations will also influence efficiency of operation and this externality is represented in Table 7 by indicating the existence of an interaction by a cross.

Table 6. Externality of RUVECO® technology

External variable	Operations		
	Degreasing (A)	Deleading (B)	Neutralisation (C)
V-1		X	
V-2	X	X	
V-3	X	X	
V-4		X	

Adopting such model of technology it is possible to calculate the total number of positions existing in the 24 possible technological landscapes by using equation (26) and values of equations (27) and (28):

$$G = |\Omega|*|\Gamma| = 1280*24 = 30720 \quad (29)$$

giving a total of 30720 measurements of efficiency to describe completely the 24 landscapes.

4.3. Mapping of the technological landscape

We have seen previously that complete characterisation of the 12 technological landscapes needs a very high number of efficiency measurements. This number can be reduced by introducing some simplifications in the model induced by scientific knowledge on the process. These simplifications should take account of parameters and interactions that might have a limited or negligible influence on the efficiency of the technology from the scientific or technical point of view. In this way we make a sort of mapping of the landscape isolating a limited region that could probably contain the optimal working conditions and be characterized by a much lower number of positions. In the case of RUVECO® technology we may consider that efficiency of degreasing and neutralisation operations are essentially dependent only on time using standard temperature and concentrations of the agents. On the other side the efficiency of the deleading operations may be essentially dependent on temperature, time and deleading agent concentrations neglecting bath stirring and system of positioning in the bath. Looking to instructions in Table 4 and simplifying them as cited previously the number of recipes becomes:

$$|\Omega| = 2*2*2*2*5 = 2^4*5 = 80 \quad (30)$$

Also external variables may be reduced not taking in consideration geometry of the part and testing only under conditions of the most difficult certification for determining the set of recipes complying with its standard. Adopting these simplifications in variables of Table 6 the number of external configurations becomes:

$$|\Gamma| = 3*2 = 6 \quad (31)$$

That means the total number of measurements to characterise the six technological landscapes are:

$$G = |\Omega|*|\Gamma| = 80*6 = 480 \quad (32)$$

Finally the intranality and externality of the technology may be described by integrating data of Tables 5 and 6 and adopting the cited simplifications. The interactions obtained are reported by a cross in Table 7.

Table 7. Intranality and externality of RUVECO® technology in the simplified model

Instruction/Variable	Operations		
	Degreasing (A)	Deleading (B)	Neutralisation (C)
A-2	X	X	
B-4		X	X
B-5		X	X
B-6		X	X
C-9		X	X
V-1		X	
V-2		X	

Concluding, following the simplified model the design of experiments will consider the measurement of deleading efficiency of 80 recipes in 6 different external configurations for a total of 480 measurement, and calculation of economic efficiency (cost) of the 80 recipes. The obtained deleaded samples will be submitted to verification of their acceptability following the selected certification determining the set of recipes complying with this standard. Comparing the cost of treatments of the set of complying recipes for each configuration it will possible to choose the more efficient recipe for each external configuration (technological landscape) that will correspond to the recipe with the lowest cost. The knowledge of optimal treatment recipes, as a function of the various characteristics of the part that should be deleaded, will determine reliable conditions for establishing a quality assurance program in the use of the technology.

References

Altenberg L. 1996, NK Fitness Landscape, Section B2.7.2 in The Handbook of Evolutionary Computation, ed. T. Back, D, Fogel, Z. Michalewicz, Oxford University Press, 1997

Arthur B. W. 2005, The Logic of Invention, Santa Fe Institute Working Paper 05-12-045

Auerswald P. Kauffman S. Lobo J. Shell K., 1998, The Production Recipe Approach to Modeling Technology Innovation: An Application to Learning by Doing, Santa Fe Institute Working Paper 98-11-100. Published on Journal of Economic Dynamics and Control, 2000, 24, 389-450

Bonomi A. Carrera S. Franzosi G. 2001, “Selective deleading process and bath for plumbing components made of a copper alloy” US Patent 6,284,053B1

Dosi G. 1982, Technological paradigms and technological trajectories. A suggested interpretation of the determinants and direction of technical change, Research Policy, 11, 147-162

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)

Frenken K. 2001, Understanding Product Innovation using Complex Systems Theory, Academic Thesis, University of Amsterdam jointly Université Pierre Mendès France, Grenoble

Kauffman S. Levin S. 1987, Toward a general theory of adaptive walks on rugged landscapes, Journal of Theoretical Biology, 128, 11-45

Kauffman S. Lobo J. Macready G.W. 1998, Optimal Search on a Technology Landscape, Santa Fe Institute Working Paper 98-10-09E. Published on Journal of Economic Behaviour and Organization, 2000, 43, 141-166

Nelson R.R. Winter S.G. 1977, An Evolutionary Theory of Economic Change, Cambridge MA & London: Belknap Press of Harvard University Press