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Technological clusters with a knowledge-based principle: evidence from a Delphi investigation in the French case of the life sciences

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Abstract

Recent works in the theory of technical change show the effect of irreversibility and lock-in on the diffusion and creation of innovation processes, which are able to stop the development of a generic technology. Therefore, industrial policies play a major role in selecting and supporting the innovative process. The purpose of this paper is to prove the possibility to derive a typology of future innovations in terms of generic technology from a Delphi type technology survey. Thus, it is possible to get a better understanding of the industrial dynamics and to design an interesting tool for industrial policies or for firm strategies, as far as they aim at developing stable technological trajectories. This is applied to the French case of the life sciences. The paper suggests interesting explanatory trajectories in order to fight against diseases such as cancer, Alzheimer or Schizophrenia. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Generic technology; Technological trajectory; Clustering analysis; Competencies; Foresight process

1. Introduction

In industrial economics and especially in knowledge-based economics, many studies refer to irreversibility and path-dependency in connection with the post-Schumpeterian developments of the evolutionary thought. We thus have a better understanding of the evolution of technical change with the introduction in the economic theory of the concept of generic technology and of technological trajectories. In such dynamical and complex social systems, an important point is to understand the role of determinism. The question is to know what kind of small events in today's decisions may have great importance for

tomorrow's actions and determine an irreversible evolution of the system, and what kind of events have no impact. In fact, to be able to forecast the development of knowledge and technological change in some well-known trajectories could be one of the major tasks of industrial policies in order to support innovative processes. The purpose of this paper is precisely to propose a taxonomy of future technologies, providing a better understanding of industrial dynamics. Therefore, we suggest a statistical analysis of a Delphi investigation, based on science and technological knowledge complementarities, in order to design coherent clusters, which may be considered as a theoretical tool for political decision-making. The ultimate goal is to define generic technologies and to determine some possible trajectories in order to propose some guidelines for an industrial policy, so as to

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avoid bottlenecks, to choose the best possible future as well as the path to arrive there.

The paper is organised in the following way. Section 2 develops the theoretical and conceptual settings, while Section 3 presents the data and our methodology of technological clustering. In Section 4 our results are examined and Section 5 gives some conclusions in terms of public policy.

2. Theoretical aspects

One of the starting points of our work is the assumption that agents are facing a limited number of technological opportunities. The first problem for each economic agent is to identify and successfully exploit a small sub-set of opportunities, one of the main constraints being the boundedness of the agents' own economic competences, defined as the ability to identify, expand and exploit business opportunities (Carlsson and Eliasson, 1994). As a matter of fact, in the evolutionary tradition, because of the hypothesis of bounded rationality (Simon, 1982) and complex environment of selection, each agent cannot decode the whole available information. Agents face then an additional dimension of uncertainty because of the gap between their competence in the use of information and the difficulty of their decisional problem (Heiner, 1983). In other developments of his initial work, (Heiner, 1985, 1988) the author shows that there is no interest to use an information source too distant from the agent's local experience and that the same principle applies to decision rules. Thus agents and/or firms search for new things close to the things they know and do well. Therefore, there is a tendency for a firm to stay on a technological trajectory that was successfully exploited in the past (Dosi, 1982). Similar concerns emerge in the process of innovation in the sense that an innovative firm is constrained by its current set of competencies: this sustains the notion of technological cumulativeness, i.e. the idea that technical change is gradual and incremental, since it builds on accumulated competencies in the firm's technical domain. Thus, a specific innovation generates a stream of subsequent innovation (a technological cluster), which improves gradually upon the original one. In this perspective, the development of a technological trajectory is the outcome of the intrinsically cumula-

tive nature of learning processes (Rosenberg, 1976; Nelson and Winter, 1982). The generation of new knowledge builds upon what was learned in the past, not only in the sense that knowledge constrains current research, but also in the sense that knowledge generates questions, which in turn generate new research (Malerba et al., 1997). Moreover, research is typically characterised by dynamic increasing returns in the form of learning by doing, learning to learn and the fact that today's research generates tomorrow's new opportunities (Cohen and Levinthal, 1989; Klevorick et al., 1995).

Nevertheless, technological cumulativeness and localised learning generate irreversibility, which is expressed by the property of path-dependency in the evolution of the systems (Foray, 1997). As it is well-known, there is a variety of phenomena that can be classified under the heading irreversibility such as switching costs, all classes of sunk costs, etc.¹ All those interactions between irreversibility and learning processes sustain endogenous processes of localised technological change along technological trajectories by generating localised competencies (Antonelli, 1997). Moreover, the path-dependency feature of the system is reinforced by the combination of dynamic forces (Antonelli, 1997) such as learning, network externalities, economies of scale, the simple process of reduction of uncertainty, technological complementarities and inter-relatedness which imply increasing returns to adoption and shape the dynamics of diffusion processes along the trajectories. Such systems are path-dependent in the sense that the long run equilibrium can be affected by historical events along the path (David, 1992). Thus, the mode of development of a technology (including many potential trajectories) is strongly influenced by initial decisions². Initial (or transitory) actions put the system on a path that cannot be left without costs. Three problems can appear at this stage, which can block industrial development.

1. The first one concerns the context of these initial decisions made under great uncertainty and ignorance of the respective qualities and

¹ For a complete analysis of irreversibility and path-dependency in industrial organisation, see Antonelli, (1997).

² See for example, the work on economic standard which shows that technologies selected first have greater chances to diffuse faster (Katz and Shapiro, 1986; Farell and Saloner, 1985; Foray, 1987).

properties of the various options. Taking a decision and at the same time eliminating options in a context of ignorance entail the risk of missing the best path of development because technological variants with unique properties may be lost and never properly explored (Foray, 1997). Thus the technical and economic features of a trajectory may lock the economic system in some sub-optimal alternative (David, 1985; Arthur, 1989; Cowan, 1991). Excess inertia can also arise even if the firms know that the system is at the end of a technological trajectory (Rondé, 1998). Many cases of such sub-optimal alternatives are developed in the literature of “potential regret in economic history” (Foray, 1997) with the well-known examples of the QWERTY keyboard (David, 1985), the video-cassette recorder (Cusumano et al., 1992), or nuclear power (Cowan, 1990).

2. The second problem is related to the first one and concerns bottlenecks. In fact, once committed to a technological paradigm, so that the generic technology develops and expresses itself along a stable trajectory, it is important to avoid technical bottlenecks that could block the system. Historical examples of such occurrences are numerous. If the discovery of the DNA was the starting point of the development of biotechnology and genetic engineering, this was not a sufficient condition for the generic technology to express itself fully. It was necessary to wait for the development of techniques and instruments allowing the introduction of modified genes into the described surroundings. Without the development of the instrumentation and other knowledge and ability, biotechnologies would not enjoy their actual diffusion. One can find other examples of blockage of diffusion processes, in particular in the field of metal casting (Garrouste, 1984; Foray, 1987).
3. For the recent resource based theory of the firm initiated by Barney (1986, 1990, 1996), competitive advantage comes from the dynamic resources located in the most valuable routines, dependent on experience, the learning and organisational processes and conditioned by their history. Because of market imperfections and more precisely the intangibility and non-transferability of several inputs such as the identity or the organisational experiment for example, these resources cannot be

bought, they have to be built (Teece and Pisano, 1994). The construction of those resources and competencies implies that the firm acquires and develops new knowledge (Iansiti and Clark, 1994; Henderson and Cockburn, 1996). Therefore, the firm has to carry out an external integration of knowledge and strategic information. However, in the case of important breakthroughs such as a change of technological paradigm, radical innovation is able to destroy current competencies or to modify the ability to evaluate the technological performance. In those cases of radical uncertainty, because of the local character of the learning processes the past evolution cannot help the firm and there is a need for new tools in order to identify and develop new competencies.

To avoid these problems, we argue in the light of previous studies (Arthur, 1989; Cowan, 1991; David, 1992; Witt, 1997) that industrial development requires governmental intervention. In fact, the path-dependency feature of the system implies that initial or transitory conditions in the form of a pre-existing technology base, actors, and networks play an important role. Moreover, the importance of strategies of first user choice (Benhaim and Schembri, 1995) shows the role that government can play to guide the process toward the best possible trajectory. But what kind of intervention is possible for the government? Following Le Bas and Zuscovitch (1992) we distinguish three types of relations which constitute important elements of path-dependency shaping, and being continuously shaped by, the system: the inter-agent relation (A–A), the inter-technical object relation (O–O) and the relation between agent and object (A–O) (Fig. 1).

All the inter-technical object relations may be called connectivity. The combination of connectivity, the nature of the technological paradigm (in terms of knowledge), the absorptive capacity and the selection mechanisms constitute a general framework for the analysis of technological systems and their performances (Carlsson, 1997). Our work concerns the connectivity analysis (which allows technological spillovers and then technological clusters) in relation to the nature of the paradigm. In fact, to choose the best trajectory implies a good understanding of future opportunities. It appears therefore necessary to know

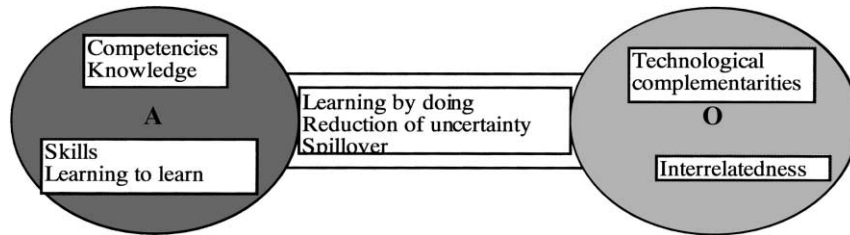


Fig. 1. A representation of the relations between agents and objects.

and list the inter-related technical objects, which could contribute to the development of a generic technology and allow alternative choices. Our methodology aims thus at identifying coherent sets of future innovations grouped together within technological clusters (GEST, 1986) based on science and technical complementarities. The final goal is the setting up of a research policy, which allows a harmonious development of techniques along the best possible trajectories.

3. Data and methodology

Our methodology of clustering is based on the national Delphi investigation. We intend to show that it is possible to use this type of survey to characterise the technological trajectories of the future and the dynamics of technical development. The Delphi base is the outcome of an investigation carried out during the years 1994–1995 in France, under the auspices of the Ministry of Higher Education and Research (DGRT-DRI). This project was led by the Consultant Company SOFRES for the material implementation and by the university laboratory BETA for the exploitation and the interpretation of the data. The Delphi method consists in collecting the “raw” opinion of experts at a time “*t*” on a series of questions and to confront these opinions with those collected through a second investigation where each expert can review his/her judgement knowing the average opinion of the first phase. This two-stage procedure is able to exhibit deviant behaviours of the first round and more consensual futures of the second round. The Delphi investigation is composed of about 1150 items concerning objects of research in advanced technologies. These items, grouped within 15 big technological domains, were submitted to 1000 experts (engineers

and researchers). An important quantity of information (more than 70,000 elementary answers) was thus collected and analysed by the BETA (1995) laboratory. In fact, each expert depicts his knowledge about the topic, the importance he allocates to it and also tries to foresee the period of realisation and evaluates its precision. Moreover, he specifies if international co-operation is necessary or not and which are the possible obstacles to the realisation of the innovations (cf. the list in Appendices A–D).

Historically, the first kind of technological forecast experiments appeared in the 1950s and the 1960s in the US, in a context essentially linked to defence technologies. It is in this setting that the Delphi “method” developed initially by the Rand Corporation (Gordon and Helmer, 1964) became well-known. In recent years, foresight studies were performed, especially in the USA, Japan, France, Italy and Germany (for an overview, see Grupp and Linstone, 1999). One of the major methodologies to structure a foresight discussion is the Delphi approach. It is in the late 60s that Japan decided to use foresight methods for validating choices of national technological policies. The experience was judged sufficiently fruitful to justify its reproduction roughly every 5 years. The NISTEP (1992), a research centre depending on the National Agency for Science and Technology in Japan was in charge of these investigations. In Germany, the BMFT (Federal Ministry of Research and Technology) decided, with a lag of 1 year, to apply the fifth Japanese Delphi. In collaboration with the NISTEP, the Fraunhofer Institute (ISI) of Karlsruhe achieved the transposition of this investigation for the Federal Ministry of Research (BMFT, 1993). The French Ministry of Higher Education and Research (DGRT-DRI) decided to adapt experimentally the same investigation in France, without substantial modifications of the content in

order to allow comparisons with the German and Japanese cases. Recently, other countries became very active in foresight processes. For example, Delphi studies were conducted in Austria in selected technological fields as well as in cultural or societal fields (Cuhls, 2000). Some Southeast Asian countries, Australia and New Zealand also started foresight activities. In Germany, in addition to the national foresight project, companies are using Delphi data for their own strategic purposes (Blind et al., 1999). Traditionally, the objective assigned to a Delphi inquiry consists in “attempting to look into the longer-term future of science, technology, the economy and society with the aim of identifying the areas of strategic research and the emerging generic technologies likely to yield the greatest economic and social benefits” (Martin, 1995). Recently, with the development of science and technology as strategic resources for firms, an additional objective became important: “helping to stimulate communication and to forge partnerships between researchers, research users, and research founders” (Martin and Johnston, 1999). In France, the objective displayed by the Delphi operation consists in (cf. Héraud et al., 1997) anticipating the real demand for technology, assessing the right moment, when public intervention will be most efficient and least expensive, stressing the role that international co-operation could play and improving the quality of interactions between engineers and researchers.

Our taxonomy of the technologies for the future, based on a common scientific and technological knowledge principle between experts is more Technology pushed than Demand pulled. As a matter of fact the main objective is to precisely identify the generic technologies define as the “whole of techniques, methods, processes knowledge and ability to create innovation flows” (Zuscovitch, 1985). Therefore, our objective is a traditional one for the foresight process. Nevertheless, we try to address the points 1, 2 and 3 above because the methodology proposed can be a tool for better understanding the different links within the national system of innovation, for providing an overview of the future and bringing out some answers to the problems of temporal or technical unsuitability that can block the development of novelties along a technological trajectory. Moreover, the methodology can be the starting point of a means to facilitate economic learning by developing and in-

creasing knowledge flows between people who work in some well-known and identified generic technologies. This fact is very important because “at the heart of the concept of the national innovation system is a belief that a better understanding of the linkages between the component actors in the system is the key to improved technological performance” (Martin and Johnston, 1999). At the end of the paper we propose some explanatory tracks to promote the knowledge flows.

Nevertheless, the approach can be criticised, especially because the French Delphi uses the Japanese survey without substantial modifications. However, using the topics of a foreign experience as a starting point was not a priori a bad idea because it provides an external and then more neutral point of view (Héraud and Cuhls, 1999). As a matter of fact, the authors note that “one should remember that it is more advantageous when the foresight project is conceived close to the scanning rather than to the monitoring edge of the potential scope of the exercise”. Moreover, the only country with a continuous history of foresight projects is Japan. Therefore, there was a learning process based on past experience of more than 30 years in Delphi investigation, which confers a very high level of relevance to the Japanese method of topic selection. Furthermore, the NISTEP reproduces the Delphi experience every 5 years with several modifications on the list of topics based on statistical analysis including past forecasting errors, non-relevant topics, etc. However, the “culture and lifestyle” questionnaire proved impossible to apply because the French experts expressed a very strong reluctance to deal with questions considered as “typically Japanese”. Except for this questionnaire, the Japanese Delphi was entirely reproduced and proposed to a set of French experts.³ All topics were judged interesting by a majority of experts and the average index of interest for the whole

³ For a critical analysis of the legitimacy of the initial sample of experts, see Héraud and Cuhls, (1999). From a general point of view, the authors remark that if one considers a public Delphi as an inquiry for anticipating the future the problem of the representativeness of the sample of experts is a serious one. But as long as Delphi is considered to be a collective strategic procedure for starting debates and putting in light some links between well-known and consensual important topics for the future, the problem is not too serious.

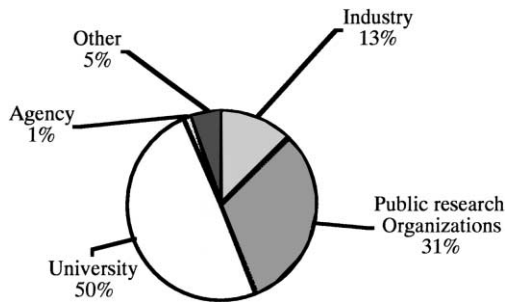


Fig. 2. Main activity of respondents.

domain of life sciences was 72/100.⁴ Especially for the field of life sciences, the number of experts, who constituted the initial sample, was 439 and the response rate about 33% (13% in Germany for the same field). Fig. 2 shows the distribution of the main activities of the respondents.

Of course, it is highly unlikely that the 98 topics selected represent the entire range of future possibilities in the field of life sciences. In fact, the topics are the results of perception and forecasting of different kinds of actors selected because of their long past experience. Nevertheless, it is only an instantaneous photography of several possibilities of the future and in any case, nobody knows all the different states of the word of the future. As pointed out by Kuwahara (1999), “the Delphi technique was not considered a tool of prediction but an instrument to systematically look into the long-term future”. Therefore, the problem of representativeness of the sample of topics does not seem to be too serious. Moreover, the Japanese topics were judged relevant for France and German because they reflected the technological capabilities of advanced countries, and not appropriate for developing country such as Korea (Shin et al., 1999). Hence, to elaborate our taxonomy, we propose the following procedure.

3.1. Hypothesis

Among the experts who replied to the Delphi investigation, we suppose that if an expert allocates

⁴ The index of importance for the field “life sciences” is an average of the indexes of all the topics. Each index is calculated with a quadratic principle: $I = [4I(1)+2I(2)+I(3)]/4\sum_{j=1}^4 I(j)$.

the maximal grade in “degree of his knowledge” for the “*i*” and “*j*” topics, it means that these two topics are close in terms of science and/or technological base. However, this hypothesis is only realistic for high levels of expertise since it clearly appears that the scientific and technical personnel are supposed to widen their domains of investigation as their career progresses and their research advances. This is why we suppose that the “*i*” and “*j*” topics are linked only if an expert “*k*” assigns the grade “1” or “2”⁵ to his knowledge of the two topics.

3.2. Methodology

Let “*T*” be the set of technologies (topics)

$$\text{with Card}(T) = n \quad (1)$$

and “*E*” be the set of experts with $\text{Card}(E) = m$. (2)

In a first stage we propose an automatic procedure to list and to identify, for each “*i*” technology, the experts whose self-estimated degree of knowledge is 1 or 2. Thus, we only take into account experts with a high level of knowledge for the topic considered.

So, let “*X*” be the binary ($n \times m$) data matrix

$$\text{technologies/experts.} \quad (3)$$

In a second stage, the objective is to define a similarity diagonal ($n \times n$) matrix “*S*” in which each element reflects the proximity index between two technologies in terms of knowledge-base. As shown in Nedeva et al. (1996) with Jaccard’s measure, a basic measure of association used in bibliometric analysis, “such a matrix may also be used as the basis of an analysis which measures the relationship between the fields”.

Let “*I*” be the vector column of

$$“X” \text{ for the } i \text{ technology,} \quad (4)$$

and let “*J*” be the vector column of

$$“X” \text{ for the } j \text{ technology.} \quad (5)$$

⁵ In the Delphi investigation, the grade “1” implies a very good knowledge of the subject, the grade “2” a good knowledge, the grade “3” a partial knowledge and the grade “4” no knowledge.

“*T*” is only composed of number 0 if expert “*k*” ($k = 1, \dots, m$) does not have a good knowledge of this topic, or number 1 if expert “*l*” ($l = 1, \dots, m$) does have a good knowledge of the *i* topic. The proximity index ($P(i, j)$) between topic “*i*” and topic “*j*” is calculated as the number of experts who know the two topics “*i*” and “*j*” divided per the number of experts knowing “*i*” and the number of experts knowing “*j*”

$$P(i, j) = \left(\frac{I \cap J}{I \cup J} \right). \tag{6}$$

Statistically, for the two binary vectors “*T*” and “*J*”, let

$$\alpha = \sum_{k=1}^m \min(I_k, J_k) \tag{7}$$

denote the number of corresponding positions in the vectors where a number 1 appears in both “*T*” and “*J*”,

$$\beta = \sum_{k=1}^m I_k - \alpha \tag{8}$$

the number of positions with a number 0 in “*T*” and a number 1 in “*J*”,

$$\gamma = \sum_{k=1}^m J_k - \alpha \tag{9}$$

the number of positions with a number 1 in “*T*” and a number 0 in “*J*”.

The quantity $\alpha / (\alpha + \beta + \gamma)$ gives us the proportion of positions which have a number 1 in both binary vectors “*T*” and “*J*” divided by the positions which are not simultaneous 0 for both vectors. This quantity is called the “Tanimoto coefficient” and it expresses our proximity index. It is a particularly interesting coefficient since it is a metric similarity function (*s*).

Thus we obtain a similarity diagonal

$$(n \times n) \text{ matrix } S = (s_{ij}) \tag{10}$$

in which each element reflects the proximity index between two technologies in terms of knowledge-base. For any “*i*”, “*j*” technologies in the “*T*” set, we have $0 \leq s_{ij} \leq 1$. Of course $s_{ii} = 1$ and, if there is no common knowledge-base between “*i*” and “*j*”, $s_{ij} = 0$. Now we consider $d = 1/s$, a metric distance function. With this measure, either of the magnitude of the distance between two topics, or of the magnitude of their

similarity to each other, we can use clustering algorithms in order to define homogeneous classes of technologies. We propose two types of statistical analyses to reveal them.

1. The first one corresponds to a factorial analysis of dissimilarities in order to have a visual representation of topics in a two-dimensional space. This analysis refers to multi-dimensional positioning where the two axes are identified by the first two “eigend vectors” of the matrix *S*.
2. The second type of statistical analysis is the ascending classification, a cluster analysis, which is considered very relevant when the number of topics studies is not too high (Bouroche and Saporta, 1980). It consists of constructing a succession of partitions in $n, n - 1, n - 2, \dots$ classes so that each class of a partition is included in a class of the following partition. A hierarchical tree can represent such a construction. Following the Ward method, we merge the two classes for which the loss of inertia is the weakest.

The confrontation of the different results of these extrapolative methods allows the development of a taxonomy of innovation.

Last point of the methodology, we define the “transverse” technologies as the topics which have the most direct and indirect links with the other topics. Thus technologies will be marked according to an index of transversality constructed in the following manner:

$$I_i = \left(\sum_{j=1}^{98} \text{Prox}(i, j) \right) \left(\frac{N_i}{N_{\text{tot}}} \right) \tag{11}$$

This index refers to the sum of proximity indexes weighted by the value of each topic in order to avoid that unknown topics affect too much the transversality index.

4. Main results

In this part we present the statistical outcomes of the analysis. Then, while completing the analysis by the survey of the “transverse” technologies and the foreseen periods of realisation, we propose some public political recommendations in the next paragraph.

4.1. Clustering analysis

Before carrying out the partition, we start with a factorial analysis of dissimilarities in order to obtain a representation of the clusters. This enables us to distinguish three homogeneous classes. Moreover, by the Ward's method, it appears that the most significant truncation of the tree is done at levels (0,6) with a partition in three classes. The clusters defined are the result of the common intersection of our explorative methods. All the classes are homogeneous and with some rare exceptions, do not suffer from the method of clustering chosen.⁶

Cluster 1: 1 2 3 4 6 7 8 9 11 12 21 22 23 24 25 27 31 32 40 41 42 48 58 59 61 64 71 72 73 78 79 87 88

Cluster 2: 10 14 39 43 44 45 46 49 50 51 54 55 57 60 65 66 70 74 75 76 77 86 89

Cluster 3: 13 15 16 17 18 19 20 26 28 29 30 33 34 35 36 37 38 52 53 62 67 80 81 82 84 90 92 93 94 95 96 97 98

1. The first cluster is stable according to the factorial analysis and the method of partitioning. Cluster 1 is strongly linked to new methods against cancer. It is a particularly interesting cluster since it lays down bases for constructing a generic technology to fight against this disease. From this point of view, the relevance of the analysis is confirmed. For example, future research programs will probably be based on molecular analysis in relation to protein structure (topics 1, 2, 3, 4, 9). Therefore, one can imagine a better understanding of the immunological functions of immunocytes responsible for the distinction between self and noself (topic 21), an explanation of the transmission processes of signals at the cellular level (topic 22) without forgetting methods which are linked to the cellular division and differentiation processes that one can try to block in order to avoid all propagation (topics 2, 3, 23, 24, 61). Next to it, the presence of topics 31, 64, 72, 78 and 79 which refer to the use of

techniques of gene introduction paves the way for genetic modifications in the therapy for cancer. On the other hand, the presence of topics 25, 27, 32, 58, 59 and 88 within this group raises the question whether future therapies will require the use of new techniques such as biomimetism and artificial organs. Indeed, the factorial analysis of dissimilarities includes at the margin topics 25, 27, 88 and 89, which are directly related to biomimetism. If we refer to our proximity data matrix *S*, topics 25, 27, 32, 48, 59, 87 and 88 present strong linkages with cluster 3 "artificial technologies". Moreover, in the factorial analysis of dissimilarities, those topics are at the borderline between cluster 1 and 3. The recognition of such a research trajectory should open up some interesting perspectives for public research policies because it points out the need to develop new materials linked to artificial organs for future therapies.

2. The second cluster concerns the "brain" and is composed of topics which all refer either to the molecular level or to the organic one. This cluster is very stable according to factorial analysis of dissimilarities and partitioning methods. One interesting fact is that this cluster includes the elucidation of the relationship between the brain neurone activities and the thinking processes (topic 65), the development of materials similar to organisms with self-recognising and judging functions (topic 57), of new computer technologies based on neuronal architecture (topic 60), of artificial intelligence that imitate the thinking processes (topic 66) and of interfaces enabling direct linkages between the computer and the brain (topic 89). Therefore, this cluster provides interesting elements about future technological trajectories related to medical problems such as Schizophrenia (topic 77) or the Alzheimer's disease (topic 74 and 75).
3. Finally, the last cluster is about "artificial technologies" such as bioreactor technologies, the development of biodevices, biosensors and artificial membranes etc. This cluster is less stable as shown in the factorial picture and can be divided into four sub-classes: the first sub-class (topics 13, 15, 16, 19, 36, 37, 38, 80) concerns especially artificial membranes, whereas the second sub-class (topics 26, 35, 62, 81, 82, 84, 90, 92, 93, 94, 95, 96, 97 and 98) is related to plants and all the

⁶A second clustering algorithm was used: the dynamic cloud method, which consists in doing a non hierarchical partition that one can consider as a generalisation of the *K*-means principle. From a statistical point of view, this method forces to choose the number of classes before carrying out the partition. With tree classes, except for topics 25, 27, 48, 57 and 88, the same results were obtained.

genetically engineered micro-organisms. The third sub-cluster (topics 17, 18, 20, 29, 30, 35) concerns more specifically energy and the fourth (topics 28, 33, 34, 52, 53, 67) the auto-organisation properties of systems.

The first partial finding seems to show the consistency of the method. The next step consists in studying the transversal topics, which are a central part of the diffusion problem within industry.

4.2. The quest for “transverse” technologies

Until now, the statistical analysis allowed us to group together innovations of the future into more homogeneous clusters according to given levels of aggregation or of inertia. The second contribution of this method consists in identifying the “transverse” technologies, that is to say technologies that have the most links with the other topics. Therefore, those topics constitute probably a major stake for the public decision-maker because they are the dominant topics in our technological knowledge-based network depicted by the similarity diagonal ($n \times n$) matrix $S = (s_{ij})$. Thus, they form the core of the creation and diffusion processes of innovations. In the following table we present our results for the most well-known technologies.

Topics	73	9	4	24	2	3	7	96	11	80	12	21	78
Index	0.308	0.259	0.259	0.231	0.217	0.189	0.189	0.182	0.168	0.168	0.161	0.161	0.161

According to this chart, it appears that the most transversal topics are those that refer to the finest level of analysis (the molecule). This can be explained by the fact that the knowledge of the mechanisms that govern the activity of cells, organs or even individuals, implies a good knowledge of cellular interactions mechanisms as in topics 9 or 4. Let us note nevertheless, that if this approach seems normal, the reverse (to start from the biggest to explain the smallest) is also possible. The “transverse” topic analysis provides therefore some indications on the processes of research and the manner which fundamental research is distributed among the technologies of the living.

In order to refine the analysis, one can examine topics in the neighbourhood of the transverse ones.

For example, if we take topic 9 in consideration, the preceding remarks are reinforced because all the nearest topics refer to cancer in terms of molecular analysis, signal transmission, gene identification or biomimetism mechanism. Therefore, topic 9 appears as an important element of intra-diffusion knowledge in the aggregate “cancer” technology cluster.

5. Conclusion and public policy implications

In this paper, we have presented a number of results directly based on data concerning French future innovations. The matrix survey we propose in order to analyse the results of the Delphi investigation allows the construction of a coherent typology of knowledge-based innovation. Certainly, this method of a subjective type remains partial but the large investigation guarantees the objectivity and universality of the information. Furthermore, the analysis has been thought as a preliminary stage aiming to clear some possible futures.

Methods of classification offer a first generic technology construction draft. In our view, the main contribution is the identification of several technological clusters based on knowledge relations. More precisely, we have highlighted the base of a generic technology of therapy against cancer. In this cluster, fundamental

knowledge linked to molecular mechanisms, more technical know how and more explanatory trajectories such as genetics or biomimetism were recognised. In the same way, other clusters linked to artificial technologies or to the brain were identified. In this latter case the analysis provides also interesting explanatory technological trajectories in order to fight against diseases such as Alzheimer or Schizophrenia. Therefore, by providing a clear and synthetic representation of the different links between technical, technological, scientific topics and those of a know-how order, our analysis appears as an interesting tool for public or private decision-makers. In fact, within the framework of the Resources and Competencies Model initiated by J.B. Barney, our typology is interesting for the

external knowledge integration process of the firm: the manager has relevant indications about the future competencies needed to innovate in future trajectories characterised by generic technologies.

The next stage consists in orienting the public decision-maker. This can be done while studying cluster periods of realisation, the possible obstacles and the transverse technology survey. As we have specified from the beginning, one objective of the work is to pave the way for more targeted methods of technological foresight and assessment with interviews of experts and construction of scripts for example and therefore our principal guidelines for public intervention are synthesised in Appendix C. Once again, this method is only exploratory and our main conclusions are the following:

1. If the major obstacles to innovation often appear to be of a technical (1) or financial (2) order, there is also a deficit of qualification in the domain of brain, fundamental research and artificial technologies (6) probably due to a lack of researchers.
2. Genetic engineering and new artificial technologies play a specific role in the technological development process, in particular for the emergence of innovative methods against diseases such as cancer, Alzheimer's or Schizophrenia.
3. Fundamental research in molecular analysis is at the core of the diffusion process of all the technologies linked to life sciences.

Finally, our analysis is complementary to the micro-economic analysis of clusters developed by Prevezer and Swann (1994), Bergeron et al. (1998), the statistical view built by Patel and Pavitt (1995) and the institutional box suggested by Carlsson and Stankiewicz (1991). Of course the analysis is more subjective and insofar more open to criticism because it deals with the future. But it is also an advantage because public intervention is then able to shape the construction of the techno-industrial clusters. In a way, we thus have a first picture of the French National System of Innovation in life sciences.

Certainly, this analysis is only a first step aiming at highlighting some future opportunities. In order to propose more targeted results of technological foresight, one possible improvement of the method consists in combining different kinds of knowledge through the co-operation of the different actors listed by our $n \times m$

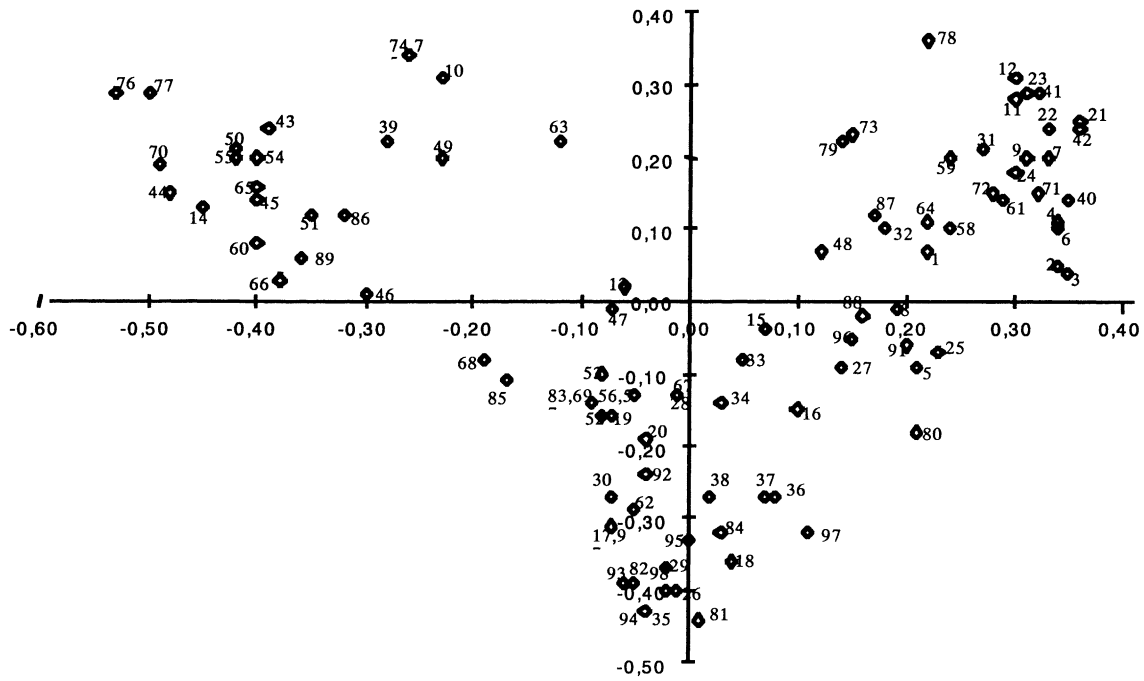
data matrix. As a matter of fact, for each technological cluster identified it is possible to list the whole sample of experts, knowing one or several topics of those clusters. Therefore, by mapping the different competencies of those experts, the objective could be to develop learning processes in order to have a better view of each of the future trajectories and to detect in which fields consensus already does or does not exist. Thus a potential conflict can be identified in advance. In fact, government activities aimed at assessing technical development and providing opportunities for informal technical exchange try to stimulate communication in so-called "communities" of scientists, engineers and business people (Grupp and Linstone, 1999). Moreover, for each cluster, the primary "communities" could be extended by new methods of co-nomination as it was the case in the British Delphi (Nedeva et al., 1996) or by involving more laypersons and stakeholders as it was the case in the German Delphi in order to experiment discursive approaches (van den Daele, 1997; Cuhls, 2000). For example, the co-nomination database provides a means of benchmarking the networks, which existed at the start of the Technology Foresight Programme. The deliberate promotion of knowledge flows within informal circles can contribute an important input to innovation.

Hence, in the line of the two main objectives generally attributed to actual foresight processes (identifying generic technologies and promoting knowledge flows), the tool we proposed allows us, under the specific hypothesis of the work, to identify generic technologies and the competencies needed, and to get a first step in order to stimulate knowledge flows in some well-known groups of experts, working on some well-known technological trajectories.

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Appendix A. Results of the dissimilarities analysis

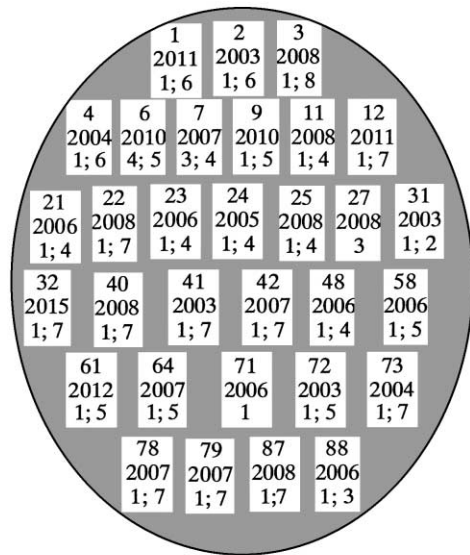


Appendix B. The major obstacles to innovation listed by the Delphi investigation

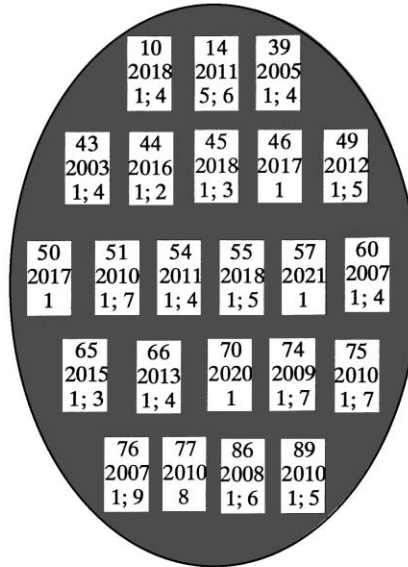
1: Technical problems; 2: regulation; 3: cultural factors; 4: cost factors; 5: problems of liquidity; 6: qualification and formation; 7: R&D organisation; 8: access to scientific information; 9: other factors.

Appendix C. Representation of clusters, foreseen period of realisation and major obstacle of realisation

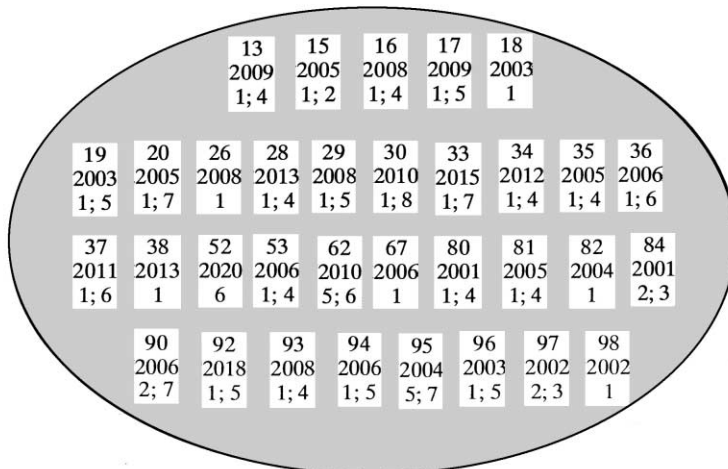
therapy for cancer



brain



artificial technologies



Appendix D. Life science: topics Delphi 3

A. Molecules

1. Elucidation of relationships between the higher-order structures and functions of the nuclei of eukaryotic cells.
2. Establishment of technologies enabling prediction of the three-dimensional structures of proteins from their amino acid sequences.
3. Establishment of technologies enabling prediction of the functions of proteins from their higher-order structures.
4. Elucidation of molecular mechanisms of particular interactions between proteins or between proteins and nucleic acids.
5. Elucidation of molecular mechanisms of the heat resistance of proteins.
6. Completion of a comprehensive human protein data library.
7. Determination of the entire DNA base sequences in human chromosomes.
8. Development of methods determining directly DNA base sequences by physical means including X-rays.
9. Thorough elucidation of the structures and functions of signal transducing molecules.
10. Elucidation of the morphogenic and developmental processes of the brain at the molecular level.
11. Elucidation of the mechanisms of the immune response at the level of molecular biology.
12. Identification of all genes inhibiting cancer and elucidation of the relationships between those genes and carcinogenesis.
13. Elucidation of the mechanisms of complex effects by more than one compound as seen in herbal medicines.
14. Elucidation of the whole aspect of the mechanisms of sleep.
15. Practical use of bioreactor technologies to produce new physiologically active substances without relying on cell culture techniques.
16. Development of organic catalysts with better functional characteristics than enzymes.
17. Development of biodevices (for example, protein, transistor) that can be use in electronics.
18. Widespread use of highly integrated biosensor.
19. Development of biometric devices (stable molecules which have the same functions as those of biological molecules and which are made up of components other than peptide).
20. Systematisation of the basis concepts of bio-computer architecture.

B. Cell

21. Elucidation of the functions of immunocytes responsible for the distinguishment between self and noself.
22. Elucidation of the whole aspect of the signal transduction in the carcinogenesis of cells.
23. Common use of the medical treatments for differentiating carcinogenic cells.
24. Elucidation of the mechanisms of replication and (cell) division of eukaryotic cells.
25. Development of technologies for developing germinal stems cells (germinal cells in the very early stage) to individuals by themselves.
26. Elucidation of the mechanisms of signal perception in plants.
27. Elucidation of the molecular mechanisms of morphogenesis and being possible to control them artificially controlling them.
28. Elucidation of weightless physiological actions and development of measures for preventing deterioration in biological functions caused by the weightless state.
29. Practical use of technologies enabling solar energy to be converted into, or stored as biochemical energy.
30. Development of engineering technologies, such as biomotors, using the biological energy conversion mechanisms.

31. Development of technologies enabling the introduction of foreign genes or chromosome fragments into any desired position in a chromosome *in vivo*.
32. Development of technologies for synthesising artificial cells that replaces cellular functions.
33. Development of technologies for synthesising organisms that have self-multiplication functions.
34. Development of production systems utilising functions of three-dimensional molecular aggregate such as chloroplasts and other organelles.
35. Practical uses of technologies for producing useful materials such as amino acids by fixing nitrogen.
36. Development of technologies for synthesising membranes having active transport function that are similar to cellular membranes.
37. Development of artificial membranes with the similar ability to convert energy as biological membranes.
38. Development artificial membranes systems mimicking the ability of living organisms to receive and transmit information
39. Development of experimental techniques for recording a single unit activity from a large numbers of neurones simultaneously during several days.

C. Tissue and organ

40. Development of medicines preventing the development of cancers
41. Development of highly sensitive techniques for simple and early diagnoses of cancers, using blood serums or other.
42. Practical use of effective means to prevent metastasis of cancer.
43. Development of non-invasive encephalometry technologies for analysing macro-brain activities.
44. Elucidation of the encoding and retrieval mechanisms of memories in the brain.
45. Elucidation of the mechanism of logical reasoning in the brain.
46. Elucidation of basic molecules concerning with higher order functions in the brain.
47. Elucidation of the molecular mechanisms of concerning with organ regeneration.
48. Use of technologies for long term (semipermanent) culture and preservation of organ.
49. Elucidation of the action mechanisms of neuropeptides and other substances in the CNS.
50. Development of artificial peripheral nerves.
51. Establishment of technologies that link computers to biological sensory organs.
52. Development of devices with self-recovering capabilities.
53. Development of biosensor capable of processing information.
54. Elucidation of the mechanisms of self-organisation of neural networks.
55. Elucidation of the elasticity of neural networks in interaction with the environment.
56. Development of self-organising electric circuits.
57. Development of materials similar to organisms, which have self-recognising and judging functions.
58. Practical use of artificial organs (pancreases, kidneys, livers, etc.) incorporating human cells and tissues.
59. Clinical application of organ implants by multiplication and regeneration of there owns cells.
60. Development of neuro-computers that have new logical structures based on advanced functions.

D. Individual

61. Elucidation of the outlines of the molecular mechanisms of development and differentiation.
62. Elucidation of the mechanisms which determine the size and shape of a tree.
63. Elucidation of the mechanisms of aging.
64. Elucidation of the whole aspect of the functions of homeobox genes in a vertebrate.
65. Elucidation of the relationship between the brain's neurone activities and the thinking processes.
66. Development of artificial intelligence technologies that imitate the thinking processes.
67. Development of technologies that distinguish and recognise three-dimensional and complex patterns.
68. Elucidation of the mechanisms of higher mental activity responsible to intuitive solutions of problems.

69. Scientific elucidation of the presence of “ki” (psychic energy) such as in “sakki” (psychic attack).
70. Elucidation of neuro-biological basis of feelings.
71. Establishment of methods enabling identification of threshold values for the cellular and genetic toxicity of environmental mutagens.
72. Development of technologies for non-invasive measurement the expression of only desired genes in living state of higher organisms.
73. Development of test methods that can replace to the use of tests animals.
74. Possibility of prevention of Alzheimer’s disease.
75. Possibility of healing of senile dementia’s such as Alzheimer’s disease.
76. Elucidation of the cause of manic-depressive psychosis at the molecular level.
77. Elucidation of the cause of Schizophrenia.
78. Full-fledged medical application of the generic manipulation of genetic disorders.
79. Being possible to use artificial manipulation in the expression of genetic information in higher organisms at the individual level.
80. Establishment of controlling technologies and practical application of technologies that use complex system of micro-organisms to produce useful substances.
81. Development of plants, micro-organisms, and other organisms that can concentrate specific ions.
82. Practical use of plants storing carbohydrates in high concentrations as fuel source.
83. Development of technologies for breeding and cultivating organisms in (Cosmo) space.
84. Widespread use of new plant, produced through gene manipulation, as foods.
85. Elucidation of biological homeostasis and development of automatic controllers applying biological homeostasis.
86. Elucidation of the mechanisms of biorhythms in living organism.
87. Possibility of local control over immunity systems.
88. Development of artificial placentas or of technologies for complete in vitro culture system foetuses of small mammals.
89. Development of interfaces enabling direct linkages between the computer and the brain.
90. Establishment of technologies enabling prediction of the effects of human activities on natural ecosystem.
91. Elucidation of the relationship between molecular evolution and morphogenetic evolution.
92. Elucidation of the molecular basis of animal’s actions such as contacting, sexual behaviour, etc.
93. Possibility of increased food production by improvement of photosynthetic ability in plants.
94. Practical use of (breeding methods to produce) plants with drought and salt tolerance at a high degree to stop the spread of desert environments.
95. Elucidation of the mechanisms of extinction of endangered species and establishment of corrective measures.
96. Possibility of classification at the DNA level and clarification of the concept of species.
97. Elucidation of the behaviours of micro-organisms in the biosystem and practical use of genetically engineered micro-organisms released into environments.
98. Elucidation of the role of the biosphere with respect to the behaviours of atmospheric carbon.

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