Paper to be presented at

European Meeting on Applied Evolutionary Economics

7-9 June 1999, Grenoble, France

Geographical Dispersion of Research.
A Historical Analysis.

Giovanna Vertova[1]

Organised by the Institute for Energy Politics and Economics
Organisé par l'Institut d'Economie et de Politique de l'Energie /
IEPE, BP 47, 38040 Grenoble Cedex 9, France

And the INRA-Unit of Sociology and Economics of Research and Development
Et l'unité Sociologie et Economie de la Recherche Développement de l'INRA
INRA/SERD, BP 47, 38040 Grenoble Cedex 9, France

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[1] Address for correspondence:

Istituto Affari Internazionali (IAI), Via A. Brunetti 9, 00186 Rome, Italy.

Tel: +39.063224360, Fax: +39.063224363, E-mail: g.vertova@iai.it

Abstract:

Research and development activities, as well as all other economic activities, do not occur in a spaceless economy, but are related to particular geographical areas. This paper investigates to what extent technological activities have a tendency to concentrate in centers of excellence or to diffuse across many countries. The attention is here concentrated towards the process of geographical convergence or diffusion of research in different centers of excellence in the last 100 years. Technological activities can follow different trends according to the ways they develop geographically. On one side, there is the earlier version of the product cycle model, which states that during the growing phase of a new technology, research should be geographically concentrated in centers of excellence. On the contrary, the Schumpeterian hypothesis suggests that during the growing phase of a new technology geographical diffusion should occur due to the tendency of competitors to imitate in the attempt to technologically 'catching up'. The statistical analysis of this paper is based on the use of patent statistics and the patent records used in this paper are based on the patent database compiled by Professor John Cantwell at the University of Reading, containing patents granted in the US between 1890 and 1990. The growth rate of the total number of patents and the Coefficient of Variation are used for the creation of a framework for the identification of different technological trends. The main findings of this paper is the existence of four different technological trends, two of them connected to the characteristics of the national system of innovation of countries and the other two related to the particular features of technology. Therefore, the paper shows that the typical product cycle model cannot be applied regardless the type of products, and therefore technology, concerned.

1. Introduction

This paper deals with the geographical dispersion of research over time. Research and development activities, as well as all other economic activities, do not occur in a spaceless economy, but are related to particular geographical areas (Krugman 1991). Economic geography is therefore an important discipline of economics and strictly related to the concept of the national system of innovation (Freeman 1987, 1992, 1955; Lundvall 1988, 1992; Nelson 1993; Porter 1990). This paper investigates to what extent technological activities have a tendency to concentrate in centres of excellence or to diffuse across many countries. Since specific factors account for a tendency towards geographical concentration or dispersion, according to different technological activities related to different industries, different countries become centres of excellence for the development of a particular technology in different historical periods. Moreover, since technological change proceeds as a cumulative and path-dependent process (Nelson and Winter 1977, 1982; Rosenberg 1976), these centres of excellence tend to maintain their position over time. Yet, change in centres of excellence can occur when there is a shift in the highest technological opportunities and new centres of excellence became more dynamic than previous and established major ones. Cantwell (1991c) in his analysis based on national shares of patenting has found that Japan has considerably increased its importance as a research centre since the mid-1960s. The birth of new centres of excellence is very likely to happen when established centres of excellence become ‘locked-in’ an old path of technological development, which no longer yields the greatest technological opportunities (Arthur 1989).

Technological activities can follow different trends according to the ways they develop geographically. On one side, there is the earlier version of the product cycle model (Vernon 1966), which states that the production process passes through conceptually distinct stages, stemming from the law of industrial growth. In an early stage, production is geographically concentrated into firms/countries which develop a new technology and which therefore become technological leaders in that particular new process or product. At this stage, the innovation process involves the rapid exploitation of unexpected exchanges of ideas. When production becomes more standardised, it moves from innovation markets to foreign markets and is therefore geographically relocated. New locations grasp this ‘mature’ production, while old technological leaders might develop new innovative products and processes. In this phase, ‘mature’ production diffuses across many firms/countries, due to the ability of the followers to catch up. By applying Vernon’s (1966) product cycle to the context of countries’ profiles of technological specialisation, it becomes possible to identify a ‘technological life-cycle’. This means that, at the beginning of the development of a new technology, research should be geographically concentrated in a few countries. Therefore, increasing patenting activity, which indicates the initial phase of a new technology, should occur together with geographical concentration of research in a few number of countries. Over time and with the maturity of that technology, research should become increasingly geographically diffused across many countries. Other countries become able to technologically catching up, thus spreading this technology in many geographical areas. Therefore, declining patenting activity, which indicates the maturity phase of a particular technology, should occur together with geographical dispersion of research across many countries.

On the other side, Schumpeter (1934) argued that leading companies would pioneer a new area of technological development and, if successful, they would be followed by a wider number of competitors that would quickly imitate them and ‘catch up’. By applying the Schumpeterian hypothesis to countries, increasing patenting activity, which indicates the initial phase of a new technology, should be associated to geographical dispersion of research across many countries, due to the imitation and ‘catching up’ processes. By working at the firm level, Cantwell and Andersen (1996) find that there is a relationship between the diffusion of innovation and the fastest growing technological opportunities. This is possible because of the characteristics of the new technology. New technological knowledge can be diffused across many countries also during its initial phase of development because this new technology is so influential as to enter in the product line of many other products. In cases such as these, von Tunzelmann (1995) speaks about ‘pervasive technology’. Therefore, for the so-called ‘pervasive technology’, the maximum rate of growth of patenting is associated with the fastest diffusion across many countries. Biotechnology and microchips are typical examples of ‘pervasive technology’.

It is worth noticing that, patenting activity can increase also due to the increasing complexity of technology. This phenomenon can lead to two opposite results. On one hand, increasing technological complexity and inter-relatedness might lead to geographical concentration of research in a few numbers of countries because those are the only countries with the proper technological expertise and competencies to enable them to use the new technology. On the other hand, increasing technological complexity and inter-relatedness might lead to geographical diffusion of research because a high number of economic agents want to research in that technology due to its inter-relatedness with other products. Furthermore, concentration of research might be related to the high specificity of that particular technology. If a technology is heavily dependent on some particular inputs (i.e. natural resources, raw materials, particular labour skills, strong entrepreneurial spirit, etc.), which are geographically located only in some countries, geographical concentration is doomed to occur.

Geographical concentration or diffusion may occur in different stages of the development of a new technology and not only, respectively, during its initial phase and its mature phase, as the traditional product cycle model states. The aim of this paper is to investigate the existence of different technological trends in different historical periods. This paper is divided in 5 sections. Section 2 explains the database and section 3 the statistical methodology adopted to identify the technological trends over time. Section 4 gives the empirical results and section 5 closes the paper with some general considerations.

2. The database

For the purpose of this paper, patent statistics are used as a proxy for the underlying pattern of technological activities of countries. It is not an aim of this paper to argue the merits of patent statistics over other indicator of technological performance. Nevertheless, many studies have shown how patent statistics can be a very rich source of empirical evidence on issue related to technology, an not just a direct measure of inventions (Archibugi, 1992; Basberg, 1987; Griliches, 1990; Mansfield, 1986; Pavitt, 1985; Scherer, 1983; Schmookler, 1966; Soete and Waytt, 1983), despite the need for caution in the use of patent statistics. The main problem of patent data is that not all inventions are patented while others are not technically patented, therefore patent data cannot cover all the phenomena of inventions. Scherer (1983) finds that the propensity to patent can differ widely according to different industries, technologies and firms. Yet, the great advantages of patent data are that inventions can be broken down into detailed technological fields and that long time series for specific technological activities can be created. Moreover, other works have shown that patents can be useful indicators of invention and innovation activities because they are highly correlated to another important indicator of technological performance, R&D expenditure (Acs and Audresch, 1989; Pavitt, 1982).

Problems arising in international comparisons can be overcome with the use of foreign patents in a common third country, so that all patents have undergone a similar screening process and international comparisons are therefore possible. The choice of the US as recipient country is due to the fact that the American market is widely recognised as the largest and the most technologically advanced in the world. Patents granted in the US are expected to be of higher quality than domestic patents, because it is reasonable to assume that only inventions with the highest expected profit will be patented abroad due to the time and costs involved in the process. Moreover, US patent statistics are more reliable indicators because of the common screening procedures imposed by the American Patent Office (Pavitt, 1988). Needless to say, this choice discriminates the US because total domestic patents must be used instead of total foreign ones. The international comparison would be between foreign firms/inventors patenting in the US versus American firms/inventors patenting in their own domestic market. Since domestic patenting is somehow differently motivated than foreign patenting, in the American case, the sectoral distribution of domestic patenting may differ from that one of foreign patenting. In particular, individuals (vs. firms) have a higher propensity to patent in their domestic market than abroad and, moreover, individuals patent more simple mechanical devices and less science-based developments. Therefore, the sectoral distribution of patenting of the US may be more heavily geared toward mechanical fields than that of other countries. Moreover, the historical perspective of this paper contributes to increase these difficulties because, historically, individual inventors played a greater role. Cantwell and Barrera (1993) find that American individual inventors were responsible for about 63% of the total patents in the US in the 1920-24 period, and this percentage decreased to 13% only in the most recent 1987-90 period. These results show the importance of individual inventors in the American profile of technological specialisation, especially in the period up to the Second World War.

The patent records used in this paper are based on the patent database compiled by Professor John Cantwell at the University of Reading, containing patents granted in the US between 1890 and 1990. For the purpose of this paper, the patents used are those granted to both individual inventors and companies (mainly large firms), classified by host country of research and invention. According to this classification, patents become indicators of the location of research and invention. Since each patent is classified according to the type of technological activity, the 399 original patent classes identified by the American Patent and Trademark Office (PTO) are grouped into 56 technological sectors in the Reading database, collecting together technologically related patent classes. These 56 technological sectors cover all chemical, electrical/electronic, mechanical and transport technologies, together with a residual class of non-industrial technologies. Throughout this paper each technological sector will be put within inverted commas with the number of the Reading database classification, so that it will be easy for the reader to remember that technological sectors generally contain more than one patent class (see Table 1).

Since this paper has a historical perspective, the 100-year period under investigation is divided into four historical periods, the preWW1 period (1890-1914), the WW1/interwar period (1915-39), the WW2/postwar period (1940-64) and the most recent period (1965-90). The rationale behind the choice of these historical periods is to take into account big historical events, such as the First and Second World War, which may have witnessed structural breaks in the national patterns of technological specialisation. Each of the two world wars is included in one single period for two main interrelated reasons. The first one is that, due to the small number of patents granted immediately after the two wars, the split of the periods in any different way would have given rise to the problem of small number of patents for all countries, thus undermining the statistical work. The second reason is that, since patenting activity takes time because it comes after the time consuming activities of inventing and testing, both the WW1/interwar period and the WW2/postwar period can better take into account this long process and can better reflect the post-war effects.

3. Statistical methodology

The empirical work of this paper is based on the Revealed Technological Advantage index (RTA) which was firstly developed by Soete (1980). Since its development, many authors have used it as an index of technological specialisation. The Science Policy Research Unit (SPRU) at the University of Sussex has extensively used this index for international comparison among countries (see Patel and Pavitt 1987a, 1987b, 1989a, 1989b, 1991; Pavitt 1988a; Pavitt and Patel 1988, 1990). At the University of Reading, Professor John Cantwell has extensively used this index in a historical perspective at the firm level (Cantwell 1993, Cantwell and Fai 1997a), at the industry level (Cantwell and Andersen 1996) and at the country level (Cantwell 1991b, 1992, 1995). The RTA index used in this paper is calculated across the 56 technological sectors of the Reading database and on the accumulation of patent stock, from the beginning of the period to the end. Accumulated patent stock is an appropriate measure of countries' system of innovation because it is related to the notion of accumulated technological expertise, competency and capability. Attention is not concentrated on a single patent *per se*, but on the accumulated patent stock, which is consistent with the theoretical notion of technological change as a cumulative, path-dependent and incremental process.

The RTA is used as an indicator of countries' technological specialisation and is define as follows:

$$RTA_{ij} = (P_{ij} / \sum_i P_{ij}) / (\sum_j P_{ij} / \sum_i \sum_j P_{ij})$$

where P_{ij} is the number of patents of country i in sector j. The formula shows that the RTA index of country i in a particular technological sector j is given by the national share of patenting in that particular sector divided by its national share of total patenting in all sectors. The index varies around unity. A RTA index above unity shows a relative technological advantage, while a RTA index below unity shows a relative technological disadvantage. It is important to keep in mind that the RTA index is a *relative* measure of technological advantage. Therefore when the RTA index of a country is below one, thus showing a relative technological disadvantage, the country may still patent but it does not patent as much as all other countries or as much as in other sectors.

The statistical methodology used in this paper requires unbiased RTA distributions. Therefore, to reduce problems associated with the small number of patents, which can lead to biased RTA distributions, conditions are imposed both at the level of each technological sector and at the level of countries' patenting activity. All technological sectors whose accumulated patent stock is less than 100 patents in each initial sub-period are omitted from the analysis. This restriction leads to the omission of five technological sectors in the preWW1 period and one in the WW1/interwar period. No problems arise for the last two historical periods and all technological sectors meet the imposed restrictions. Yet, it has been noticed that also after the imposition of this restriction, the RTA distributions of some countries are found to be biased. It is believed that this problem can be eliminated by imposing another cut-off point, this time at the country level. Therefore, all countries whose total number of patents is less than 1,000 in each historical period are not considered in the analysis, because their RTA distributions are inevitably biased. This problem occurs only for Italy and Japan and only in the first historical period, thus leading to their omission in the preWW1 period. Therefore, the choice of the countries to be included in this analysis is constrained by this latter cut off point. In the Reading database, the only countries with a reasonable historical patenting activity are the US, Germany, the UK, Italy, France, Japan, Switzerland and Sweden. No other countries could meet the condition imposed by the cut-off point at the country level. It is worth mentioning that the introduction of these two different cut-off points are considered sufficient conditions for the construction of unbiased RTA distribution, as demonstrated elsewhere (Cantwell, 1991b).

The statistical analysis is aimed to the identification of different technological trends. The PCM states that during the growing phase of a new technology, research should be geographically concentrated in a few countries, which are the technological centres of expertise carrying out most of the inventions and innovations. Later on, when the technology reaches its maturity level, research should become geographically diffuse across many countries, because more countries are now able to grasp the new technology. On the contrary, the Schumpeterian hypothesis suggests that during the growing phase of a new technology geographical diffusion should occur due to the tendency of competitors (either countries or firms) to imitate in the attempt to technologically ‘catching up’. To test these hypotheses, two different indicators are used. From one historical period to the next, the growth rate of the total number of patents (TP) for each of the 56 technological sectors is used as a proxy for the growing or declining phase of a technology. This growth rate is compared with the average growth rate across all technological sectors within the historical period and:

- a technological sector showing a growth rate above the average is identified to be a growing technological sector;
- a technological sector showing a growth rate below the average is identified to be a declining technological sector.

The Coefficient of Variation (CV), expressed in percentage and calculated on the RTA distributions of the countries of the sample, is used as a proxy for geographical concentration/diffusion. The CV is measured as follows:

$$CV_{RTAi} = (\sigma_{RTAi} / \mu_{RTAi}) * 100$$

where the subscript *i* refers to the country in question, σ_{RTAi} represents the standard deviation of the RTA distribution and μ_{RTAi} the mean of the same RTA distribution. This coefficient is a better measure of the simple standard deviation for two main reasons. Firstly, it takes into account possible changes in the mean over time, thus embodying a relative concept of dispersion. Furthermore, it is related to the Herfindahl index of diversification, which is more frequently used. In fact, $H = (CV^2 + 1) / n$, where *n* is the number of sectors in the distribution (Hart 1971). Keeping in mind that the CV is directly related to the standard deviation, which is a measure of dispersion around the mean, there are two possible outcomes:

- a high value of the CV for a particular technological sector indicates that the RTA values of all countries are very dissimilar, some are very high and some very low. This means that some countries are highly specialised in that particular technological sector while some others are not, therefore, research in that particular technological sector is concentrated only in a few countries;

- a low value of the CV for a particular technological sector indicates that the RTA values of all countries are very similar and very close to the mean. This implies that many countries are specialised in that particular technological sector, therefore research in that particular technological sector is geographically diffused across many countries.

The attention is concentrated on the evolution of the CV over time and not on its level at a certain point in time. It is therefore interesting to see when research in certain technological sectors has become increasingly geographically concentrated or dispersed. Having calculated the CV for each technological sector in each historical period, its percentage change from one historical period to the next is afterwards calculated, and:

- a positive percentage change indicates increasing geographical concentration over time;
- a negative percentage change indicates increasing geographical diffusion over time.

The CV as an indicator of the degree of technological specialisation is widely used in other statistical works (Cantwell and Andersen 1996; Cantwell and Fai 1997a, 1997b; Cantwell and Piscitello 1997).

A framework for the identification of technological sectors following the PCM or the Schumpeterian hypothesis becomes indispensable. Technological sectors in a growing phase follow the PCM when, contemporary to this phase, increasing geographical concentration occurs. Technological sectors in a declining phase follow the PCM when, contemporary to this phase, increasing geographical diffusion occurs. By contrast, technological sectors follow the Schumpeterian hypothesis when they are in a growing phase and, simultaneously, geographically diffused across many countries. Technology following this kind of trend represents the so-called *pervasive technology*.

Finally, there are technological sectors in a declining phase that are, simultaneously, geographically concentrated in a few countries. In this case, this kind of trend is more likely to be related to the specific characteristics of the country, which still carries out research in that particular technology, although it shows declining technological opportunities. Technology following this kind of trend has been called *country-specific technology*. Figure 1 gives the framework of the identification of these trends.

4. Empirical Results

Tables 2, 3 and 4 show the percentage change of the CV (%CV) and the growth rate of the Total Patents (%TP) across all 56 technological sectors over all historical periods. The following four sections deals with the main interesting results for each historical period, by focusing the attention on the technology following the growing PCM model and on the *pervasive technology*. The main idea is that, technology following the growing PCM model enables the identification of centres of technological excellence, while the *pervasive technology* identifies the highest technological opportunities in each historical period.

WW1/interwar period (1915-39)

In this period, Germany and Switzerland were the main technological centres of expertise for most chemical technology. R&D in ‘10: bleaching and dyeing’, ‘12: pharmaceuticals and biotechnology’ and related technology (‘5: chemical processes’, ‘3: inorganic chemicals’) was mainly concentrated in these two countries. Germany was highly specialised in dyestuff technology and Switzerland in some chemical niches. Both these countries presented national systems of innovation which could foster this technology, such as the state support to the education system to assure the supplied of highly specialised chemists, the presence of large firms in the chemical industry, the favourable geographical conditions enabling an abundance of natural resources (see Keck 1993 for Germany and Schröter 1993, 1997 for Switzerland). Moreover, the pharmaceutical industry of that period was a by-product of the German and Swiss industry (Haber 1971). It must also be noted that, in the inter-war period, Germany had the biggest chemical cartel ever seen in the history of the chemical industry. The I.G. Farben was formed by a nation-wide merge among the leading dye makers (Bayer, Hoechst, BASF) and the first mover in the electrochemical industry (Griesheim-Elektron), and it became a reality in 1925. This cartel was an undisputed technological leader in the chemical industry in the inter-war period (Freeman 1982). The fact that Germany and Switzerland were the main centres of excellence for research carried out in the same chemical technology is confirmed by the similarity of their profiles of specialisation, at that time (Vertova 1998).

The US and Germany were centres of technological expertise for R&D in '51: coal and petroleum product'. Due to the development of the automobile industry and to the abundance of raw materials, it is not surprising that the US became centre of excellence of the newly developed petrochemical industry, which was dominated by the Standard Oil of New Jersey and Standard Oil of Indiana and their new processes related to the catalytic and thermal cracking (Landau and Rosenberg 1992). Moreover, the US 'invented' the chemical *engineering profession* in order to deal with this new industry and, as early as 1920s, MIT introduced a separate course of study with a separated department to train scientists in the new discipline. At that time, the American chemical industry was a by-product of the general petroleum refining industry (Nelson and Wright 1994). As far as Germany was concerned, as already mentioned, the creation of the I.G. Farben led the country to diversify its specialisation in many chemical technologies.

While Germany, Switzerland and the US were centres of excellence for chemical technologies, most of the R&D carried out in ‘42: internal combustion engine’ and ‘44: aircraft’ was conducted in France. Since the turn of the century, the French specialisation was all dominated by the engine technology due to the long tradition of practical engineering (Grelon 1993). Laux (1976, 1992) remarks that the French were the first to successfully and commercially developed the automobile, despite the head start achieved by Germany in the engine-related technology, because the French entrepreneurs were willing to invest and take the risk in the new industry. The techniques developed in the car industry gave birth to the aircraft industry and, in this case, France could benefit from its accumulated expertise. At the beginning of the First World War, France was the biggest producer of aircraft (von Tunzelmann 1995).

In this period, the *pervasive technology* was most related to the development of an international chemical industry. The inter-war period witnessed the development of the chemical industry worldwide. The big chemical firms were the ones accounting for the highest share of total US patenting in the inter-war period, starting with a share of about 13% in the first half of the 1920s and reaching 36% in the second half of the 1930s (Cantwell and Barrera 1993). Among the biggest, there were the American Du Pont, the German IG Farben, the British ICI and the Swiss CIBA. Before the First World War, with the exception of Germany and Switzerland, the organic chemical industry of many countries was still embryonic. Yet, within 4 years, the US, the UK and to a lesser extent France, Italy and Japan created their own dyestuff industry with related activities (Haber 1971). R&D related to the development of an organic chemical industry (‘11: other organic compounds’, ‘2: distillation processes’) was thus spread across many countries. Moreover, the world development of the chemical industry, together with the material shortage due to the war, gave birth to the synthetic industry. Synthetic materials differ from similar older man-made materials, such as glass and ceramics, in their organic origins and they are composed of giant molecules of organic substances based on long chains of carbon atoms. Before the First World War, polymer chemistry was not able to understand the factors which determine the formation of large molecules however, between the wars, the production of both cellulose fibre and cellulose plastic developed extensively. Cellophane, the famous transparent wrapping, was introduced in France during the war. In 1926, alkyd resins, essential to the rapid finishing of automobiles, were first produced in America. Urea formaldehyde was first manufactured by a British firm in 1928. Polyvinyl acetate was jointly introduced in Germany and America in the same year. During the early 1930s, Germany invented two of today's largest volume plastics, polystyrene and polyvinyl chloride. Later in the decade, the British company ICI invented high-pressure polythylene. Leading firms in the production of all different kinds of synthetic materials, such as rubber, plastic and synthetic fibres, were the American Du Pont, the German IG Farben and BASF, and the British ICI (Hufbauer 1966). Research related to the production of synthetic materials ('9: synthetic resins and fibres') was therefore diffuse across many countries.

The WW1/interwar period witnessed the boom of the radio and communication industry. The invention of the telegraph and the telephone, which occurred in the previous period, gave an empirical demonstration that waves can be transmitted. During the First World War, there were innumerable improvements in the components, circuits and techniques used in telecommunications. Technological breakthroughs were the impact of the thermionic valve, and the use of a wide spectrum of frequency, leading to the introduction of the amplitude modulation (AM), frequency modulation (FM) and short wave transmission (Freeman 1982). Moreover, the war showed the strategic importance of this new industry. The data shows that, due to the importance of this technology, R&D in ‘33: telecommunications’ and related field (‘37: illumination devices’) was diffuse across many countries. The great strategic potential of radio technology was also related to the invention of the RADAR (Radio Detection and Ranging), which occurred at that time. The first patent for a radio detection system was granted in 1904, but no working prototype was produced. Although the US and several European countries experimented with radio waves to detect aircraft and ships, no progress was made. Moreover, until the beginning of the 1930s research in this field was hidden as wartime secrets. Eventually in 1935, Sir Robert Watson-Watt developed the first practical radar for the detection of aircraft, based on his demonstration that the reflection from electromagnetic waves could be projected on a fluorescent screen. Furthermore, in 1933 K.G. Jansky at the Bell Telephone Laboratories discovered that radio waves were generated by stars, and a new radio-astronomy era begun. Yet, together with military purposes there were also peaceful purposes increasing the interest in telecommunication technology. In the 1920s, the radio industry was transformed by the growth of public broadcasting and companies such as the American Telephone and Telegraph (ATT), General Electric (GE), Westinghouse, Radio Corporation of America (RCA), Marconi, British Broadcasting Corporation (BBC), Siemens, AEG and Telefunken, were the signposts in the development of the radio-broadcasting industry (Maclaurin 1949).

Research in ‘41: office equipment and data processing system’ was spread across many countries due to the development of the business and office machine. Since the computer had not been invented yet, the increasing number of total patents in ‘41: office equipment and data processing systems’ was probably due to the patent class [235: register]. The eighteenth and early nineteenth century witnessed the invention of various types of writing machines, but their extensive use started at the turn of the century with the American invention of the typewriter machine. The Remington Company put the first reliable typewriter on the market in 1873. At that time, the increasing size of business enterprises called for systematic correspondence and record-keeping. This was a flourishing period for the development of all kinds of office and business machines, such as typewriters and adding machines, comptometers, calculation machines, cash registers and duplication machines. Despite the initial American leadership, the European countries enter this market just before the First World War with German, English, French, Italian and Swiss companies (Chandler 1990).

WW2/postwar period (1940-64)

At that time, as in the previous period, Germany and Switzerland were the main centres of excellence for R&D carried out in ‘12: pharmaceuticals and biotechnology’, due to their accumulated expertise. Yet, Italy was another relative centre of excellence due to the presence of two very famous and innovative Italian large firms, the Montecatini and the Edison. Moreover, during the 1950s, the collaboration between Montecatini and Professor Natta, from the Polytechnic of Milan, led to the discovery of a new process for manufacturing isotactic polypropylene, which awarded the Nobel Prize to the Italian professor. These two Italian companies conducted brilliant research in anticancer drug, at that time (Freeman, Clark, Soete 1982).

As in the previous period, R&D in ‘51: coal and petroleum products’ was mainly concentrated in Germany and the US. These two countries were centres of excellence in this technology due to the accumulated technological expertise developed from the previous period. Moreover, R&D in ‘6: photographic chemistry’ was concentrated in the same countries, which had been both technological leaders since the turn of the century. In the US most R&D was carried out by the Eastman Kodak and in Germany the Big Three (i.e. Bayer, Hoechst, BASF) diversified their research effort in photographic technology, since the beginning of the century (Chandler 1990). By contrast, R&D in ‘41: office equipment and data processing system’ was mainly concentrated in the US. Many authors have emphasised the importance of the war and of the NASA on the development of the American computer industry after the Second World War (Mowery 1992; Mowery and Rosenberg 1993; Nelson 1988, 1990). At that time, IBM was an undisputed leader and his laboratories carried out most of the research in the newly borne industry.

The *pervasive technology* of that period was mainly related to the development of new materials. Research in ‘40: semiconductors’ was diffuse across many countries due to its importance for the newly computer industry, which, by the 1960s, could account of 26 American firms, 7 British, 3 German, 2 Dutch, 1 French and 1 Italian firm (Margerison 1978). The semiconductor industry was effectively born in 1947 when the first transistor was developed at Bell Laboratories, although semiconductor properties of some material have been known since the end of the last century. The next revolutionary innovation was the development of the integrated circuit (IC), by Texas Instruments and Fairchild in 1961. Research in ‘40: semiconductors’ was carried out in order to manufacture an advance computer, as the history of technology tells. The ‘first generation’ of computers was designed with electronic valves or vacuum tubes as switching elements. In 1947, the Bell Laboratories developed the ‘transistor’ and, finally, in 1956 the same company succeeded in building the first experimental transistorised computer. Philco, IBM and General Electric immediately followed and offered transistorised computers in 1958. This ‘second generation’ of computers made with transistors terminated in the middle 1960s, when in 1964 semiconductor manufacturers were able to offer a revolutionary improvement in reliability by incorporating on a single ‘chip’ of silicon all computer components. The ‘third generation’ of computer based on chips came into life.

As in the previous period, R&D in ‘9: synthetic resins and fibres’, in ‘11: other organic compounds’ and in related technology (‘5: chemical processes’) was diffuse across many countries, due to their importance for the development of the organic and synthetic chemical industry. All countries had understood, as earlier as the beginning of the First World War, the importance of having a technologically advance chemical industry. The Second World War had also shown the importance of the communication industry and R&D in ‘35: special radio systems’ was spread across many countries. Furthermore, another pervasive technology was ‘4: agricultural chemicals’, due to the dramatically increasing use of pesticides after the Second World War across many countries (Peel 1978).

Most recent period (1965-90)

The most recent period witnessed the information and communication revolution with an increased on R&D in all electrical/electronic technology (Freeman and Perez 1988). Yet, R&D in ‘41: office equipment and data processing systems’ was mainly concentrated in the US and Japan. While the US was continuing the specialisation of the previous period; Japan started to appear on the international scenario as a centre of excellence for the information and communication revolution (Freeman 1987). In fact, most of the R&D related to the new technological paradigm (‘6: photographic chemistry’, ‘52: photographic equipment’, ‘36: image and sound equipment’, ‘53: other instruments and controls’) was mainly concentrated in Japan. The ability of Japan to grasp the importance of the new paradigm was due to a mixture of factors, the flexibility of the industrial structure, the capacity to identify the crucial areas and to mobilise very large resources, the emphasis on education and training and the key role played by the government through the MITI (Ministry of International Trade and Industry) (Odagiri and Goto 1993). Furthermore, Cantwell (1992) and Vertova (1997) find a strict relationship between the patenting activities of the largest Japanese companies and the highest technological opportunities of the period, which were strictly related to the information and communication paradigm.

Finally, R&D in '4: agricultural chemicals' was mainly concentrated in Switzerland. Again, these countries could enjoy the accumulated technological expertise of a century. Moreover, the technological strategy of any small country is to find some niches of specialisation and to stick to them (Walsh 1987, 1988). Therefore, due to the past technological achievement of companies such as CIBA, Geigy, Hoffman-La Roche, Switzerland did not shift away from such specialisation. In fact, it has been found elsewhere that small countries need a very long period to change their pattern of specialisation (Vertova 1999).

This period was characterised by two main technological paradigms, biotechnology and the information and communication revolution. However, while research in the computer and related technology was concentrated in the US and Japan; that one in biotechnology was spread across many countries. Therefore, '12: pharmaceuticals and biotechnology' was a pervasive technology at that time. The birthday of contemporary biotechnology is usually traced back to two precise dates. In 1973, Chang and Cohen at Stanford and Boyer and Helling at UCLA in San Francisco developed the recombinant DNA. In 1975, Millstein and Kohler in Cambridge employed hybridoma technology to produce monoclonal antibodies. Molecular biology was then born. Since then, established pharmaceutical companies and new small biotechnology firms started intensive research in all over the world (Orsenigo 1989).

Moreover, while R&D in the computer technology was concentrated in the US and Japan, that one in ‘40: semiconductors’ was spread across many countries. The importance of this technology, together with the technology related to all new materials, is witnessed by the fact that also ‘9: synthetic resins and fibres’ and related technology *pervasive technology* of that period. Since the end of the Second World War, new materials, either chemical or electrical, has always been *pervasive technology*. This can be explained by the increasing complexity of technology and by the shortening of the product life cycle (von Tunzelmann 1995).

5. Main findings and conclusions

The main findings of this paper are that, the typical PCM trend cannot be applied regardless the type of products, and therefore technology, concerned. Research in different technologies follows different trends because different technologies require different efforts of implementation for their development (Pavitt 1984). Therefore, technology follows different technological trends according to the historical period under consideration. This paper demonstrate the evidence of three other different technological trends besides the PCM trend, declining PCM, *pervasive technology* and *country specific* technology. Moreover, this paper shows a contrast between the technological trends related to the characteristics of the country and those related to the features of the technology. On the one side, there is the growing PCM trend and the *country specific* technology, all related to the characteristics of the country. On the other side, there is the *pervasive technology* and the declining PCM trend, strictly related to the characteristics of the technology.

The growing PCM trend and the *country specific* technology are all related to the concept of national system of innovation. The growing PCM trend identifies the centres of technological excellence, which are the countries where R&D in that particular technology is mainly carried out. Countries can become centres of technological expertise when they have a national system of innovation, which fosters and enhances the development of the leading technological paradigms. For example, historically, the lack of government intervention is seen as one of the causes of the British backwardness in the chemical industry in the inter-war period, when compared with the German one (Coombs, Saviotti, Walsh 1987). The British government adopted a *laissez-faire* policy, while the German government supported the chemical industry through the development of a proper banking system, transport concession, preferential duties on certain raw materials, favourable amendment to patent law and support for scientific and technical education and research. The *country specific* technology is when the concentration of research is related to the inclination of some countries to carry out research in certain technology, with declining technological opportunities but considered important for their industrial development. This process of geographical concentration may be explained by the specificity of the technology itself. When technology heavily depend upon specific natural resources or raw materials, geographical concentration is more likely to occur because research is concentrated in those countries enriched of those particular inputs. Moreover, it must be kept in mind that *country specificity* is connected to technology with declining opportunities. It is therefore reasonable to assume that the reason underneath is that the particular technology is strictly related to the characteristics of the country in question. Nevertheless, it must be acknowledged that, *country specificity* may also be caused by the fact that the country in question was locked in old and inferior technological paths (Arthur 1989).

By contrast with the previous technological trends, the existence of *pervasive technology*, whose research simultaneously increases and geographically diffuses across many countries, is due to the interrelatedness of this technology in the production line of other related, or even unrelated, products. Von Tunzelmann (1995) speaks about the entrepreneurial problem of scope and scale in the late twentieth century, as if the interrelatedness of technology is a recent phenomenon. Yet, the results of this paper show that *pervasive technology* existed also in other historical periods. A good example of this is the technological sector '9: synthetic resins and fibres', which was a *pervasive technology* across all historical periods. Therefore, the findings of this paper show that *pervasive technology* exists historically and is related to the development of specific technological paradigms. Finally, there is the declining PCM trend, which is related to the characteristics of the technology. In this case, declining technological opportunities are diffused across many countries because they represent old technological paths or mature technology, which everybody can adapt and exploit.

From these results, some conclusions with respect to public policy can be drawn. In the evolutionary tradition, national specificity remains important and strictly related to the capacity to produce, acquire, adopt and use new technology. Therefore, only countries with a proper national system of innovation are likely to become centres of technological expertise. Moreover, the acquisition of new technological knowledge occurs with a *social* process of learning (Dalum, Johnson, Lundvall 1992). Both the state intervention and the public sector have a central role in creating, maintaining and developing national systems of innovation. Furthermore, the public sector can work as a regulator in order to create a dynamic industrial environment in which private firms may flourish (Gregersen 1992). Yet, the role of public policy can be twofold, especially if countries are locked into technological and institutional dead ends, as in the case of *country specific* technology. On the one hand, it might stimulate the progress along the prevailing trajectories. On the other hand, it might support and help the shift from old trajectories to new ones. However, some problems may occur because to abandon old technological routines takes time and efforts and needs a complete restructuring of the national systems of innovation. Institutions need to learn how to adapt and change in order to sustain technological change and the introduction of a new technological paradigm. Besides, institutions may be inflexible and institutional change may be lagging behind technical change, thus leading to a mismatch between the productive structure of society and the institutional set-up. In this case, 'institutional drags' and 'institutional sclerosis' become obstacles to the capacity of learning in society (Johnson 1992). Therefore, government intervention should be used as a bridging mechanism between the economic side of a new technological paradigm and the institutional side, thus supporting the diffusion of new technology within the social and institutional framework and thus avoiding the 'locked-in' kind of situation.

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Table 1 List of the 56 technological sectors

1	Food and Tobacco Products	Mechanical
2	Distillation Processes	Chemical
3	Inorganic Chemicals	Chemical
4	Agricultural Chemicals	Chemical
5	Chemical Processes	Chemical
6	Photographic Chemistry	Chemical
7	Cleaning Agents and Other Compositions	Chemical
8	Disinfecting and Preserving	Chemical
9	Synthetic Resins and Fibres	Chemical
10	Bleaching and Dyeing	Chemical
11	Other Organic Compounds	Chemical
12	Pharmaceuticals and Biotechnology	Chemical
13	Metallurgical Processes	Mechanical
14	Miscellaneous Metal Products	Mechanical
15	Food, Drink and Tobacco Equipment	Mechanical
16	Chemical and Allied Equipment	Mechanical
17	Metal Working Equipment	Mechanical
18	Paper Making Apparatus	Mechanical
19	Building Material Processing Equipment	Mechanical
20	Assembly and Material Handling Equipment	Mechanical
21	Agricultural Equipment	Mechanical
22	Other Construction and Excavating Equipment	Mechanical
23	Mining Equipment	Mechanical
24	Electrical Lamp Manufacturing	Mechanical
25	Textile and Clothing Machinery	Mechanical
26	Printing and Publishing Machinery	Mechanical
27	Woodworking Tools and Machinery	Mechanical
28	Other Specialised Machinery	Mechanical
29	Other General Industrial Equipment	Mechanical
30	Mechanical Calculators and Typewriters	Electrical
31	Power Plants	Mechanical

32	Nuclear Reactors	Other
33	Telecommunications	Electrical
34	Other Electrical Communication Systems	Electrical
35	Special Radio Systems	Electrical
36	Image and Sound Equipment	Electrical
37	Illumination Devices	Electrical
38	Electrical Devices and Systems	Electrical
39	Other General Electrical Equipment	Electrical
40	Semiconductors	Electrical
41	Office Equipment and Data Processing Systems	Electrical
42	Internal Combustion Engines	Transport
43	Motor Vehicles	Transport
44	Aircraft	Transport
45	Ships and Marine Propulsion	Transport
46	Railways and Railway Equipment	Transport
47	Other Transport Equipment	Transport
48	Textile, Clothing and Leather	Other
49	Rubber and Plastic Products	Transport
50	Non-Metallic Mineral Products	Mechanical
51	Coal and Petroleum Products	Chemical
52	Photographic Equipment	Electrical
53	Other Instruments and Controls	Mechanical
54	Wood Products	Other
55	Explosive Compositions and Charges	Chemical
56	Other Manufacturing and Non-Industrial	Other

Table 2 Identification of the PCM trend, WW1/interwar period

			% CV	% TP
Sectors following a growing PCM				
C	51	Coal and Petroleum Products	226,4	711,4
T	44	Aircraft	18,1	298,6
C	10	Bleaching and Dyeing	47,7	240,0
C	5	Chemical Processes	69,3	225,6
C	12	Pharmaceuticals and Biotechnology	73,0	212,8
M	23	Mining Equipment	15,2	210,8
E	38	Electrical Devices and Systems	341,1	196,1
C	3	Inorganic Chemicals	3,5	192,7
T	42	Internal Combustion Engines	22,5	176,8
M	13	Metallurgical Processes	124,8	175,7
C	7	Cleaning Agents and Other Compositions	122,0	160,3
Sectors following a declining PCM				
T	43	Motor Vehicles	-24,9	130,7
E	39	Other General Electrical Equipment	-24,9	120,3
C	55	Explosive Compositions and Charges	-22,3	69,5
M	53	Other Instruments and Controls	-67,6	66,1
E	34	Other Electrical Communication Systems	-26,9	66,0
Z	48	Textile, Clothing and Leather	-26,4	62,5
T	49	Rubber and Plastic Products	-42,3	61,0
M	16	Chemical and Allied Equipment	-70,9	50,7
M	28	Other Specialised Machinery	-22,5	45,6
M	19	Building Material Processing Equipment	-26,8	35,3
M	25	Textile and Clothing Machinery	-52,4	33,7
M	29	Other General Industrial Equipment	-12,3	30,0
M	17	Metal Working Equipment	-2,8	24,2
M	22	Other Construction and Excavating Equipment	-38,6	24,2

M	27	Woodworking Tools and Machinery	-19,4	-28,7
Pervasive technology				
C	9	Synthetic Resins and Fibres	-44,9	911,9
C	6	Photographic Chemistry	-18,5	299,1
C	2	Distillation Processes	-45,6	290,2
C	11	Other Organic Compounds	-30,7	274,7
E	41	Office Equipment and Data Processing Systems	-17,5	236,5
C	4	Agricultural Chemicals	-18,5	173,9
E	37	Illumination Devices	-3,3	173,4
E	33	Telecommunications	-29,4	150,9
Country-specific technology				
M	18	Paper Making Apparatus	80,8	98,4
M	1	Food and Tobacco Products	177,6	97,1
M	50	Non-Metallic Mineral Products	41,4	77,3
M	15	Food, Drink and Tobacco Equipment	291,1	71,7
E	52	Photographic Equipment	0,1	69,3
M	31	Power Plants	67,9	38,7
Z	56	Other Manufacturing and Non-Industrial	12,3	37,0
E	36	Image and Sound Equipment	19,5	36,9
T	45	Ships and Marine Propulsion	140,7	34,2
M	20	Assembly and Material Handling Equipment	7,2	32,5
M	14	Miscellaneous Metal Products	1,1	31,2
M	26	Printing and Publishing Machinery	7,4	22,9
T	47	Other Transport Equipment	96,5	9,8
E	30	Mechanical Calculators and Typewriters	35,7	6,7
Z	54	Wood Products	18,0	3,4
T	46	Railways and Railway Equipment	8,4	-20,3
M	21	Agricultural Equipment	11,5	-35,9
C	8	Disinfecting and Preserving	n.a.	n.a.
M	24	Electrical Lamp Manufacturing	n.a.	n.a.
Z	32	Nuclear Reactors	n.a.	n.a.
E	35	Special Radio Systems	n.a.	n.a.
E	40	Semiconductors	n.a.	n.a.

Average		27,3	131,6

Table 3 Identification of the PCM trend, WW2/postwar period

			% CV	% TP
Sectors following a growing PCM				
C	12	Pharmaceuticals and Biotechnology	0,5	159,1
M	31	Power Plants	5,1	143,0
C	6	Photographic Chemistry	58,0	135,9
E	41	Office Equipment and Data Processing Systems	17,1	106,1
C	2	Distillation Processes	6,6	99,5
C	51	Coal and Petroleum Products	16,0	85,7
M	24	Electrical Lamp Manufacturing	24,3	68,0
E	34	Other Electrical Communication Systems	24,9	63,9
Sectors following a declining PCM				
E	38	Electrical Devices and Systems	-20,0	31,6
M	23	Mining Equipment	-18,8	20,9
M	1	Food and Tobacco Products	-34,8	14,6
E	39	Other General Electrical Equipment	-24,8	14,2
C	3	Inorganic Chemicals	-18,2	8,9
E	33	Telecommunications	-29,8	5,3
M	13	Metallurgical Processes	-26,2	-0,6
C	10	Bleaching and Dyeing	-37,1	-1,1
M	20	Assembly and Material Handling Equipment	-40,1	-1,4
E	36	Image and Sound Equipment	-12,6	-10,5
M	16	Chemical and Allied Equipment	-10,7	-11,3
M	50	Non-Metallic Mineral Products	-50,5	-17,9
T	45	Ships and Marine Propulsion	-46,2	-18,1
M	17	Metal Working Equipment	-9,6	-23,3
M	21	Agricultural Equipment	-20,6	-33,6
E	30	Mechanical Calculators and Typewriters	-1,8	-36,9
T	47	Other Transport Equipment	-23,5	-44,2

M	26	Printing and Publishing Machinery	-27,5	-44,9
T	42	Internal Combustion Engines	-1,2	-50,9
Pervasive technology				
E	40	Semiconductors	-8,2	1012,1
E	35	Special Radio Systems	-13,4	379,1
C	9	Synthetic Resins and Fibres	-11,3	327,9
C	11	Other Organic Compounds	-31,9	230,6
C	4	Agricultural Chemicals	-70,4	110,5
C	8	Disinfecting and Preserving	-39,5	91,1
C	7	Cleaning Agents and Other Compositions	-51,0	55,7
C	5	Chemical Processes	-18,4	47,3
Country-specific technology				
E	52	Photographic Equipment	115,4	30,5
C	55	Explosive Compositions and Charges	99,7	15,4
M	53	Other Instruments and Controls	5,1	6,7
T	44	Aircraft	1,4	-1,2
E	37	Illumination Devices	1,5	-3,7
M	18	Paper Making Apparatus	16,6	-9,9
M	15	Food, Drink and Tobacco Equipment	19,6	-18,7
M	28	Other Specialised Machinery	43,8	-21,4
Z	54	Wood Products	4,4	-25,6
T	49	Rubber and Plastic Products	48,5	-25,7
Z	56	Other Manufacturing and Non-Industrial	1,1	-26,8
M	25	Textile and Clothing Machinery	25,9	-28,1
M	29	Other General Industrial Equipment	38,1	-28,7
M	27	Woodworking Tools and Machinery	19,5	-29,7
M	22	Other Construction and Excavating Equipment	15,0	-29,8
M	14	Miscellaneous Metal Products	20,9	-31,5
Z	48	Textile, Clothing and Leather	21,0	-32,7
M	19	Building Material Processing Equipment	46,7	-40,1
T	43	Motor Vehicles	7,6	-47,3
T	46	Railways and Railway Equipment	19,0	-72,2
Z	32	Nuclear Reactors	n.a.	n.a.

Average	11,7	65,5

Table 4 Identification of the PCM trend, most recent period period

			% CV	% TP
Sectors following a growing PCM				
E	41	Office Equipment and Data Processing Systems	37,6	464,7
C	6	Photographic Chemistry	4,7	365,7
C	4	Agricultural Chemicals	328,1	337,4
E	52	Photographic Equipment	13,0	266,4
E	36	Image and Sound Equipment	171,0	203,6
T	42	Internal Combustion Engines	53,4	158,9
M	53	Other Instruments and Controls	38,0	127,0
Sectors following a declining PCM				
T	49	Rubber and Plastic Products	-52,1	114,7
T	45	Ships and Marine Propulsion	-10,8	111,4
C	11	Other Organic Compounds	-14,0	101,9
M	24	Electrical Lamp Manufacturing	-41,7	96,1
E	39	Other General Electrical Equipment	-2,7	94,6
C	7	Cleaning Agents and Other Compositions	-23,4	80,9
M	1	Food and Tobacco Products	-34,4	80,2
E	38	Electrical Devices and Systems	-27,6	68,5
Z	56	Other Manufacturing and Non-Industrial	-23,3	68,1
M	31	Power Plants	-32,5	66,6
T	47	Other Transport Equipment	-46,0	55,9
M	17	Metal Working Equipment	-2,0	43,8
M	29	Other General Industrial Equipment	-18,0	41,3
C	51	Coal and Petroleum Products	-35,3	30,9
M	15	Food, Drink and Tobacco Equipment	-23,0	29,7
E	37	Illumination Devices	-18,5	29,0
M	14	Miscellaneous Metal Products	-16,0	24,7
M	19	Building Material Processing Equipment	-8,8	21,8

Z	54	Wood Products	-54,4	19,6
Pervasive technology				
C	12	Pharmaceuticals and Biotechnology	-70,7	570,8
E	40	Semiconductors	-49,4	510,0
Z	32	Nuclear Reactors	-19,0	322,7
E	34	Other Electrical Communication Systems	-9,9	247,3
C	9	Synthetic Resins and Fibres	-30,4	216,3
C	8	Disinfecting and Preserving	-37,3	212,0
C	5	Chemical Processes	-59,5	198,2
M	50	Non-Metallic Mineral Products	-10,2	154,4
T	43	Motor Vehicles	-49,0	136,0
M	13	Metallurgical Processes	-57,4	134,6
C	55	Explosive Compositions and Charges	-46,7	123,4
Country-specific technology				
C	10	Bleaching and Dyeing	32,0	102,4
C	3	Inorganic Chemicals	12,4	102,2
M	23	Mining Equipment	10,2	98,9
E	33	Telecommunications	7,7	92,9
M	16	Chemical and Allied Equipment	18,1	65,8
E	35	Special Radio Systems	18,2	57,1
M	20	Assembly and Material Handling Equipment	0,5	53,3
M	27	Woodworking Tools and Machinery	25,4	48,6
M	18	Paper Making Apparatus	29,0	47,3
C	2	Distillation Processes	6,3	43,6
M	28	Other Specialised Machinery	3,3	29,8
E	30	Mechanical Calculators and Typewriters	108,4	25,3
M	26	Printing and Publishing Machinery	22,2	22,5
M	22	Other Construction and Excavating Equipment	31,8	21,7
M	21	Agricultural Equipment	55,5	4,3
T	46	Railways and Railway Equipment	23,1	2,5
T	44	Aircraft	0,7	1,1
M	25	Textile and Clothing Machinery	57,8	-2,7
Z	48	Textile, Clothing and Leather	137,1	-14,6

Average	5,3	120,9