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The ICT Component of Technological Diversification:

Is there an underestimation of ICT capabilities among the world's largest companies?

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1. Introduction

This empirical paper focuses on the intersection between the trend towards technological diversification among contemporary large firms and the development of information and communication technologies (ICTs). The objectives of this research can be seen in a sequence of two steps. First, we emphasise the uneven attraction of different technologies when companies patent outside their traditional competencies. Second, besides arguing that some technologies seem to be more relevant than others in the context of the technological diversification trend, we test the hypothesis that ICTs are distinctively important for corporate technological diversification when compared with other technologies.

This analysis uses patent counts and classifications based on the SPRU-OTAF database for nearly 500 of the world's largest innovating companies from 1980 to 1996 as ranked by sales revenues. We find that technological diversification in large companies has certainly occurred in ICT but that for other technologies patterns are ambiguous. The ICT-related change in the competence portfolio of large firms has been widespread across sectors and considerably swift for a time period of 17 years. As could be expected there is considerable industry variation when companies patent in ICT:

[*] Comments and suggestions by Keith Pavitt, Pari Patel and Nick von Tunzelmann on earlier versions of this paper are gratefully acknowledged. Later versions benefited from the rigorous scrutiny of Alfonso Gambardella, Ed Steinmueller, Camilla Noonan, Felicia Fai, and Fernando Santiago-Rodriguez. A special note must be made of the fruitful discussions with Jan Fagerberg, Franscesco Lissoni, Richard Nelson and other participants of ESSID 2001.Access to SPRU's, University of Sussex, US patent database is also gratefully acknowledged. Susan Lees carefully revised the last draft, improvingly it greatly. This research benefited from a scholarship for advanced studies from CISEP-ISEG, Technical University of Lisbon. The usual disclaimer applies.

a) ICT is important, and increasingly so, for the Photography & Photocopy, Motor Vehicles & Parts, Aerospace, Machinery industries;
b) ICT is not so important, but rising fast in importance, for Metals and Materials;
c) ICT is apparently not so important for Chemicals and related sectors (Pharmaceuticals, Food, Drink & Tobacco, Paper, Mining & Petroleum, Rubber & Plastics).

As a conclusion we suggest that the widespread and intensive development of corporate capabilities in the key technologies of the emerging ICT paradigm is a stylised fact in need of stronger emphasis in current research. We suggest that the technological diversification trend can be related to the concept of *Long Waves* (LW) of techno-economic change. However, more research needs to be carried out to generate new and robust information on the recent evolution of competencies within multi-technology corporations.

This paper draws on previous empirical and conceptual work on the Multi-technology Corporation (MTC) by Granstrand, Patel, Pavitt and others (e.g. Granstrand and Sjölander, 1992; Patel and Pavitt, 1994b). One basic result by Granstrand, Patel and Pavitt (1997), who used the same data, was to show that the technological base of most large companies is much wider than their product range. Our contribution seeks to add to this line of research but tries to ask new critical questions about the existence of relevant sub-patterns in the technological diversification trend. We focus on the specific patent classes in which large companies tend to patent more when they patent outside their traditional technical domains. Our focal point can thus be regarded as closely complementary to the analysis of Gambardella and Torrisi (1998) and von Tunzelmann (1999) who have concentrated on the dynamics of technological diversification of the ICT sectors themselves. Here the emphasis is the reverse: *how have ICT technologies been developed outside ICT sectors?*

Section 2 presents the theoretical and historical frameworks that provide the necessary guidance to empirical exploration. Section 3 discusses the data and appraises the potential of patents as an indicator of technological capabilities. Section 4 presents evidence on the key patterns found. Section 5 discusses the results in the light of conceptual frameworks, discusses the importance of the findings for economic growth and highlights some unsettled questions for innovation strategy and R&D policy. Section 6 concludes.

2. Theoretical framework

Following Schumpeter's celebrated advice, we draw on *theory* and *history* to understand the patterns emerging from our *statistical analysis*. The conceptual framework we chose is the *Dynamic Capabilities* approach and the reasoned historical viewpoint that serves as a background is the neo-Schumpeterian *Long Wave* theory.

2.1 The internal workings of business organisations

Recent literature on technological diversification consistently draws attention to the variety of directions and rates of change of corporate patenting activities. An output of this research has been the empirical content it has given to notions such as corporate learning, firm-specific technical competencies and knowledge networks. In a pioneering article, Granstrand and Sjölander (1990, p. 36) defined the MTC as a "corporation that operates in at least three different technologies." The inspiring feature of large innovating companies is therefore the wide range of fields in which they command technical expertise. A crucial lesson that emerges from such an insight is that the notion of Multi-*technology* Corporation must be set apart from that of multi-*product* corporation. That stream of research allows us to say that contemporary big business institutions exhibit a much broader portfolio of technologies or competencies than of products (Patel and Pavitt, 1997). Although capabilities are unobservable, unlike the complex products and systems they help to create and market, these authors suggest a number of ways and proxies that could be used to measure the degree of technology diversification such as expert panels, academic disciplines and professions represented in the R&D personnel, and, not least, patent statistics.

Such an enquiry into the nature of the development of business organisations has understandably illustrated the persistent importance of the theoretical perspectives on the nature of the firm going back to the pioneering work of Penrose (1957,1995). Penrose and the authors who adopt the resource-based perspective see the set of productive resources and the idiosyncratic ways in which they can be put into use as the cause of the perceived heterogeneity and growth dynamics of the companies inhabiting the real world. For the purpose of our analysis we will join Teece and Pisano (1994) in defining dynamic capabilities as organisational and production methods (routines) and tacit knowledge "which allow the firm to create new products and processes, and respond to changing market circumstances" (1994, p. 541). Following this conceptualisation, the technological capabilities of the world's largest manufacturing companies will constitute our unit of analysis. The operationalisation of this approach will lead us to scrutinise the specific areas of technological knowledge that are being diversified into using patent indicators. Stated in another way, the ICT capabilities of our large companies, as expressed by patents in given technological areas, will constitute the main variables to explore.

2.2 Organisations and technologies in historical context

The emergence of the large innovative firm, as a fundamental locus of technology research and development, is a historically recent phenomenon. Before the 1870s, big companies were scarce, either in the US or elsewhere in the world. But by the 1920's, "big business had already become the most influential non-government institution in all advanced industrial market economies" (Chandler and Daems, 1982, pp. 2-3). Large companies continued to develop throughout the twentieth century and some early movers still continue to play an important role today, e.g., Ford, Bayer, Shell, etc.

If iron and steam power were at the core of the first industrial revolution, as well as the cotton industry, the railways and the factory system, the second industrial revolution broadly corresponded to the introduction and spread of electricity, synthetic chemicals and the internal combustion engine in the last quarter of the nineteenth century. According to the Chandlerian thesis, it was the organisational innovation of *the large multi-divisional manufacturing joint-stock firm* that realised the potential of the second wave of radically new technologies, by channelling major investments in mass-production, marketing and professional management (Chandler, 1990). But companies and industries change through time co-evolving with technology (Nelson, 1999). So, in this light, it is likely that the multi-technology corporation that started to appear as a new organisational subspecies in the late twentieth century is also associated with the broader institutional and technological changes of its time.

Several authors of a neo-Schumpeterian bent, such as Freeman and Pérez (1988) have used the concept of *techno-economic paradigm* to explain the systemic relationships between technology and economic organisation that characterise a society at a given time. The emergence of a new techno-economic paradigm or technological style represents a new mode of producing, distributing, and managing a widening spectrum of goods and services. When a long-term perspective is embraced, the spurt and diffusion of innovations turn out to be a very uneven process and certain combinations of radical innovations may even give rise to phenomena described as *technological revolutions*. These authors argue that there are major regularities in each of the "successive industrial revolutions" of the last two and a half centuries, i.e., since the British Industrial Revolution. Major discontinuities are essentially characterised by *a*) a few key technologies, *b*) a subsequent wave of inventions and innovations, *c*) the acceleration of the rate of growth of several major new technologies, *d*) a new typical way of organising economic activity, *e*) a new support infrastructure, *f*) a new pattern of geographical location and *g*) the occurrence of a period of mis-match between the new technological possibilities and the old institutional architecture. The long periods of sustained development ignited by these factors are known as *Long Waves*.

In an important restatement and empirical assessment of the theory, Freeman and Louçã (2001) apply and develop the framework in relation to the third of the industrial revolutions, the *Information Revolution*. The key radical innovation behind its rise was the development of the electronic microprocessor. This key factor is called the *Core Input*, and its characteristics are *a*) falling relative prices, *b*) universal availability and *c*) a broad range of applications. The producers of core inputs are called *Motive Branches* (the semiconductors industry). Those new industries producing or delivering the most emblematic applications of the new paradigm are *Carrier Branches* (computers, software, and telecommunications industries). The main *Organisational Innovation* highlighted for this wave is the network. We shall adopt these categories in our analysis.

3. Data and Methodology

In this study we take patents as the prime source of information about in-house technological capabilities.[1] We argue this is a legitimate interpretation because the attribution of such a property right by a scrupulous institution like the US patent Office is a recognition of cutting-edge expertise in a certain technological field. Therefore, and for operational reasons, patent

[1] We do not assume, for instance, patents to be a proxy of an output resulting from R&D resources, thus implying a notion of "knowledge production function" akin to the much abused "linear model of innovation". This view can be avoided here (see Pavitt, 1985).

statistics will be employed to screen the *breath* and *depth* of technological competencies of companies across given patent classes.

Following Granstrand (1998) and many other authors, we will equate technology to a body of engineering knowledge. We are well aware of the epistemological difficulties of measuring the hidden knowledge structure that underlies the performance and change in the (very) large firm (see for instance Lawson, 1997). Still, we believe that patents constitute a precious window (however narrow) into that deeper ontological level, i.e., the potential to generate improved technical knowledge.

The analysis is based on data obtained from the SPRU-OTAF database: accumulated patent counts for 14 industries and 34 patent classes for the years 1980-85, 1986-90, and 1991-96. This database reports patents for 463 of the world's largest companies[2] distributed according to principal product group and represents a huge effort of consolidation of 4500 subsidiaries and divisions: different assignee names, kept or bought by the 463 up to 1992, were identified using the ownership profile of 1992 and attributed to their parent. The method of consolidation is described in detail in Patel (1999).

SPRU assigns an individual patent to one of 34 individual technological fields based on information provided by the US patent office on the industry of the company and the technical field. Working with the SPRU database therefore implies working with its original characteristics as building blocs. In the analysis below, besides using the original classifications we also adopt a further reorganisation of our own.

Three reasons lie behind this reorganisation. The first is *synthesis*, simplification is important because patterns emerging from 34 individual classes times 14 sectors during 3 time periods are difficult to bear in mind or even to visualise. Second, *new information* on unexpected patterns can be gained with a new aggregation of patent categories. Finally, the *reliability* of conclusions

[2] More specifically, the population is made up of the largest companies according to sales as reported in the Disclosure Global WorldScope database, excluding those based outside the Triad, e.g., Australia, Latin America, South Africa and South Korea.

is substantially upgraded by allowing for sensitivity testing. The new technology groups are shown in table 1 below.[3]

Table 1 *Technology Families*

Chemicals	Fine Chem	Drugs & Biotech	Materials	Mechanical	Transport	**ICT B**	Other
InOrChem	OrgCh	Drugs and bioengineering	Materials	NonElMach	VehiEngi	**ICT N**	Medical
AgrCh	ChePro			SpecMach	OthTran	Telecoms	MiscMetProd
Hydroc				MetalWEq	Aircraft	Semicond	Metallu Pro
Bleach				AssHandApp		Computers	Nuclear
Plastic				Mining		Image&Sou	PowerP
ChemApp							Food&T
						ICT +	TextWoodetc
						Instruments	Other
						Photog&C	
						ElectrDevi	
						ElEqup	

Source: *Elaborations from the SPRU-OTAF database*

An important issue here is the operational definition of ICT. The definition of ICT we use sees ICT as sets of information processing, storage and transmission technologies that were enabled by the advent of microprocessors in the early 1970s (Mansell and Steinmueller, 2001).

With this definition in mind we incorporate four patent classes into our core ICT family: *Telecommunications*, *Semiconductors*, *Computers* and *Image & Sound Equipment*. This *N*arrow group of technologies we call ICT N. The sectors that specialise in this technology set are called ICT industries (or Motive/Carrier branches in the Freeman, Louçã and Pérez terminology): Computer and Electrical/Electronics sectors.

The ICT + category was constructed to represent the family of technologies that has been strongly influenced by the advent of the microchip and included a strong digital element. The ICT + group includes *Instruments & Controls*, *Photography & Photocopy*, *Electrical Devices & Systems* and *Generically Electrical Industrial Apparatus*. Our two ICT categories can be joined in a new one, ICT B, which increases the potential for testing the sensitivity of our conclusions using different operational definitions (more or less strict) of ICT.

[3] We will refer to technological classes or individual patent classes to distinguish from technological families or groups in the forthcoming analysis. Appendix 1 shows the complete names of the 34 individual classes.

The limitations of patents as indicators of technological activity are well known and will not be discussed in detail here although much can be learnt from many contributions on the subject (Pavitt, 1985; Narin and Olivastro, 1988; Grilliches, 1990; Patel and Pavitt, 1995). Patents are an institutional record of invention and, unfortunately, cannot be assumed to be in direct and constant correspondence to innovative efforts. There are, for instance, different inter-firm propensities to patent and differences in the patenting patterns across technologies and across industries. Patents are an indicator not a measure. For the present, however, it will suffice to make reference to a set of four recent studies that strengthen the legitimacy of using US patents to assess the technological evolution of big business institutions.

First, 80% of all patents were granted to business firms in the last quarter of the twentieth century, out of these about half were granted to the world's largest innovative firms (Patel and Pavitt, 1995; Pavitt, 1998). Second, a survey questionnaire administered to 1478 R&D labs in the US manufacturing sector suggests that patents have become a more central protection mechanism and that statistics for the large firms are somewhat more reliable than in the early 1980s (Cohen, Nelson, Walsh, 2000). Third, Jaffe (2000) in a recent paper was not able to establish that the intellectual property reinforcement by US courts since the early 1980s has given rise to any significant distortions in the propensity to patent across different technologies. Fourth, Hicks et al (2001), find that the propensity to patent (patents per million dollar expenditure) in ICT has doubled in the last twenty years but with no correspondent decrease in the quality of patents as measured by patent citations, indeed a slight increase is reported. In summary, the combination of these results reveals that the rise of a pro-patent institutional environment in the US might have increased the patenting rates in most technologies but in a step-wise fashion. In the specific case of ICTs, which have grown exponentially with no quality deterioration, the possibility that the patent indicator lost reliability due to patent policy changes or patent-portfolio races is not supported.

One point worth emphasising is that this empirical engagement is mainly concerned with the "What" (what is happening?) question, not with the "Why" question. We have, therefore, an exploratory goal. Answering the "Why" question would imply a more in-depth, case-study type of analysis. Our data does not allow us to infer the main motivations behind specific patterns of technological diversification. Nevertheless, the discussion of main interpretations of the empirical findings is assessed in section 5. We believe the comparative advantage of this research lies above all in its original empirical results. It is also worth emphasising what we are not researching. First, organisational competencies such as strategic or marketing competencies cannot be assessed through this data set. Second, we will not try to establish country differences. Third, we also cannot assess intra-industry heterogeneity due to the way the data set is built. Fourth, we will not try to assess the role (facilitating or inhibiting) of ICT in the process of diversification itself.

4. The link between technological diversification and ICT: Empirical findings

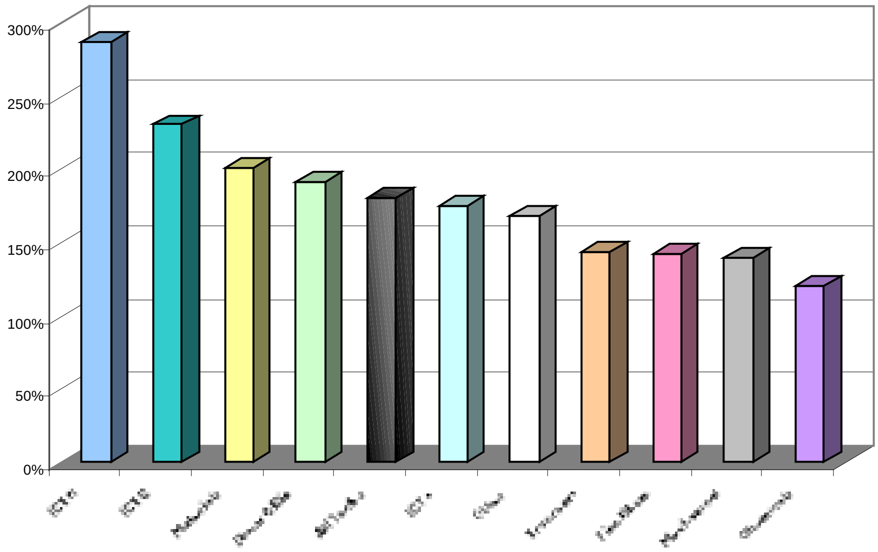
The next three sub-sections provide a view on general trends about the rate of ICT patenting and the intensity of technological diversification in different industries. The last four subsections contain the main findings of the paper, i.e., whether or not industries have been (increasingly) diversifying into ICTs and, if so, whether or not in greater proportion than in relation to other technologies.

4.1 The explosive growth of ICTs

It is widely acknowledged in the innovation literature that the accelerated development and diffusion of ICT was a distinctive feature of the last quarter of the twentieth century. Figure 1 shows that the growth of (narrowly defined) ICT depicted was striking when compared to other technological areas. As can be seen, the number of patents in ICT N in 1991-96 is about three times what it was in the period 1980-85. With the help of calculations not shown here, we found that ICT N corresponds to almost one 1/3 of total patents in the early nineties while in the early eighties it was 1/5. It also can be noted that the broadly defined ICT group or ICT B has been rising to explain almost 50% of all patents during the 1991-1996 period. [4] This behaviour contrasts, for instance, with the unchanged flow of mechanical innovations as measured by absolute patent counts, a trend emphasised by Patel and Pavitt (1994a), that has not been enough to sustain the relative fall in share of mechanical classes in total patents. It is also interesting to detect that the other most dynamic technological groups are Materials and Pharmaceuticals and Biotechnology. This comes as no surprise as numerous analysts and futurists have systematically anticipated these as key technologies in the last 30 years.

[4] The patent study by Hicks et al (2001) establishes that information and health technologies had grown by more than 400% between 1980 and 1999, with information technologies (computers, telecommunications, semiconductors, …) accounting for 25% of total US patents by the later date.

Figure 1 *Technology families size in 1991-96 in relation to 1980-85*

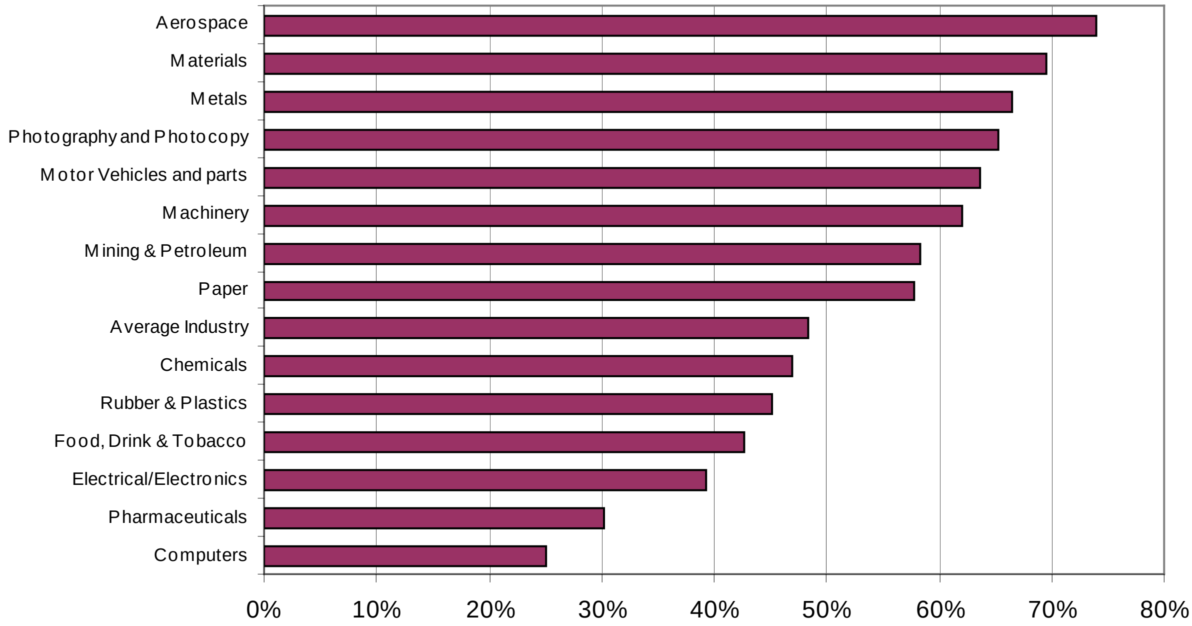


Source: *Elaborations on the SPRU-OTAF database*

4.2 Industries patenting outside the "core technical fields"

The analysis shown in figure 2 below is based in Patel's (1999) correspondence between industries and their main groups of technical fields (see *Appendix 2*). For instance, this classification puts ICT N technologies in the centre of Computer and Electrical/Electronics industries competencies, and it then becomes possible to assess the extent of technological diversity in each industry by the proportion of patents granted outside the industries' "core technical fields" (CTF). The numbers in figure 2 were calculated by simply subtracting the patents obtained in the respective core technical fields and dividing the remaining by the industries' total. We can see that all sectors have 20% of their patent portfolio in technological areas not directly related to their core business. For instance, Electrical/Electronics, Computer and the Pharmaceutical sectors are among the least diversified, which can be interpreted as indicating that the explosive patenting performance in the related technological areas has been primarily driven by the specialist sectors.

Figure 2 *Industries patenting outside "core technical fields" 1991-96*



Source: *Elaborations on the SPRU-OTAF database*

An alternative measure of technological diversification is to calculate the sum of the squares of the shares of all the classes for each industry, the Herfindhal index (*H*). A lower *H* indicates that companies or industries are spreading their patents across a broader set of fields or, in other words, it reveals that the agents command knowledge in more technologies. By calculating the *H* of the industries on the basis of the 34 patent classes we find that the Computer industry as well as the Electrical/Electronics sector appear again to be focusing on their core technological competencies over time.[5] Putting it in another way, the ICT sectors, or the Motive/Branch branches in the Freeman-Louçã-Pérez terminology, have been diminishing substantially the weight of non-ICT technologies in their portfolios. This suggests that the growth in the patents of the Computer industry has been driven by ICT (N), i.e., the core technology of the sector, something one could expect from the theory. This pattern is also in line with the findings derived from the same database by Gambardella and Torrisi (1998) and Patel (1999) and also Hagedoorn et al (2000) who used *Techline* data for a similar sample of large European, Japanese and American companies.

[5] The calculations of the *H* for the industries on the basis of individual patent classes and technology groups are not shown for reasons of economy of space.

Other industries seem to follow the inverse pattern, i.e., to be increasing the share of patents obtained outside their core technological competencies. In terms of the dynamics of over time there is not a clear trend towards increased technological diversification for the whole of the sectors. In terms of sectoral patterns it can be said with safety that five industries appear to be broadening their technology portfolio: Photography & Photocopy, Motor Vehicles & Parts, Machinery, Metals and Food, Drink & Tobacco. For three sectors, Aerospace, Chemicals, and Paper, the situation is stable whereas for the six remaining sectors there are signs of concentration in technological competencies.

4.3 Technologies broadening their industry base

When assessing trends in technological diversification or specialisation, the *H* is usually applied to companies, industries and countries. In this sub-section we apply instead the index to technologies on the basis of the industries contribution to them, that is we, calculate it the other way around. In this case, one is changing the angle of analysis and investigating the *source structure of a technology* (the extent to which different industries are contributing to total patenting in one technical field). A high index reflects concentration of technological activity: the fewer the industries “supplying” the patent class meaning that fewer industries are integrating that technical field in their knowledge portfolios in a substantive way.

In table 2, 12 technological classes out of 34 seem to be diversifying the sources where new inventions and improvements are recruited from, especially classes of the ICT groups (in bold). Three out of the four ICT N classes experience a decreasing *H*, a larger number than any other technology family. This observation represents a very interesting difference between ICT (technologies) and the ICT sectors. We also computed the *H* using the same data reorganised according to our technology families and the picture proves to be robust. In this analysis, not shown here, both ICT N and ICT + appear to be recruiting patents from a broader set of industry contributions. It seems as though more industries are entering into ICTs in a serious way and enlisting important additions to the total amount of ICT patents generated. It should be noted here that the only non-diversifying ICT N class is Computer technology, something that should be interpreted as stability of the sectoral source structure of this class (the Electrical/Electronics and Computer industries explain 77% of all Computer patents throughout the three periods). These findings set the tone for a deeper inquiry, namely into the way in which this diversification is primarily orientated towards ICT. An interesting question now is what are the most “pro-ICT” industries and what specific ICTs are attracting non-ICT specialists.

Table 2 *Herfindahl index: technology classes in terms of industries*

	1981-85	1991-96	Change	
InOrChem	0.2204	0.2422	0.0219	
AgrCh	0.5558	0.6178	0.0621	
Hydroc	0.6152	0.6446	0.0294	
Bleach	0.5746	0.5264	-0.0483	*Div*
Plastic	0.1395	0.1422	0.0026	
ChemApp	0.1113	0.1184	0.0071	
OrgCh	0.3000	0.3547	0.0547	
ChePro	0.1878	0.1790	-0.0088	*Div*
Drugs	0.4026	0.3883	-0.0144	*Div*
Materials	0.1366	0.1401	0.0035	
NonElMach	0.1845	0.2134	0.0289	
SpecMach	0.1282	0.1439	0.0157	
MetalWEq	0.1643	0.1574	-0.0069	*Div*
AssHandApp	0.1210	0.1528	0.0318	
Mining	0.5932	0.5783	-0.0149	*Div*
VehiEngi	0.6564	0.5714	-0.0850	*Div*
OthTran	0.3746	0.4836	0.1091	
Aircraft	0.5217	0.4006	-0.1211	*Div*
Telecoms	0.5139	0.4019	-0.1119	***Div***
Semicond	0.4390	0.3705	-0.0686	***Div***
Computers	0.3072	0.3137	0.0064	
Image&Sou	0.3790	0.3371	-0.0419	***Div***
Instruments	0.1825	0.1895	0.0070	
Photog&C	0.5023	0.5377	0.0354	
ElectrDevi	0.4502	0.3731	-0.0771	***Div***
ElEqup	0.2285	0.2047	-0.0238	***Div***
Medical	0.1898	0.2095	0.0196	
MiscMetProd	0.1344	0.1467	0.0122	
Metallu Pro	0.1721	0.1726	0.0005	
Nuclear	0.6630	0.7411	0.0780	
PowerP	0.2178	0.2466	0.0288	
Food&T	0.2985	0.3088	0.0104	
TextWoodetc	0.2511	0.2585	0.0074	
Other(weap.etc)	0.1148	0.1223	0.0074	
All classes	0.1307	0.1382	0.0075	

Source: *Elaborations on the SPRU-OTAF database*

4.4 How much has ICT increased in the technological portfolios of MCTs?

We have just seen that ICTs are a legitimate object of particular interest due to the evidence on *a*) their explosive growth and *b*) of a broadening industry base from which these technologies originate. Thus, if that is the case, we want to probe further the possibility that the ICT family behaves in a distinct fashion compared to others, that is, whether it has attracted patents from the generality of the largest innovative companies in our population.

Indeed, table 3 shows that all (but one) industries (Paper) increased the weight of ICT N in their technological portfolios when comparing the periods 1980-85 and 1991-96. This result is very important and it is substantially stronger for ICT N than it is for ICT +. Companies of all industries are consistently patenting into ICT and when they go the movement tends to be into ICT N, the most science based of the ICT technologies. On average, if we take the row for all industries, it is as if each industry increased its patenting by 11 percentage points (18.8% + 11.1%). Of the non-ICT sectors, it can be seen that the level of ICT N is important (above 10%) for the Aerospace and Motor Vehicles & Parts sectors, Machinery, and much more so for the Photography & Photocopy industry. Furthermore, the Metals and Materials sectors both register a step-jump rise (above 5 percentage points) in the ICT N component of their technology portfolios, which is a substantial change especially taking into account their low initial shares. The above six sectors, which reveal a strong performance in ICTs, account for half of the non-ICT sectors.

Table 3 *The ICT component of the corporate technology portfolio*

	ICT N		ICT +		ICT B	
	80-85	91-96	80-85	91-96	80-85	91-96
Aerospace	12.7%	13.3%	20.0%	19.5%	32.6%	32.8%
Motor Vehicles & Parts	9.7%	15.8%	20.0%	22.9%	29.7%	38.7%
Machinery	7.0%	12.9%	18.0%	18.2%	25.0%	31.1%
Photography & Photocopy	23.9%	36.5%	47.9%	37.5%	71.8%	74.0%
Electrical/Electronics	41.7%	53.3%	29.2%	23.6%	70.9%	77.0%
Computers	59.1%	70.2%	22.1%	17.9%	81.2%	88.1%
Metals	2.2%	7.4%	13.3%	13.8%	15.5%	21.2%
Mining & Petroleum	2.5%	2.6%	7.6%	7.0%	10.1%	9.7%
Materials	1.7%	7.1%	11.1%	9.4%	12.9%	16.5%
Chemicals	1.2%	2.2%	7.7%	6.6%	8.9%	8.9%
Rubber & Plastics	2.3%	2.8%	5.2%	5.9%	7.5%	8.7%
Paper	4.2%	2.9%	9.0%	7.7%	13.2%	10.7%
Pharmaceuticals	0.5%	0.6%	2.6%	2.0%	3.1%	2.6%
Food, Drink & Tobacco	0.9%	1.0%	4.2%	4.4%	5.1%	5.4%
All Industries	18.8%	29.9%	19.2%	18.5%	38.0%	48.4%

Source: *Elaborations on the SPRU-OTAF database*

Table 4 allows a comparative statement of relative increases in diversification. The table registers the change in the shares the different technology families represent in the industries total patenting. For illustration, the Aerospace industry obtained 243 patents in the Chemicals technology group in the period between 1980 and 1985, that represented roughly 4.05% of its total patenting. The same industry received grants for 357 patents in the period 1991-96 for the same family of technologies, that stock represented 4.14% of all its accumulated patents. The change was therefore roughly 0.08 percentage points, this being the number in the upper left hand corner of the table. The table represents positive increases with bold figures. Aerospace, in fact, increased the weight of Chemical technology when all industries on average decreased it.

Table 4 *Changes in the components of the industries' technological portfolios: (91-96)-(80-85)*

	Chemicals	Fine Chem	Drugs & Bio	Materials	Mechanical	Transport	ICT N	ICT +	ICT B	Other
Aerospace	0.08	-1.09	0.21	1.33	-2.36	-0.03	0.56	-0.41	0.14	1.72
Motor Vehicles & Parts	-1.07	-0.61	0.03	0.41	-2.29	-4.70	6.05	2.97	9.02	-0.79
Machinery	-0.02	-0.64	0.25	1.50	-6.96	-1.12	5.89	0.24	6.13	0.86
Photography & Photocopy	-0.06	-1.97	-0.52	0.87	0.15	0.04	12.60	-10.44	2.17	-0.68
Electrical/Electronics	-0.83	-2.13	0.08	-0.33	-2.93	0.20	11.63	-5.55	6.08	-0.12
Computers	-0.86	-0.79	0.03	-0.04	-5.14	-0.25	11.14	-4.23	6.91	0.13
Metals	-3.66	-1.87	1.58	2.14	-4.41	0.22	5.29	0.46	5.75	0.24
Mining & Petroleum	-4.62	6.59	0.25	1.01	-1.13	-0.35	0.14	-0.52	-0.37	-1.38
Materials	-0.55	1.45	1.64	1.49	-6.33	0.16	5.38	-1.72	3.66	-1.52
Chemicals	-3.08	0.13	2.54	2.48	-1.02	-0.07	0.97	-1.02	-0.05	-0.93
Rubber & Plastics	1.82	-1.52	-0.68	-1.30	-1.62	-0.08	0.51	0.66	1.17	2.23
Paper	-0.54	5.85	0.58	7.36	-5.11	-0.03	-1.27	-1.30	-2.57	-5.53
Pharmaceuticals	-0.46	-13.80	8.39	-0.21	0.55	0.01	0.06	-0.60	-0.54	6.06
Food, Drink & Tobacco	-0.47	-0.67	5.00	0.19	2.33	-0.04	0.08	0.20	0.28	-6.62
All Industries	-2.51	-4.12	0.31	0.39	-3.17	-0.84	11.10	-0.63	10.46	-0.53
Strengthening =	2	4	12	10	3	5	13	5	10	6
Rank of Technologies	9	7	2	3	8	5	1	5	-	4

Source: Elaborations on the SPRU-OTAF database

The table supplies further information in the bottom rows. The number of industries that increase their "participation" in given technology families is given in the row *Strengthening*; for instance, Aerospace was one of the only two industries that increased their share of chemicals in this time span. Below this information there is a row giving the "ranking" of those technology families with more "entries"; for example, ICT N was the group registering more net increases into its individual patent classes (all but one industry diversified into it, i.e., 13), followed by Drugs & Biotech and Materials. The last row gives the standard deviation of the technology families columns; ICT N is the group with the highest internal variation, certainly due to the decisive increases, for instance, Photography & Photocopy, Electrical/Electronics and Computers industries.

Generally speaking companies are patenting more in ICT N, Drugs & Bioengineering and Materials technology than they used to. The ICT family registered the most intense pattern and it was, in fact, the most pervasive in technology development. This can be interpreted as indicating that technical knowledge about ICT is increasingly getting dispersed across industrial sectors, confirming what was suggested in the previous section.

However, these results have to be taken with a pinch of salt. This stylised fact is very strong but the increase in the ICT N share of the industries' portfolios was slower during the period 1991-96.[6] There were industries for which the relative weight of ICT N patents in their total patents slightly decreases, i.e., Aerospace, Mining & Petroleum, Pharmaceuticals, Food, Drink & Tobacco. The sectors of Mining & Petroleum and Rubber & Plastics even decreased the absolute number of patents granted in ICT N classes, Paper, on the other hand, increased. Nonetheless, ICT N was still the technology family that increased more on the average portfolio, even though more industries registered a net increase in the Drugs & Bioengineering category in this field. In our database, the jump in the importance of ICT N patents for non-ICT sectors happened, therefore, during the 1980s.

We should also add two further comments in interpreting our results. Both these caveats point out that, if anything, the ICT N trend across sectors is underestimated in our analysis. First, if we break down ICT N for the Aerospace industry it emerges that Telecommunications and Semiconductors have been registering sharp rises (therefore the rise of only 0.08% in table 5 might be underestimated). Second, if we could account for software activity the performance of the Pharmaceuticals sector in ICT N would probably be much stronger due to the innovative use of computer simulation technology in this sector (Nightingale, 2000). The same is true for the Aerospace industry in the precise case of the digitalisation of the engine control systems (Prencipe, 2000).

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[6] From our data it is not at all clear why this happens or if that slowdown is likely to persist in the second half of the nineties. This topic falls outside the scope of this paper but should arouse some curiosity for future related research.

4.5 Patenting outside the "core technical fields" into ICT

Measuring the extent of technological diversity in each industry by the proportion of patents outside the industries' "technological competencies" yields a list of the most preferred technologies when companies patent outside their traditional technological competencies. The propensity to patent in ICT[7] when companies patent outside their "core technical fields" (CTF) can be formally described as:

$$\text{P.P. ICT} = \frac{\text{Patents granted in ICT}}{\text{Total patents granted outside CTF}}$$

Applying this indicator makes the Motor Vehicles & Parts, Photography & Photocopy, Machinery and Aerospace sectors stand out as those with the highest propensity to engage in ICTs when patenting outside their CTF. Also with this indicator, the secondary importance of ICT N for Chemical and associated sectors (Pharmaceuticals, Mining & Petroleum, Paper, Rubber & Plastics, Food, Drink & Tobacco) becomes more apparent. Table 5 presents results from this line of inquiry.

Table 5 *Ranking of ICT N share in the technological portfolios of the industries*

Industry	Ranking of ICT patent share in technological portfolio in 1991-96 (Change from 1980-85 to 1991-96)
Photography & Photocopy	1st (no change in relative position)
Motor Vehicles & parts	2nd (4th in1980-85)
Aerospace	2nd (no change)
Average of all industries	2nd (6th in 1980-85)
Machinery	3rd (no change)
Materials	4th (5th in 1980-85)
Metals	5th (6th in 1980-85)
Paper	6th (no change)
Food, Drink & Tobacco	6th (7th in 1980-85)
Rubber & Plastics	7th (no change)
Chemicals	7th (6th in 1980-85)
Mining & Petroleum	7th (6th in 1980-85)
Pharmaceuticals	7th (no change)

Source: Elaborations on the SPRU-OTAF database

[7] Two notes: *1*) this concept is an extension of the Propensity to Patent concept; and *2*) naturally it makes no sense when applied to ICT sectors.

Overall industries tend to have a stable ranking of technology families when they patent outside their core technological field competencies. However, if there was a change in this path-dependent corporate knowledge structure, this was driven by ICT. As we can see in table 5, ICT N climbed up the ranking of corporate diversification in five of our industries, it remained in the same relative position for 6 and only fell in 2 industries. This table provides ordinal information derived from computing the sectors' propensity to patent in ICT (data not shown). For the average of the companies, ICT N climbed from the 6th position it was occupying during 1980-85 to 2nd position in 1991-96. Changes in the propensity to patent in ICT N are striking. In the first period, only 8.3% of the patents were obtained in ICT N when companies patented outside their core technological competencies, whereas for the later period on our database that figure was 15.8%. The propensity to patent in ICT N doubled (on average), making it the second "most demanded" technology only behind ICT +.

4.6 Industries' contributions to ICT N patenting

This sub-section is devoted to assess the contribution of the different industries to total patenting in ICT N. Table 6 shows the percentage of ICT patents in 1980-85 and 1991-96 that are explained by ICT sectors, i.e., the Computers and Electrical & Electronics sectors. The figures indicate that the ICT sectors have by no means the monopoly of ICT patenting[8] and that their share has indeed decreased from 1980 to 1996. Our previous sections showed the existence of an increase in the share of the ICT N component in almost all our industries. It can now be seen that this trend is behind an increase in the share of their contribution to overall ICT N patenting, even in the face of the very fast and accelerating rate of growth of patenting by the Computers and Electrical/Electronics sectors.

Table 6 *Percentage of ICTs explained by the ICT sectors*

	ICT N	ICT +	ICT B
ICT sectors in 80-85 =	77.3%	46.1%	61.6%
ICT sectors in 86-90 =	73.9%	46.4%	61.7%
ICT sectors in 91-96 =	74.5%	44.9%	63.2%

[8] In contrast, Pharmaceuticals & Bioengineering-related sectors account for 90.9% of all the patents in the Drugs & Bioengineering field while the Materials-related sectors account for 20% of patents in material technology.

Source: *Elaborations on the SPRU-OTAF database*

This result is in line with the Hicks et al (2001) study on the composition of patenting activity in the US. In this study "information technology" companies are found to be responsible for the production of three-quarters of the "IT" patents (broadly corresponding to our ICT N category) between 1993 and 1998. However, if our methodology is correct, the increase in ICT N patents, or "IT" in the Hicks et al (2001) terminology, comes from a broader range of sectors than their findings suggest.

Table 7 below displays the contribution to the increase in patenting defined as the difference between the number of patents in the three periods. Hicks et al (2001, p. 686) found the "IT" sector to be responsible for 98% of the growth in "IT" patents while our figures point to a considerably lower degree of concentration even though that share increased in the later period of 1991-96. The Computer and Electrical/Electronics sectors (our "IT sector") were on the whole responsible for just 73% of the increase in ICT N patents. It is important therefore to check the sensitivity of these results by evaluating the effect of including the Photography & Photocopy sector in the class of ICT industries. In this case the percentage of ICT N patents generated by ICT sectors averages at 89% for 1991-96 with an increasing trend as well. Either way, the divergence with Hicks et al (2001) remains.

Table 7. *Sectoral contributions to the increase in ICT N patents*

	Growth between 1980-85 and 1986-90	Growth between 1986-90 and 1991-96	Total Growth in the period 1980-96
ICT Sectors	68.9%	75.4%	73.0%
Non-ICT Sectors	31.1%	24.6%	27.0%
ICT Sectors including the Photography & Photocopy sector	85.8%	90.9%	89.0%

Source: *Elaborated from SPRU-OTAF database*

The non-ICT sectors contribution to ICT N (patent counts and percentage) is depicted in table 8 for the 12 non-ICT industries. As can be seen in column (*a*), this is a highly skewed distribution, those that contribute substantially to ICT N contribute a lot: the four largest contributing sectors are equivalent to 80% of the patents. Photograph & Photocopy accounts for more than 50% of the total of ICT N that is generated by non-ICT sectors in 1991-96 while the next three contributing sectors, Motor Vehicles & Parts, Machinery and Aerospace, have a combined weight of nearly 37%

Table 8 *Non-ICT contributors to ICT N*

	1980-85	1991-96	a	b	c
Aerospace	761	1144	5.5%	50%	14.5%
Chemicals	325	899	4.3%	177%	4.0%
Food, Drink & Tobacco	18	37	0.2%	106%	1.1%
Machinery	684	2344	11.2%	243%	19.7%
Materials	57	212	1.0%	272%	75.6%
Metals	106	526	2.5%	396%	19.6%
Mining & Petroleum	309	352	1.7%	14%	2.8%
Motor Vehicles & Parts	1545	4129	19.7%	167%	25.1%
Paper	65	65	0.3%	0%	0.0%
Pharmaceuticals	49	85	0.4%	73%	0.61
Photography & Photocopy	2537	11117	53.0%	338%	43.2%
Rubber & Plastics	35	58	0.3%	66%	4.2%
Total	6491	20968	100.0%	223%	43.7%

a - Contribution of each industry to the total increase of ICT N patents in 1991-96
b - Net growth in patent counts from 1980-85 to 1991-96
c - ICT N as percentage of total increase in patenting of each industry between the periods

Source: *Elaborations on the SPRU-OTAF database*

A number of other interesting patterns can also be detected with the help of table 8. First, column (*b*) shows that several industries have recently registered a huge increment in the absolute number of patents in ICT N: Metals (396%), Photography & Photocopy (338%), Materials (272%), Machinery (243%). Second, statistics in column (*c*) tell us that almost half (43.7% - the total row), of the increase in total patenting in our database between 1980-85 and 1991-96 was responsible for a growth in patenting the ICT N (the whole of classes in ICT B account for 61.4% of total patent growth). It is also worth noting that ICT N represented almost 76% of the increase in the number of patents obtained by the Materials sector, 43% for Photography & Photocopy, 25% for Motor Vehicles & Parts, and 20% for Machinery and Metals sectors.

Third, although strong trends are detectable, some caveats should be kept in mind: *a*) the increase of ICT contribution of non-ICT sectors is less strong in the later period; *b*) patenting has been consistently higher in the Computers and Image & Sound Equipment classes as we shall see in the next sub-section; *c*) finally, the Computer industry continues to increase its patenting share in the total of ICT N patents generated by the ICT sectors at the expense of the Electrical & Electronics sector.

4.7 Inside ICT N: Where are industries patenting when they patent in ICT N?

This sub-section carries out a more fine-grain analysis of the change that has happened in individual classes as non-ICT industries developed their own ICT N patenting. We open the ICT "box", so to speak, in order to assess the possibility to discriminate between sub-areas of ICT activity. Table 9 shows a matrix of patent counts (to give a correct impression of magnitude of performance) and the share that the specific ICTs have in the total ICT N patenting of sectors. We can see, for instance, *Computers* and *Image & Sound* as the two most patented categories. In terms of industries, the bulk of the Computer industry patenting is in Computers technology while the Photography & Photocopy industry patents the most in Image & Sound. The patenting behaviour of Electrical/Electronics is rather homogeneous across technologies. The Aerospace, Machinery and Motor Vehicles & Parts industries have the substantial proportion of their patents located in Computers and Telecommunications. The Telecommunication technology is also a very strong ICT N component for Materials, Rubber & Plastics and Chemicals. The industries of Pharmaceuticals and Food, Drink & Tobacco obtain substantial portions of their ICT N patents in Computers and Image & Sound.

In terms of changes over time, comparing 1991-96 with 1980-85 (table not shown), one change has been an increase in importance of Computer technology in total ICT patenting. For two industries, Aerospace and Materials, patenting in Telecommunications becomes more important than the Computers industry in the later period. For the Computer industry the relative patenting in Telecommunications increases slightly. The Computing technology becomes a more important class for Machinery. It is also noteworthy that for the Metal sector Semiconductor technology became the highest ICT N class, representing a large relative rise.

Three further observations can be made about the sub-ICT B patterns: *a*) we can now see that if data on individual ICT N technologies are not shown a great deal of understanding about variance across sectors is lost; *b*) the ICT sectors exhibit a secondary relative performance when it comes to Image & Sound, where the Photography and Photocopy industry occupies an increasingly important role; *c*) The ICT + classes are dominated by the dynamism of the Instruments & Controls class (table not shown).

Table 9 *Industries patenting in ICT N classes, 1991-96*

	Telecoms	Semicond	Computers	Image&Sound	ICT N
Aerospace	223	84	73	3	383
	58.2%	**21.9%**	**19.1%**	**0.8%**	**100%**
Motor Vehicles and parts	756	397	1259	172	2584
	29.3%	**15.4%**	**48.7%**	**6.7%**	**100%**
Machinery	353	200	807	300	1660
	21.3%	**12.0%**	**48.6%**	**18.1%**	**100%**
Photography and Photocopy	381	455	2179	5565	8580
	4.4%	**5.3%**	**25.4%**	**64.9%**	**100%**
Electrical/Electronics	4844	3688	7827	6515	22874
	21.2%	**16.1%**	**34.2%**	**28.5%**	**100%**
Computers	2483	2845	8021	2916	16265
	15.3%	**17.5%**	**49.3%**	**17.9%**	**100%**
Metals	94	176	117	33	420
	22.4%	**41.9%**	**27.9%**	**7.9%**	**100%**
Mining & Petroleum	38	0	8	18	64
	59.4%	**-**	**12.5%**	**28.1%**	**100%**
Materials	90	9	0	58	157
	57.3%	**5.7%**	**-**	**36.9%**	**100%**
Chemicals	179	146	112	137	574
	31.2%	**25.4%**	**19.5%**	**23.9%**	**100%**
Rubber & Plastics	16	0	0	8	24
	66.7%	**-**	**-**	**33.3%**	**100%**
Paper	2	0	0	0	2
	100%	**-**	**-**	**-**	**100%**
Pharmaceuticals	11	1	20	4	36
	30.6%	**2.8%**	**55.6%**	**11.1%**	**100%**
Food, Drink, Tobacco	0	0	6	13	19
	-	**-**	**31.6%**	**68.4%**	**100%**
Grand Total	9470	8001	20429	15742	53642
	17.7%	**14.9%**	**38.1%**	**29.3%**	**100%**

Source: *Elaborated from SPRU-OTAF database*

5. Electronics everywhere: A tentative discussion of the findings

5.1 Appraisal of the ICT-MCT link: Fatal attraction or spurious result?

The first words of comment must acknowledge the possibility that our results could simply be explained by artificial shifts in the indicator, i.e., the propensity to patent in ICT having changed over time in comparison to the propensity to patent in other technologies. But we take aboard the recent studies on patent practice (Cohen et al 2000; Hicks et al 2001; Jaffe 2000) to argue that there is no solid evidence implying that the observed shift in patenting shares towards ICT is not due to confounding variation in the indicators.

Furthermore, the results are strengthened in three ways: *a*) they are tested against reclassifications of the data and qualifications were offered when variance was detected; *b*) we also attempt various approaches and techniques in order to filter robust empirical regularities, those that do not change with different ways of measuring different aspects of the same phenomena; *c*) whenever possible the findings are compared with similar studies using SPRU-OTAF and other databases. One solid conclusion, therefore, has to be that the movement towards technological diversification is not evenly distributed across technological fields. Moreover, while the ICT industries (Computers and Electrical/Electronics companies) have focused in their technology scope there is evidence that the ICT N technologies have progressively diversified the sectoral base from which new patents are originating. This implies that there is compelling evidence to believe that there is a significant "bias" or leaning towards ICT in corporate technological diversification.

5.2 Appraisal of the theory: Dynamic technological capabilities

In our sample the cluster of ICT-related technologies is, simultaneously, *a*) the technology group growing the most in terms of number of patents granted and *b*) the area where companies are developing capabilities faster on average. Dalum et al (1999, pp. 112-3) see the generalised growth rate of ICT patents as the result of corporate research encouraged by high technological opportunities and profit prospects.

The patterns derived for the particular case of the ICT-related industries are in accordance with results of Gambardella and Torrisi (1998) and von Tunzelmann (1999) who, using SPRU-OTAF data, found evidence of increasing technological convergence within the ICT sectors coupled with a low level of extra-ICT diversification. These patterns of "internal cross-fertilisation" and "deepening" can be understood as indicative of the long-term technological (and competitive) potential of ICT capabilities.

However, and as we wish to emphasise in our study, cutting-edge ICT capabilities are not exclusive of ICT sectors. Hagedoorn and colleagues (2000) confirm our results using patent and alliance indicators from Techline and SDI databases. The comparison between patent and alliance data made by these authors provides interesting complementary information: *a*) the Mechanical sector concentrates its technological alliances in Semiconductors and Computers, *b*) the Automotive sector in Computers and Telecommunications, *c*) for the Aerospace industry, the second most important kind of alliances involves Computer technology, *d*) for the Chemical sector Computer technology is the third most important type of alliance, *e*) the second most important technology alliance developed by the Pharmaceutical sector concerns Medical Equipment & Medical Electronics. Their key finding, in what concerns this paper, is that the external acquisition of ICT capabilities was a top priority for many non-ICT industries during the 1990s:

> "It is interesting that in non-IT sectors - such as automotive, aerospace, machinery and chemical sectors - computer technologies, including software, appear in the top three positions of receiving technological alliances ... Companies that do not have internal competencies to master such technologies seem to use external strategies to acquire or jointly develop them." (Hagedoorn et al, 2000, p. 20)

Recent results brought forward by Cantwell and Noonan (2001) on technological relatedness measured by the degree to which different technologies are co-patented by the same industrial sectors, also suggests that ICTs may be termed as increasingly pervasive. This paper contributes with evidence that ICT appears increasingly associated with other technological groups, namely chemicals and transports. The upsurge in the technological relatedness of electronic technologies is felt in the period 1969-1995 and is driven by telecommunications, special radio systems, semiconductors, image and sound equipment and office/data processing systems.

Our work exhibits, however, a discrepancy in relation to Hicks et al (2001) who used the Techline patent database of the CHI consultancy company. We find that large non-ICT companies have been responsible for 15% to 25% of the ICT patents generated in the early 1990s and not just 2% as claimed in that paper. In trying to account for such a disparity we should first point to differences between the samples; in fact, their analysis is based on patent counts for about 560 US Companies for the years 1989-98. Second, differences may stem from possible disharmonies between the data classifications, which are not infrequent in patent analysis[9]. Although these factors probably explain part of the divergence between the two studies, there certainly remains an uncounted residual.

5.3 Appraisal of the historical framework: Changing capabilities and the new techno-economic paradigm

Can the insights on technological diversification help us in establishing the existence of a technological revolution? Our interpretation is that the evidence on the (widening) pervasiveness of ICT capabilities can be used to support the neo-Schumpeterian LW hypothesis that a period of *structural change* is triggered by a new key productive factor (the Core Input) and the new set of technological combinations associated with it.

Large companies of all sectors are dynamically expanding their ICT capabilities, the engine of growth in the last quarter of the twentieth century. The impact of ICT on large companies in many sectors suggests a link between multi-technology trend and the rise of a new technological paradigm. This link can be explained with the help of Helpman and his colleagues (1998) who suggest that ICT is a typical general-purpose technology by evidencing strong complementarities with other technologies. Furthermore, our findings are in line with a study by Fai and von Tunzelmann (2001) on the historical evolution of technological scale and scope The long-term patent analysis in that paper, using Reading University's database, points to the preponderance of a diversification strategy in technological capabilities, or scope over scale, in the last quarter of the twentieth century. Their hypothesis, for which they present preliminary evidence, is the following:

> " ... in the guise of emerging technological paradigms, firms may extend their patenting into these fields and relatively diminish that in their old areas of strength. In such cases, the technological scope of a firm may increase without any necessary change of in technological scale. On the other hand, if the technological opportunities of a rising paradigm were exploited in extreme, it might appear that technological concentration occurs, again with uncertain impacts on technological scale." (Fai and von Tunzelmann, 2000, p.8)

Our research confirms that the *Core Input* behaves as expected by the LW theory: Semiconductors is the single fastest moving patent class (an explosive growth technology by

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[9] That is why we also controlled for the inclusion of Photography and Photocopy sector in our ICT sectors as part of our sensitivity analysis.

all accounts) and is basically produced by the specialist sectors (the Electrical/Electronics and Computer industries account for over 80% of the Semiconductors patents throughout the three time periods). The *Motive/Carrier Branches* of the emerging paradigm also exhibit a growth pattern that is consistent with the theory: the ICT sectors, i.e., the computer industry (in particular) and the Electrical/Electronics industry, are among the fastest growing sectors in terms of patents produced. The last element of the LW we can pronounce about is *Organisational Change.* With the help of other pertinent work, notably Hagedoorn et al (2000), we are able to draw attention to the association between the rise of ICT in technological diversification and the phenomena of networks for ICT development, which again confirms the reasoned historical account of Freeman and Louçã (2001).

Therefore, the pervasive, though uneven, development of ICT knowledge among large companies has implications for economic growth debates. For instance, a paper by Harberger (1998) presents a distinction between two types of growth: “mushrooms” versus “yeast”. In the latter case growth starts from one point and spreads uniformly. Mushrooms instead grow randomly, and not in a uniform way. Harberger argues that modern US productivity growth is driven largely by the internal growth of some sectors in a given period whereas in other periods other industries assume that role implying the “mushrooms” hypothesis. Our findings invite for extra caution in growth accounting exercises when technologies such as ICT are involved. ICT capabilities are not only developed by the specialist sectors and their diffusion is highly structured. What we pick up from studying our specific period in the evolution of corporate capabilities is that the impact of ICT on aggregate trends is likely to be qualitatively complex. In this sense our findings point to forces pervasive enough to have far-reaching effects in the population of the world’s largest manufacturing firms, a “general-purpose” feature that David and Wright (1999) would interpret as further evidence that the 1990s were a decade of “yeast-like” productivity growth. Moreover, the economy-wide adjustments required for exploiting ICT are bound to take their time, which only a historical perspective can fully appreciate (Pavitt and Steinmueller, 2001).

5.4 Questions for future research: The question of incomplete corporate coherence and the relational role of R&D

This research is insufficient to allow us to make any strong statement about the microeconomic and technological reasons behind the depicted trends. The database would have to be much larger and more detailed to allow us to know what exactly those ICT patents are and what they mean for those non-ICT specialist firms that obtain them. For instance, the database could be expanded to encompass the multiple technological fields into which each patent is classified, other information could show citations of ICT patents granted to ICT and non-ICT firms, patents in which software technology was incorporated, etc. However, case studies cannot be easily replaced as a source of empirical knowledge. Indeed, it would also be valuable to investigate if and how business organisations from non-specialist sectors have contributed to other general-purpose technologies identified by economic historians. For the remainder of this paper we wish only to present two hypotheses that could be researched using these and other approaches.

First, an interesting question is the extent to which R&D is increasingly being used as an instrument of external coordination. R&D can be seen as a strategic asset that companies use with the intention to strategically manage technological and productive relations with other players of the national (and international) system of innovation and web of relations in which the firm is embedded. This source of advantage can be used to manage relations with innovative suppliers, (but also with) rivals, buyers, potential entrants, producers of substitute products, universities, government laboratories, regulators, etc. Knowledge is power, and big business institutions might be found to use it to obtain more knowledge and sustain themselves as central knots in a network of technological and economic relations. We might suggest that there is room for future interesting research on the "third face of the R&D" in connection with the view of ICT as the most strategic technology for corporate development in the late twentieth century.

Following this speculation, alliances and other loose-coupling governance mechanisms should be at the centre-stage of multi-technology analysis in the future. Another interesting question is the extent to which ICT has functioned as a catalyst of diversification by facilitating the processes of social interaction and sustained networking or market exchanges among different specialists. These ideas are compatible with the findings from a variety of sources: *a*) of Cohen, Nelson and Walsh (2000) on the new rationales for patenting; *b*) the discussion of modularity in product innovation (Brusoni et al, 2001); *c*) the signalling incentives behind the publishing of scientific papers by companies as pointed out by Hicks (1995); *d*) the increasing role in Intellectual Property Management (Granstrand, 1999); *e*) the rise of the importance of markets for technology (Arora et al, 2001). Potential managerial and public policy implications could be explored. For instance, the necessities of networking imply an increase for social skill among engineers as well as other employees can imply the integration of social sciences in higher courses of natural sciences and engineering.

A second question considers enlarging the notion of multi-technology corporation. A large company active in *natural science-based technologies* might sooner or later need to develop *social science-based technologies* carried out by "social R&D units" in order to improve managerial competence in uncertain socio-economic environments. Dosi, Teece and Winter (1992), addressing the issue of corporate coherence from the product side, argue that companies, as a rule, "diversify into 'related product lines', and that this 'coherence' is relatively stable over time" (1992, pp.185). They present as a first page example the case of Royal Dutch/Shell that, having spent the twentieth century in the oil business, "diversified into petrochemicals and little else." (p. 185) The authors fail to note that Shell tried to diversify into other energy businesses, like nuclear power, with dismal success. But why were conglomerates (product line incoherence) unsuccessful and multi-technology companies apparently very successful? A famous, yet still secret, report of Shell Group Planning staff dating from the early eighties, when the company was facing serious trouble, supplies interesting clues. The Shell report, named *Corporate change: A look at how long-established companies change*, argued that the most long-lived companies in the world (Sumitomo, Du Pont, Procter & Gamble, etc) have been historically "tolerant of activities at the margin: outliers, experiments, and eccentricities within the boundaries of the cohesive firm, which kept stretching their understanding of possibilities." (de Geus, 1997, p.14).

Long term corporate survival implies regeneration and this means keeping technological options open because they are costly to develop and the evolution business environment is uncertain. In this sense, a certain degree of tolerance for impurity technological activity may be a formula to prevent competencies becoming rigidities. As Hodgson (1999, p. 126) states in his description of the so-called impurity principle, every socio-economic system relies on at least one "structurally dissimilar subsystem" in order to function. Incomplete coherence or impurity in technological activity could be, in this sense, a necessary condition to facilitate corporate learning and change. This is, indeed, what Shell, DaimlerChrysler and other large companies have assigned to their strategy departments, which act as internal consultancies in technology foresight and business environment monitoring[10].

6. Conclusions

In this paper we looked at the relation between the multi-technology trend and the new information and communication technologies by using patent data as a proxy for dynamic capabilities. We attempt to establish that technological diversification is not spread randomly across technologies and there is evidence indicating a *pro-ICT bias* when large companies of all industries patent outside their main technological competencies. While ICT industries (Computers and Electrical/Electronics companies) have themselves been focusing their technology scope, (narrowly defined) ICTs have progressively broadened the industry base from which new patents are harvested.

Dynamic capabilities in ICT are, therefore, more widespread than previously emphasised in the literature. The following qualification should therefore be kept in mind when thinking about MTCs: diversification is directed more to some technologies than to others in given time periods and the increasing pervasiveness in the development of ICT should not be underestimated. It emerges that ICT capabilities, the engine of growth in the last quarter of the twentieth century, are the key for an increasing number of large corporations. In a nutshell our main empirical results show that:

a) Technological diversification certainly occurred in ICT, for other technologies findings are less obvious;
b) There is considerable inter-industry variance in the level and pace of increase in ICT patenting;
c) There are differentiated trends among specific ICTs (Semiconductors, Computers, Telecommunications, Image & Sound).

[10] For an account of the cases of Shell and DaimlerChrysler and for an exploration of the connection between social sciences and organisational competencies see Mendonça (2001a, 2001b).

We argue that the increasing component of ICTs in technological diversification can be related to the neo-Schumpeterian *Long Wave* hypothesis as conceptualised by Freeman, Louçã and Pérez. Our findings show the usefulness of the operational categories of this thesis and present a successful test for its propositions. In this way we attempt to show that the MTC and the LW literatures are linked for they deal with related phenomena. Indeed, the expansion of the ICT component in the corporate knowledge base is possibly one of the less conspicuous ways in which an ongoing structural change is taking place.

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Appendix 1 - *The SPRU-OTAF Patent Classes*

1 Inorganic Chemicals
2 Organic Chemicals
3 Agricultural Chemicals
4 Chemical Processes
5 Hydrocarbons, mineral oils, fuels and igniting devices
6 Bleaching Dyeing and Disinfecting
7 Drugs and Bioengineering
8 Plastic and rubber products
9 Materials (inc glass and ceramics)
10 Food and Tobacco (processes and products)
11 Metallurgical and Metal Treatment processes
12 Apparatus for chemicals, food, glass, etc.
13 General Non-electrical Industrial Equipment
14 General Electrical Industrial Apparatus
15 Non-electrical specialized industrial equipment
16 Metallurgical and metal working equipment
17 Assembling and material handling apparatus
18 Induced Nuclear Reactions: systems and elements
19 Power Plants
20 Road vehicles and engines
21 Other transport equipment (exc. aircraft)
22 Aircraft
23 Mining and wells machinery and processes
24 Telecommunications
25 Semiconductors
26 Electrical devices and systems
27 Calculators, computers, and other office equipment
28 Image and sound equipment
29 Photography and photocopy
30 Instruments and controls
31 Miscellaneous metal products
32 Textile, clothing, leather, wood products
33 Dentistry and Surgery
34 Other - (Ammunitions and weapons, etc.)

Appendix 2 - *Correspondence between Industry and "Core Technical Fields"*

Industry (ie, Principal Product Group)	"Core Technical Field"
Aerospace	Aircraft; General Non-electrical Industrial Equipment; Power Plants
Chemicals	Organic Chemicals; Agricultural Chemicals; Drugs & Bioengineering
Electrical/Electronics	Telecommunications; Semiconductors; Electrical Devices; Computers; Image & Sound Equipment
Food, Drink & Tobacco	Food & Tobacco; Chemical Processes; Drugs & Bioengineering
Machinery	General Non-electrical Industrial Equipment; Metallurgical & Metal Working Equipment; Chemical Apparatus; Vehicles Engineering; Mining Machinery; Specialised Machinery
Materials	Materials
Metals	Metallurgical & Metal Treatment Processes; Materials; Metallurgical & Metal Working Equipment
Mining & Petroleum	Organic Chemicals; Inorganic Chemicals; Mining Machinery
Motor Vehicles & Parts	Vehicles Engineering; General Non-electrical Industrial Equipment; Other transport Equipment
Paper	Materials; Specialised Machinery
Pharmaceuticals	Organic Chemicals; Drugs & Bioengineering
Photography & Photocopy	Photography & Photocopy; Instruments & Controls
Rubber & Plastics	Plastics & Rubber Products; Materials

Source: Adapted from Patel (1999)