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# The Revolution Within: ICT and the Shifting Knowledge Base of the World's Largest Companies

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# The revolution within: ICT and the shifting knowledge base of the world's largest companies

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This empirical paper analyses the importance of information and communications technologies (ICT) in the technological diversification trend among the world's largest manufacturing firms during the 1980s and 1990s. The objective of the research is twofold: firstly, to emphasise the emerging differences among technologies when companies from different industries patent outside their traditional technological capabilities; secondly, to investigate whether the tendency among large companies from all industries to patent in ICT is distinctive when compared with the tendency to patent in other technologies. We find that technological diversification in large companies has clearly occurred in ICTs. Non-ICT specialist industries increasingly develop, rather than just utilise, the cluster of ICT-related technologies. We conclude that the development of corporate capabilities in the key technologies of the emerging ICT paradigm is more widespread than previously emphasised in the literature. One implication of this observation is that technological diversification and the information revolution may be related phenomena.

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# The revolution within: ICT and the shifting knowledge base of the world's largest companies

## 1. INTRODUCTION[*]

This empirical paper focuses on the intersection between the trend towards technological diversification among large innovative firms and the dramatic development of new information and communication technologies (ICTs) in the last decades of the twentieth century. There are two main objectives to this research. Firstly, we seek to emphasise the uneven attractiveness of different technologies for companies patenting outside their traditional competencies. Secondly, we seek to compile convincing evidence that ICTs are distinctive, compared with other technologies, in the degree to which they account for corporate technological diversification.

The analysis uses patent counts and classifications based on the SPRU database for nearly 500 of the world's largest innovating companies from 1981 to 1996, as ranked by sales revenues. This material allows us to confirm that technological diversification in large companies has certainly occurred in ICT while for other technologies the patterns are less conclusive. ICT-related change in the competence portfolio of large firms has been widespread across sectors and rapid over a period of 17 years. As might be expected there is considerable industry variation when companies patent in ICT, given that:

*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; and,
*c*) ICT is apparently not so important for Chemicals and related sectors (Pharmaceuticals, Food, Drink & Tobacco, Paper, Mining & Petroleum, Rubber & Plastics).

The results of studying the internal transformations of large established firms in already existing sectors are remarkable. There is much theoretical and empirical evidence suggesting that the relevant knowledge resources for many firms in many industries are not internal to the industry

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[*] Comments and criticisms by Keith Pavitt, Pari Patel and Nick von Tunzelmann were very useful in the early stages of this research. Later versions of the work benefited from the interaction with Alfonso Gambardella, Ed Steinmueller, Camilla Noonan, Felicia Fai, Fernando Santiago-Rodriguez, Isabel Oliveira and Dan Ward. Finally, three anonymous referees constituted a fertile source of suggestions that helped to further advance the arguments present in the paper. The usual disclaimer applies.

(Pavitt 1984; Smith 2002; Malerba 2005). However, according to our account, non-specialist sectors show themselves not to be passive users of ICT knowledge, but rather drivers of change. As a conclusion we suggest that the intensive development of cutting edge corporate capabilities in the key technologies of the emerging ICT paradigm by non-specialist industries is a robust stylised fact in need of further research. We also suggest that the technological diversification trend may be related to the upswing phase of a new Long Wave (LW) of techno-economic development, as hypothesised by Freeman and Louçã (2001). Indeed, according to recent historical accounts, ICT had much more economic impact even before the mid-1990s than steam technology during heydays of the British Industrial Revolution (Crafts 2004; Crafts and Mills 2004). Growth economists' interest in the arrival of new core inputs or General Purpose Technologies (GPT) is mainly linked to macroeconomic outcomes. Jorgensen (2005) has recently estimated that the contribution of information technology capital has accounted for nearly half the surge in productivity growth from 1995 to 2000. The central message of our paper is that contributions to cutting-edge ICTs are not a monopoly of the ICT equipment industry but also come from a variety of other, non-specialist industries.

This paper draws on previous empirical and conceptual work on the Multi-Technology Corporation (MTC) pioneered by Granstrand, Patel, Pavitt and others (e.g. Granstrand and Sjölander 1992; Patel and Pavitt 1994a). The basic stylised fact is that the technological base of virtually all innovative large companies is much wider than their product range. Moreover, industries held persistent diversified profiles of technological competencies for most of the twentieth century (Fai, 2003). Evidence to date, albeit statistically weak, has broadly pointed toward a positive association between corporate technological diversification and economic performance (Gemba and Kodama 2004; Piscitello 2004).

Our contribution seeks to add to this work whilst also asking new questions about the existence of relevant sub-patterns in the trend of technological diversification. We focus on the specific technological classes in which large companies tend to accelerate patenting when they patent outside their traditional technical domains. Moreover, since ICT becomes the most dynamic body of knowledge for most contemporary giants, our perspective can 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. In our contribution the question is the reverse: how have ICT technologies been developed outside ICT sectors?

The paper proceeds as follows. Section 2 presents the conceptual and historical framework that provides the necessary guidance to empirical exploration. Section 3 discusses the data and assesses 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, whilst also discussing the implications of the findings for the analysis of economic growth and highlighting some outstanding questions for innovation strategy and policy. Section 6 concludes.

## 2. THEORETICAL FRAMEWORK

Following Schumpeter's celebrated advice, we draw on *theory* and *history* to understand the patterns emerging from *statistical analysis*. The chosen conceptual framework is the Penrosian and evolutionary capabilities approach, with Neo-Schumpeterian LW theory is used to provide a background historical viewpoint.

### 2.1 The internal workings of business organisations

The corporate knowledge base became more complex during the twentieth century. The literature on technological diversification consistently draws attention to the variety of directions and rates of change of corporate patenting activities (Cantwell *et al*. 2004). 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 contemporary 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* Corporations must be set apart from that of multi-*product* corporation. In fact, the big business institutions of today exhibit a much broader portfolio of technologies and 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 a line of inquiry 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 companies in the real world. For the purpose of our analysis we take technological capabilities to mean the command over specific scientific and technical principles that exist in the minds of individuals and the routines that link the members of an organisation (see Dosi *et al.* 2003). Such capabilities, although cumulative and path dependent in nature, may also be dynamic in the sense that they “allow the firm to create new products and processes, and respond to changing market circumstances” (Teece and Pisano 1994, p. 541). Following this conceptualisation, the technological capabilities of the world’s largest manufacturing companies will constitute our unit of analysis. To implement this approach, we scrutinise the specific areas of technological knowledge that are being diversified into, using patent indicators.

## 2.2 Big business 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. However, 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.

During the first industrial revolution the factory system and steam power were at the core of industrial change, especially in the cotton industry and in transportation. About one hundred years later, with what came to be known as the second industrial revolution, the introduction and spread of electricity, synthetic chemicals and the internal combustion engine constituted the key cluster of innovations. 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). However, companies and industries change through time co-evolving with technological change (Nelson 1999). Therefore, 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.

### 2.3 The story behind technological evolution

As Landes (1991) has stated, historians try to explain changes in the mode of production that economists usually take for granted. Several authors of a neo-Schumpeterian inclination, 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 evolving in historical time. The emergence of a 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 over time 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 a recent restatement and empirical assessment of this perspective, Freeman and Louçã (2001) analyse 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. This concept is analogous to the major innovations labelled as GPTs by Helpman (1998) and colleagues. The producers of such 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* attributed to this revolutionary time 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 this property right by such a demanding institution as the US Patent Office is a recognition of cutting-edge expertise in a given technological field. Therefore, and for operational reasons, patent statistics will be employed to screen the *breath* and *depth* of technological capabilities of manufacturing companies.

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 database: accumulated patent counts for 14 industries and 34 patent classes for the years 1981-85, 1986-90, and 1991-96. This database reports patents for 463 of the world's largest companies[2] (it does not include patents by individuals or research institutions) 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

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[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).

[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.

1992 and attributed to their parent company. The method of consolidation is described in detail in Patel (1999).

The SPRU database 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 these inherent characteristics and limitations. In the analysis below, besides using the original classifications we also adopt a further reorganisation of our own. Three reasons lie behind this reorganisation. Firstly, *synthesis* to simplify the patterns emerging from 34 individual classes times 14 sectors during 3 time periods, patterns which are otherwise difficult to bear in mind or even to visualise. Secondly, *new information* on unexpected patterns can be gained with an aggregation of patent categories. Finally, the *reliability* of conclusions is substantially upgraded by allowing for sensitivity testing. The new technology families are shown in table 1.[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 | |

*Key*: See Appendix 1
*Source*: Elaborations from the SPRU database

An important issue here is the operational definition of ICT. The definition of ICT we use takes 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

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

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

The limitations of patents as indicators of technological activity are well known and will not be discussed in detail here although much could be said based on the many contributions on the subject (Pavitt 1985; Narin and Olivastro 1988; Grilliches 1990; Patel and Pavitt 1995; Smith 2005). Patents are an institutional record of invention and, although increasingly used in economic research, 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. Nevertheless, the combination of the conclusions of three recent studies on the patent indicator (Cohen *et al.* 2000; Jaffe 2000; Hicks *et al.* 2001) gives us fresh assurance of the relative reliability of this indicator for the purposes of this paper. We will return to these issues in section 5, but for now it will suffice to note that the rise of a pro-patent institutional environment in the US might have increased the patenting rates in most technologies, but only in a step-wise fashion. Moreover, in the specific case of ICTs, which have grown exponentially, there is no unambiguous evidence of a deterioration in quality of the technological ideas being protected by patents.

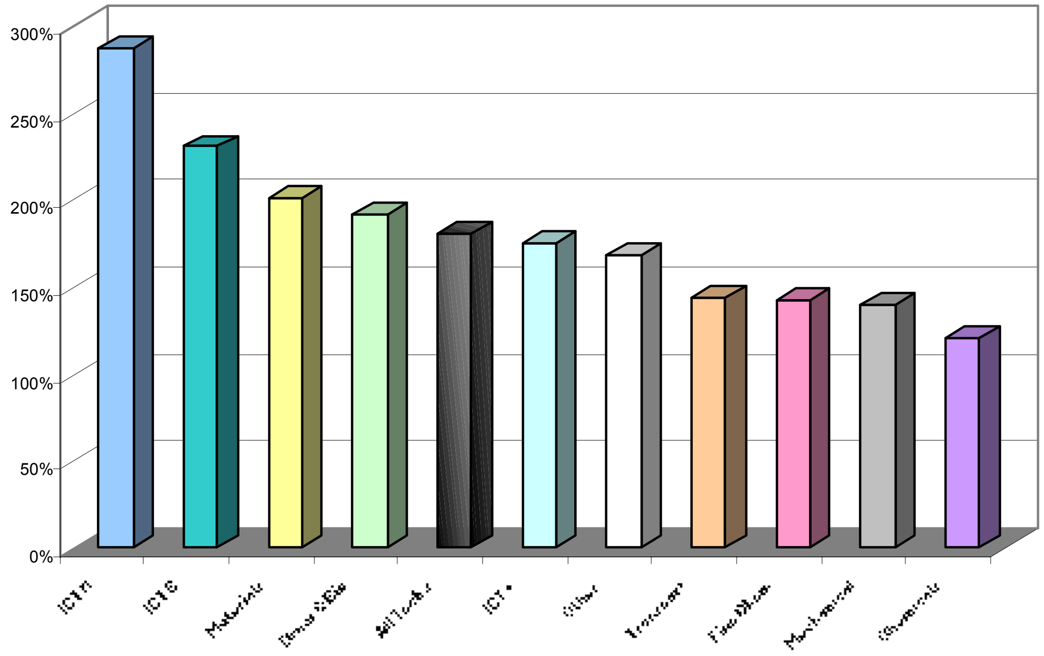
## 4. THE EMPIRICAL LINK BETWEEN ICT AND TECHNOLOGICAL DIVERSIFICATION

In the light of the capability view of the firm assumed in this paper, the process of corporate technological diversification refers not to multiple technologies being *used* but rather to patents from multiple technologies being *registered* to a company classified in a given industry or product group. The following two sub-sections provide a view on general trends exhibited by the diversified technological portfolios of corporations belonging to different industries. The remaining 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 (e.g. Bruland and Mowery 2005). Figure 1 shows that overall patenting is heavily skewed in terms of types of technologies. The growth of (narrowly defined) ICT depicted is 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 1981-85. We also find that ICT N corresponds to almost one third of total patents in the early nineties while in the early eighties it was one fifth. It also can be noted that the broadly defined ICT group, or ICT B, has been rising to account for almost 50% of all patents during the 1991-96 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 (1994b), which has not been enough to avoid the relative fall in share of mechanical classes in total patents. It is also interesting to observe that the other most dynamic technological groups are Materials and Pharmaceuticals & Biotechnology (these trends are explored in Mendonça 2003). This comes as no surprise since numerous futurists and analysts have systematically anticipated or highlighted these as key technologies for the last 30 years.

Figure 1. *Technology families' size for 1991-96, in relation to 1981-85*



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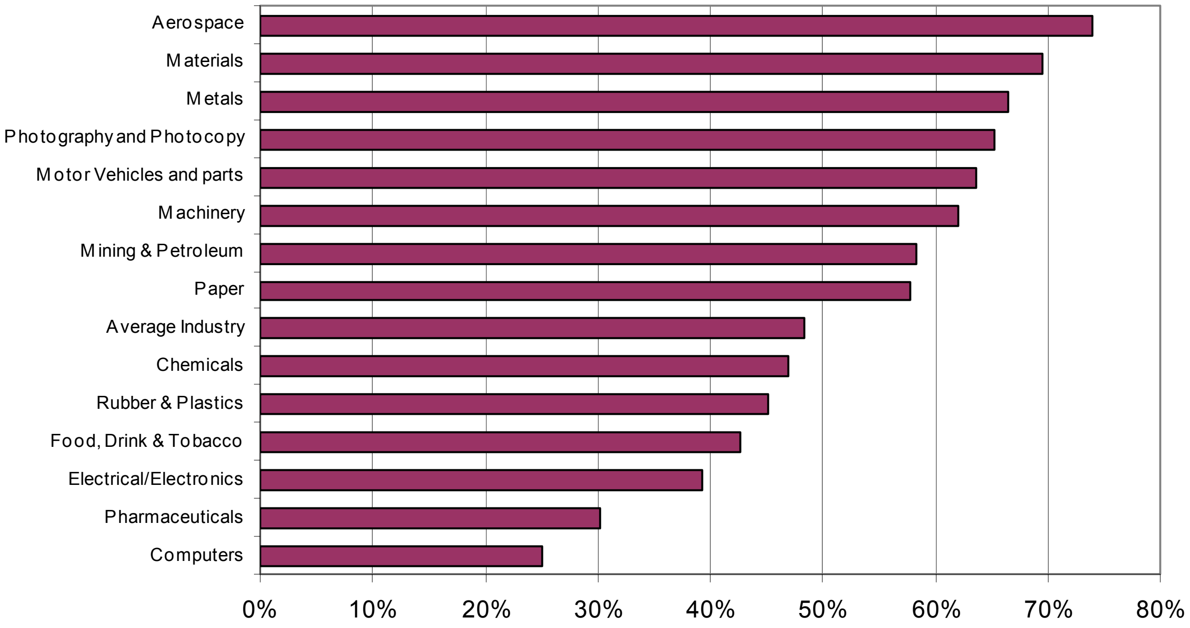
*Source*: Elaborations on the SPRU database

## 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 example, this classification places ICT N technologies in the centre of Computer and Electrical/Electronics industries competencies. It then becomes possible to assess the extent of technological diversity in each industry by the proportion of patents granted outside the industry's "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 industry's total. We can see that all sectors have at least 20% of their patent portfolio in technological areas not directly related to their core business. For example, Electrical/Electronics, Computer and the Pharmaceutical sectors are among the least diversified, 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 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, appears again to be focusing on their core technological competencies over time.[5] Putting it in another way, the ICT sectors, or the Motive/Carrier branches in the Freeman-Louçã-Pérez terminology, have been diminishing substantially the weight of non-ICT technologies in their portfolios. This suggests that the patent growth in the Computer industry has been driven by ICT (N), i.e. the core technology of the sector, something one could expect from theory. This pattern is also in line with the findings by Gambardella and Torrisi (1998), Patel (1999) and Hagedoorn *et al.* (2000) who analyse data for a similar sample of large European, Japanese and American companies.

Other industries seem to follow the inverse pattern, i.e. to be increasing the share of patents obtained outside their core technological competencies. Although there is not a clear trend towards increased technological diversification for all sectors, five sectors in particular are 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. However, in this sub-section we apply the *H* to technologies on the basis of the industries contributing to them, i.e. we calculate it the other way around. With this angle of analysis one is investigating the *source structure of a technology* (the extent to which different industries are advancing the total patenting performance in a given technical field). A high index reflects a concentration of technological activity, i.e. fewer

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[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 parsimony.

industries “supplying” the patent class, and thus fewer industries incorporating that technical field into their knowledge portfolios in a substantive way.

In table 2, 12 technological classes out of 34 seem to be diversifying the industry sources from which new inventions and improvements are recruited, especially classes of the ICT groups (in bold). Three out of the four ICT N classes experience a decreasing *H*, a larger proportion than any other technology family. This observation represents a very interesting contrast between ICT (technologies) and the ICT sectors: while ICT sectors are highly concentrated on the technologies close to their production activities, ICT knowledge is rather dispersed, and increasingly so, across a variety of sectors.[6]

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

| Technologies | 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 | |

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[6] Bergeron *et al.* (1998, pp. 740-1) in their analysis of French firms’ patenting behaviour between 1985 and 1990 have suggested that ICT is a case in which technological opportunities can be characterised as mainly endogenous to the industry (explaining why the ICT industry is the key contributor to ICT patents) but at the same time application of this core technology is widely diversified across other businesses.

| | | | |
|---|---|---|---|
| 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 database
*Notes*: as there are 14 industries, the *H* ranges from a minimum of 0.0714 (or 1/n) to 1, in the case of maximum concentration; the highlighted technologies are diversifying ICTs, broadly defined

We also computed the *H* using the same data aggregated 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 account for 77% of all Computer patents throughout the three periods taken together). These findings set the tone for a deeper inquiry, namely into the way in which technological diversification is primarily orientated towards ICT. An interesting question to now address is what are the most "pro-ICT" non-ICT specialists.

### 4.4 How much has ICT increased in the technological portfolios of large firms?

We have just seen that ICTs constitute an 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, i.e. whether it has attracted contributions from the generality of the largest innovative companies in our population.

Indeed, table 3 shows that all industries (except one: Paper) increased the weight of ICT N in their technological portfolios when comparing the periods 1981-85 and 1991-96. This result is noteworthy and is in contrast to the slight overall decrease in ICT+. Companies of all industries are consistently patenting more in ICT, and in particular into ICT N; the most science based of the ICT technologies. The results shown for "all industries" suggest that, on average, each industry increased its patenting of ICT N by 11%. Of the non-ICT sectors, the level of ICT N is above 10% for Aerospace, Motor Vehicles & Parts, Machinery, and (significantly higher for) Photography & Photocopy. Furthermore, the Metals and Materials sectors both register a step-jump rise (above 5%) in the ICT N component of their technology portfolios, which is a substantial change, especially taking into account their low initial shares. It is also worth noting the decline ICT + by "all industries", a trend that reinforces the operational content of the narrower ICT definition. In spite of this slight decline ICT B increased almost as much as ICT N.

Table 3. *The ICT component of the corporate technology portfolio by industry*

| | ICT N | | ICT + | | ICT B | |
|---|---|---|---|---|---|---|
| Industries | 1981-85 | 1991-96 | 1981-85 | 1991-96 | 1981-85 | 1991-96 |
| 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 database

Measuring the extent of technological diversity in each industry by the proportion of patents outside the industry's "technological competencies" produces a list of the most preferred technologies for companies patenting outside their traditional technological competencies. By applying this method, 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. This method also shows that ICT N has a secondary importance for Chemicals and associated sectors (Pharmaceuticals, Mining & Petroleum, Paper, Rubber & Plastics, Food, Drink & Tobacco).

Overall, industries tend to have a stable ranking of technology families when they patent outside their core technological field competencies. However, any change that has occurred in this path-dependent corporate knowledge structure has been driven by ICT. Over time ICT N was the technology group registering more net increases into its individual patent classes (all but one industry diversified into it, i.e. 13 industries), followed by Drugs & Biotech and Materials. In other words, ICT N climbed up the ranking in terms of relative weight corporate patent portfolios in five of our industries, whilst it remained in the same relative position for six and only fell in two industries. For the average company, ICT N climbed from 6th position in 1981-85 to 2nd position in 1991-96. These changes 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%.

To sum up, 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 new technology development. This can be interpreted as indicating that technical knowledge about ICT is increasingly being dispersed across industrial sectors.

These results, however, should be read with caution. The increase in the ICT N share of an average industry's portfolio slowed down during the period 1991-96.[7] Moreover, in this period there were industries for which the relative weight of ICT N patents in their total patents slightly decreased, 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 (whilst Paper – an exception – increased). ICT N was the technology family that increased the most on the average portfolio. However, more industries registered a net increase in Drugs & Bioengineering than in ICT N. Therefore, in our database, the jump in the importance of ICT N patents for non-ICT sectors happened during the 1980s.

We should also add two further comments in interpreting our results, both pointing out that, if anything, the ICT N trend across sectors is underestimated in our analysis. Firstly, if we break down ICT N for the Aerospace industry it emerges that Telecommunications and

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[7] From our data it is not at all clear why this happens or if that slowdown was likely to persist in the second half of the 1990s. One way to account for the slowdown in 1991-96 is to link it to the slow down in economic climate in the early 1990s; in this case the general patenting trend would reverse during the second half of the 1990s. However, this topic falls outside the scope of this paper.

Semiconductors have been registering sharp rises (therefore the rise of only 0.08% in table 5 might be underestimated). Secondly, 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 due to the digitalisation of the engine control systems (Prencipe 2000).

### 4.5 Industry's contributions to ICT N patenting

This last empirical sub-section is devoted to assessing the influence of the specialist and non-specialist industries on total patenting in ICT N. A striking conclusion of this analysis is that the percentage of ICT N patents accounted for by ICT sectors between 1981-85 and 1991-96, i.e. the Computers and Electrical & Electronics sectors, fell from 77.3% to 74.5%. Applying a test to the equality of proportions makes it clear that the probability of such a difference being a product of chance is extremely low ($r = 0.978$; $p<0.000$). This implies that the ICT sectors do not have, by any means, a monopoly on ICT patenting[8], and that their share has significantly decreased from 1981 to 1996. The previous sections showed 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.

This result is partially 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, our study finds that large non-ICT sectors have been responsible for up to 25% of the ICT patent growth generated in the early 1990s and not just 2% as claimed in their paper. Table 4 displays the contribution to the increase in patenting defined as the difference between patenting in the three periods. In trying to explain such a discrepancy we should first highlight two differences between the samples. Firstly, the analysis of Hicks *et al.* (2001) is based on patent counts for about 560 US companies for the years 1989-98. Secondly, differences may arise from possible discrepancies between the data classifications,

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[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.

which are not infrequent in patent analysis[9]. Although these factors probably account for part of the divergence between the two studies, an unaccounted for residual certainly remains. If our methodology is correct, the increase in ICT N patents is coming from a much broader range of sectors than their findings suggest.[10]

Table 4. *Sectoral contributions to the increase in ICT N patents*

| | Growth between 1981-85 and 1986-90 | Growth between 1986-90 and 1991-96 | Total growth in the period 1981-96 |
|---|---|---|---|
| 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*: Elaborations on the SPRU database

The non-ICT sectors contribution to ICT N (patent counts and percentage) is depicted in table 5 for the 12 non-ICT industries. As can be seen in column (*a*), this is a highly skewed distribution, with those that contribute substantially to ICT N contributing a lot. The three largest contributing sectors are equivalent to 89% of new ICT N patents. Photograph & Photocopy accounts for almost 60% 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 Chemicals, together accounted for 33%.

Table 5. *Non-ICT contributors to ICT N*

| | 1981-85 | 1991-96 | *a* | *b* | *c* |
|---|---|---|---|---|---|
| Aerospace | 761 | 1144 | 2,6% | 50% | 14.5% |
| Chemicals | 325 | 899 | 4,0% | 177% | 4.0% |
| Food, Drink & Tobacco | 18 | 37 | 0,1% | 106% | 1.1% |
| Machinery | 684 | 2344 | 11,5% | 243% | 19.7% |
| Materials | 57 | 212 | 1,1% | 272% | 75.6% |
| Metals | 106 | 526 | 2,9% | 396% | 19.6% |
| Mining & Petroleum | 309 | 352 | 0,3% | 14% | 2.8% |
| Motor Vehicles & Parts | 1545 | 4129 | 17,8% | 167% | 25.1% |
| Paper | 65 | 65 | 0,0% | 0% | 0.0% |

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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.

[10] Patent data analysed by Rao *et al.* (2004, p. 369) from the period 1981-2000 points in the same direction: they find that "new players in and out of the ICT sector increased their share of ICT patents relative to our sample of mostly large and mature firms."

| | | | | | |
|---|---|---|---|---|---|
| Pharmaceuticals | 49 | 85 | 0,2% | 73% | 0.61 |
| Photography & Photocopy | 2537 | 11117 | 59,3% | 338% | 43.2% |
| Rubber & Plastics | 35 | 58 | 0,2% | 66% | 4.2% |
| All industries | 6491 | 20968 | 100% | 223% | 43.7% |

*Key*: *a* – Contribution of each industry to the total increase of ICT N patents in 1991-96; *b* – Variation rate in patent counts from 1981-85 to 1991-96; *c* – ICT N as a percentage of total increase in patenting of each industry between the periods
*Source*: Elaborations on the SPRU database

A number of other interesting patterns can also be detected with the help of table 5. First, column (*b*) shows that several industries have recently registered a huge increase in the absolute number of patents in ICT N: Metals (396%), Photography & Photocopy (338%), Materials (272%), Machinery (243%). Second, statistics in column (*c*) show that almost half (43.7% - the total row) of the increase in total patenting in our database between 1981-85 and 1991-96 was due to growth in patenting of ICT N (all the 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 once more be kept in mind: *i*) the increase of the ICT contribution of non-ICT sectors is weaker in the later period; *ii*) patenting has been consistently higher in the Computers and Image & Sound Equipment classes; *iii*) 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.

## 5. DISCUSSION OF THE FINDINGS

This paper explores the growing involvement of the world's largest companies in ICTs. In seeking to base an account of late twentieth century corporate technological diversification evolution one must start by demonstrating that the results are too powerful to be explained by problems with the patent data. In this section we also discuss the usefulness of the theoretical views adopted and present challenges for future research.

### 5.1 Appraisal of the ICT-MTC link: fatal attraction or spurious result?

A number of precautions have been taken in forming the conclusions outlined in this paper, namely by analysing the data in a plurality of ways and by confronting the emerging patterns with what is already known from the existing literature. Nevertheless, 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. However, we refer to 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. There has indeed been a "patent explosion" starting in the early 1980s in the US (Hall 2005; Jaffe and Lener 2004). A surge in patents was especially felt in the semiconductors business (Hall and Ziedonis 2001). Such a dramatic increase should result in the quality of patents decreasing. In contrast, what has been found is an increase in the citations per patent in ICT (Hicks *et al.*2001, p. 702). The implication is that there is little reason to attribute the broad patterns we found to problems in the indicator. Moreover, if such a complex set of factors have influenced the behaviour of ICT patents, it is likely that these factors would affect ICT and non-ICT industries alike, in which case our comparative arguments should hold.

Given that we are aware that patents are an imperfect indicator we strengthened our results in three ways: *a*) results were tested against reclassifications of the data and qualifications were offered when variance was detected; *b*) various approaches and techniques were also attempted in order to filter robust empirical regularities, i.e. those that do not change with different ways of measuring different aspects of the same phenomena; *c*) whenever possible the findings were compared with similar studies using SPRU and other databases.

### 5.2 Appraisal of the theory: changing technological capabilities

According to our results, the cluster of ICT-related technologies is, simultaneously, *a*) the technology group growing the most in terms of the number of new patents and *b*) the field in which large manufacturing are developing capabilities fastest on average. As Dalum *et al.* (1999, pp. 112-3) elucidate, the high growth rates of ICT patents can be interpreted as the product of corporate research encouraged by high technological opportunities and profit prospects.

The patterns exhibited by the ICT industries are in accordance with results of Gambardella and Torrisi (1998) and von Tunzelmann (1999) who, relying on other parts of the SPRU database, also found evidence of increasing technological convergence within the ICT sectors coupled with a low level of extra-ICT diversification. Rao *et al.* (2004) who analysed a sample of the top global ICT firms, sorted on the basis of R&D expenditures, from telecommunications, ICT hardware, electronics & electrical and software & ICT services, also found the same patterns from the 1980s and 1990s. In particular, they found that ICT firms retained a high-degree of technology within a broad spectrum of ICT-related patent classes. These patterns of "internal cross-fertilisation" and "deepening" can be understood as indicative of the long-term technological (and competitive) potential of ICT capabilities.

Nevertheless, and as we wish to emphasise in our study, cutting-edge ICT capabilities are not exclusive of ICT sectors. Hagedoorn *et al.* (2000) and Giuri *et al.* (2001) 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 relation to 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)

Further complementary evidence is supplied by Cantwell and Noonan (2001) on technological relatedness, measured by the degree to which different technologies are co-patented by the same industrial sectors. Their work also suggests that ICT capabilities are increasingly pervasive across the industrial landscape. Their paper shows that ICT appears increasingly associated with other technological groups, namely chemicals and transports. A rise in the technological relatedness occurs in the period 1969-1995 and is driven by telecommunications, special radio systems, semiconductors, image and sound equipment and office/data processing systems.

### 5.3 Appraisal of the historical framework: the new techno-economic paradigm and economic growth

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.

A wide variety of industrial sectors dynamically expanded their ICT capabilities, the engine of growth in the last decades of the twentieth century. The impact of ICT on large companies in many sectors suggests a connection between the multi-technology trend and the rise of a new technological paradigm. This link can be explained with the help of Helpman (1998) and his colleagues who suggest that ICT is a typical GPT given the complementarities it exhibits with other technologies. The work by Fai and von Tunzelmann (2000) on the historical evolution of technological scale and scope can also be of value here. The long-term patent analysis in that paper, using Reading University's database, points to the prevalence of a diversification strategy in technological capabilities, i.e. scope over scale, in the last quarter of the twentieth century. Their hypothesis 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)

The implication is that the *Core Input* behaves as expected by the LW theory: Semiconductors is the single fastest moving patent class (an explosive growth technology by all accounts) and is mainly carried to the market by the specialist sectors (the Electrical/Electronics and Computer industries account for over 80% of the Semiconductors patents throughout the three time periods). Another theoretical construct involved in the neo-Schumpeterian discussion of long-term structural change is that of *Motive/Carrier Branches*. These rising industries of the emerging paradigm also exhibit a leading role in terms of growth patterns 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 economic importance of these sectors is made clear by Jorgensen (2005) in his analysis of growth in the information age, the ICT equipment industries constituted the key driver behind the US productivity resurgence after 1995. What our paper highlights is that, while ICT firms remain the largest applicants of ICT patents, about a quarter of ICT innovation as measured by patents has been sourced from outside these ICT equipment sectors. Thus, although our results show that ICT capital goods firms are the main installers of the new technology in the economy, echoing a point made by Rosenberg (1963), our results also show that the other industries have needed to develop and sustain their own non-trivial expertise to apply ICT to their production and commercial processes. An efficient and separately identifiable "ICT-tools" or ICT capital goods industry seems insufficient to bring about the productivity gains made possible by the new technology. Division of manufacturing labour (in terms of the existence of highly specialised ICT equipment producing branches) does not imply clear boundaries in terms of division of cognitive labour (a competence overlap appears to be needed in order for the new ICTs to be proven economically useful).

In terms of the *Organisational Change* element, it is possible to draw an association between the rise of ICT in technological diversification and the phenomena of networks for ICT development. Assuming MTCs as the flip side of networks is compatible with the reasoned history account by Freeman and Louçã (2001). Large firms are emerging as systems integrators (Pavitt 2003), mediators and orchestrators that contribute to the alignment of networks engaged in technology development processes. This may be a way to understand the co-evolution between governance and technology (von Tunzelmann 2003) in the midst of the Third Industrial Revolution. Large technology diversified companies may be one way in which history (the legacy of the Second Industrial Revolution) meets the revolutionary challenges posed by networked society so eloquently described by Castells (2000).

This all means that the pervasive, though uneven, development of ICT knowledge among large companies has implications for contemporary debates on economic growth. For instance, a paper by Harberger (1998) presents a distinction between two modes of growth: "mushrooms" versus “yeast”. The mushroom metaphor points a random and non-uniform sectoral growth pattern in the economy. By contrast, yeast denotes growth that starts from one point and then spreads uniformly; this epitomises the GPT idea. In this work Harberger argues that modern US productivity growth is driven largely by the internal growth of some sectors in some specific periods while in other periods other industries assume that role. This confirms the “mushrooms” hypothesis: over time different industries provided a significant contribution to the growth of total factor productivity, while others have remained behind.

Our findings invite reflection in growth accounting exercises when technologies such as ICT are involved. A satisfactory answer is likely to be a fuzzy one: there seems to be room for both stories, at least for the time being. As time moved on ICT capabilities did not stay confined to specialist sectors, and their diffusion was highly uneven. Sectors changed from the inside, and some more than others. The rise of the ICT ingredient in corporate capabilities has 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 was a decade of “yeast-like” productivity growth. In this sense our findings point to forces pervasive enough to require economy-wide adjustments in order to economically exploit ICT. Time-consuming evolutionary phenomena such as this can only be fully appreciated by future historical accounts (Pavitt and Steinmueller 2001).

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

Our research has been insufficient to enable us to make strong statements about the microeconomic and technological *causes* underlying the patterns described. More detailed quantitative and qualitative data would have to be collected to identify precisely what the ICT patents refer to and what they mean for those non-ICT specialist firms that obtain them. Examples of ways to further understanding of the growing involvement of the world’s largest companies in ICT would include the exploration of databases encompassing the multiple technological fields into which each patent is classified, as well as information on citations of ICT patents granted to ICT and non-ICT firms. Understanding more about patents by non-ICT firms in which software was part of the claims would also yield potentially interesting insights into the full extent of ICT-related technological capabilities of very large firms. An alternative possibility, unrelated to the theoretical framework offered in this paper, would concern financial diversification and investment in rapidly growing sectors, such as ICT. In this case, the integration of knowledge by such financial holdings is neither guaranteed nor necessarily intended. In terms of economics history, it would also be valuable to put together case studies and investigate how and why non-specialist firms have contributed to the other general-purpose technologies of the past such as steam technology. The rest of this section presents two key questions for further research.

Firstly, the extent to which in-house R&D is increasingly being used in inter-organisation co-ordination is of great interest. R&D can be seen as a strategic resource that companies use with the intention of strategically managing technological and productive relations with other players of the national and sectoral systems of innovation and the broader web of relations in which the firm is embedded. Superior and diversified technical knowledge can be used to orchestrate the firm's affairs with innovative suppliers, (but also with) rivals, buyers, potential entrants, producers of substitute products, universities, government laboratories, regulators, etc. Big business institutions may strategically use internal knowledge to mobilise external knowledge and sustain themselves as central nodes in ever thickening technological and production networks. We might suggest that there is room for future interesting research on the "third face of R&D" or the *co-ordination capacity* of corporations. Our study reveals ICT knowledge as the most strategic technology for corporate development in the late twentieth century.

This hypothesis is consistent with the findings from a variety of sources: *a*) of Cohen, Nelson and Walsh (2000) on the new strategic rationales for patenting; *b*) the discussion of modularity and systems' integration 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 of intellectual property management (Granstrand 1999); *e*) the wider range of technological capabilities when compared to technological external agreements (Giuri *et al.* 2004), and; *f*) the rise of the importance of markets for technology (Arora *et al.* 2001). Following this reflection, alliances and other loose-coupling governance mechanisms should be at the centre-stage of multi-technology analysis in the future. Another interesting and related 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. Potential managerial and public policy implications could be explored. For example, the necessities of networking require an increase of social skills among engineers as well as other employees, suggesting the integration of social sciences in higher courses of natural sciences and engineering.

A second question considers the challenge of expanding the notion of the multi-technology corporation. A large innovative company active in *natural science-based technologies* might sooner or later need to develop *social science-based technologies* carried out by in-house "social R&D units" in order to subvert established decisional routines and leverage managerial competence in uncertain socio-economic environments (Mendonça 2004). Teece *et al.* (1994), addressing the issue of corporate coherence from the product side, argue that companies, as a rule, diversify coherently into related product lines and that this coherence is relatively stable over time. But does the success observed in product line coherence strategies necessarily imply that technological or knowledge coherence is also a sustainable strategy in the long run?

An interesting, 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 survival equates to corporate regeneration. Keeping technological options open is prudent since the evolution of the business environment is uncertain and technologies are costly and time-consuming to develop. In this sense, a certain degree of tolerance for impurity (or incoherence) in technological activity may be a formula to prevent capability stagnation. Hodgson (1999, p. 126) uses what he calls the impurity principle to point out that every socio-economic system relies on at least one "structurally dissimilar subsystem" in order to keep on surviving and functioning properly. Incomplete coherence or impurity in technological activity could be, in this sense, a necessary condition to facilitate corporate learning and evolution.

## 6. CONCLUSIONS

> "The tendency to variation is the chief cause of progress."

Alfred Marshall, *Principles*[11]

In this paper we argued that large manufacturing companies nurture a variety of paradigms in their technological portfolios but that internal variety is evolving in important ways. We reached two main conclusions. First, a key trend in the late twentieth century is that ICT is an irreducible component of the technological diversification phenomenon. Thus, large firms from a wide variety of industries have a capability of knowledge creation in the central technologies of the new tecno-economic paradigm. Second, non-specialist industries increasingly emerge as contributors to ICT. Existing industries, that do not produce or commercialise ICT products, have increased their share of total ICT patenting over time, even in face of a tremendous performance by ICT sectors. The speed and sectoral reach of this change in corporate knowledge bases is remarkable.

Our approach was to look 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. Our hypotheses were that technological diversification is not spread randomly across technologies and that there is evidence indicating a *pro-ICT bias* when large companies of all industries patent outside their main technological capabilities. 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 obtained. Most ICT innovation continues to be concentrated in the ICT sectors. However, by the mid nineties a quarter of ICT patents had originated outside those ICT sectors. This constitutes an intriguing, but robust, stylised fact.

Cutting-edge capabilities in ICT are, therefore, more widespread than previously emphasised in the literature. Although this specific technological trajectory initially developed in the context of specialists, a significant proportion of ICT opportunities are being explored across a wide variety of industries that would not be normally associated with these technologies. The following qualifications 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 entry into ICT development should not be underestimated. It emerges that ICT capabilities, the

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[11] Quoted in Maskell and Törnqvist (2001).

engine of growth in the last quarter of the twentieth century, are key for an increasing number of large corporations. In a nutshell our most important empirical results show that:

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

Thus, we argue that the increasing ICT element in technological diversification can be related to the neo-Schumpeterian *Long Wave* hypothesis as conceptualised by Freeman, Louçã and Pérez. This connection is made explicitly in this paper. Our findings show the usefulness of the operational categories of that theory and present a successful, although limited, test for its propositions. In this way we attempt to show that the MTC and the LW literatures are linked because they deal with related phenomena. Our results shed some light on the process of internal change experienced by a population of concrete economic institutions in real time. Indeed, the expansion of the ICT component in the corporate knowledge base is possibly one of the most important, but inconspicuous, ways in which an ongoing structural change is unfolding in the contemporary economy.

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## APPENDIX 1 - *The SPRU 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 (i.e. Principal Product Group) | "Core Technical Field" |
|---|---|
| Aerospace | Aircraft;<br>General Non-electrical Industrial Equipment;<br>Power Plants |
| Chemicals | Organic Chemicals;<br>Agricultural Chemicals;<br>Drugs & Bioengineering |
| Electrical/Electronics | Telecommunications;<br>Semiconductors;<br>Electrical Devices;<br>Computers;<br>Image & Sound Equipment |
| Food, Drink & Tobacco | Food & Tobacco;<br>Chemical Processes;<br>Drugs & Bioengineering |
| Machinery | General Non-electrical Industrial Equipment;<br>Metallurgical & Metal Working Equipment;<br>Chemical Apparatus;<br>Vehicles Engineering;<br>Mining Machinery;<br>Specialised Machinery |
| Materials | Materials |
| Metals | Metallurgical & Metal Treatment Processes;<br>Materials;<br>Metallurgical & Metal Working Equipment |
| Mining & Petroleum | Organic Chemicals;<br>Inorganic Chemicals;<br>Mining Machinery |
| Motor Vehicles & Parts | Vehicles Engineering;<br>General Non-electrical Industrial Equipment;<br>Other transport Equipment |
| Paper | Materials;<br>Specialised Machinery |
| Pharmaceuticals | Organic Chemicals;<br>Drugs & Bioengineering |
| Photography & Photocopy | Photography & Photocopy;<br>Instruments & Controls |
| Rubber & Plastics | Plastics & Rubber Products;<br>Materials |

*Source: Adapted from Patel (1999)*