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The nanotechnology revolution in Barcelona: innovation & creativity by universities

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Article abstract

This paper analyses the state of the art for nanotechnology in Barcelona, focussing on the scientific and economic challenges arising from nanotechnologies and the creative and innovative framework in Barcelona that could be used to meet them. Nanotechnology is an endless source of innovation and creativity at the intersection of medicine, biotechnology, engineering, physical sciences and information technology, and it is opening up new directions in R + D, knowledge management and technology transfer. Given the huge economic investment and cutting-edge research in the field of nanotechnology, a creatively managed and cooperation-based university industry is more in demand than ever before.

The nanotechnology revolution in Barcelona: innovation & creativity by universities

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Résumé

Ce document analyse l'état de l'art de la nanotechnologie à Barcelone, en mettant l'accent sur les défis scientifiques et économiques et le cadre créateur et novateur de Barcelone, qui pourrait être utilisé pour les atteindre. La nanotechnologie est une source inépuisable d'innovation et créativité à l'intersection de la médecine, la biotechnologie, l'ingénierie, les sciences physiques et les technologies de l'information, en ouvrant de nouvelles directions dans la R+D, la gestion de la connaissance et le transfert de technologie. Compte tenu de l'énorme investissement économique et la recherche de pointe dans le domaine des nanotechnologies, la coopération université-industrie et une gestion créative est plus en demande que jamais.

Mots clés : système régional d'innovation et création, transfert de technologie, gestion de la connaissance, nanotechnologie, nanomédecine.

Abstract

This paper analyses the state of the art for nanotechnology in Barcelona, focussing on the scientific and economic challenges arising from nanotechnologies and the creative and innovative framework in Barcelona that could be used to meet them. Nanotechnology is an endless source of innovation and creativity at the intersection of medicine, biotechnology, engineering, physical sciences and information technology, and it is opening up new directions in R+D, knowledge management and technology transfer. Given the huge economic investment and cutting-edge research in the field of nanotechnology, a creatively managed and cooperation-based university industry is more in demand than ever before.

Keywords: regional system of innovation and creation, technology transfer, knowledge management, nanotechnology, nanomedicine.

Resumen

Este documento analiza el estado del arte de la nanotecnología en Barcelona, centrándose en los desafíos científicos y económicos y en el marco innovador y creativo de Barcelona que podría facilitar su alcance. La nanotecnología es una fuente inagotable de innovación y creatividad en la intersección de la medicina, la biotecnología, la ingeniería, las ciencias físicas y las tecnologías de la información, y abre nuevas orientaciones en I+D, gestión del conocimiento y transferencia de tecnología. Dada la ingente inversión económica y la investigación puntera en el campo de la nanotecnología, la cooperación universidad-empresa y una gestión creativa es ahora más demandada que nunca.

Palabras claves: sistema regional de innovación y creación, transferencia de tecnología, gestión del conocimiento, nanotecnología, nanomedicina.

This paper discusses several R+D and city indicators in order to demonstrate that Barcelona is one of the world's top locations in terms of scientific and creative output. A subsequent analysis suggests that the university is a key player in the area of nanotechnology transfer and innovation, and thus the universities of the Barcelona area have a fundamental role in fostering the innovation and creativity that are emerging from the social and industrial nano-revolution. A set of strategic indicators (such as R+D university investment and the number of researchers, projects and patents) is used to analyse the role of the university in the Catalan Innovation & Creation System (CICS), with special attention being paid to a nanotechnology application: nanomedicine. In this regard, Catalan nanotechnology could take full advantage of the Spanish R&D expenditure convergence to the European GERD average by 2010, although Spanish policy-makers need to prioritize nanotechnology research strategies.

The innovative and creative environment is discussed for the case of Barcelona. After tracking several R+D indicators the university system is analysed as a nano-technology provider. The paper also identifies related system-elements for an innovative nanomedicine[1] cluster in Barcelona, as well as the factor-elements fostering its creativity.

To that end, this paper is conducted through a four sections survey with the aim to answer to the following four questions: What is nanotechnology? How is the Catalan Innovation & Creation System (CICS)? How is Barcelona performing at the nanofield? Which is the creative & economic framework of Barcelona?

All things considered, there are three key elements that place Barcelona's universities at the core of the CICS, and which provide a great opportunity for nanotechnology development in the research and industrial markets at international level: the arrival of the nanotechnology revo-

1. For the purpose of this vision document, nanomedicine is defined as the application of nanotechnology to health. It exploits the improved and often novel physical, chemical, and biological properties of materials at the nanometric scale. Nanomedicine has a potential impact on the prevention, early and reliable diagnosis, and treatment of diseases.

lution, the strong position of the university system, and the urgent need to reduce the GERD gap between Spain and the EU average. While public funds are going to be invested, networks and trade alliances reinforced, and Barcelona's competitiveness preserved, the city's university system is taking advantage in order to transfer nanotechnology developments to Catalan society and the global market, this process being encouraged by the region's creativity, productive diversity and entrepreneurial culture.

Nanotechnology: the third industrial revolution

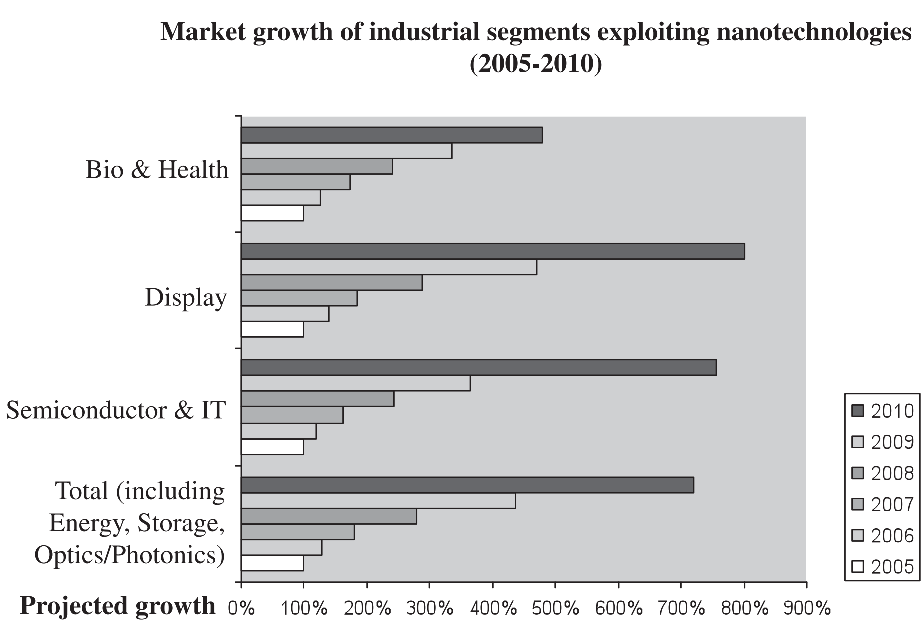
Nanotechnology embraces a whole spectrum of scientific and industrial activities related to the study, manipulation and control of matter at the nanoscale (1 nm = 10^{-9} m), where the distinction between quantum physics, molecular chemistry, material science and biotechnology becomes blurred. This strong interdisciplinary character, combined with the possibility of manipulating a material atom by atom, opens up unknown fields and provides an endless source of innovation and creativity.

The sentence "There's plenty of room at the bottom," at the end of Feynman's classic lecture in 1959, focused scientific interest on the possibility of manipulating and controlling things on a very small scale. Since then, researchers have increasingly turned their attention to achieving atomically precise manufacturing (APM). APM is expected to provide a wide array of practical and profitable technologies and products as research and development in nanotechnology proceeds. Indeed, nanotechnology is widely predicted to drive the next "industrial revolution" (European Commission, 2002), one referred to as "the materials age" and which is the result of a sequence of preliminary revolutions in electronics, ICT and biotechnology.

Nanotechnology is expected to make a rapid impact on society (Roco and Bainbridge, 2005): creation of future economic scenarios, stimulation of productivity and competitiveness, converging technologies, and new education and human development. The increasing speed of the changes in markets, products, technologies, competitors, regulations and even in society means important structural variations that modify what is strategic for organizations (Teece, 1998). Evidence for the rapid impact of nanotechnology can be gleaned from figures for government investment in nanotechnology R+D activities, facilities and workforce training. The 2008 USA National Nanotechnology Initiative budget request for nanotechnology R+D across the Federal Government is over US$1.44 billion (NNI, 2007), more than triple the estimated US$464 million spent when the initiative started in 2001 and an increase of 13% over the 2007 request. In Europe, the VIIth Framework Programme (FP) will contribute about 600 million per year to nanotechnology research until 2013, with an additional, similar amount being provided by individual countries. This gives Europe a larger yearly spend on nanotechnology than the United States or Japan (Swarup, 2007), and it is expected that Europe will take advantage of its strong scientific background to lead the worldwide nanorevolution (European Commission, 2002).

FIGURE 1

Chart based on Fuji-Keizai USA market research



Products based on nanotechnology are already in use and analysts expect markets to grow by hundreds of billions of euros during the present decade. According to the last Lux Research Report (Lux Research, 2007), governments, corporations and venture capitalists in 2006 spent US$11.8 billion on nanotechnology R+D globally, while emerging nanotechnology was incorporated into more than 50 billion dollars worth of nano-enabled products sold worldwide, ranging from pharmaceuticals to cosmetics or power tools (Worldwide Market Research, 2007). In 2005, emerging nanotechnology was incorporated into 30 billion dollars worth of manufactured goods (Rensselaer Polytechnic Institute, 2006), which implies a 66% market increase in 2006. Indeed, nanotechnology is considered by many as one of the key technologies of this century, with an expected market volume of US$1 trillion in 2015. The industry will directly employ more than 30,000 "white-coat" nanotech developers by the end of 2008; an additional 2 million blue-collar jobs in areas such as manufacturing and 5 million jobs worldwide in support fields and industries will follow within a decade (Roco, 2003).

During the next ten to twenty years the use of APM for the design and development of new products and systems will have potential input into a wide range of fields with significant socio-economic impact, such as medicine and pharmacy, the food and agricultural industries, the aerospace industry, information society technologies, and energy and environmental sciences. After a long R+D incubation period, several industrial segments are already emerging as early adopters of nanotech-enabled products (Fuji-Keizai, 2007); in this context, surprisingly rapid market growth is expected and high mass market opportunities are envisaged (Figure 1) for targeted research sub-segments (Table 1).

According to recent reports (Battelle Memorial Institute, 2007) nanotechnology is suitable for potential products in energy production, healthcare, computation, materials, instrumentation, and chemical processing. These include:

- Precisely targeted agents for cancer therapy
- Efficient solar photovoltaic cells
- Efficient, high-power-density fuel cells
- Single-molecule and single-electron sensors
- Biomedical sensors (*in vitro* and *in vivo*)
- High-density computer memory
- Molecular-scale computer circuits
- Selectively permeable membranes
- Highly-selective catalysts
- Display and lighting systems
- Responsive ("smart") materials
- Ultra-high-performance materials
- Nanosystems for atomically precise manufacturing

TABLE 1

Targeted research sub-segments

Segment	Sub-segment
Semiconductors & IT	Organic Semiconductors
	CMOS Sensors
Storage	Magnetic Head
	Optical Pickup
	AFM-based Memory
	CNT-based Memory
	Molecular Memory
Display	Photonic FED
	Organic Electroluminescents
	Electronic Paper
Optics/Photonics	Photonic Crystal Fibre
	Optical Waveguides
	Optoelectronic IC
Energy	Fuel Cells
	Li-ion Batteries
	Electric Double-Layer Capacitor
	Microcrystalline Thin Film
	Solar Cells
	Dye-sensitized Solar Sells
Bio/Health	Drug Delivery Systems
	Immunochromatography
	Regenerative Medicine
	Biosensors
	Nanobubble Generators
	Nanocosmetics
	Nanotextiles

The US market had a share of 28% in 2005, followed by the Japanese market with about a 24% share. The Western European market also had a quarter of the market share, with major investment in countries such as Germany, the UK and France. The remaining market share was held by countries such as China, South Korea, Canada and Australia (RNCOS Market research, 2007). As is argued in some reports (Lux Research, 2007) the twenty-year transition from lab to market has now led to increased production and quality of basic nanomaterials such as carbon nanotubes and ceramic nanoparticules, while prices are falling, and these materials are thus becoming relevant for new applications. The $49 million carbon nanotube market, for example, grew by 87% in 2006, with the entry of large suppliers such as Bayer Material Science and Mitsui threatening the position of start-ups like Hyperion Catalysis and Nanocyl.

In Spain the Grupo Antolín Company has been producing carbon nanofibres since 1999 and in production and quality terms it is now as competitive as the best American or Japanese providers. In 2007, there were 211 Spanish projects in the nano field (including 567 subprojects), involving 294 industries as partners or end users, as well as 5,000 researchers (2,400 doctors)[2]. Since 2004 the Spanish NanoTechnology Think Tank has sought to link public research institutions and private companies by exploiting innovative market opportunities from nanotechnologies. Over fifty applications in biomedicine and pharmacology, energy, electronics, ICT, aeronautics, chemistry and advanced materials have been launched onto the market in the search for development agreements (Juanola-Feliu et al., 2004).

Scientific papers and patents in the nanotechnology sector have grown exponentially over the last two decades. In 2007 over 15,000 nanoscience and nanotechnology-related papers were published, and there is now intense activity as regards intellectual property (IP) in the nanoscale field. IP refers to the ownership of innovations, inventions, ideas and creativity. Nanotechnology is increasing the shift towards a knowledge-oriented economy, so intellectual property is in a position to increase wealth creation, growth and development across the world (Aditeya, 2007a). Several reports have sought to map nano-related patents (Sheu et al., 2006), and figures for nanotechnology-related IP are startling. In the European Patent Office a nanotechnology working group (NTWG) was created in 2003 and 90,000 patents were tagged to class Y01N. The proportion of nanotechnology patents more than doubled between the mid-1990s and the mid-2000s (USA 40%, Japan 19%, and Germany 10%). The Compendium of Patent Statistics 2007 (Dernis, 2007) provides the latest internationally comparable data on patents. Before 1980, 250 nanotechnology-related patents were granted annually to universities worldwide, but by 2003 this number had increased 16-fold to 3,993 patents, which have been filed for fundamental building blocks, materials and tools required to develop this technology. The US patent office has received applications regarding the composition of matter, devices, apparatus, systems and control of nanomaterial and devices, and methods. Cross-industry patent claims are being made for single nanoscale innovations that may have diverse applications. Thus, applications have been identified in major patent classes such as electricity, human necessities, chemistry and metallurgy, performing operations and transporting, mechanical engineering, physics, fixed construction, fabrics and paper.

In order to analyse the impact on the industrial sector the OECD has categorized nanotechnology patents into six fields of application: *Electronics*, *Optoelectronics*, *Medicine and biotechnology*, *Measurements and manufacturing*, *Environment and energy*, and *Nanomaterials*. Most nanotechnologies, especially those related to *Electronics* and *Optoelectronics*, seem to be developed through a top-down process in which nano-structures are created by the miniaturisation of existing technologies. However, another group of nanotechnologies is developed through a bottom-up process[3]. The development of such technologies, i.e. nano materials, has been particularly intense over the past decade and has been fuelled by scientific discoveries such as carbon nanotubes. At this stage, bottom-up nanotechnology is likely to have a relatively small impact on fields of application, and it will take some time before its presence is felt in social and economic terms.

It is estimated that universities now hold 70% of key nanotechnology patents. In the future, nanotechnology development is likely to shift from large publicly-funded organizations and universities to small start-up companies, similarly to what has occurred in the biotechnology industry.

The Catalan Innovation & Creation System (CICS)

Spain is the second-ranked OECD country in terms of geographical innovation concentration, which is strongly located in Catalonia, the Basque Country and Madrid. According to the last COTEC report (*Tecnología e Innovación en España, 2007*), the private sector accounted for 66% of R+D expenditure for 2006 in Catalonia (above the 56% of Spain, but below the 75% objective set out in the 2000 Lisbon Conference conclusions). In 2006, Catalan SMEs accounted for 24% of Spanish innovation expenditure, followed by the Madrid region with 18%. This means that innovative Catalan SMEs were responsible for the highest amount of expenses (over 1.3 billion) in innovation carried out in Spain, while the amount invested by innovative companies set up in Catalonia was over 3.4 billion.

2. Data source: Spanish Strategic Action for Nanoscience and Nanotechnology, Ministry of Science and Innovation

3. Top-down and bottom-up are used as two approaches for assembling nanoscale materials and devices. Top-down approaches seek to create nanoscale devices by using larger, externally-controlled ones to direct their assembly, while bottom-up approaches seek to have smaller (usually molecular) components arranged themselves into more complex assemblies. The top-down approach often uses the traditional workshop or microfabrication methods. Bottom-up approaches, in contrast, use the chemical properties of single molecules to cause single-molecule components to automatically arrange themselves into some useful conformation. Such bottom-up approaches should be able to produce devices in parallel and much cheaper than top-down methods, but could potentially be overwhelmed as the size and complexity of the desired assembly increases.

TABLE 2
Economic, R&D and innovation indicators

	Catalonia	Spain	EU-27	*Year*
Population (inhabitants)	7,134,697	44,708,964	494,675,000	*2006*
Gross Domestic Product (GDP) at market prices. Base year 2000. In millions of euros	195,283	976,189	11,583,403	*2006*
GDP per inhabitant. In euros	27,823	22,152	23,500	*2006*
Real GDP growth rate	3.6	3.7	2.9	*2007*
GDP per capita in Purchasing Power Standards (PPS). Units: UE-27=100	123	107	100	*2007*
R+D expenditure / GDP (%)	1.35	1.12	1.84 (s)	*2005*
companies (%)	63.5	53.9	54.5	
universities (%)	25.1	29.0	34.8	
administrations (%)	11.4	17.1	10.7	
High-tech exports. Units: % over exports of industrial products	9.3	4.9	16.7	*2007*
University students (1,000)	226 (2)	1,479 (2)	18,53 (1)	*(1) 2004/05 (2) 2006/07*
Science and technology graduates. Units: X per thousand of the population aged 20 to 29	17.2	11.8	13.2	*2005*
Researchers (1,000)	22	110	1,218	*2005*
% over population	0.31	0.25	0.25	*2005*
% over active population	0.65	0.57	-	*2005*

Source: Eurostat, Idescat, and Department of Innovation, Universities and Enterprise. (s) Eurostat estimate

Other economic, R&D and innovation indicators are shown in table 2.

Although public R+D expenditure in Catalonia is 0.50% of GDP (less than the Spanish average of 0.52% and well below the 0.77% in Madrid), findings suggest that Catalan innovation outputs are the best performers in Spain. For instance:

• In 2006, Catalonia was awarded 269 projects by the Industrial & Technological Development Centre-CDTI (compared to 126 in Madrid and a total for Spain of 1,016), this amounting to a total budget of over 290 Meur for Catalan projects (Madrid: 179 Meur; total Spain 1,145 Meur).

• 40.2% Catalan research groups in CIBER projects granted by the Ministry of Health (June 2006).

• 29% *Consolider* projects granted by the Ministry of Education under Catalan coordinators (June 2006).

• 24% of VIth FP Spanish turnover.

• 3rd European region for international inward investment projects (368 projects) during the period 2000 to 2004 (1st: Greater London, 2nd: Île de France).

• 42% increase in foreign investment from 2004 to 2005 (The Barcelona Chamber of Commerce highlights that the greatest investment flows are attracted by sectors with a high added value: telecommunications, computer activities and company services).

According to the Global Entrepreneurship Monitor international project, the start-up rate for new companies in Catalonia was 6.8% in 2005. This means that almost 7 out of every 100 Catalans were involved in some activity related to business start-ups, either previous or new, during the year in question. These figures exceed the OECD average (6.7%), as well as the averages of the EU (5.5%) and

Spain (5.7%), and thus reflect one of the highest levels of company start-ups in Europe. Another creativity indicator is the number of patents: in 2006 Catalonia filed 200 patents per million inhabitants, a figure that is twice the Spanish average. As regards the inventive performance of Catalonia, this can be consulted via the OECD Compendium of Patent Statistics (Dernis, 2007), which provides the latest internationally comparable data on patents. Here, Spain is ranked fourth as regards patents filed under university-owned PCT (after Singapore, Israel and Ireland), while the proportion of patents owned by industries is only 53%. Furthermore, there is a high degree of co-location of international firms and half of all patents for nanotechnology inventions in Spain have foreign ownership. Last but not least, Catalonia is a frontrunner in providing biotechnology patents, due to a Spanish average annual growth rate of 14.1% for the period 1995-2003. As a consequence, the university system is a key factor in intellectual property, innovation and creativity, as well as a key player in the Catalan knowledge-based economy.

Universities produce and commercialize knowledge for socio-economic improvement, focusing on the diffusion of research knowledge through conferences and scientific publications, the training of a skilled labour force and the commercialization of knowledge (Landry, 2006). The knowledge infrastructure of the CICS is mainly provided by 12 universities (7 public) and over 30 advanced research centres funded by the Catalan Government. The university conglomerate (university departments, research groups, science parks, technology platforms, research centres and institutes) now boasts a qualified work-force, cutting-edge facilities and private partnerships that could quickly develop and benefit the industrial network and society through nanotechnology. According to the report "Technology and Innovation in Spain 2007" by the Spanish organisation COTEC, Catalan universities are frontrunners in terms of the production and commercialisation of knowledge. For instance, the University of Barcelona carried out 550 R&D projects[4] with companies and local agencies with a total income over 16 Meur in 2007.

The amount of investments and the number of people employed in R+D by Catalan universities is the highest in Spain and, in fact, one in two Catalan researchers works in the university system. Furthermore, Catalan universities have created and invested in technology incubators and consultancy activities, promoted academic entrepreneurship, achieved great success in R+D projects funded by the Spanish government, and have obtained an excellent success rate in recent European FP calls.

At the same time the university system has developed new structures to promote spillovers between researchers and industrial sectors; examples here would be adding-value agencies, patent offices and management teams for innovation and technology transfer. In this new creating technology context, the most common ways for innovation and nanotechnology transfer could be labelled as "managing innovation" and "contracting out and R&D outsourcing" (Amesse and Cohendet, 2001). As a result, there is a network of science and technology parks, institutes and research centres, and technology platforms and incubators that provide a solid knowledge infrastructure with which to tackle new scientific and market opportunities.

At present the CICS has particularly highlighted two key goals related to nanotechnology: technology transfer and workforce training. A successful nanotechnology transfer to Catalan industry might consider the following major barriers (Nanoforum Report, 2007):

• The specific nature of nanotechnology as a research area.

• The difficulties of building an ideal nanotechnology transfer team with a combination of skills in physics, chemistry, biology, materials science, modelling, business and management.

• The communication barriers resulting from the broad range of fields covered by nanotechnology.

• The production of nanostructured metals, 40 nm electronic chips, or nanoparticles for drug delivery involve completely different technologies, but they are all labelled "nanotechnology". A negative assessment of one area of nanotechnology may lead to negative assessments of the other fields.

An important challenge for nanorevolution success is N&N education for society as a whole (Kulik, 2007). The Nanotechnology Skills and Training Survey (Aditeya, 2007) aimed to identify the skills gaps and training needs of the workforce in the emerging area of N & N. The survey found that the three relatively important natural science competencies were knowledge of material science, nanobiology interface and nanoscale effects. In addition, soft skills such as team working and lateral thinking were also in great demand.

According to a 2004 report by the German Federal Ministry of Education and Research (BMBF) any shortage of well-trained scientists could lead to bottlenecks in innovation and limit the development of nanotechnology. The Catalan universities are increasing the investment in the education of young scientists and encouraging the next generation to consider nanotechnology as a career in order to boost competitiveness and technology-based economic growth. Actually, N&N were regarded as areas of special interest in the III Research Plan of Catalonia (2001-04) and a Special Nanotechnology Action Plan car-

4. Data from the University of Barcelona Centre for the Transfer of Knowledge, Technology and Innovation www.fbg.ub.es/images/pdf/PDFIngles/projects2007.pdf

ried out a programme of grants to facilitate the training of young researchers in internationally renowned University or research centres abroad (NANO Grants). As a result, eighteen students were granted by the end of 2004 (Oliva, 2005) and some of them have already finished their period abroad and have been reincorporated into Catalan universities and research centres, boosting N&N in Catalonia. Last but not least, the European Research Council (1st Starting Grants call, 2007) granted 15 Catalan young star scientists among the best 300 in Europe (9,000 applicants); it means an inhabitant rate of 1/500,000 in Catalonia, higher than the Spanish (1/2,000,000) and the European (1/1,600,000).

Nowadays, there is a wide range of training and educational activities in Catalonia: since July 2003 the Catalan Institute of Nanotechnology (ICN) is training young scientists and disseminating knowledge about the N&N field; in 2005 the University of Barcelona launched an ambitious interuniversity Master in Nanoscience and Nanotechnology[5], which is internationally recognised; in 2007 the Barcelona Science Park organized a public display of nanotechnology in the context of the Nano2Life European project; and since 1999 the University of Barcelona has co-organized some of the training program of the Swiss Foundation for Research in Microtechnology.

Nanoscience and nanotechnology in Barcelona

Taking the above section into account, nanotechnology implies a new approach to research strategies and it is needed to enhance co-location and coordination, as well to improve integration between public and private partners, encouraging multidisciplinary training programmes and working teams and helping to identify new solutions and products (Morrisson, 2005). Bozeman (2007) points out that the arrival of a radically new technology generates new knowledge dynamics, new roles of the institutions and new technological and industrial opportunities. Clustering in nanotechnology has interesting dynamics and the success and failure of a cluster to be stimulated is in part related to the degree of success in agglomeration of technology platforms (Douglas, 2007). As a result, academics and policy makers are investigating the performance of inventors working in the emerging field of nano science and technology, as well as the effectiveness of different institutional regimes (Thoma, 2007). Indeed, the scientific and technical challenges of working at this scale are huge, and future progress depends not only on the sharing of knowledge about tools and techniques but also on the exchange of expertise regarding the atomic and molecular interactions along this new scientific frontier. Furthermore, nanomanipulation equipment is relatively scarce, and cooperation is thus crucial at this time. This can be achieved by sharing equipment and knowledge in networks and virtual teams, as well as by the setting up of cooperative, multidisciplinary and public-private ventures such as Minatec (Grenoble) in France or MESA+ (Twente) in The Netherlands. In the Barcelona case, there is a process of clustering and alliances focused in the nanomedicine niche as a strategy to "catch up" the windows of opportunity currently offered by biotechnology and nanotechnology. This strategic approach could overcome barriers to entry (Niosi, 2007) and Barcelona may be able to take advantage of more opportunities in the future.

It is widely accepted that knowledge infrastructure, research institutes and higher education institutions are the main pillars of regional innovation systems (RIS) (Vang, 2007). Moreover, universities are considered by policy-makers as engines of knowledge-based growth (Bennewortha, 2007). Innovation in a region depends on its own R&D efforts, its innovative tradition and its human capital endowments. In this regard, the performance differences of clusters in Europe may be attributed to the fact that some regions are better able to attract a critical mass of key resources such as star scientists, venture capital, investment bankers and specialised law firms (Niosi, 2005). Indicators of innovation activity rank Catalonia as the strongest innovation region in Spain (Cabrer-Borràs, 2007) and several clusters are fostered in the Barcelona area (medical devices, ICT, aeronautics, media, energy), all of which implies that the region can avoid becoming locked into medium and low technology sectors.

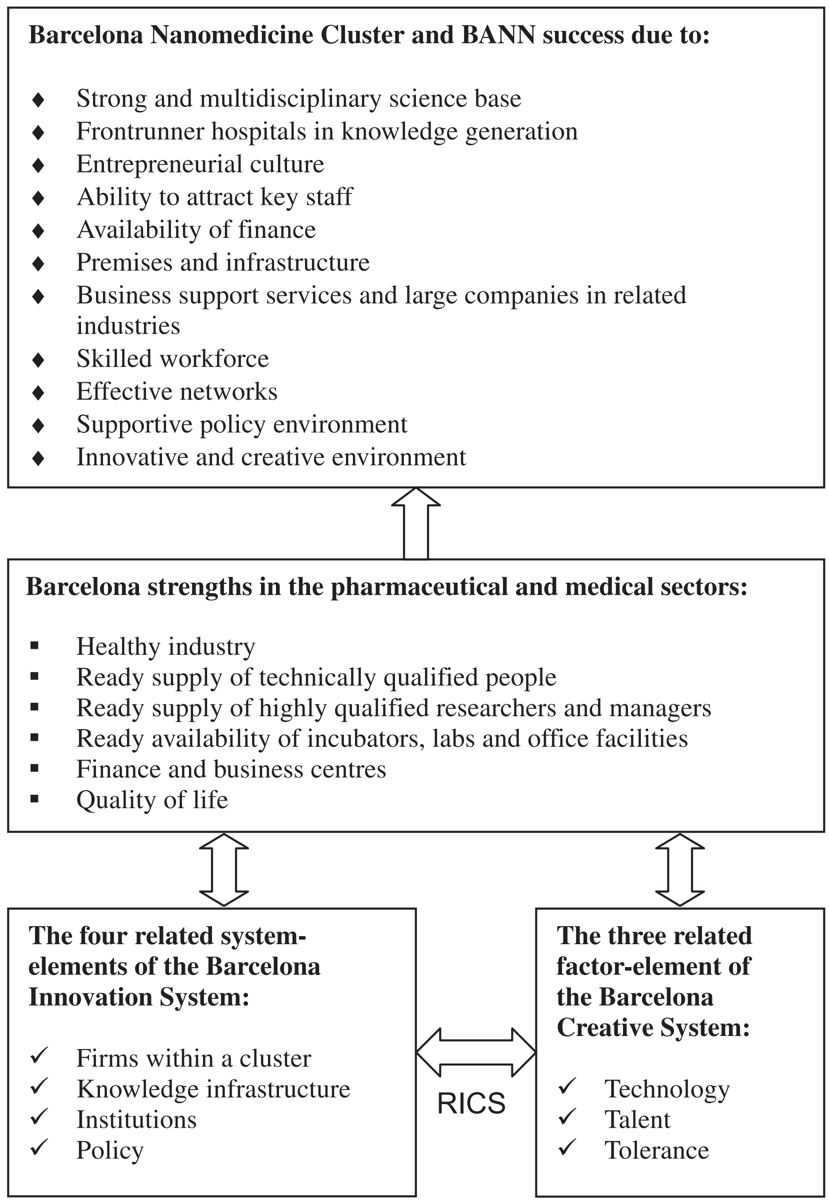
As creativity derived from nanotechnologies is closer to bottom-up technologies (in contrast to innovation, which is more related to top-down technologies) it is necessary to consider whether the Catalan innovation system is creative as well as innovative and, therefore, able to take advantage of the nanorevolution. Creation refers to certain innovation activities in which the value chain experiences a strong perturbation; as a result, a new industrial opportunity appears and a new product or service is launched onto the market. From this point of view, creativity is a step beyond innovation, and it would appear to be well established in Barcelona. Thus, Barcelona could be considered a melting pot for nanotechnology and creativity that is able to generate new products or services.

In the case of Barcelona's innovation system the four related system-elements (firms within a cluster, knowledge infrastructure, institutions and policy) (Doloreux, 2002) can be easily identified for the nano-activity in certain areas, especially in nanomedicine. Moreover, the three T's (Technology, Talent and Tolerance) related to the Harvard Creativity Index (Harvard Business Review, 2004) are predominant in Barcelona: presence of high-tech industry, a highly-educated workforce, and a diverse population. The confluence of these conditions in Barcelona will enhance the innovation and creativity that emerges from nanotechnologies and the university system could boost small- and

5. Master's in Nanoscience and Nanotechnology, University of Barcelona, 19-03-08, www.ub.es/nanotec/index_en.php

FIGURE 2

The RICS framework focused on the Barcelona nanomedicine cluster



medium-sized companies (SMEs) with nano-enabled products as entrepreneurs' innovativeness and personality is playing a key role in the adoption of innovations in SMEs (Marcati, 2008).

Nanotechnology activities in Spain are coordinated through the Ministry of Science and Technology. The importance of nanotechnology was identified and included in the National Research, Development and Innovation plan which ran from 2004 to 2007. Specifically, this was addressed through Strategic Action for Nanoscience and Nanotechnology, a national programme which supported the coordination and creation of material, human and social infrastructure in order to foster major developments in this area. The Working Program for the 2008-2011 National R&D&I and Innovation Plan has a Strategic Action called Nanoscience and Nanotechnology, New Materials and New Industrial Processes with seven actions (Human Resources, Fundamental Research Projects in R&D and Innovation, Institutional Strengthening, Infrastructures, Using Knowledge, System Articulation and Internationalization, and Networks). Actually, the other four Strategic Actions are close to the N&N activity: Healthcare, Energy and Climate Change, Telecommunications and Information Society, and Biotechnology.

Furthermore, several institutions support N & N in Spain: Nanospain[6], INASMET[7], CIDETEC[8], IBERNAM[9], CNM[10], etc. In Catalonia, the regional government has implemented its Research and Innovation Plan 2005-2008, in which N&N is a priority cross-disciplinary area. In addition, R+D+I policy for Catalonia highlights nanotechnology and biotechnology as an economic sector of strategic importance as regards technology.

In the context of European policy, N&N is a key area for the European Commission[11]: the priority objectives for *Nanotechnologies and nanosciences* set out under the 6th European Research Framework Programme (FP) included basic knowledge in this area, as well as the development of new materials, new generations of processes and products, and the emergence of new industrial sectors. In addition, nanotechnology research was also at the heart of other priority areas put forward by the 6th FP, notably *Genomics and biotechnologies for health* and *Information society technologies*. However, in the 7th FP (2007-2013) there is a specific programme for *Nanosciences, nanotechnologies, materials and new production technologies* with a budget of 3,475 million (10.72% of the 7th FP total budget). Moreover, several specific programmes are involved in nanoscale research, and thus the total budget invested in nanoactivities will be increased by several thousands of millions (Meur) coming from the following programmes: *Health* (6,100 Meur), *Food, agriculture and biotechnology* (1,935 Meur), *ICT* (9,050 Meur) and *Energy* (2,350 Meur).

Box 1: Public key players involved in nanotechnology research activity and identified to date

- Universities: University of Barcelona (UB), Technical University of Catalonia (UPC), Autonomous University of Barcelona (UAB), Pompeu Fabra University (UPF).
- Spanish National Research Council (CSIC): National Microelectronics Centre-Barcelona Institute of Microelectronics (CNM-IMB), Institute of Materials Science of Barcelona (ICMAB).
- Institutions: Institute of Nanoscience and Nanotechnology UB (IN2UB), Institute of Photonic Sciences (ICFO), Institute for Bioengineering of Barcelona (IBEC), Catalan Institute of Nanotechnology (ICN), Centro de Investigación en Nanociencia y Nanotecnología-CIN2 (CSIC-ICN), Barcelona Nanotechnology Cluster-Bellaterra (BNC-b), Barcelona Science Park (PCB), Centre for Regenerative Medicine in Barcelona (CMR-B), Barcelona Biomedical Research Park (PRBB), Chemical and Environmental Research Institute of Barcelona (IIQAB), Catalan Institute of Oncology (ICO), Bellvitge Institute for Biomedical Research (IDIBELL), Institute of Biomedical Research August Pi i Sunyer (IDIBAPS), Vall d'Hebron Research Institute

Box 2: Research lines

The main research lines in Barcelona's university system are as follows (a second list level is given for the research lines closer to nanomedicine):

- Modelling and simulation of systems and properties of matter on the nanoscale
- Nanomagnetism, nanoelectronics and nanophotonics
- Nanostructured materials
- Nanoenergy: production, storage and environment
- Nanobiotechnology
    - Functionalisation of surfaces
    - Cellular and molecular biomechanics
    - Biomimetic structures and systems
    - Nanofluidics and nanorobotics. Nanomotors
    - Diagnosis in nanomedicine: marking and molecular observation
    - Nanobiosensors; DNA chips and proteins; Lab on chip.
- Nanopharmacotherapy
    - Nanostructured systems for drug-release control. Nanoencapsulation.
    - Interactions between nanostructured systems and biological structures
    - Bioavailability, toxicity and therapeutic. Effectiveness of nanostructured systems
    - Genic Therapy; Non viral vectors. Pharmacogenomics and nutrigenomics.
    - Molecular internalisation and molecular marking. Detoxification.

The scientific and economic success of Barcelona's university system within the Spanish R+D+I Plan, as well as in the 6th FP, have strengthened the position of Catalonia on the nanotechnology world map. Findings suggest that nanoactivities in Barcelona are developed by public institutions and companies, as well as by trade alliances and networks. However, according to the figures provided by several orga-

6. NANOSPAIN http://nanospain.org/nanospain_English.htm (accessed 29/12/07)

7. INASMET www.inasmet.es/home.aspx?tabid=110 (accessed 29/12/07)

8. CIDETEC www.cidetec.es (accessed 29/12/07)

9. IBERNAM http://ibernam.rediris.es/ (accessed 29/12/07)

10. CNM-Microelectronics National Centre www.cnm.es (accessed 29/12/07)

11. European Commission, Nanotechnology http://ec.europa.eu/nanotechnology/index_en.html (accessed 27/02/08)

nizations the intensive public research in nano-activity being conducted by the universities makes them a frontrunner in the field, especially in nanomedicine. The Research Network for Bioengineering, Biomaterials and Nanomedicine (CIBER-BBN) is a consortium of 46 Spanish groups from public hospitals, universities and research centres, of which 48% are from Catalonia. In addition, in another strategic Spanish alliance, the Spanish Nanomedicine Platform, 34% of the working groups come from Catalonia.

Boxes 1, 2, and 3 provide information on N & N in the Barcelona area:

With more than 14,000 researchers this cluster brings together knowledge, expertise and facilities in the field of N&N, and it is currently estimated that over 1,200 researchers are working at the nanoscale. Across all sectors there is evidence to suggest that the research infrastructure in Barcelona is such that the city could take a leading worldwide role in nanomedicine. In this regard, the University of Barcelona is promoting the Barcelona Alliance for Nanotechnology and Nanomedicine (BANN) with the aim of fostering scientific collaboration, coordinating facilities, and stimulating private partnerships. Box 4 shows a quick overview of the firms within the chemical and medical cluster[12]:

Box 3: Facilities

Facilities in Barcelona include imaging, analysis and manufacture at the nanoscale:

- Scanning electron microscope (SEM)
- Atomic force microscope (AFM)
- Scanning near optical microscopy
- Time-of-Flight Secondary Ion Mass Spectroscopy (ToF-SIMS)
- White light interferometric profiler
- Stylus profiler
- Focused ion beam lithography (FIB)
- Hot embossing
- Nanoimprint lithography (NIL)
- Polymer processing
- Metallization
- RIE, dip-pen lithography
- Synchrotron light source (this will be operative at the end of 2008, with 125 people providing services to more than 150 research groups and nearly 750 researchers)
- Mare Nostrum Supercomputer Centre (the world's fourth supercomputer began operating in 2005)

Box 4: Companies within the chemical and medical cluster

- 46% of pharmaceutical companies in Spain are located in Catalonia, accounting for 60% of production.
- 38% of Spanish medical devices companies.
- 40 biotech companies, 20 of them as core sector.
- Catalan medical technologies sector:
- 109 companies
- 6,700 employees
- Turnover of 950 Meur in 2005 (600 Meur in 2000)
- Mare Nostrum Supercomputer Centre (the world's fourth supercomputer began operating in 2005)

The universities of the Barcelona area are developing an important number of spin-off companies in the field of nanotechnology and nanomedicine. As several studies suggest (Bennewortha, 2007) there is keen demand for space in a campus-based nanotechnology commercialisation site. Therefore, the university might invest in and create an innovation centre for nanotechnology (housing incubation and consultancy activities) next to the faculties and research centres. In the last five years over twenty nanotechnology spin-offs have been promoted by the Barcelona's university system, especially at the science parks, and the number of new nano-related companies could rise considerably insofar as nanotechnology and nanomedicine are more suitable for industrial applications (Morrow, 2007). Several studies underline the role of the strategy of focusing, corporate networks, and R&D investments on the rising of spin-offs (Iturriaga, 2008). Bioincubator of the universities and scientific parks promote to bridge the gap between creativity and innovation and are bringing new ideas into the market. Box 5 shows a quick overview of the companies generated in the bioincubator hosted in the Barcelona Scientific Park (June 2008).

In the period 2007-2010, the Bioincubator PCB-Santander will welcome more than ten new technology-based companies, which will come to form the second generation of companies incubated within the PCB setting.

Finally, although nanomedicine is currently the main nanotechnology being developed in Barcelona, important R+D activity is also underway in the other top five fields in terms of global business: energy, materials, electronics, ICT and environment/sustainability. Several studies about the economic potential of nanotechnologies in Barcelona

12.Data from Strategic *Programme for the Catalonia Medical Technologies Cluster* (2nd Urban Clusters Workshop-22@, Ribas E., February 2008) and Biocat (BioRegion of Catalonia)

Box 5: Companies of the Bioincubator PCB-Santander

The five companies that made up the first generation were graduated in 2006:

- CRYSTAX, Accelerating Drug Discovery
- Enantia
- ERAbiotech
- ORIZON Genomics
- OED, Oleoyl-estrone developments

In 2007, 11 new companies were hosted within the PCB setting:

- AGRASYS
- AROMICS, Applied Research Using Omic Sciences
- BARNAGEN
- BIOCONTROL TECHNOLOGIES
- BIOINGENIUM
- Genmedica Therapeutics
- Infinitec Activos
- Intelligent Pharma
- Neuroscience Technologies
- Omnia Molecular
- Research UBAN, Unidad Biotecnológica Analítica

In the period 2007-2010, the Bioincubator PCB-Santander will welcome more than ten new technology-based companies, which will come to form the second generation of companies incubated within the PCB setting.

are now in progress and some of these will be published shortly.

The creative & economic framework of Barcelona

As several research markets show, nanotechnology is about to impact all economic sectors, and thus institutions and firms might adopt policies to promote greater innovation and creativity in higher-end sectors. The nanotechnology revolution is reaching Barcelona at a time when Spanish government forecasts are for 2% of GDP to be invested in R&D by 2010, the driving force being the European Union strategy objective of reaching 3%. The Catalan total R&D expenditure in 2006 was 1.43% of GDP, above the Spanish average (1.20%) but lower than the figures for Europe-25 (1.83%), Québec (2.67%), Canada (2.01%) and the OECD (2.25%). In Spain, the goal of achieving R&D expenditure at 2% of GDP by 2010 means that additional finance of more than 16 billion must be invested by public and private sectors.

The "Knowledge Regions" initiative of the VIIth FP, aimed at enhancing regional clusters, and the Spanish R&D Ingenio 2010 Programme (Consolider Program, CENIT Program and Avanza Plan), linked to regional policies that stimulate R&D activities, might achieve the ambitious objective of 2% GERD of GDP. However, what is perhaps more important is that nanotechnology is becoming a key area within Catalonia and could take great advantage of public expenditure in R+D+I, which is set to increase by 25% over the next two years.

Barcelona could be considered a "technological agglomeration", *i.e.* a geographical co-location of different scientific and technological fields where coordination and dependencies create cumulative advantages for certain specific areas (Douglas et al., 2007) such as life sciences, ICT, materials, energy, and aeronautics. Co-location is encouraged in the Barcelona area by public and private institutions and this could offer benefits to both firms and research centres through the sharing of facilities, the mobility of human resources and information feedback (Landry and Amara, 2002). According to a study conducted by the Autonomous University of Barcelona in 2005, the city has a high degree of specialisation in knowledge-intensive areas: 45% of employment is knowledge-intensive based, as well as 26.6% of business, 38.1% of production, and 79.5% of manufacturing exports; in Barcelona, 33.9% of professionals are employed in science and technology sectors, and 28.3% of the working-age population holds tertiary education. Moreover, a study conducted by Eurostat in 2004 ranked Catalonia as the fifth European region in terms of technology employment. Given the above, the Barcelona economy is clearly specialized in knowledge-intensive activities.

In 2007, and for the ninth consecutive year, European executives chose Barcelona as the European city with the highest quality of life for its employees, and the city was also rated as the fourth European location in terms of investor preference (Cushman & Wakefield Consulting and Mercer Human Resource Consulting). In addition, Barcelona was ranked twenty-third in the world according to salary level and thirty-first in terms of cost of living. Other reports (OECD, 2006) also rank Barcelona fifty-eighth in the world according to GDP (Madrid is 50th, Montreal 49th, Sydney 34th), while the Anholt City Brands Index, which gathers a wide range of city information to provide a list of the top twenty world cities in 2007, shows Barcelona ranked seventh (Madrid 13th, Montreal 10th, Sydney 1st). Finally, in 2005 Barcelona was fifth in the world cities' ranking as regards organising congresses and conventions, as reported by the Union of International Associations. As a consequence, Barcelona is a suitable city for transferring or attracting executives and researchers, it being one of the most competitive European cities.

Having identified the related system-elements of the Catalan Innovation System it would now be useful to consider the system-factors that enhance creativity and which could move the Catalan Innovation System towards being a creative system: these factors are Technology, Talent and Tolerance (Harvard Business Review, 2004). Firstly, as described above, Barcelona is a high-tech city where R+D+I activities are present in a wide range of value chains; secondly, a trained workforce is available due to the strong Catalan university system, with 230,000 registered students and 66,283 graduate students (2005-06 academic year); thirdly, multiculturalism and open-minded people are the reservoir of a highly tolerant society. Finally, there are other relevant aspects that, although they are more difficult to measure, should be borne in mind when considering the innovation and creation mechanisms of Barcelona: these aspects include the rich cultural infrastructure, which promotes open access to culture, multilingualism, interactivity, and the blending of cultures, etc., and the local environment, which improves people's quality of life and also includes aspects such as leisure and entertainment options, friendly urbanism, easy mobility, a healthy lifestyle, and balanced weather or sunlight hours.

Conclusions

Nanotechnology is critical for the future of economic and regional competitiveness, job creation, and technological superiority. As an endless source of innovation and creativity, whether from bottom-up nanotechnology (new materials) or top-down nanotechnology (miniaturization), the field sits at the intersection of medicine, biotechnology, engineering, physical sciences and information technology. After two decades, the increasing number of patents and nanotechnology applications is evidence of the shift from R+D laboratories to the market.

Nanotechnology requires huge investments in R+D facilities and workforce, and new approaches to public-private partnerships, commercialization and technology transfer are needed to launch nanotechnology innovations onto the market. Thus, it is clearly important to specialize in such multidisciplinary technology; among the suitable, specialized nanoclusters in the Barcelona area (ICT, materials, medicine, energy) the elements and factors related to a nanomedicine cluster are the strongest in the region, and there is also the necessary critical mass to ensure that Barcelona can take a leading role in this exciting new area.

When considered within Spain as a whole, Catalonia contributes above its economic weight and significance on measures such as patents, start-up businesses and research outputs, especially as regards biotechnology, a sector in which innovation and creativity are themselves competitive advantages. In a context of increasing R+D expenditure, the universities of the Barcelona area are bringing together some of the best models and practises from research, industry and financial strategies. As a result there is a network of science and technology parks, institutes and research centres, and technology platforms and incubators that are ready to meet the new scientific and market challenges.

Barcelona is able to attract and retain a critical mass of key resources such as a talented workforce, foreign investment, venture capital, and specialised law firms. Therefore, it is recognized that Barcelona is a suitable environment for intensive creativity and entrepreneurship activities, one in which the university system plays a key role in terms of promoting Barcelona as an advanced knowledge-based economy. At all events, the university system is now called upon to drive the nano-revolution towards Catalan society and the market in years to come, providing training programmes, high-tech skilled researchers and managers, and cutting-edge facilities. To conclude, the availability of trained and talented nano-workers, as well as shared public-private infrastructure, will help Catalan companies achieve the excellent levels of innovation and creativity that are required to develop new and advanced industrial nano-processes or nano-products.

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