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Author(English)	ALFONSO AVILA ROBINSON
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Understanding the Dynamics of Emerging Technologies through Knowledge Structures – The Case of Micro/Nanotechnologies

by

Alfonso Ávila Robinson (09D46053)

Department of Innovation
Graduate School of Innovation Management
Tokyo Institute of Technology

Thesis Supervisor

Kumiko Miyazaki, Professor

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After the bit less than four years I spent on my Ph.D. research, I have come to very much agree with Prof. Elizabeth Garnsey's (University of Cambridge) metaphor of research as an expedition; in my case, an expedition into the fascinating 'terrain' of Technology and Innovation Management (TIM). This expedition has been an intensive, arduous, and at times tedious challenge, but at the same time an enriching, intellectually motivating and life-changing experience from professional and, most importantly, personal aspects. Despite the typical notion of a Ph.D. as an independent endeavor, along the way I have realized the key role that many people have played in the completion of this four-year academic expedition.

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"When a person really desires something, all the universe conspires to help that person to realize his dream."

Paulo Coelho, 'The Alchemist'

"…don't believe what your eyes are telling you. All they show is limitation. Look with your understanding, find out what you already know, and you'll see the way to fly."

Richard Bach, 'Jonathan Livingston Seagull'

Summary of the Thesis

This study set out *to bring forth a research framework to quantitatively understand the dynamics of emerging technologies*. At present, there is no other technological field depicting an archetype of emerging technologies as much as the field of micro/nanotechnologies. In this study, this field was visualized in terms of a *value chain* consisting of four blocks: materials, intermediate products, instrumentation and tools, and end-products. For each of these blocks, a representative emerging technology was selected: *zinc oxide nanostructures, micro/nano-electromechanical technologies, micro/nanofabrication technologies, and micro/nanofluidic-based point-of-care diagnostic systems*. The research framework of this study comprised of four main hypotheses; each of them investigating the dynamics of emerging technologies, as reflected in the changes of knowledge, from different perspectives. For that purpose, an intensive use of quantitative approaches was made. Here, conventional *bibliometric mapping methods* – co-word, co-citation, and co-classification networks – were integrated with additional quantitative methods and theoretical concepts to bring forth plausible and novel research approaches.

The analyses of this study began with the evaluation of the dynamics of technological emergence through the study of the *changes undergone by their underpinning knowledge bases*. Here, the empirical case of MEMS/NEMS technologies was used. It was found that the patterns of growth of emerging technologies were reflected in highly dynamic, collaborative, and complex, yet 'narrow' and lowly diffused knowledge bases. Additionally, by relying on the concept of 'problems', the cognitive contents of emerging knowledge bases were denoted by a strong focus on the earliest stages of problem search and solution. What is more, their cognitive clusters were characterized by a formative nature: fewer in number, larger in size, highly interconnected, and generally-oriented contents. Moreover, the patterns of growth and cognitive fluidity appeared to be highly coupled; it is believed that the cognitive fluidity calls for an ever intense experimentation and active construction aimed at better defining the emerging technological field.

The next analysis aimed at the investigation of the dynamics of the innovation systems building around emerging technologies over time. This analysis centered on the case of zinc oxide nanostructures. In line with the previous analysis, it is argued that the types of problems confronted by an innovation system, and in turn its dynamics of change, may be *imprinted on the nature of the underlying knowledge bases*. By analyzing how their longitudinal, structural and cognitive properties changes over time, the results of this analysis revealed that emerging knowledge bases are gradually redistributing in cognitive terms. Here, a shift from upstream towards downstream was observed. In particular, the cognitive patterns of change exhibited two paradoxes: 1) structurally, emerging technologies follow high accelerated rates; yet, cognitively, they appear to be largely stepwise and cognitive in nature; 2) despite the still low significance of applications in terms of their shares, they were characterized by taking predominant locations with the knowledge structures. It was shown that the latter has to do with the roles of knowledge accumulation and applications in the evolution of emerging technologies. These results were complemented with the study of the co-evolutionary relationships between technologies and knowledge

for the case study of nanogenerators. In this analysis, it was shown that the development of nano-enabled devices is punctuated by a complex set of feedbacks, co-evolving and highly cumulative in nature.

Relying on the empirical case of micro/nanofabrication technologies, the next analysis aimed at the understanding of the relationships between the *paths of knowledge evolution* and *the way actors cope with these changes*. The findings of this analysis revealed the rapidly increasing and highly diversifying knowledge structures underpinning this field. It was shown that the latter is far from entailing a mere transition from micro into nano-domains; instead, the study of multiple phenomena and materials coupled with the integration of knowledge of different nature was observed. This, in turn, calls for the need to build broad knowledge bases in this field. Despite this, the patterns of specialization revealed that only few countries/regions appeared to be aligned to these simultaneously diverse and convergent trends. In this analysis, it was inferred that the nature of the building up of nano-capabilities should be playing a role, as it is characterized by long-term capital investments and scientific capabilities, but also it being impacted by higher-level aspect such as the creation of new workforce and production methods.

Finally, the empirical case of the micro/nanofluidic-based point-of-care diagnostic systems was used to investigate the dynamics of emerging innovation systems through the study of the *structure and the patterns of change undergone by the actors active in a particular innovation system* and the *knowledge networks they build*. The results of this analysis revealed the greater role that large firms play in the evolution of emerging technologies through spin-outs and M&As. In a subsequent step, the R&D collaborations of firms in this emerging technological field were mapped. These depicted a rapidly growing, yet sparse network structure. Regarding the collaborating partners, they were mainly large firms, but SMEs and public research institutes appeared to be growing. Finally, by making use of a novel co-classification approach combining scientific, technological and market-related aspects, this analysis exhibited the greater interactions between scientific and technological domains over time. Despite this, great difficulties were observed in the capabilities of these firms to bring about commercial products.

In summary, this thesis has attempted to understand the dynamics of emerging technologies by understanding the way knowledge evolves, changes, and transform. Despite these efforts, further experimental efforts are required to complement the analyses presented in this thesis, such as the use of additional conceptual ‘proxies’ besides knowledge, complementary methodological approaches, and so on. Nevertheless, it is believed that the results of this analysis have thrown some light on the understanding of the complexities behind technologies of an emerging nature.

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1. Introduction

Over time, waves of technological change have increased in frequency and severity. Such relentless change is resulting, among other aspects, in the formation of continuous waves of new technologies – completely new or recombination of new and old technologies – propagating across countries, industrial sectors, and markets. These new technologies, referred as *emerging technologies*, are unique as they depict the very early stages of technological development. They are typically characterized by involving a transition into something new, a rapid recent expansion, a heavy scientific weight, and potentially disruptive effects (Cozzens et al., 2010). Certainly, technological emergence is not a new phenomenon. New technologies have emerged, have been used, and have diffused from the very early stages of human development. Nevertheless, in this thesis it is argued that global trends – the rapid and incessant change, globalization, etc. – have radically changed the impact of emerging technologies in the world economy. Within this context, emerging technologies have been regarded as essential to successful growth, employment, competition and sustainability, and thus in the formation of new or transformed industries (Hung and Chu, 2006). The latter is directly related to their visualization as rich sources of economic and market opportunities (Day et al., 2000). Furthermore, emerging technologies have been depicted as natural outcomes of the renewal waves of technological change in the sense that they define the variety "that needs to be replenished for growth and transformation to continue" (Foster and Metcalfe, 2001). From what has been said, it can be readily seen that the study of emerging technologies is far from being a trivial issue.

Technological development has been traditionally depicted to be evolving along an 'S curve', delimiting different phases or stages over time, such as emergence, growth, maturity, and demise (Ayres, 1994; Christensen, 1992; Foster, 1986; Nieto et al., 1998). As previously noted, emerging technologies depict the very early stage of technological development. This stage is characterized by the rapid development of new ideas, fast changes of knowledge, and the continuous increment in the number of organizations active in the field (Mina, 2009; van der Valk et al., 2009). As such, it depicts the early stages of the building up of a 'critical mass' of knowledge reflected in the formation of a network structure, sparse and porous at first, among a small number of heterogeneous actors and organizations (van Merkerk and Robinson, 2006). This, in turn, results in a formative technological innovation system building around emerging technologies (Jacobsson and Johnson, 2000). Furthermore, the knowledge bases underpinning these embryonic innovation systems are forming, changing, and transforming (Corrocher et al., 2003; Day et al., 2000). Such knowledge has been regarded as 'fluid' and as undergoing intense experimentation (Mina et al., 2007), and also as heavily science-driven (Cozzens et al., 2010). Later sections will discuss 'emerging technologies' in greater detail. Within this background, this thesis has been mainly driven by two main aspects. First, frequent voices have been raised on the need to better understand the emergence and dynamics of new technologies and the innovation systems building around them (Bergek et al., 2008; Carlsson, 2003; Geels, 2006; Malerba, 2005). Second, literature has highlighted the need to conceptualize and to operationalize, i.e. to measure, emerging technologies (Cozzens et al., 2010). Thus, so how do emerging technologies change and evolve over time? And how these dynamics can be quantitatively assessed and measured? These are the main research questions that are attempted to be responded in this thesis. In this process, two crucial decisions have to be made: What proxies can be used to measure the dynamics of emerging technologies? And what methods can be used to measure the dynamics of emerging technologies?

From a large array of proxies possible, building upon the close co-evolutionary interrelationships between technology and knowledge, this thesis makes use of knowledge as a proxy for understanding and measuring the dynamics of emerging technologies. This is one of the main premises behind this thesis. Thus, in a sense, it is inferred that the understanding of how *knowledge* changes, grows and transforms is expected to provide crucial insights into the *dynamics* of *evolution* of *emerging technologies*. Here, three aspects should be highlighted. First, the growth of new technologies is associated with the formation of *technological innovation systems* building around these technologies. Second, *co-evolutionary mechanisms*, particularly those between technology and knowledge, are highlighted in this thesis. Third, acknowledging the difficulties in defining what constitutes *knowledge*, this thesis visualizes knowledge in terms of the general, or collective, knowledge being built around a particular technological field. Later chapter will discuss these aspects in greater detail. In particular, three properties of knowledge will be exploited throughout this thesis:

- *conceptual 'malleability'* which makes possible to visualize and to approach knowledge through different conceptual 'textures' or 'shapes', such as knowledge flows, knowledge bases, knowledge domains, and knowledge stocks, among others. In particular, this thesis regards *knowledge structures* as the general concept embracing these different visualizations of knowledge.
- *co-relational structure* which enables the visualization of knowledge into networks.
- *codifiability* which allows to quantitatively trace knowledge-related aspects by bibliometric data.

The last two properties of knowledge, in turn, open the way to the potential methods that can be used to measure the dynamics of emerging technologies. In this thesis, an intensive use of bibliometric approaches was made. Relying on Porter and Detampel (1995), this thesis visualizes bibliometrics broadly as encompassing the use of publications, patents and/or their citations targeting the measurement and interpretation of scientific and technological advances. In particular, the backbone research method used in this thesis is *bibliometric mapping* which allows the visual representation of the structure and dynamics of research through networks derived from bibliometric data. As it will be shown, throughout this thesis, novel uses integrating conventional bibliometric and social network analysis methods are made.

At present, there is no other technological field depicting an archetype of emerging technologies as much as the field of nanotechnologies. In particular, this thesis visualizes nanotechnological-enabled change in terms of a *nanotechnology value chain* embracing the following blocks (LuxResearch, 2007): materials, intermediate products, instrumentation and tools, and end-products. For the purposes of this thesis, these blocks were divided into two main technological sets: micro/nano-enabled technologies (materials, intermediate products, and end-products) and micro/nano-enabling technologies (instrumentation and tools). The latter are referred in this thesis as micro/nanotechnologies. The approach taken in this thesis consisted in selecting representative emerging technologies for each block of the value chain. At the end, the following technologies were chosen: Zinc Oxide one-dimensional nanostructures (ZnO nanostructures) for materials; Micro/NanoElectroMechanical Technologies (MEMS/NEMS) for intermediates; Micro/Nanofabrication Technologies for tools and instrumentation; and Micro/Nanofluidic-based Point-of-Care Diagnostic Systems for end-products. In broader terms, the selection of these technologies relied on the evaluation of technical literature and discussions with experts in each of those fields.

From what has been said in the previous paragraphs, the main purpose of this thesis is, thus, to bring forth a research framework, i.e. a set of hypotheses and conceptual models, to quantitatively understand the dynamics of emerging technologies, particularly micro/nano-enabled technologies and micro/nanotechnologies, through the evaluation of the changes undergone by knowledge. Particularly, the research framework comprised of four main hypotheses analyzing the dynamics of emerging technologies through knowledge. The first hypothesis examines whether the *dynamics* of the *knowledge bases*, in terms of their rates and directions, may be used to infer the growth and fluidity of emerging technologies. Following, the second hypothesis evaluates if the changes in the *cognitive* properties of the *knowledge bases* may provide insights into the *dynamics* of the technological innovation systems building around emerging technologies. The third hypothesis studies whether the dynamics of emerging technologies may be reflected in the relationships between the *paths of knowledge evolution* and the way actors cope with such changes as revealed in their *patterns of scientific specialization*. Finally, the fourth hypothesis examines whether the dynamics of evolution of emerging innovation systems may be traced by the analysis of the *structure* and the *patterns of change of actors* and the *knowledge networks* they build.

The overall structure of this thesis takes the form of nine chapters, including this introductory chapter (Fig. 1.1). Chapter 2 begins by describing the theoretical underpinnings upon which this thesis rests. Here, aspects such as technological emergence and emerging technologies, evolutionary theory, knowledge, and innovation systems are defined. This chapter finalizes with the discussion of the analytical framework used in this thesis. Chapter 3 is concerned with the case studies under consideration in this thesis, namely micro/nano-enabled technologies and micro/nanotechnologies. However, before that, a general description of the field of nanoscience and nanotechnology is provided. Following, Chapter 4 provides an overview of the research methods and the sources of data used in this thesis. From Chapter 5 the different hypotheses and case studies are analyzed. By focusing on the case of MEMS/NEMS technologies, Chapter 5 presents the evaluation of the rates and directions of scientific knowledge bases as proxies for technological emergence. Subsequently, Chapter 6 continues with the evaluation of the evolutionary paths of change of emerging nanotechnological innovation systems for the case of ZnO nanostructures. Following, Chapter 7 focuses on the analysis of the paths of knowledge evolution and the patterns of scientific specialization for the case of Micro/nanofabrication technologies. Chapter 8 finishes the analytical section with the case of Micro/nanofludics-based Point-of-Care systems by presenting the results of the use of the patterns of change of the actors active in a technological field and the knowledge networks being built as reflections of the evolution of emerging innovation systems. Drawing upon the results of the previous four chapters, Chapter 9 concludes by providing a brief summary of the findings of this thesis, as well as a discussion of the implications of these findings. Finally, a series of areas for future research are identified.

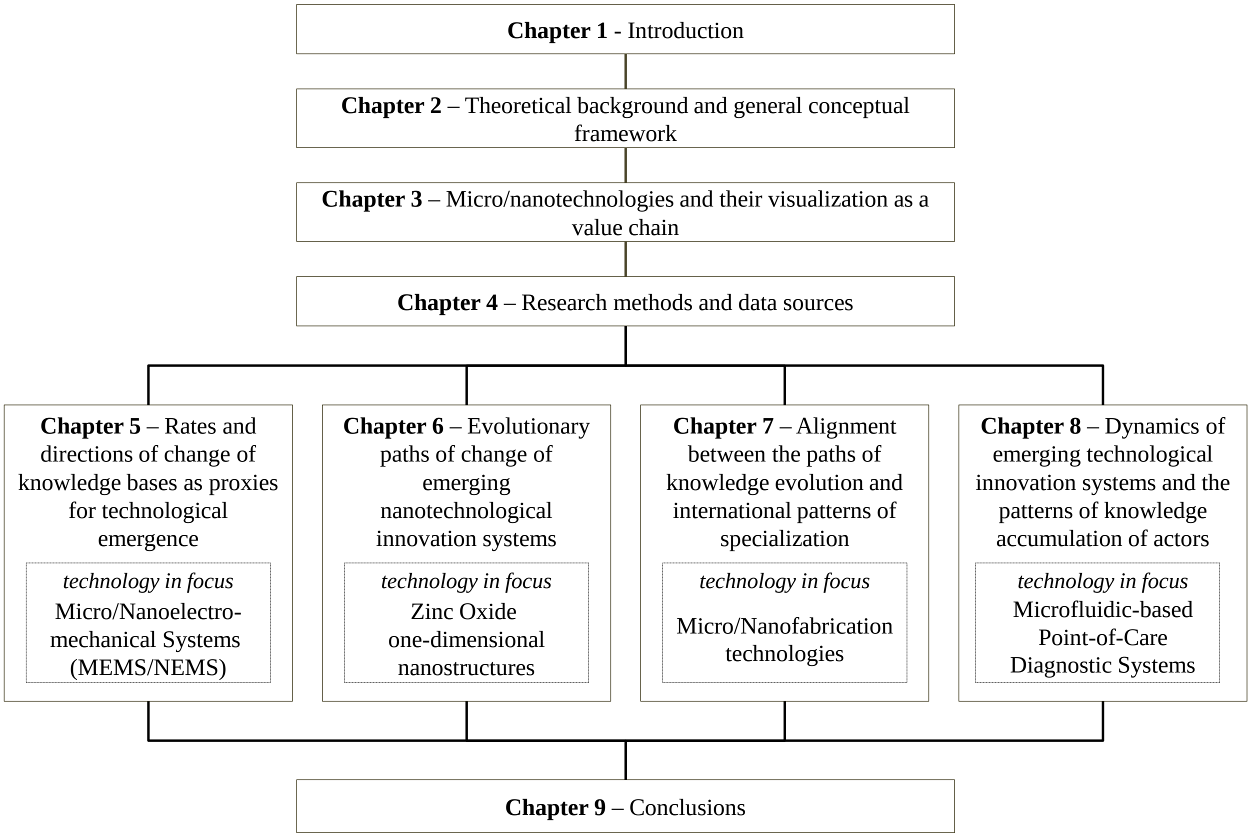

Fig. 1.1 General structure of the thesis

2. Theoretical Background and Analytical Framework

The main purpose of this chapter is two-fold: a) to describe the differing theoretical research streams underpinning this thesis, and b) to discuss the analytical framework that will guide the remainder of this thesis. As noted in the previous chapter, this study is aimed at the quantitative understanding of the dynamics of evolution of emerging technologies in the field of micro/nanotechnologies and micro/nano-enabled technologies. As may be inferred, the complexities behind the changes in technologies of an emerging nature call for an analytical framework drawing from a variety of theoretical streams. In particular, this chapter discusses four main theoretical streams: technological emergence and emerging technologies, evolutionary theory, knowledge-related aspects, and innovation systems, among others. These theoretical streams are then used for the construction of the analytical framework. As will be seen, the analytical framework consists of the evaluation of four main hypotheses directed towards the understanding of the dynamics of emerging technologies. Each of these hypotheses is visualized through a conceptual model.

This chapter is organized as follows. The description of the theoretical concepts is discussed from Section 2.1 to Section 2.4. Section 2.5 moves on to the discussion of the analytical framework. For that purpose, four key visualizations of the dynamics of evolution of emerging technologies are discussed, which are subsequently integrated into a general analytical framework of this thesis. Finally, Section 2.6 summarizes this chapter.

2.1. Technological emergence

Emerging technologies are at the center of this thesis. In order to prevent any ambiguities in their usage, this section provides an exhaustive description of the phenomenon of emergence, emerging technologies, and the processes of emergence of new technologies that have been discussed in the literature. This will provide key insights for the definition of the analytical framework.

2.1.1. The phenomenon of emergence

Emergence is one of those concepts that can be intuitively understood, yet no agreement on its definition has been reached. Here, attention is focused on two approaches that have visualized emergence from different perspectives. On the one hand, emergence has been regarded from a more temporal/chronological perspective as the processes or events of coming into existence (van Merkerk and Robinson, 2006). Within this context, emergence is directly related to the very early stages of technological development. On the other hand, the field of complexity theory has approached emergence in terms of parts-whole relationships. From this perspective, novel and coherent structures, patterns and properties observed at the macro-level are expected to dynamically arise from the non-linear interactivity among the constituent parts at the micro-level (Corning, 2002; De Wolf and Holvoet, 2005; Goldstein, 1999). Hence, this approach visualizes emergence from a more synergetic/systemic and dynamic-oriented perspective. As later sections will discuss, this duality in the meaning of emergence – temporal and synergetic/systemic – is complementary rather than substitutive; this will prove useful for the subsequent arguments of this thesis.

2.1.2. Emerging technologies

By visualizing processes of technological (and social) renewal and recombination in terms of phases or stages within a technological lifecycle, emerging technologies are located, as already noted, at the very early stages of technological development (van Merkerk and van Lente, 2008). Over the years, different labels and terminologies have been proposed to describe technologies of an emerging nature, such as formative, nascent, embryonic, and emerging, among others. This thesis makes use of the term ‘emerging technologies’. A first glimpse into technologies of an emerging nature may be gained from Table 2.1 which lists the top-ten emerging technologies defined by the Massachusetts Institute of Technology (MIT)’s magazine ‘Technology Review’ for the years 2009 to 2011.

Table 2.1 Top-ten list of emerging technologies by MIT Technology Review

2009	2010	2011
Intelligent software assistant	Real-time search	Social indexing
DNA nanofluidic chip	Mobile 3D	Smart transformers
Nanowire-based ultradense memory chip	Engineered stem cells	Gestural interfaces
Biological machines	Solar fuels	Cancer genomics
Paper-based diagnostics	Nanoparticle-enhanced thin-film photovoltaic cells	Solid-state batteries
Liquid battery	Social TV	Homomorphic encryption
Traveling-wave reactor	Green concrete	Cloud streaming
Nanopiezoelectronics	Implantable electronics	Crash-proof code
HashCache – cache storage	Dual-action antibodies	Separating chromosomes
Software-defined networking	Cloud programming	Synthetic cells

At first sight, two aspects may be drawn from Table 2.1. First, the wide range of industries, sectors, and application domains embraced by this table infers about the pervasive nature of emerging technologies. Second, Table 2.1 also illustrates the broad nature of emerging technologies as this list comprises of parts, devices, sub-systems, systems, and full products (Hilgartner and Lewenstein, 2004). The pervasiveness and ubiquitousness described above have made some to visualize emerging technologies as a *general phenomenon* involving “a peculiar ‘speculative space’ found at the edges of technological systems, where innovations are being most actively constructed and transformed” (Hilgartner and Lewenstein, 2004). Within this backdrop, emerging technologies are visualized as the *variety* “that needs to be replenished for growth and transformation to continue” (Foster and Metcalfe, 2001).

A series of researchers have attempted to conceptualize ‘emerging technologies’. In their pioneering work, Day et al. (2000) regarded emerging technologies as those technologies whose knowledge bases are expanding, existing markets are under strong innovative pressures, and new markets are created or exploited. For them, emerging technologies encompass both discontinuous technologies, as well as more evolutionary technologies formed by convergence. More recently, based on a literature review up to 2005, Cozzens et al. (2010) have enumerated a series of major concepts entailed by emerging technologies: fast recent growth, transition into something new, market or economic potential, and an increasing science-driven nature. Building upon these major concepts, the following paragraphs provide a detailed description of the meaning of emerging technologies based on recent literature sources.

First, emerging technologies are characterized by faster ‘recent growth rates’. This brings with it the rapid development of new ideas, fast changes of knowledge, and a continuous increment in the population of organizations active in the field, among others (Mina, 2009; van der Valk et al., 2009).

Second, emerging technologies depict ‘transitions or changes to something new’. As defined by van Merkerk and Robinson (2006), growth in emerging technologies is coupled with the formation of linkages, sparse and porous at first, among a small number of heterogeneous actors and organizations. These represent the early stages of the building up of a ‘critical mass’ of knowledge. Such early linkage formation has been depicted as embryonic structures around which formative technological innovation systems are being built (Jacobsson and Johnson, 2000). This premature network formation leads to a higher interaction among actors which, in turn, fosters the exchange of knowledge and interactive learning, and results in the creation of a ‘shared vision’ (Vandeberg and Moors, 2008). Moreover, these formative stages involve the creation of legitimate new rules, which are typically against the familiarity and conformity of actors to existing institutional arrays (te Kulve, 2010; Vandeberg and Moors, 2008). As such, a space of ongoing institutional innovation ensues (Hilgartner and Lewenstein, 2004). Furthermore, technological emergence is also associated with the formation, change and transformation of the underlying knowledge bases (Corrocher et al., 2003; Day et al., 2000). This typically implies the interconnection or combination of different scientific and technological domains or fields (Bakker et al., 2010; Mytelka, 2003; Robinson and Propp, 2008). Furthermore, these knowledge bases are characterized by their fluidity, i.e. their instability, and their intense experimentation (Mina et al., 2009), as well as by their heavy science-driven nature (Cozzens et al., 2010). Finally, a series of patterns of change have been also associated with technological emergence, such as the levels of technological concentration among active firms (Corrocher et al., 2003), the creation of 'specialist firms' – venture firms, entrepreneurs, etc. – targeting the exploitation of the new opportunities (van der Valk et al., 2009), among others.

Third, Hung and Chu (2006) visualize emerging technologies as potential catalyzers of change which, if properly fostered, may lead to the formation of new or transformed industries. Emerging technologies are characterized by "the potential to create new industries or transform an existing one" (Day et al., 2000). Some others go far beyond to regard them as essential to successful growth, employment, competition and sustainability (Hung and Chu, 2006). This is directly related to their visualization as rich sources of economic and market opportunities (Day et al., 2000). Others have associated emerging technologies with their impact on future technologies in terms of their technological and scientific pervasiveness (Corrocher et al., 2003). Furthermore, the impact of emerging technologies is believed to go beyond economic aspects to exert a direct influence on society (Carlsen et al., 2010; Shapira et al., 2010). In broader terms, these aspects denote the "unmistakable connotations of revolutionary potential" that emerging technologies convey (Hilgartner and Lewenstein, 2004).

Fourth, disruptiveness is inherent in emerging technologies; yet, in a latent state, i.e. about to unfold. This is closely related to the 'speculative' features surrounding emerging technologies, in which expectations, controversies, and even hype play a crucial role in their development (Hilgartner and Lewenstein, 2004). This is particularly mirrored in the high levels of uncertainty and 'fluidity'. On the one hand, emerging technologies are characterized by high levels of market and technical uncertainty. This is reflected in: (a) an unknown or unarticulated demand; that is, products are new or yet about to be developed, and hardly any commercially available (Mina, 2009; van der Valk et al., 2009; van Merkerk and van Lente, 2005; Vandeberg and Moors, 2008); (b) the difficulty for potential customers to articulate their demands, as well as to meet potential suppliers (Jacobsson and Johnson, 2000); (c) the absence of market knowledge; (d) the still formative nature of usage patterns and behavior; and (e) the significantly higher levels of unpredictability which make it difficult for actors to fully assess, if possible, what the technology will bring (van Merkerk and van Lente, 2005). Furthermore, the early stages in which emerging technologies take place are characterized by 'fluidity' across a range of aspects. This is reflected in the absence of transparent and structured relations among actors, the emerging nature of institutions, the availability of multiple paths, the inexistence of dominant designs, and the inexistence or the still emergence of architectures and standards, among others (Day et al., 2000; Robinson and Propp, 2008; van Merkerk and Smits, 2008; van Merkerk and van Lente, 2008). Despite its uncertain nature, fluidity offers the possibility of maneuvering, with relative easiness, the course of development of a technology about to emerge, which is referred in the literature as the Collingridge's dilemma (van Merkerk and Robinson, 2006). Given their nature, uncertainty and fluidity make predominant a whole array of cognitive reactions among the different actors, such as expectations, public attitudes, and social implications (Kostakos et al., 2005; Selin, 2007), as well as problems of political legitimacy and decision-making (Hilgartner and Lewenstein, 2004).

2.1.3. The 'Emergence' of Emerging Technologies

This section now turns to the discussion of conceptual approaches that have been proposed for the understanding of how emerging technologies come about and evolve. As will be seen, this is an important aspect as it will set the ground for the definition of the conceptual framework to be described at the end of this chapter. After the conduction of a literature review, five different research approaches on the 'emergence' of emerging technologies were discerned: evolutionary, systemic, technological dynamics, cognitive and multi-level-oriented perspectives. Of course, each of these research streams is, in one way or another, interrelated; nevertheless, for the sake of this discussion they were classified according to the main conceptual features they highlight. Following, these research approaches are briefly explained.

As implied by its name, *evolutionary approaches* visualize the emergence of new technologies in terms of evolutionary processes. Section 2.2 discusses evolutionary thinking in greater detail. In this regard, Corrocher et al. (2003) conceptualize the emergence of new technologies for the case of ICT technologies as an evolutionary process of technical, institutional, and social change taking place simultaneously at three different levels: individual firms, social and institutional context, and nature and evolution of knowledge and the related technological regime. Also, Nygaard (2008) has highlighted the role of the co-evolution among technology, institutions and markets for the evolution and growth of innovation systems in their formative phase. He particularly examines the role of a series of stabilization mechanisms in the field of fuel cell technologies, such as technology specific platforms, political networks, codes and standards, knowledge search, demonstration projects, market networks, and hybridization, among others.

Another research stream frequently encountered in the literature is that relying on *innovation systems approaches*. These approaches relate the emergence of a new technology to the formation of a technological innovation system (TIS), still at an embryonic state, building around a particular technology (Hekkert and Negro, 2009; Jacobsson, 2008; Jacobsson and Johnson, 2000). For Jacobsson (2008) this embryonic structure involves a series of processes, such as institutional alignment, the entry of new organizations, and the formation of new networks. The formation and evolution of emerging TIS have been regarded as a long, uncertain, and painful process (Jacobsson and Johnson, 2000). As the conceptual framework proposed in this thesis heavily relies on this approach, Section 2.4.1 provides further discussions on it.

On the other hand, *technological dynamics* approaches visualize the understanding of the emergence and evolution of new technologies by evaluating the interactions among technologies. In this regard, Srinivasan (2008) has described two main types of mechanisms. First, ‘relay race evolution’ refers to the ability of underperforming technologies at its outset to mature and even to over-perform current technologies over time. This is the core thinking behind the pioneering works of Christensen (1997) and Foster (1986) on disruptive technologies. Second, ‘revolution by application’ describes the situation when relatively small technological developments result in significant changes in the market. This mechanism emulates Adner and Levinthal (2001)’s process of technology speciation.

Another set of research approaches rely on *socio-cognitive aspects*. Here, van Merkerk and van Lente (2005) and van Merkerk and Robinson (2006) have highlighted the role of emerging ‘irreversibilities’ as those cognitive aspects constraining and enabling future technological development. Robinson and Propp (2008) discussed the possibility of explaining the dynamics of emergence of science and technology through the study of ‘socio-technical paths’. Focusing on the particular case of nanoscience and nanotechnology, Andersen (2005, 2007) has highlighted the role of the attention and search rules of firms as crucial aspects for the dynamics of emerging technologies. Finally, Verbong and Geels (2010) have stressed the role of internal diversity in technological emergence; for them, internal diversity involves endogenous dynamics and consisting of beliefs, decisions, and actor interactions.

Finally, some research approaches have visualized the emergence and evolution of new technologies from *multiple levels of analysis*. This research stream is particularly rooted in the belief that new technologies emerge out of “the interactions between co-evolutionary dynamics at multiple levels” (Geels, 2006). These levels include: a macro-level or landscape, a meso-level or regime, and a micro-level or niches. Each of these levels of analysis is characterized by particular properties. In particular, these approaches highlight that immature, fluidic technologies rely on niches for their development (Agnolucci and McDowall, 2007; Rip, 1995; Schot and Geels, 2007). Further discussions on this type of approach will be provided in Section 2.4.1.

In summary, the complexity of technological change have prevented (and will prevent) researchers from developing an all-encompassing approach to understanding the emergence and evolution of emerging technologies. Instead, as seen in this section, a series of complementing approaches have been elaborated over time allowing the visualization of these processes from different perspectives. As later sections will discuss, the analytical framework used in this thesis draws from many of the approaches presented above.

2.2. Evolutionary Thinking

2.2.1. General Description

Evolutionary thinking is one of the foundational theoretical underpinnings of current innovation studies, also defined as *neo-Schumpeterian*. The present thesis is not an exception. From the pioneering efforts in the field of biology, evolutionary thinking has spread over a wide range of fields including physics, anthropology, psychology, and economics, among many others. Nelson and Winter (1982)'s work represents the pioneering applications of biological metaphors in the understanding of innovation processes. Their work relied on stressing the role of the firm's internal *routines*, understood as behaviors or repetitive patterns of activity in a certain setting, as selective mechanisms influencing the search actions of firms in their efforts toward the improvement of profits (Silva and Teixeira, 2009)[1].

Rather than attempting to draw one-to-one correspondences between the biological and economic worlds, evolutionary thinking in economics has been regarded as a style of reasoning independent from biological and related sciences (Metcalfe and Georghiou, 1997). For Metcalfe and Georghiou (1997), "biologists simply got there first". Metcalfe (1995) has proposed two perspectives for visualizing evolution. On the one hand, evolution has been defined as the gradual unfolding of phenomena in a cumulative and path-dependent way. Besides highlighting the gradual change in evolutionary thinking, this definition stresses a series of crucial aspects that may be visualized as the conceptual building blocks underpinning evolution: (a) *cumulativeness* or the dependence of future knowledge on previously produced knowledge; (b) *path-dependency* which refers to the dependence of innovation on historical-conditioning factors (David, 1985); c) *partial irreversibility* and *lock-in* expressing self-reinforcing mechanisms that make difficult to change to another route once a particular technological path has been chosen (Arthur, 1989); d) *positive* and *negative feedbacks*; e) *bounded-rationality* acknowledging that actors are limited in their ability to solve problems (Simon, 1991); f) *non-linearity* and *open-endedness*, and g) *co-evolution* which defines the joint evolution of entities. These properties have shaped the way researchers' view and approach processes of technological and social change. On the other hand, evolution has been defined in terms of the dynamics of system behavior which creates change and

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[1] Silva and Teixeira (2009) provide a recent bibliometric account on evolutionary economics focusing on its main research paths and contributions.

emerging structure from variety. In particular, this definition highlights the main dynamics of change in evolutionary thinking (Loasby, 2002; Metcalfe, 1994): the introduction of *variety* into an economy in terms of innovations, and the processes altering competing alternatives in terms of *selective* mechanisms such as markets, technologies, institutions, and public policy, among others. Continuing with Metcalfe (1994), variety and selection co-evolve; that is, variety drives selection and variety shapes selection. Besides variety and selection, evolution is also about stability or *retention* as if everything changes then nothing can be relied on (Loasby, 2001). These three processes, namely variety, selection and retention, depict the continuously repeating cycles keeping alive evolutionary processes.

In summary, from an evolutionary-thinking perspective, innovation is largely visualized as 'search and selection processes' and 'learning and knowledge accumulation' is regarded as a crucial aspect in innovation processes (Kumaresan and Miyazaki, 1999).

2.2.2. Co-evolutionary approaches

This thesis pays particularly attention to co-evolutionary mechanisms. Co-evolution is defined as the interactivity in the evolution of different entities, be it technologies, firms, institutions, methods, knowledge, etc. (Loasby, 2002). As such, co-evolution is a reflection of the complex and systemic features surrounding technological (and social) change. As defined by (Geels, 2005, 2006), co-evolution is not a new concept; it has always been a key issue in the field of sociology with its emphasis on 'seamless webs', the interaction among heterogeneous elements, and co-construction.

Geels (2005, 2006) provides an exhaustive description of the different aspects of co-evolution that have been researched over the years: the co-evolution between technology and users (Coombs et al., 2001; Lundvall, 1988); the co-evolution between technology, industry structure, and policy institutions (Leydesdorff and Etzkowitz, 1998; Nelson, 1994; Rosenkopf and Tushman, 1994); the co-evolution of science, technology and the market (Callon et al., 1992; Stankiewicz, 1992); the co-evolution of science and technology (Kline and Rosenberg, 1986); the co-evolution of artefacts, beliefs, and evaluation routines (Garud and Rappa, 1994); the co-evolution of technologies and networks (Kumaresan, 2001); and the co-evolution of technology and society (Freeman and Soete, 1997; Rip and Kemp, 1998).

In this regard, it should be highlighted that these co-evolutionary mechanisms will not be measured; but rather, building upon their existence this thesis attempts to trace the dynamics of emerging technologies through the evaluation and measurement of change in knowledge structures.

2.3. Knowledge and Knowledge Bases

As has been repeatedly stated in this thesis, knowledge works as a conceptual instrument through which the dynamics of emerging technologies will be inferred. Thus, it is believed necessary to clearly define what is meant by knowledge and to define their main properties. This section will attempt to do so.

2.3.1. Knowledge in General

It has been repeatedly stated even reaching the level of a cliché that a transition toward a 'knowledge-based economy' is currently taking place (Smith, 2002) in which *knowledge* is being portrayed as the most important and strategic resource and learning as the most important process (Lundvall, 1992). As such, knowledge has been placed at the heart of economic growth and social well-being. David and Foray (1995) visualize innovation processes in terms of "the sustainable generation, distribution and utilization of new economically relevant knowledge that continuously accumulates and recombines in the economy". Researchers have typically visualized knowledge as an outcome but also a condition for the generation of innovations (Carlsson, 2003). In this case, it has been pointed out that such knowledge and ideas are *embodied* in the products, processes, methods, organizations or recombinations coming out of the innovation processes (David and Foray, 2002).

Knowledge is a conceptually 'malleable' term; over the years it has been visualized from a plethora of conceptual 'shapes' and 'textures': from knowledge flows, knowledge stocks, knowledge bases, knowledge networks, to knowledge domains, and pools of knowledge, among others. As previously noted, these different terms are aggregated in this thesis in the concept of *knowledge structures*. Typically, literature has classified knowledge into a dichotomy: tacit also referred as 'sticky' or embodied knowledge (Polanyi, 1966; Szulanski, 2003) and explicit also referred as codified or disembodied knowledge. The former is constructed from the experiences of individuals and that people possesses, and involve mental models, perceptions, insights, assumptions, etc. (Nonaka and Konno, 1998; Polanyi, 1966), thus it is often difficult to articulate or codify (Winter, 1987). The latter represents knowledge that can be codified into a tangible form and, as such, easy to communicate and store including academic and technical publications, manuals, mathematical expressions, patents, etc. Within this background, Consoli and Ramlogan (2009) regard tacit knowledge as critical for shaping individuals' responses and codified knowledge as critical to facilitate exchange and interactions. For them, both types of knowledge complement each other. By attempting to exploit these complementarities, this thesis mainly sets its sights on codified knowledge.

Different categorizations have been proposed for classifying knowledge. One of these that has withstood over the years that by Lundvall and Johnson (1994) who classified knowledge into four main categories: know-what, know-why, know-how, and know-who. In broader terms, ‘know-what’ refers to knowledge about ‘facts’, ‘know-why’ refers to knowledge about principles and laws in nature, in the human mind and society, ‘know-how’ refers to skills, and ‘know-who’ involves knowledge about who knows what and who knows what to do. In this regard, another crucial aspect is the difference between knowledge and information. Whereas the former is based on a cognitive capacity, information refers to structured and formatted data-sets remaining inert and passive until they are interpreted and processes into knowledge (David and Foray, 2002).

As for its dynamics, knowledge is considered to be cumulative and path-dependent. Its growth has been considered as uncertain, open-ended, and as a dynamically uneven process (Consoli and Ramlogan, 2009; Nelson, 2003). Continuing with Consoli and Ramlogan (2009), this growth is rarely the outcome of isolated action, but rather of collective learning and cumulative interactions.

2.3.2. Knowledge Bases

One of the most common ‘textures’ of knowledge are knowledge bases. They have been defined as the underlying cognitive and physical structures from which actors draw upon to innovate (Breschi et al., 2000; Dosi, 1988). ‘Knowledge bases’ have been regarded as critical aspects for differentiating the nature of technology, innovation and technological change across firms, sectors, industries, and innovation systems, among others (Asheim and Coenen, 2005; Breschi et al., 2000; Carlsson et al., 2002). Knowledge bases are complex entities that are characterized by:

- *Multi-faceted nature* encompassing aspects as different as information, skills, capabilities, knowledge, etc. Asheim and Coenen (2005) have classified industrial knowledge bases into three partly overlapping types: analytical (science-related), synthetic (engineering-related), and symbolic (arts-related). Furthermore, Smith (2002) has visualized knowledge bases at multiple levels ranging from firm-specific (localized, specific to specialized product characteristics in firms), sector or product field specific (bodies of understanding and practice influencing the performance of all firms in an industry), and widely applicable knowledge bases (general scientific knowledge bases).
- *Distributed nature* as knowledge bases are likely to be spread over a wide range of technologies, sectors, and industries (Smith, 2002).
- *Dynamic and co-evolutionary in nature*. Literature has particularly highlighted the inherent dynamic nature of knowledge bases. They evolve, grow, and transform (Mina et al., 2007). They involve a

series of co-evolutionary mechanisms among aspects as different as actors, institutions, and networks, among others (Carlsson et al., 2002; Consoli and Mina, 2009; Mina, 2009).

Recent research efforts have attempted to quantitatively characterize knowledge through a series of bibliometric-based properties: Quatraro (2009) classified knowledge bases into variety, coherence and cognitive distance; D'Este (2005) divided knowledge bases into categories such as breadth, variety or differentiation, and persistence; and Brusoni and Geuna (2003) classified knowledge bases into persistence and integration, among others. This thesis will make use of some of these bibliometric-based properties.

2.3.3. Knowledge and Technology

Technology is one of those basic concepts in the field of Technology and Innovation Management for which a wide array of definitions exist. Here, Table 2.2 lists some definitions that have been discussed in the literature.

Table 2.2 List of definitions for the concept of 'technology'

"… complex set of human know-how" (Nelson, 2005)	"… state of knowledge concerning ways of converting resources into outputs" (OECD, 2001)
"… application of scientific and engineering knowledge to achieve a practical result" (Roussel et al., 1991)	"… technology as a tool… as a system… as value" (Drejer, 1997)
"… set of pieces of knowledge, both directly 'practical' and 'theoretical', know-how, methods…physical devices and equipment" (Dosi, 1982)	"…means to fulfill a human purpose…assemblage of practices and components…entire collection of devices and engineering practices available to a culture" (Arthur, 2009)

Despite their differences, the definitions listed in Table 2.2 share some properties in common: a) technology inherently involves knowledge, b) technology is regarded as a means or tool converting inputs into outputs, c) technologies involve physical and cognitive components, and d) technology is visualized as an assemblage or a set of sub-components. As discussed in the previous chapter, for the purposes of this thesis, the close interrelationship between technologies and knowledge take a prominent position. In this regard, any technology, be it a product, process, or method, embodies knowledge (David and Foray, 2002). Section 2.5.1 will provide more detailed discussions on the close interrelationships between technologies and knowledge. Knowledge, it has been said, is what makes technologies possible (Arthur, 2009) (center of Fig. 2.1). As the next section discusses, in this thesis it is argued that an innovation system is building around a particular technology (small circles shown in Fig. 2.1). The actors of an innovation system rely, in turn, on a series of knowledge sources of a scientific, technological, and market-related nature, among others, to innovate. Here, Section 2.3.1 and Section 2.3.2 have already discussed the different typologies and categorizations of knowledge described in the literature. In particular, this thesis relies on the collective knowledge, i.e. the general codified knowledge on which actors active in a particular technological field draw upon to innovate. It is further argued that the collective knowledge can be traced and captured through bibliometric data (scientific publications, patents, and their citations).

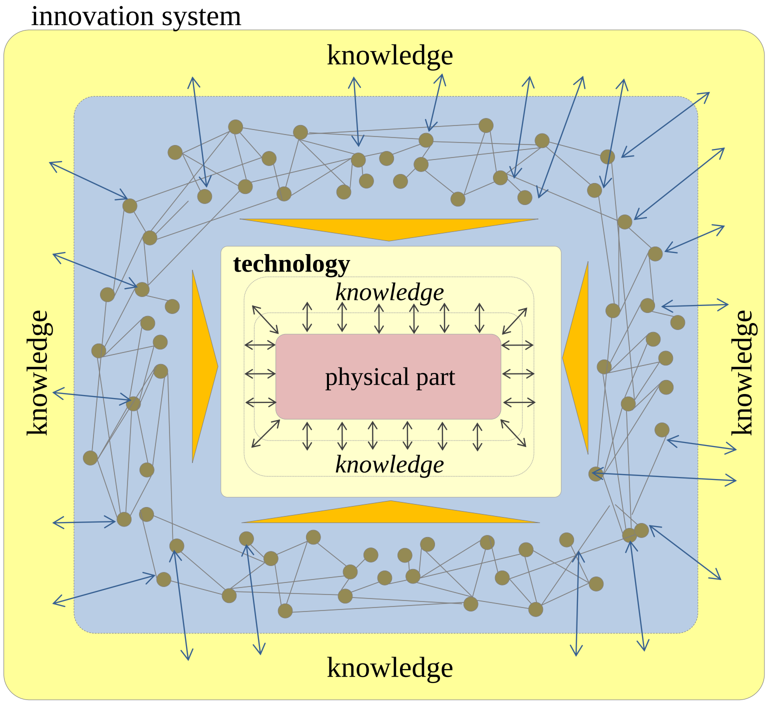

Fig. 2.1 Relationships between technology and knowledge

2.4. Innovation Systems

Technological innovation is inherently uncertain, cumulative and specific, differentiated, and demanding continuous and intensive collaboration (Pavitt, 1990); as such, innovation is seldom the result of isolated and independent efforts, but of complex co-evolving processes involving a network of tightly interacting actors working under an ‘institutional blanket’ towards the creation, commercialization and diffusion of technological innovations. This is what has been referred in the literature as an innovation system. Innovation systems are constantly changing; they emerge and evolve; they are inherently dynamic, particularly in a largely unplanned manner without following any particular pattern or trajectory (Carlsson, 2003; Edquist, 2004). Over time, new systems are ‘born’, other systems evolve, whereas others mature and dissolve. Here, of particular interest lies the dynamics of emergence and evolution of new, fluidic innovation systems (Carlsson, 2003; Malerba, 2005). Different innovation system approaches have been conceptualized over the years: sectoral systems of innovation (Breschi and Malerba, 1997), technological innovation systems (Carlsson and Stankiewicz, 1991), national systems of innovation (Lundvall, 1988; Nelson, 1993), large technical systems (Hughes, 1987), regional innovation systems (Cooke, 2001), multi-level perspective (Geels, 2006), and distributed innovation systems (Coombs et al., 2003). It should be highlighted, as defined by Bergek et al. (2008), that the innovation systems approach is primarily an analytical construct aimed at understanding the dynamics and performance of systems. Hence, continuing with Bergek et al. (2008), a system may not exist in reality fully developed; it may be emerging with weak interactions among the different components. Moreover, the interactions within a particular system may be unplanned and unintentional, i.e. these actors may not be consciously working together toward fulfilling the system’s purpose. This is an important aspect for the formative innovation systems building around emerging technologies.

2.4.1. Technological Innovation Systems (TIS)

A Technological Innovation System (TIS) is the structure building around a particular technology composed of actors and their competence, networks, institutions, and technological factors (artefacts and technological infrastructures) (Jacobsson, 2008; Suurs et al., 2010). As defined by Jacobsson and Johnson (2000), there is a TIS for each technology and each system is unique in its ability to develop and diffuse technologies. Furthermore, a TIS is not solely focused on technological aspects but on all components influencing the innovation process for a particular technology (Bergek et al., 2008). As such, a TIS includes both aspects conducive to the diffusion and utilization of technology (supply-side) and aspects exploiting technical possibilities through entrepreneurial activity (demand-side) (Carlsson and Eliasson, 2003).

Technological systems emerge and evolve. Within the TIS framework, the emergence and evolution of innovation systems is believed to be taking place along three stages: formative, growth and maturation. For this thesis, as may be inferred, the formative stage is of utmost importance. In this regard, the composition of actors and their roles vary over time as the magnitude and direction of the underlying driving forces shift. For the particular case of formative TIS, four structural mechanisms of formation have been highlighted in the literature (Jacobsson and Johnson, 2000): market formation through the exploration of niche markets, the entry of firms and other organizations, institutional alignment, and the formation of technology-specific advocacy coalitions or networks. This formative stage is also characterized by its high levels of uncertainty in terms of technologies, markets and institutions, a lengthy process of formation, and by an evolutionary process depicted by the accumulation of small changes, the search of legitimacy, as well as by early premature markets, among others.

As a TIS matures, innovations begin to be diffused. This is coupled with a higher entry of firms and organizations, stronger network links, denser knowledge bases, and higher institutional alignment (Hekkert and Negro, 2009). In terms of the dynamic properties of systems, Carlsson et al. (2002) has defined robustness, flexibility, ability to generate change and respond to changes in the environment as the most important attributes. The dynamics of change of a TIS may be generated endogenously (internally) or caused by external factors to the TIS (Carlsson et al., 2002; Jacobsson, 2008). The former may involve the introduction or exit of components, changes in the relationships among the components, and attributes (capabilities of actors, nature and intensity of the links among actors, etc.), among others (Carlsson et al., 2002). Moreover, Hekkert et al. (2007) have discussed that the understanding of technical change demands obtaining insights into the relations between the incumbent technology and the incumbent system and the emerging technology and its system around it. Here, Jacobsson and Johnson (2000) stress the role of the way the competence of actors, institutions and networks are altered in the definition of the path the new system will follow and its ability to compete with other systems (Jacobsson and Johnson, 2000).

More recent research efforts on TIS have approached innovation systems from a functional perspective. Within this framework, the purpose of a TIS – "to develop, apply, and diffuse new technological knowledge" (Hekkert et al., 2007) – has been defined to be served by fulfilling a set of system functions (Suurs and Hekkert, 2009). As such, functions bridge the gap between structure and performance (Jacobsson, 2008). These functions are directly associated with structural aspects (Suurs and Hekkert, 2009). Here, different mechanisms have been proposed to evaluate whether interactions among TIS functions are reinforcing or diminishing the fulfillment of the system purpose: cumulative causation or motors of innovation (Suurs and Hekkert, 2009), system failures or blocking mechanisms (Negro and Hekkert, 2008).

Also recently, research streams within the field of innovation systems are attempting to combine the analytical strengths of the different systems approaches. Here, Markard and Truffer (2008)'s efforts should be highlighted. In their approach, they combined TIS and the Multi-level Perspective (MLP) approaches. MLP provides a way to visualize the complex dynamics of sociotechnical change. It consists of three nested analytical levels: the niche, the sociotechnical regime, and the sociotechnical landscape, representing the micro, meso and macro levels, respectively (Rip and Kemp, 1998; Geels, 2006). The sociotechnical regime embodies the established structure, and thus characterizes by incremental improvements along defined trajectories and by a relative dynamic stability. In contrast, niches embed radical innovations. They depict protected 'brewing' spaces for new technologies. Geels and Schot (2007) defined niches as entities with weak structuration, unstable social networks, undeveloped markets, disarticulated cognitive structures, among others. Finally, the sociotechnical landscape relates to external uncontrollable changes, e.g. environmental and demographic, political changes, etc. The main tenet in MLP states that change is the result of the "interactions between co-evolutionary dynamics at multiple levels" (Geels, 2006). Markard and Truffer (2008)'s TIS-MLP approach operationalizes the niche by conceptualizing it as a TIS, which in turn interacts with one or more socio-technical regimes and other TIS of a competitive or complementing nature, as well as with a landscape or external forces. For them, a TIS is defined as "a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a *new* technology and/or a new product" (Markard and Truffer, 2008). Within this context, the niche itself is not a mere technological entity but may be visualized as a nurturing point around which a TIS forms (Bergek et al., 2008; Markard and Truffer, 2008). Along a more or less similar vein, Steward et al. (2008) and Piterou and Steward (2011) conceptualize both the niche and regime levels of MLP as sociotechnical networks for the cases of nanoparticles and deinking in print-on-paper and e-book, respectively.

2.4.2. Problem-oriented approaches of technological change and their use in Technological Innovation Systems (TIS)

Problem-oriented approaches have had a long tradition in the innovation field. Rosenberg (1969) defines 'focusing devices' – also called 'imbalances' or 'bottlenecks' – as those imminent technical problems attracting the attention of actors and thus depicting the specific pathways along which technological change tends to be channeled. For him, problems induce technological change. Similar concepts are those of Sahal (1985)'s 'reverse salients' and Hughes (1987)'s 'technological constraints', among others. Along the same line, Parayil (1991) visualizes technological change as a problem-solving activity; as a process of knowledge change, integrally cognitive in nature. More recently, Arthur (2009) has discussed the problem-oriented nature of technologies.

As cognitive entities, problems and paradigms – of a scientific (Kuhn, 1996) or technological nature (Dosi, 1982) – are interrelated. As indicated by Metcalfe (1995), paradigms provide the cognitive framework for the definition of problems and the identification of their solutions. Hence, paradigms shape the perception of problems, i.e. how problems are interpreted and the types of approaches believed to be (or not to be) appropriate for the solutions of those problems (Consoli and Ramlogan, 2008). Continuing with Consoli and Ramlogan (2008), paradigms bias research efforts, which reflect in the particular trajectories of problems along which innovation systems are orientated.

Recently, Consoli and Ramlogan (2008), Metcalfe et al. (2005), and Mina (2009), among others, have extended this line of thought by coupling 'problems' with innovation systems. These sources depict crucial theoretical underpinnings for the present thesis. For them, 'problems' entail autocatalytic phenomena guiding the dynamics and directions of innovation systems. As innovation systems tackle imminent problems, new ones are created for which new solutions should be found; those recurrent patterns of problem search and problem solution have been defined as 'problem sequences' (Metcalfe et al., 2005). As 'problem sequences' imply a shift in the focus of innovation efforts, they involve the mobilization and coordination of resources and capabilities in order to find a solution to a problem (Gee and McMeekin, 2011).

As a variety of efforts are conducted to advance a particular technology (Nelson, 2003), it is clear that different problems are tackled concurrently. These problems are highly interrelated; feedback loops are present among them. Despite that, given the cumulative nature of knowledge, it is expected that the different problem areas to be cognitively dependent in the sense that the earliest phases of problem search should be partly cleared out and a certain amount of knowledge accumulated before attempts into subsequent phases are conducted (Dosi, 1988; Miyazaki, 1994; Nelson and Winter, 1982). It follows that problems may be visualized, from a macro perspective, as a loosely defined chain composed of upstream and downstream stages. In turn, it would be expected for emerging technologies to direct their cognitive efforts at different locations along the problem chain compared to those of mature technologies.

2.5. Analytical framework for the understanding of the dynamics of emerging technologies

As repeatedly noted, the main premise behind this thesis is that insights into the dynamics of emerging technologies may be gained from the understanding of how knowledge changes, evolves, and transforms. In a sense, knowledge is used in this thesis as a proxy for analyzing the dynamics of emerging technologies (Fig. 2.2). What enables the latter to be done is the already discussed close interrelationships, co-evolutionary mechanisms, between technologies and knowledge (Fig. 2.2). As a proxy, obviously, knowledge is an imperfect approximation of the dynamics of emerging technologies. Nevertheless, it is argued, as the rest of the sections of this chapter will discuss, that knowledge embodies a suitable proxy for technological dynamics.

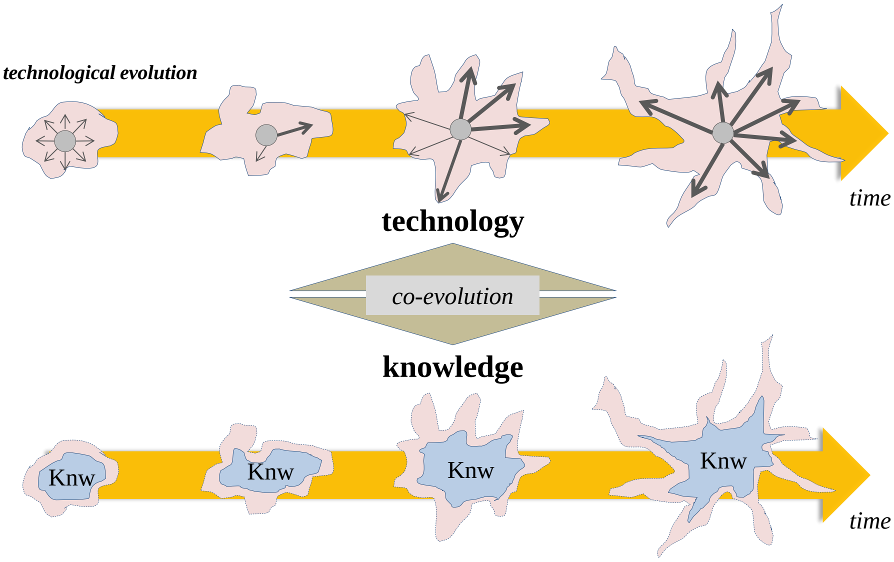

Fig. 2.2 Knowledge as proxy for measuring technological dynamics

It should be remarked that this thesis does not set out to measure the co-evolutionary relationships between technology and knowledge. Nevertheless, some case studies related to the co-evolution between technologies and knowledge will be provided in later sections. Instead, building upon these co-evolutionary relationships, what this thesis attempts to do is to measure the dynamics of emerging technologies through the reflection of their changes on knowledge. For that purpose, an analytical framework comprised of four hypotheses is described in the remainder of this section. Each of these hypotheses evaluates the measurement of the dynamics of emerging technologies through knowledge. Furthermore, these hypotheses were visualized through a series of conceptual models.

2.5.1. Dynamics of emerging technologies through the evaluation of the rates and directions of knowledge bases

The evolution of technology has been defined to be resting on the processes of generation, testing and modification of knowledge (Loasby, 2002). It has been said that new technologies are likely to transform the whole knowledge base of an industry, which in turn may lead to fundamental changes in the actors, networks and institutions supporting an industry (Carlsson et al., 2002). Following Arthur (2009), technology is referred to 'a means to fulfill a purpose: a device, or method, or process'. Previous sections have already described technology in greater detail (Section 2.3.3). For Arthur (2009), a technology does something; it is executable. Within this context, knowledge is visualized as the understanding making these 'executables' possible. As such, knowledge has been regarded as the 'signatures' of technologies (Mina et al., 2007). Both technologies and knowledge are constantly growing, changing, and transforming

(Arthur, 2009; Mina et al., 2007). From what has been said, it is assumed that the dynamics of technologies and knowledge are closely intertwined.

Regarding the dynamics of emerging technologies, literature has particularly stressed the increasing and accelerating rates of growth experienced by these technologies. Nevertheless, such intense growth often comes with a price, namely the inherent uncertainty and fluidity surrounding technologies of an emerging nature (For more detailed discussion on uncertainty and fluidity in emerging technologies the reader is referred to Section 2.1.2). Within this context, it is inferred that a better understanding of the dynamics of emerging technologies may be gained from considering both aspects: the patterns of growth and the uncertainty/fluidity. Relying on the close interrelationships between technology and knowledge, it is inferred that the dynamic properties of the knowledge bases underpinning emerging technologies may provide insights into the dynamics of emerging technologies (Fig. 2.3).

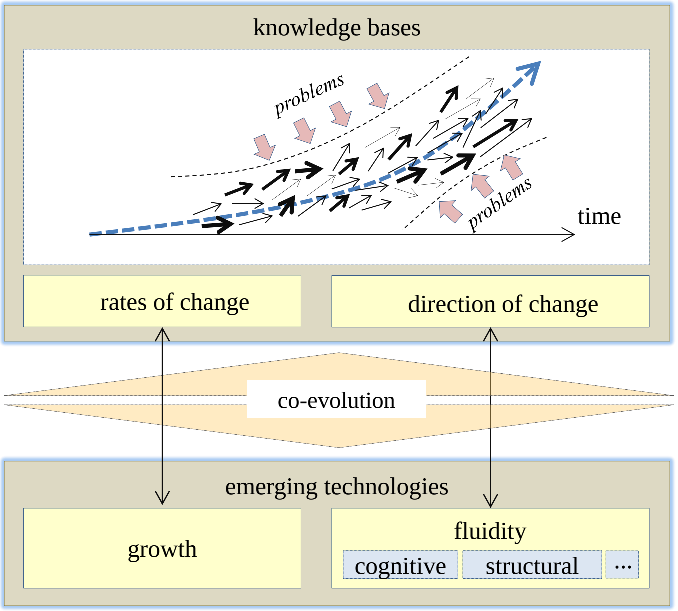

Fig. 2.3 Co-evolution between technologies and knowledge bases

In broader terms, the knowledge bases underpinning emerging technologies are expected to be broadening, expanding, and diversifying (Corrocher et al., 2003; Day et al., 2000). This appears to be closely related to the interconnection of different scientific and technological domains (Mytelka, 2003; Robinson and Propp, 2008). Moreover, these knowledge bases are at a fluid state and under intense experimentation (Mina, 2009). From what has been said, as shown in Fig. 2.3, the dynamic properties of knowledge bases, in terms of their rates and directions of change, may be used as proxies for the understanding of the patterns of growth and the fluidity surrounding emerging technologies. On the one hand, the rates of change experienced by the knowledge bases are expected to reflect the patterns of growth undergone by emerging technologies. What is more, these rates of change can be characterized over a range of categorizations, such as complexity, the variety, and the growth of the knowledge bases, among others. On the other hand, the directions of change along which the growth of knowledge bases are orientated are assumed to be related to the ‘problem sequences’ confronting a technological field at a particular time (Consoli and Ramlogan, 2008). As described in Section 2.4.2, problem sequences refer to the recurrent patterns of problem search and solution tackled by the innovation systems building around technologies (Consoli and Ramlogan, 2008; Mina, 2009; Mina et al., 2007). It is inferred that as problems demand knowledge for their solution, the nature of the knowledge underlying technologies is expected to leave a sort of a ‘cognitive imprint’ reflecting the problems encountered at particular stages of technological evolution. Hence, such ‘cognitive imprint’ may be used to infer about the directional dynamics of knowledge bases, which in turn relates to the fluidity, in cognitive terms, of technologies.

From what has been said, the first hypothesis to be considered is as follows:

- **H1**: Visualized as dynamic entities, knowledge bases evolve and grow at certain rates and along particular directions. These dynamic properties are expected to vary depending on the dynamics of technologies, which are, in turn, dependent on the level of technological maturity.

2.5.2. Dynamics of the innovation systems building around emerging technologies through the evaluation of the cognitive properties of knowledge bases

Knowledge bases are not isolated entities or ‘silos’; but rather, they are embedded into innovation systems from which actors feed into and draw upon to innovate (Carlsson et al., 2002). From this perspective, the emergence and evolution of innovation systems has been articulated in terms of the creation, distribution and maintenance of advanced knowledge (Smith, 1999). Hence, both knowledge and innovation systems co-evolve (Andersen, 2007; Asheim and Coenen, 2005; Breschi et al., 2000; Consoli and Ramlogan, 2008; Mina et al., 2007). Similar to the previous section, this section takes advantage of the close interrelationships between technologies and knowledge. In particular, this section visualizes the emergence and evolution of new technologies as involving the formation of innovation systems around those technologies (Hekkert et al., 2007; Jacobsson, 2008; Jacobsson and Johnson, 2000), as shown in Fig. 2.4. Previous sections have defined these emerging innovation systems as entailing embryonic structures with linkages, sparse and porous at first, among a small number of heterogeneous individuals and organizations gradually turning into more formal innovation systems. Despite their ‘immaturity’, formative innovation systems are also composed of networks, institutions, actors and their competences, and knowledge bases (Fig. 2.4). Please refer to Sections 2.1.2 and 2.4.1 for detailed descriptions of the properties of formative innovation systems.

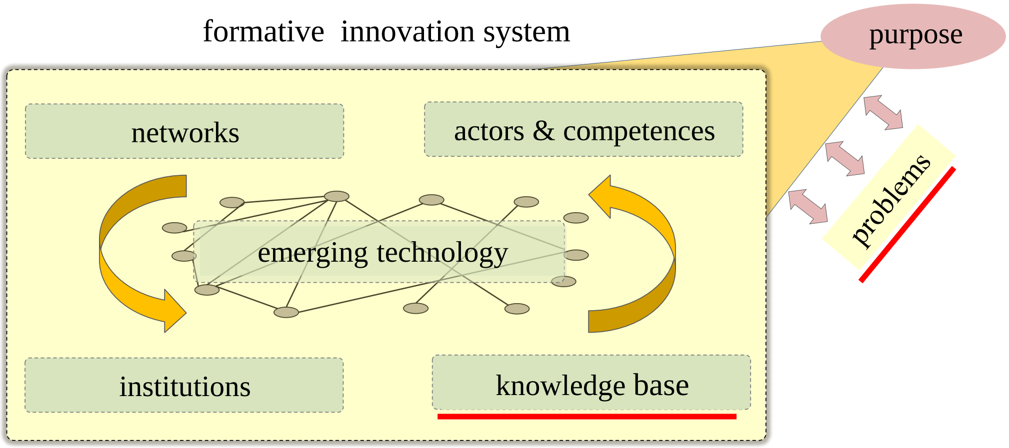

Fig. 2.4 Co-evolution between technological innovation systems and knowledge bases

Similar to the previous section, ‘problem sequences’ prove again to be a useful ‘conceptual instrument’ for gaining insights into the dynamics of emerging technologies. Within this context, the dynamics of change of the innovation systems building around emerging technologies are expected to be reflected on the recurrent patterns of problem search and solution (Consoli and Ramlogan, 2008; Metcalfe et al., 2005; Mina, 2009). Problems should be solved and sorted in order for innovation systems to continue evolving and growing toward the fulfillment of their main purpose, namely to produce, use and diffuse innovations (Edquist, 2004). In this sense, problems partly guide innovation systems toward particular paths of evolution. Problems vary in terms of their complexity and nature; they encompass technological, scientific, and organizational aspects, etc. Innovation systems embed the knowledge bases from which they draw upon to solve those problems (Breschi and Malerba, 1997; Carlsson et al., 2002). As shown in Fig. 2.4, this section focuses on the close interrelationships between problems and knowledge bases. Here, as innovation systems channel their research efforts toward particular directions, they tend to rely on knowledge of a particular nature. Over time, as new problems emerge it is expected that the nature of the extant knowledge bases to follow suit and to be redirected toward that demanded by the new ‘problems’. From what has been said, the dynamics of problems are believed to be *imprinted* on the nature of the knowledge embedded in the knowledge bases underpinning innovation systems. Hence, this dynamics may be used for discerning the changes undergone by innovation systems. This combination of knowledge and problems allows, in turn, the characterization of the dynamics of emerging innovation systems from a cognitive perspective. Later chapter will relate these dynamics in terms of an evolutionary nature. Furthermore, the operationalization of these cognitive characteristics calls for the definition of a series of indicators which will be defined in later chapters.

From what has been said, the second hypothesis to be considered in this thesis is as follows:

- **H2**: Change in emerging technologies is often considered as radical and disruptive in nature; nevertheless, their paths of change are expected to be highly evolutionary in nature. Within this context, it is argued that the cognitive nature of the knowledge bases may provide useful proxies for assessing the nature of evolutionary change in emerging technologies.

2.5.3. Dynamics of emerging technologies through the study of the paths of knowledge evolution and the processes of competence building

It has been previously noted that technology and knowledge are closely interrelated. By relying on this fact, this section now tries to understand the dynamics of emerging technologies through the evaluation of the paths along which knowledge changes and evolves, and the way actors cope with these changes.

This section highlights that the growth of knowledge is the result of collective learning and cumulative interactions (Consoli and Ramlogan, 2009). The latter involves coherent directions of change underpinned by the generation of knowledge dependent on previously obtained knowledge, which is reflected in the formation of technological trajectories (Ramlogan et al., 2007). At the firm-level, Miyazaki (1994, 1995) has discussed the particularities of the formation of search trajectories in the field of optoelectronics. Furthermore, at a higher level of analysis, Kumaresan and Miyazaki (2001) defined the concept of innovation trajectory for the case of the Japanese robotics industry. But what steers the growth toward specific directions of progress? This thesis stresses the role of the aggregate of individual contributions of actors (black small arrows on Fig. 2.5) as those aspects channeling a field along particular directions of change. As inferred from the differences in the thickness of these arrows, the degree of these individual contributions varies. Nevertheless, in broader terms, their aggregate – referred in this section as ‘knowledge paths’ (thick, dotted line in Fig. 2.5) – may provide insights into the directions of change followed by a particular field.

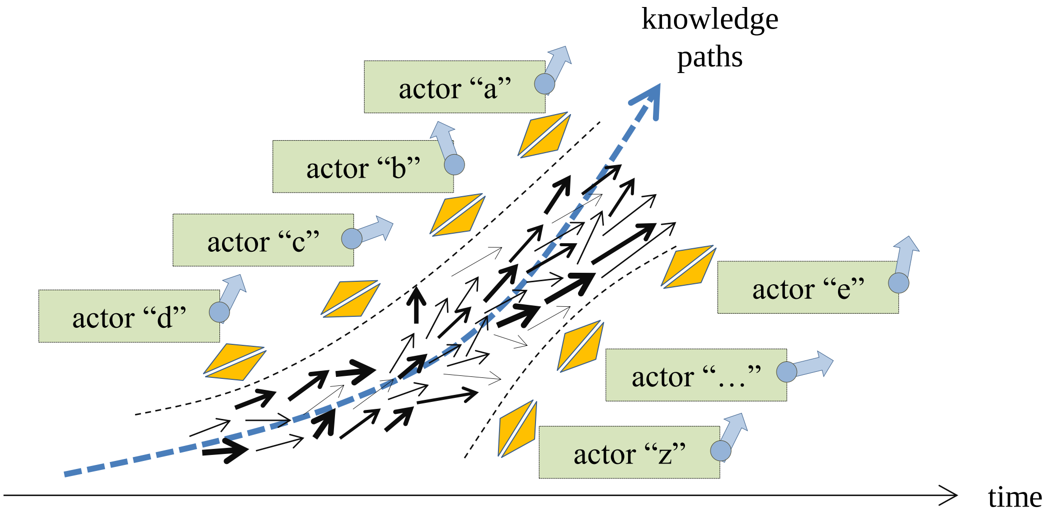

Fig. 2.5 Interrelationships between the paths of knowledge evolution and competence building (drawing of the curve inspired by Geels (2006))

This thesis also pays particular attention to the contribution of actors. By actors, it is meant the individuals or organizations active in particular field, be it public research organizations, universities, firms, government agencies, individuals, etc. Actors are those system components performing innovation activities and pursuing deliberate strategies. They are characterized by particular learning processes, competencies, beliefs, objectives, organizational structures and behavior interacting through processes of communication, exchange, cooperation, competition, and command (Malerba, 2005). Within this backdrop, actors actively contribute and shape the directions along which a particular field is being channeled. In particular, the nature of their patterns of knowledge search and accumulation appear to be prominent, which is, in turn, reflected in the nature of their processes of competence building. As defined by Miyazaki (1995), competences embrace different aspects: technological, financial, organizational, production, and marketing, among others. Continuing with Miyazaki (1995), actors develop procedures enabling them to progress along certain trajectories (blue arrows coming out of each of the actors on Fig. 2.5). In particular, it is stressed that an alignment between the directions towards which knowledge is being channeled and the trajectories followed by the actors should be regarded as a crucial aspect for grasping the opportunities arising from new technologies.

From what has been said, the third hypothesis to be considered in this thesis is as follows:

- **H3**: The dynamics of emerging technologies may be reflected in the interrelationships between the paths of knowledge evolution and the way relevant actors active in a particular technological field cope with such changes as revealed by their patterns of scientific specialization.

2.5.4. Dynamics of emerging technologies through the evaluation of the patterns of change in actors and knowledge structures

Jacobsson and Johnsson (2000) define four structural mechanisms active in emerging innovation systems: market formation through the exploration of niche markets, the entry of firms and other organizations, institutional alignment, and the formation of technology-specific advocacy coalitions or networks. In particular, this section pays particular attention to two of those mechanisms, namely the dynamics of the entry of firms and the formation of networks. It is believed that the study of how the actors in a particular field and the changes in the knowledge networks they build may provide insights into the dynamics of emerging technologies.

Previous research efforts have stressed the role of actors in the evolution of emerging innovation systems. In line with M'Chirgui (2009), this thesis visualizes the emergence of new innovation systems as involving the participation of diverse actors endowed with different knowledge, competences, and specializations. For the case of new technologies, small and medium enterprises (SMEs) have been regarded as crucial actors in inventive and innovative processes (Fernandez-Ribas (2010) citing Breitzman and Hicks (2008) and Audretsch (2002)). For some, young, innovative SMEs may be more innovative than large firms (Michael and Pearce II, 2009). They are, by no means, important sources of employment growth and innovation (Audretsch, 2001). Particularly in high-tech sectors, such as biotechnology, life sciences, pharmaceuticals, and medical devices, SMEs appear to be disproportionally active innovation loci (Youtie et al., 2011). What makes SMEs so special? Despite their low resource endowment, SMEs have been regarded as more flexible to grasp the opportunities arising from new technologies (Hicks and Hegde, 2005). However, generalizations, particularly for the case of the nanotechnology field, may not be fully true, given the high capital investments, streamlined R&D processes, and well-defined knowledge acquisition channels may favor established large firms (OECD, 2010). Recently, Genet et al. (2012) have discussed that nanotechnology technology transfer does not appear to have SMEs as its central economic actors. In contrast, they have pointed out that nanotechnology is being developed within large firms; thus, mostly following the early patterns of the microelectronics industry rather than those of biotechnology. Within this background, this study attempts to trace the changes undergone by the actors, particularly firms, active in an emerging innovation system (Fig. 2.6).

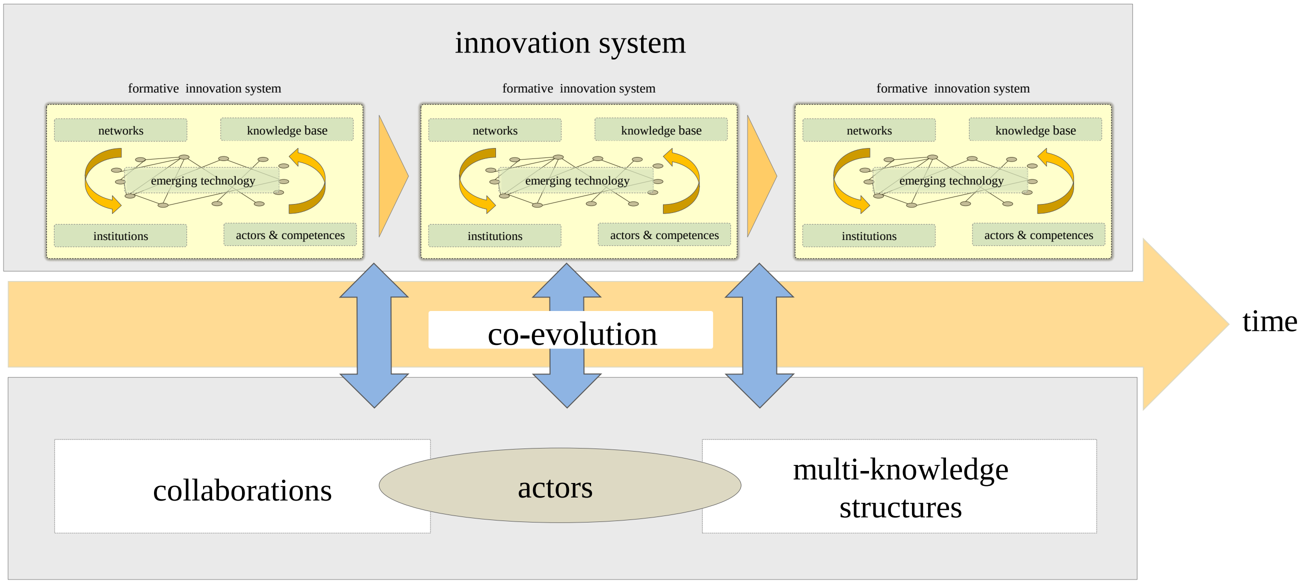

Fig. 2.6 Co-evolution between innovation systems and knowledge structures

Furthermore, it is well known that firms form close relationships with other firms. What is more, these networks lie at the heart of innovation systems. The rationales behind such collaboration are cost advantages due to the access of complementary resources, knowledge and competences; economies of scope coming from the proliferation of new and ever-more specialized scientific fields; as well as the development of specialized expertise in the use of scientific instrumentation (M'Chirgui, 2009; Consoli and Ramlogan, 2012). Jacobsson (2008) defines two different types of networks: learning networks which embrace user-supplier networks, networks between related firms, networks between competitors, and university-industry networks; and those networks established to influence the political agenda. For him, networks constitute important modes for the transfer of tacit and explicit knowledge. Within this background, as shown in Fig. 2.6, another important aspect of this thesis is to discern the dynamics of emerging innovation systems through the study of the changes undergone by knowledge networks. To do so, two types of knowledge structures are defined: R&D collaborations and multi-knowledge structures. In this regard, R&D collaborations have been traditionally used for observing the dynamics of industries or innovation systems (M'Chirgui, 2005, 2009). Besides 'physical' knowledge networks through R&D collaborations the different actors within a system are cognitively interrelated across scientific, technological and market fields they share. These do not imply a 'physical' connection between actors, but rather a cognitive connection being built through the nature of the shared knowledge. The closer their knowledge overlapping, the higher is their degree of cognitive interrelation. As later chapters will discuss, these cognitive-related networks, referred in this thesis as multi-knowledge structures, may be regarded as reflections of the nature of the knowledge accumulated in a particular field. Hence, it is inferred that tracing the changes of both knowledge networks may provide insights into the dynamics of emerging innovation systems.

From what has been said, the fourth hypothesis to be considered in this thesis is as follows:

- **H4**: The evolution of formative innovation systems can be inferred from the patterns of change experienced by the actors active in a particular field, as well as by the knowledge networks, physical and cognitive in nature, built by these actors.

2.5.5. General analytical framework

This section now combines the different frameworks proposed in the previous sections into a general analytical framework (Fig. 2.7). Also, this general framework is used to identify the different hypotheses to be evaluated in this thesis. Repeating, these are:

- **H1**: Visualized as dynamic entities, knowledge bases evolve and grow at certain rates and along particular directions. These dynamic properties are expected to vary depending on the dynamics of technologies, which are, in turn, dependent on the level of technological maturity.
- **H2**: Change in emerging technologies is often considered as radical and disruptive in nature; nevertheless, their paths of change are expected to be highly evolutionary in nature. Within this context, it is argued that the cognitive nature of the knowledge bases may provide useful proxies for assessing the nature of evolutionary change in emerging technologies.
- **H3**: The dynamics of emerging technologies may be reflected in the interrelationships between the paths of knowledge evolution and the way relevant actors active in a particular technological field cope with such changes as revealed by their patterns of scientific specialization.
- **H4**: The evolution of formative innovation systems can be inferred from the patterns of change experienced by the actors active in a particular field, as well as by the knowledge networks, physical and cognitive in nature, built by these actors.

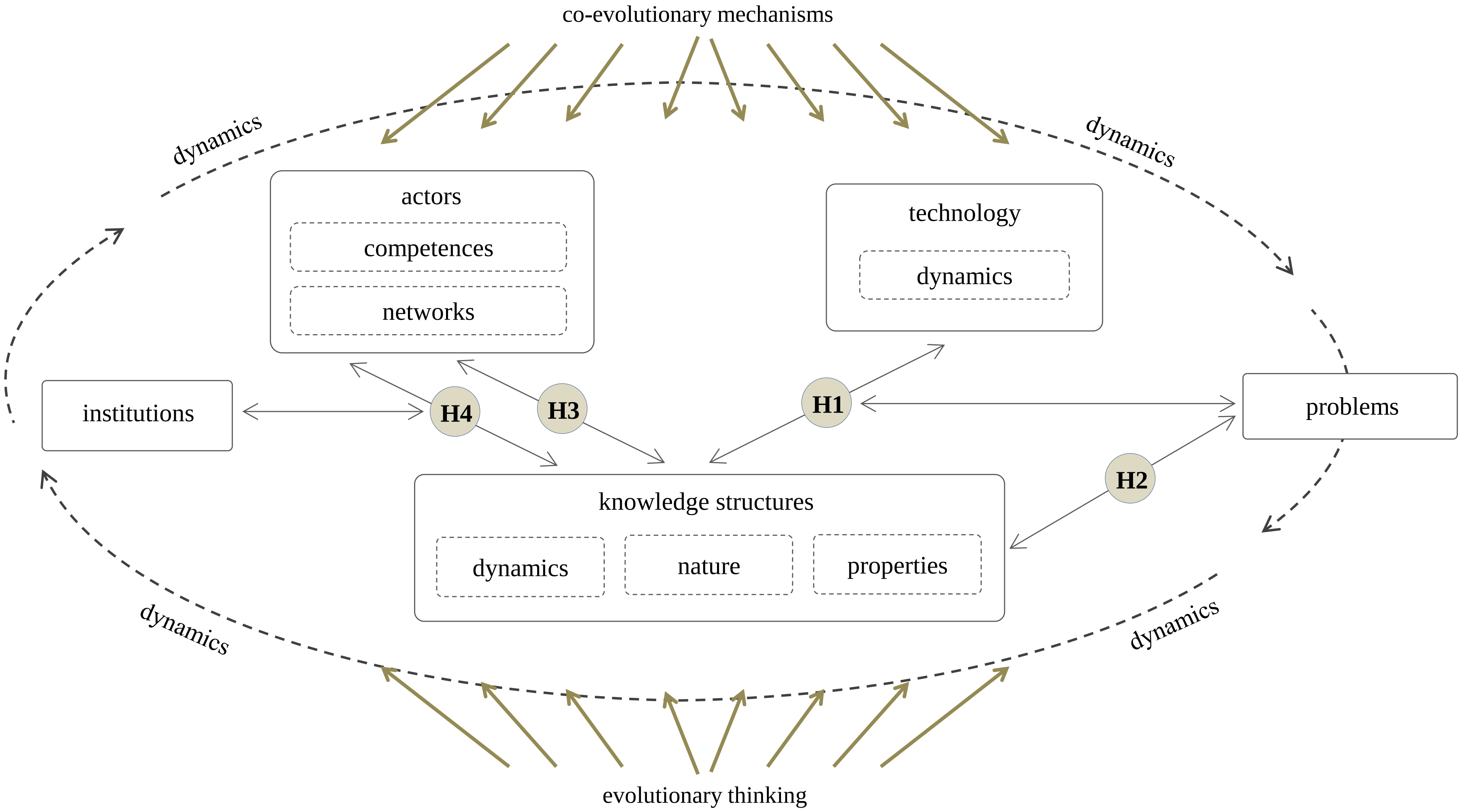

Fig. 2.7 General analytical framework

2.6. Summary

This chapter has described the theoretical streams underpinning the rest of the chapters of this thesis. Here, it was observed that the complexity behind the dynamics of technologies calls for the need to integrate different theoretical streams. In particular, four main aspects were highlighted: technological emergence and emerging technologies, technological innovation systems, evolutionary thinking and co-evolutionary mechanisms, and knowledge theory. Besides the technology and innovation management-related research streams, crucial insights for this thesis were gained from the technical literature (please refer to the next chapter). Building upon the co-evolutionary relationships between technology and knowledge, this study relies on the main premise that the understanding of how knowledge changes, evolves, and transforms may provide crucial insights into the dynamics of emerging technologies. This chapter also discussed the analytical framework for this thesis. As discussed, four main hypotheses considering the measurement of the dynamics of emerging technologies through knowledge structures were defined. Each of these hypotheses was visualized through the construction of a conceptual model. The final section of this chapter integrated these four different conceptual models into a single framework.

Before moving on to the next chapter, it should be highlighted that the discussions of this chapter have been mainly focused on the conceptual description of the models. Chapter 4 will discuss the research methods to be used to operationalize these conceptual models. In the meanwhile, the next chapter provides an overview of the technologies to be studied in this thesis: micro/nanotechnologies and micro/nano-enabled technologies.

3. Micro/nanotechnologies and Micro/nano-enabled Technologies

3.1. Introduction

As previously described, this thesis revolves around the empirical cases of micro/nanotechnologies and micro/nano-enabled technologies. The main purpose of this chapter aims at describing the specific technological cases to be analyzed in this thesis. Within these fields, given their current predominance, nanotechnologies and nano-enabled technologies will be emphasized in this chapter.

This chapter is structured as follows. Section 3.2 characterizes micro/nanotechnologies and micro/nano-enabled technologies. Here, a series of general definitions are complemented with a brief account of the origins and the potential impacts of micro/nanotechnologies and micro/nano-enabled technologies. Subsequently, two conceptual models for the understanding of the impact of nanotechnologies are described, namely ‘nanotechnology product generations’ and the ‘nanotechnology value chain’. Building on the conceptual model ‘nanotechnology value chain’, Section 3.3 continues with the description of the specific technological case studies to be analyzed in this thesis. This chapter finalizes with a brief summary in Section 3.4.

3.2. Characterization of micro/nanotechnologies and micro/nano-enabled technologies

As previously noted, the world is experiencing accelerated rates of technological and scientific progress along a wide array of fields, such as biotechnology, biomedicine, information and telecommunications, and aerospace, among others. Such rapid technological and scientific progresses coupled with on-going societal changes are opening up a wide array of opportunities with potential economic, social and environmental impacts (Russell and Hall, 2008). Within this backdrop, *small technologies* (Kautt et al., 2007) led by *micro and nanotechnologies* are positioning themselves as key enabling technologies to exploit and to capture the benefits of such opportunities (Tolfree and Jackson, 2008). As such, micro and nanotechnologies are expected to provide the basis for the creation of new or improved technology product paradigms or solution sets over a wide range of industries (Kautt et al., 2007).

3.2.1. Micro/nanotechnologies and micro/nano-enabled technologies

Microtechnology is defined as the practical application of scientific knowledge enabling the design and development of structures with features sizes reaching few microns (1-100μm) [1]. Current microtechnologies have been mainly derived from semiconductor fabrication technologies, usually referred as microelectronics technologies. These technologies particularly leverage electrical skills (Kautt et al., 2007). Another set of microtechnologies consists of microelectromechanical systems (MEMS) or microsystems technologies. These technologies set their sights on the development of mechanical microstructures, such as sensors and actuators. These technologies conflate electrical and mechanical skills with fields such as biology, chemistry, physics and materials science (Kautt et al., 2007). An intuitive way to understand the differences between microelectronics and MEMS technologies is by visualizing the former as the 'brain' and the later as the 'eyes, nose, ears, arms and legs' of a micro-device.

A different, yet interrelated, technology with the other two technologies described above is nanotechnology. Literature has typically differentiated between *nanoscience and nanotechnology (N&N)*. Whereas the former deals with the study of the phenomena and properties at the nanoscale, the latter relates to the application of nanoscale science, engineering and technology for the production of novel materials and devices (Romig Jr et al., 2007). Specifically, nanotechnology has been referred as "the control and restructuring of matter at the nanoscale, at the atomic and molecular levels in the size range of about 1-100 nm, in order to create materials, devices, and systems with fundamentally new properties and functions because of their small structure" (Roco et al., 2011)[2]. In this regard, the significance of the nanoscale not only lies in the size per se but in the novel properties and functions arising from these minute dimensions. N&N has been characterized by the following aspects: it embodies a technological field rather than a single technology, it is mainly science-driven, cross-disciplinary, as well as enabling, ubiquitous and spectacular in nature (Andersen, 2005). From these, it should be highlighted that nanotechnology is a generic term comprising of a wide range of disciplines and applications, such as engineering, materials science, biotechnology, medicine, physics, chemistry and information technology (Hodge et al., 2010). Given this heterogeneity, for some, the label 'nanotechnology' appears to inaccurately describe the immense range of technologies falling under it, i.e. everything that deals with molecular-scale matter (Hodge et al., 2010; Toumey, 2010). Along the same line, others have preferred to use the plural 'nanotechnologies' (Ramsden, 2005). Despite these aspects, there is a common consensus

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[1] 1 micrometer = 1μm = one millionth of a meter.

[2] 1 nanometer = 1nm = one millionth of a millimeter.

on the broad impact of N&N across markets, sectors, and industries. As such, nanotechnologies are regarded as enabling technologies, and general purpose technologies (Shea, 2005; Youtie et al., 2008), acting as both the basis for technology solutions for a range of industries, as well as the locus for the convergence of other enabling technologies (Mangematin and Walsh, 2012). These products and applications resulting from the application of nanotechnologies are referred in this thesis as nano-enabled technologies. As it will be seen in Section 3.2.4.2, this is closely related to the visualization of micro/nanotechnologies and micro/nano-enabled technologies as a 'nanotechnology value chain'.

3.2.2. Brief account of the origins of N&N

Regarding the origin of the N&N field, a series of single events have been typically defined in the literature as triggers of its birth. Building on Jones (2011), Pardo-Guerra (2011) and Toumey (2010), the next paragraphs discuss a series of narratives that have contributed to the emergence of the N&N field:

- The lecture 'There's plenty of room at the bottom' delivered by *Richard Feynman* to the America Society of Physics in 1959 in which he emphasized the potential impacts of extremes forms of miniaturization and the manipulation of matter at the atomic level. For some, Feynman's vision has been regarded as the 'inspirational' thrust that has driven the N&N field.
- The creation of the concept 'nanotechnology' by Norio Taniguchi in 1974 in the article 'On the basic concept of nano-technology' to the Japanese Society of Precision Engineering. Although his visualization of 'nanotechnology' had a heavy mechanical connotation derived from his research on ultra-precision machinery, the coinage of the term provided a certain legitimation to the field.
- The works from Richard Smalley, the scientist behind the discovery of the fullerenes, and George Whitesides whose trajectories of development were mainly conducted within the fields of chemistry, and, years later, of biotechnology. Their work highlighted the critical role of materials science in general and self-assembly technologies within the N&N field.
- K. Eric Drexler's visions of the atom-by-atom control of matter by nanomachines resulting in the creation of 'molecular nanomanufacturing' through his work 'Engines of Creation: The Coming Era of Nanotechnology' in 1986.
- The developments of the Scanning Tunneling Microscope (STM) in 1981 by G. Binnig and H. Rohrer at IBM Research Laboratory in Zurich, and years later, in 1986, of the Atomic Force Microscope (AFM) by G. Binnig, C.F. Quate and Ch. Gerber. Related to these works, D. Eigler and E.K. Schweizer's (IBM, USA) experiment should be highlighted in which 35 xenon atoms were precisely controlled and arranged to spell out the acronym 'IBM' with the help of a STM microscope in 1989.

From this section, it can be seen that the onset of N&N is regarded to be the result of the combinations of diverse factors, even coming outside of science (Jones, 2011; Toumey, 2010). More detailed information on the origins of the field of nanotechnology is discussed in Islam and Miyazaki (2006).

3.2.3. Nanotechnology and their impact on markets

Since its outset in the early 1980s the field of nanoscience and nanotechnology (N&N) has been surrounded by an 'aura' of significantly high expectations, for some even reaching the level of hype and over-exaltation, about its future potentials and far reaching effects on the economy and society (Andersen, 2007). Economically, the latter has translated into global R&D annual investments on N&N from private and public sources of around 15 billion dollars and a value of products incorporating nanotechnology as a key component of about 200 billion dollars in 2008 (Roco et al., 2011). This has led to increasing R&D investments on N&N across countries, an ever growing body of scientific publications and patent applications, and greater attention by policy makers, industry and the general public (Huang et al., 2011). Despite mammoth efforts, N&N still remains at an early stage of development, very science-driven and consequently mainly exogenous to the economic system (Nikulainen and Palmberg, 2010). Yet, gradually nanotechnology-enabled products are entering the marketplace. For example, different authors have evidenced a transition from discovery to innovation and commercialization (Shapira et al., 2011; Subramanian et al., 2010).

In this regard, the Project on Emerging Nanotechnology (PEN) from the Woodrow Wilson International Center for Scholars (USA) provides interesting data for capturing the nature of nanotechnology-enabled products available for commercialization (PEN, 2010). Basically, PEN consists of an inventory of nanotechnology-based consumer products (products whose information can be readily found on the internet). As of March 11th 2011, this inventory listed 1,317 products, which are produced by 587 companies spreading over 30 different countries, which represents a twenty-four-fold increment in comparison to 2005 when the inventory started (Invernizzi, 2011). Similar strong rates of innovative growth in N&N are described in the inventory of nanotechnology-enabled products collected by the Helmut Kaiser Consultancy, which includes a total of 2,500 nanotechnology-based products and applications on the markets worldwide; this is a large increment from the 300 identified in 2001 (Invernizzi, 2011). Despite such commercial dynamism, as observed by Shapira et al. (2011), the majority of the nano-enabled products entail incremental rather than radical innovations. These are more in line with evolutionary technologies, i.e. those supporting the current technology-product paradigm rather than with revolutionary technologies, i.e. those creating a new or superior technology-product paradigm

(Romig Jr et al., 2007). Within this context, it has been argued that success, at least for nanomaterials, is more likely to happen when nanomaterials can be integrated into *existing* value chains as dramatic changes may take too long or may not be profitable at all (Manoharan, 2008).

From what has been said, the real value of the N&N field boils down to its ability to bring about commercial products into the market. Here, the previous paragraphs have highlighted the still impending market potential of N&N solutions. Insights into the trajectories of nano-enabled products can be gained from a series of conceptual models. Two of these conceptual models are described in the next section.

3.2.4. Conceptual models for the development of nanotechnology-enabled products

This section describes Roco (2004)'s generations of nanotechnology products and processes and LuxResearch (2007)'s nanotechnology value chain. Following, each of these conceptual frameworks are described in detail.

3.2.4.1. Generations of nanotechnology products and processes

For Roco (2004) nanotechnology capabilities appear to be evolving along four overlapping generations of products and processes (Fig. 3.1). In turn, each of those generations is related to particular goals, applications, and R&D foci (Roco, 2004).

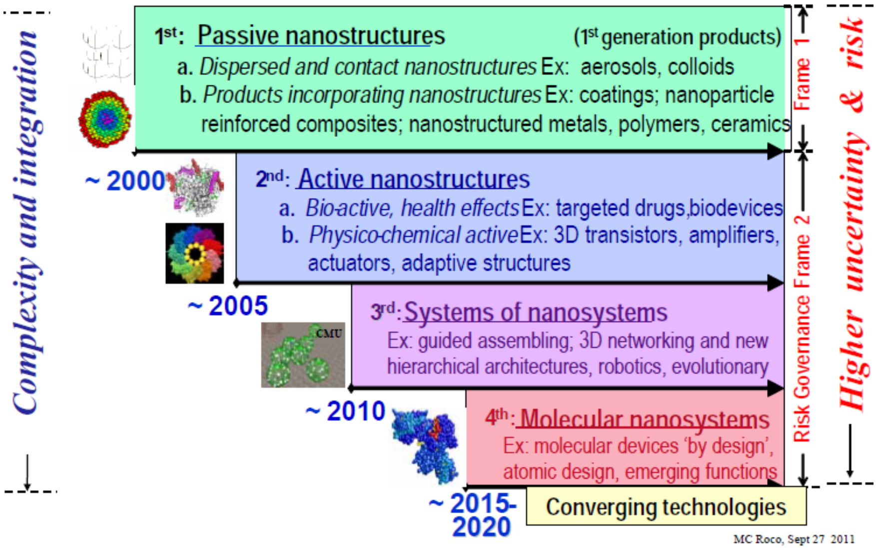


Fig. 3.1 Nanotechnology product generations (Roco, 2011a)

Following, each of the nanotechnology product generations are explained (Renn and Roco, 2006; Roco, 2001, 2004):

- **Passive nanostructures** – These encompass nanostructured materials with steady or quasi-steady structures and functions during their usage. Applications include nanostructured coatings, dispersion of nanoparticles, nanolayers, and bulk materials (nanostructured metals, polymers, and bulk materials). R&D focuses on nanostructured materials and measurement/control of nanoscale processes.
- **Active nanostructures** – These nanostructures change their state in time during their operation, such as transistors, amplifiers, targeted drugs and chemicals, actuators, sensors, nano-scale fluidics, and adaptive structures. R&D is focused on devices and device architectures.
- **Three-dimensional (3D) nanosystems and systems of nanosystems** – Efforts are directed at the engineering and manufacturing of three-dimensional heterogeneous nanosystems. Examples include multi-scale self-assembling, the networking of structures and devices at the nanoscale, nanosystems with long-scale order, etc. R&D efforts focus on heterogeneous nanostructures and supramolecular system engineering.
- **Heterogeneous molecular nanosystems** – Nanosystems in which each molecule has a specific structure and plays a different role. Applications include molecules as devices, cells as nanobiosystems, multi-scale self-assembled systems, etc. R&D is aimed at the atomic/molecular design, nano-bio-info-cognitive convergence, among others.

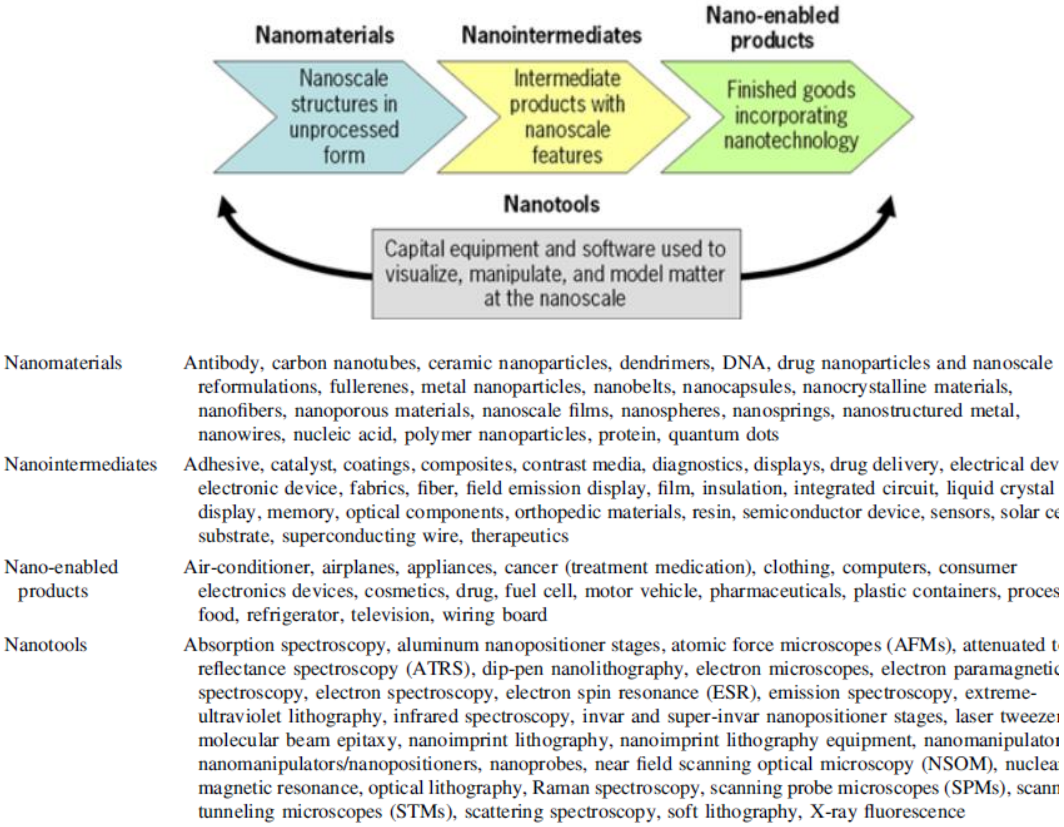
As discussed in Roco (2011a), each transition toward a subsequent process/product generation is accompanied by increased levels of uncertainty and risk coupled with greater levels of complexity, dynamics, and interdisciplinarity. Up to now, the majority of current application embraces passive nanostructures used as components to enable new products or to improve current products (Roco et al., 2011). From 2005, more complicated active nanostructures have begun to flourish; slowly heading to nanosystems in 2011 (Roco, 2011a). In this regard, recently Subramanian et al. (2010) has evidenced a transition into active nanostructures, at least in terms of publications.

Roco (2004)'s framework of nanotechnology generations is mainly centered on products; hence, it reveals little about the locations in which nanotechnology-enabled innovations take place. This can be better understood through the nanotechnology value chain.

3.2.4.2. Nanotechnology value chain

Lux Research – a U.S. consultancy company – introduced the framework of the nanotechnology value chain to track the performance of companies active in the application and commercialization of nanotechnology (Wang and Guan, 2012). The main premise behind the 'nanotechnology value chain' framework is that commercialization efforts in nanotechnology are conducted across the whole value chain, going from nanomaterials to nanointermediates to nano-enabled products, and supported by nano-tools and nanofabrication technologies (LuxResearch, 2007; Shapira et al., 2011).

Fig. 3.2 illustrates the value chain for nanotechnology-based products, as well as it provides a series of examples of technologies for each of the four blocks of the nanotechnology value chain.



Nanomaterials	Antibody, carbon nanotubes, ceramic nanoparticles, dendrimers, DNA, drug nanoparticles and nanoscale reformulations, fullerenes, metal nanoparticles, nanobelts, nanocapsules, nanocrystalline materials, nanofibers, nanoporous materials, nanoscale films, nanospheres, nanosprings, nanostructured metal, nanowires, nucleic acid, polymer nanoparticles, protein, quantum dots
Nanointermediates	Adhesive, catalyst, coatings, composites, contrast media, diagnostics, displays, drug delivery, electrical dev electronic device, fabrics, fiber, field emission display, film, insulation, integrated circuit, liquid crystal display, memory, optical components, orthopedic materials, resin, semiconductor device, sensors, solar ce substrate, superconducting wire, therapeutics
Nano-enabled products	Air-conditioner, airplanes, appliances, cancer (treatment medication), clothing, computers, consumer electronics devices, cosmetics, drug, fuel cell, motor vehicle, pharmaceuticals, plastic containers, proces food, refrigerator, television, wiring board
Nanotools	Absorption spectroscopy, aluminum nanopositioner stages, atomic force microscopes (AFMs), attenuated t reflectance spectroscopy (ATRS), dip-pen nanolithography, electron microscopes, electron paramagnetic spectroscopy, electron spectroscopy, electron spin resonance (ESR), emission spectroscopy, extreme-ultraviolet lithography, infrared spectroscopy, invar and super-invar nanopositioner stages, laser tweeze molecular beam epitaxy, nanoimprint lithography, nanoimprint lithography equipment, nanomanipulato nanomanipulators/nanopositioners, nanoprobes, near field scanning optical microscopy (NSOM), nuclea magnetic resonance, optical lithography, Raman spectroscopy, scanning probe microscopes (SPMs), scann tunneling microscopes (STMs), scattering spectroscopy, soft lithography, X-ray fluorescence

Fig. 3.2 The nanotechnology value chain (LuxResearch, 2007; Wang and Guan, 2012)

Following, the remainder of this section briefly describes each of the blocks of the nanotechnology value chain. Nanomaterials refer to those nanoscale structures in unprocessed state that are characterized by their properties stemming from their minute dimensions. In a subsequent step these unprocessed nanostructures acquire value through their incorporation into nanointermediate products, which, in turn, act as individual components for the final nano-enabled products. Further downstream, these nanointermediates are then used in the fabrication of the final nano-enabled products which embody the finished goods. Finally, the block comprising capital equipment, instrumentation and software block refers to the toolbox necessary to visualize, manipulate and model matter at the nanoscale. As illustrated in Fig. 3.2, this block influences the rest of the blocks. As may be inferred, this block is largely similar to the micro/nanotechnologies discussed in Section 3.2.1.

The main benefit of the nanotechnology value chain is that it approaches the ‘sphere of influence’ of micro/nanotechnologies from a broader perspective. Nevertheless, the nanotechnology value chain is mainly linear, and thus it largely overlooks the complex feedbacks and the overlapped and geographically dispersed chains characterizing technological change and innovation in N&N. Recently, Nightingale et al. (2008) have proposed a different visualization from that of Fig. 3.2 as an ‘hour-glass model’ (Fig. 3.3). Acknowledging the enabling properties of N&N, in this model “a broad range of inputs, from a variety of institutional sources converge on a range of technologies that share an ability to exploit nanoscale phenomena, and then are diffused to a wide range of product markets and customers” (Nightingale et al., 2008).

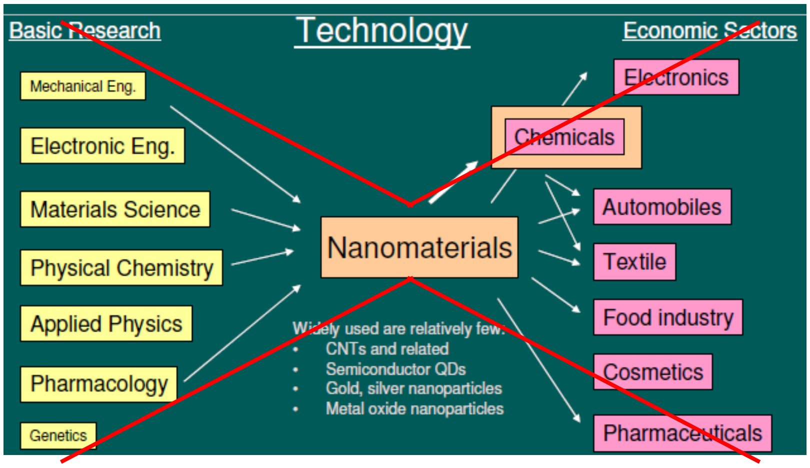


Fig. 3.3 Hourglass model (Nightingale et al., 2008)

Despite its inherently simplifying assumptions, the nanotechnology value chain is regarded as a way to visualize the different stages involved in the development and manufacturing of nano-enabled products. In this thesis, as previously mentioned, the nanotechnology value chain model provides the building blocks for the arrangement of the subsequent chapters of this thesis. Next section describes each of the case studies selected for this thesis.

3.3. Description of the Case Studies

This section now turns to the description of the different case studies to be analyzed in the following chapters of this thesis. As previously noted, for each of the blocks of the nanotechnology value chain, a representative technology was selected. Following, each of these technologies will be briefly explained.

3.3.1. Nanomaterials – Zinc Oxide one-dimensional nanostructures

Nanomaterials are defined as materials with one or more external dimensions in the nanoscale range (1-100 nanometers) exhibiting properties that differ from those of the same materials without nanoscale features (BSI, 2007). Nanomaterials are not new; gold and silver nanoparticles were used in Roman glass hundreds of years ago (Pitkethly, 2004). However, it was not until the late 1970s – early 1980s that a more formalized approach toward the understanding, manipulation and use of nanomaterials took on. Here, the invention of instrumentation such as the scanning tunneling microscope (STM) and the atomic force microscope (AFM) were decisive events. For the particular case of nanomaterials, the discoveries of the Buckminsterfullerenes and carbon nanotubes in the late 1980s – early 1990s were also fundamental to catapult this field (Pitkethly, 2004).

Nanomaterials have spearheaded the accelerated growth experienced in the field of N&N. Their importance lies on the increasing number of applications, the improved product performance, and the competitive advantage and value creation they offer (Pitkethly, 2004). Rafols et al. (2011) defines two characteristics of nanomaterials that impact the structure of an industrial value chain: a) flexibility of application as nanomaterials can be used in a variety of applications, as well as different materials can fulfill similar functions; and b) distributed nature of innovation as nanomaterials are incorporated into long, branching value chains. These characteristics endow nanomaterials as building blocks inducing innovation in other products; in that sense, as defined by Nightingale et al. (2008) and Rafols et al. (2011), nanomaterials are not consumer products, but 'capital' products that may be used in a variety of applications in a variety of industries and commercial sectors. Over the years, hundreds of nanomaterials have been developed. Here, Fig. 3.4 depicts the 'star materials' stretching from 1981 with the pioneering discoveries of the quantum dots and fullerenes in 1985 to topological insulators, graphene, and ZnO nanowires during the early and mid-2000s. Technical literature has typically classified nanomaterials into four groups according to their dimensionality: zero-dimensional nanostructures *(0D)*, such as quantum dots, nanocrystals, nanoparticles, etc.; one-dimensional nanostructures *(1D)*, such as nanotubes, nanowires, nanorods, nanowhiskers, etc.; two-dimensional nanostructures *(2D)*, such as nanosheets, graphene, self-assembled monolayer, etc.; and three-dimensional nanostructures *(3D)*, such as bulk materials, nanohybrids, nanocomposites, etc.

In this thesis, the case of *Zinc Oxide (ZnO) one-dimensional nanostructures* is particularly reviewed. The selection of this technology relied on two aspects. First, it is one of the few dominant nanomaterials for nanotechnology (together with carbon nanotubes and silicon nanowires) (Wang, 2009b). Second, it is an emerging nanomaterial but with a history long enough for retrieving sufficient data for the conduction of dynamic analyses presented in this thesis.

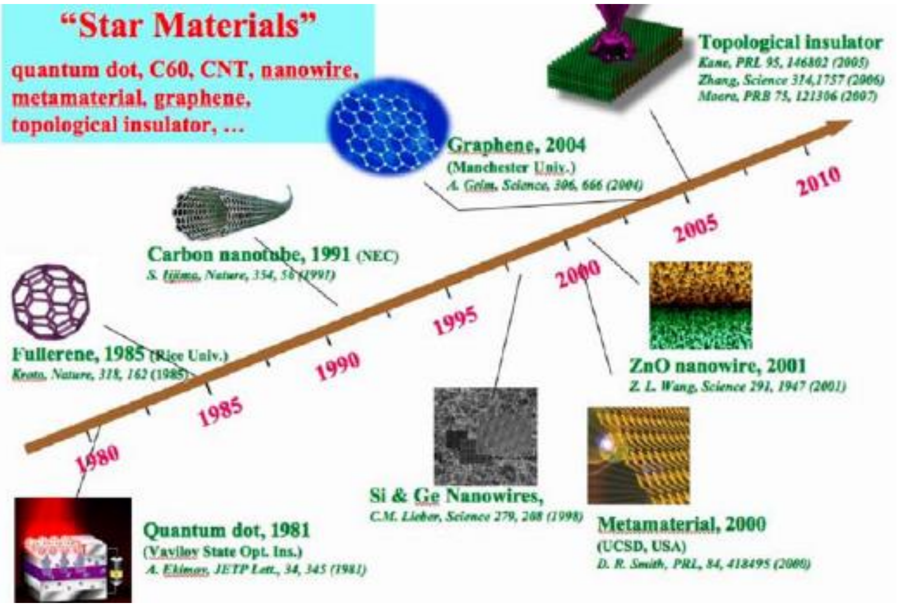
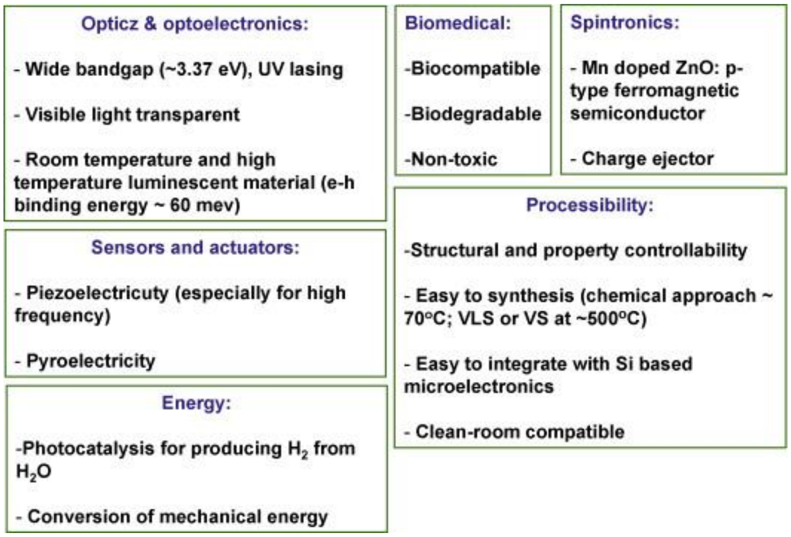


Fig. 3.4 Timeline for nanostructures (Mirkin and Tuominen, 2011)

ZnO is a semiconductor material, particularly a semiconducting oxide. Research on ZnO traces back to the first quarter of the 1900s; its research has experienced peaks from time to time but particularly during the last 5-10 years it has experienced an extreme revival (Klingshirn et al., 2010), particularly due to the development of ZnO nanostructures. ZnO, in general, has a wide range of applications such as in optics, optoelectronics, sensors, actuators, energy, biomedical sciences, and spintronics (Wang, 2009b), as shown in Fig. 3.5. Each of the applications blocks of Fig. 3.5 describes the properties of ZnO that have been exploited to realize those applications, such as their wide-bandgap, semiconducting, piezoelectric and pyroelectric properties, biodegradability, and easy synthesis, among others.



Opticz & optoelectronics:

- Wide bandgap (~3.37 eV), UV lasing
- Visible light transparent
- Room temperature and high temperature luminescent material (e-h binding energy ~ 60 mev)

Biomedical:

-Biocompatible

-Biodegradable

-Non-toxic

Spintronics:

- Mn doped ZnO: p-type ferromagnetic semiconductor
- Charge ejector

Sensors and actuators:

- Piezoelectricuty (especially for high frequency)
- Pyroelectricity

Processibility:

-Structural and property controllability

- Easy to synthesis (chemical approach ~ 70°C; VLS or VS at ~500°C)
- Easy to integrate with Si based microelectronics
- Clean-room compatible

Energy:

-Photocatalysis for producing H_2 from H_2O

- Conversion of mechanical energy

Fig. 3.5 Applications and properties of ZnO (Wang, 2009b)

ZnO nanostructures refer to the synthesis of nanostructures at the nano-scale. In particular, ZnO one-dimensional nanostructures define those ZnO nanostructures with one dimension less than 100 nanometers. Examples of one-dimensional nanostructures are nanowires, nanobelts, nanorods, nanorings, nanosprings, nanospirals, among many others (Wang, 2009b). ZnO one-dimensional nanostructures have recently drawn considerable attention due to their novel properties vis-à-vis conventional ZnO materials (e.g. bulk, thin films, etc.) and their potential applications in transparent electronics, optoelectronics, spintronics, and chemical and biological sensing, among others (Wang, 2004) .

3.3.2. Intermediates – MEMS/NEMS

Intermediate products refer to nanomaterials or other materials with nanoscale features that are used in the fabrication of final nanotechnology-enabled products. The case-study selected for this block is that of micro/nanosensing and actuation technologies, also known as *MEMS/NEMS technologies*. MEMS is an acronym for 'micro-electro-mechanical systems', also referred as micromachines or microsystems technologies. MEMS defines both an interdisciplinary portfolio of downscaling techniques and processes, also defined as micromachining, and the parts, devices and subsystems, typically sensors and actuators, with feature sizes down to the micro/nano-scale enabled by those technologies (Maluf and Williams, 2004). In particular, this section focuses on the latter definition. Some examples of the micromachined components for a series of MEMS devices are shown in Fig. 3.6.

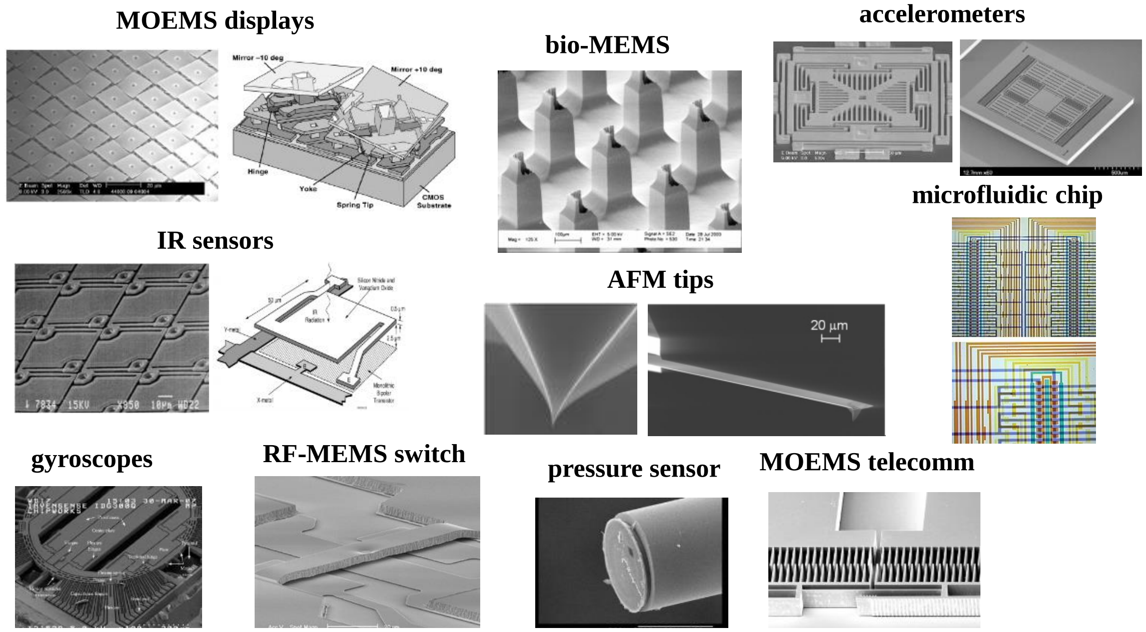


Fig. 3.6 Examples of micromachined components for some MEMS devices

A MEMS product refers to a complete micro-electromechanical systems; they are autonomous miniaturized systems capable of performing sensing or actuation functions by themselves or as part of larger systems (Tadigadapa and Najafi, 2003). As such, MEMS products consist of a micromachined component including signal conditioning circuit, self-testing and calibration, and packaging with the necessary I/O ports and terminals (Tadigadapa and Najafi, 2003).

The history of MEMS technologies is highly coupled to that of silicon integrated circuits (ICs) as the fabrication processes of the former relied heavily on those of the latter. The earliest origins of MEMS date back as far as 1954 with the research of C.S. Smith (Bell Telephone Co.) on the measurement of piezoresistivity coefficients in germanium and silicon which paved the way for today's piezoresistive sensors (Ko, 2007). In terms of prototypes, the earliest demonstration of a micro actuator was H. Nathanson's (Westinghouse Labs, USA) resonant gate transistor in 1967. Thereafter, coupled with the development of sensor-specific technologies the 1970s saw an expansion of the array of devices available, which continuously expanded during the 1980s (Wise, 2007). The earliest commercial MEMS technologies were pressure sensors for applications in the monitoring of blood pressure and industrial control in the late 1970s. These were trailed by the pioneering efforts of Hewlett-Packard in the development of silicon micromachined ink-jet printer nozzles. Continuing with Wise (2007), the 1990s were characterized by an emphasis on systems and a proliferation of MEMS into many sub-disciplines such as bio-MEMS, optical-MEMS, RF-MEMS, etc. These developments were continued during the 2000s and complemented with an increasing convergence of sensors with embedded computing and wireless technology. Accelerated progresses in nanotechnology have gradually extended the field of MEMS into NEMS (nano-electro-mechanical systems).

As key technologies within the field of sensors, MEMS/NEMS technologies are expected to play a major role in the future as they span all sectors of industry and often lead to innovative products resulting in competitive advantage (Andersen et al., 2004). MEMS/NEMS applications span a wide range of sectors; they have crystallized into different markets and application domains, as shown in Table 3.1.

Table 3.1 Overview of MEMS/NEMS technologies

Technology	Brief description and potential application domains
Accelerometers	Inertial device measuring acceleration forces.
Bio-MEMS	Biological and medical applications of MEMS. Broad encompassing field: surgical instruments, drug delivery systems, bio-sensors, pressure sensors, among others.
Gyroscopes	Sensors for measuring angular velocity. Uses in automobiles, consumer electronics, among others
Microfluidics	Handling of fluids in MEMS. It includes: micro total analysis systems, labs on a chip, and their components such as micro-pumps, micro-valves, etc.
MOEMS displays	Micro-mirror arrays, micro-gratings, etc. for display projectors, bar code readers, etc.
MOEMS telecomm	Devices for optical fiber communications, such as optical switching units, variable optical attenuators, tunable filters, among many others
Micro-tips (AFM)	Probes and tips for measuring the properties of surfaces with atomic force microscopes
Power-MEMS	Includes energy-related applications for MEMS devices, such as energy scavengers, microturbines, microthrusters, microgenerators, micromotors, among others
Pressure sensors	Main applications in automotive, industrial automation, medical, and aerospace
Printheads	Heads for inkjet printing applications
RF-MEMS	High-frequency circuits (radio frequency, micro- and millimeter waves), such as high-Q inductors, phase shifters, antennas, tunable capacitors and resonators, among others.
ZnO nanosensors	Use of Zinc Oxide nanostructures for sensing and actuation applications
Carbon nanotube nanosensors	Use of carbon nanotubes for sensing and actuation applications

3.3.3. Tools and instrumentation – Micro/nanofabrication technologies

As illustrated in Fig. 3.2, tools and instrumentation influence the rest of the blocks of the nanotechnology value chain. Researchers as early as Rosenberg (1982) have denoted the crucial role of instrumentation in technological progress. Similarly, Meyer (2007) stresses the role of tools and instrumentation as interconnectors in the field of N&N. Others have regarded tools and instrumentation as 'inventions of a method of invention' (Palmberg and Nikulainen, 2006; Roco and Bainbridge, 2007). This block includes instrumentation technologies, fabrication technologies as well as modelling and simulation technologies aiding the development and fabrication of nanomaterials, intermediates and end-products.

This study is restricted to micro/nanofabrication technologies. As a series of predominantly micro-scaled technologies are also included, the term micro/nanofabrication technologies will be used in the remainder of this study. Despite its imminent importance and the large amount of social science studies on N&N – Huang et al. (2011) evaluated more than 120 different publications – few studies have attempted to approach N&N from a manufacturing perspective. Some exceptions are those of Invernizzi (2011), Islam (2010), and Kautt et al. (2007), among others. Moreover, the majority of research efforts have mainly approached the N&N field from an aggregate perspective; hence, leaving aside the understanding of the different component technologies making up the N&N field. These are the reasons for selecting this technology.

The International Standard Organization (ISO) has recently proposed a standardized definition for nanomanufacturing as the "intentional synthesis, generation or control of nanomaterials, or fabrication steps in the nanoscale, for commercial purpose" (ISO, 2010). Other definitions tend to stress the role of nanomanufacturing in the production of nanotechnology-enabled products "in market-appropriate quantities in a reliable, repeatable, economical and commercially viable manner" (Postek and Lyons, 2007). Furthermore, USA's National Nanomanufacturing Network (NNN) defines nanomanufacturing as "all manufacturing activities that collectively support practical approaches to design, produce, control, modify, manipulate, assemble, and measure nanometer scale elements or features for the purpose of realizing products or systems that exploit properties seen at the nanoscale" (NNN, 2011). From these definitions, it can be clearly seen that nanomanufacturing embraces a broad nature, particularly aimed at producing nano-enabled products ready for commercialization. In contrast, nanofabrication depicts the scientific and technological toolbox available to N&N actors for supporting their nanomanufacturing-related activities. Here, nanofabrication has been defined as "the set of techniques to pattern, grow, form and remove material with near nanometer control, repeatability and precision" (Dew and Stepanova, 2012). Technically, literature has typically classified micro/nanofabrication technologies into two general categories: 'top-down' and 'bottom-up' approaches (Islam and Miyazaki, 2006). The former relates to traditional technologies such as lithography, etching, cutting, etc. which break a bulk material into smaller desired features. The latter entails the use of materials at atomic or molecular scales as building blocks for more complex nanoscale assemblies, some examples are chemical synthesis, self-assembly, etc. (Tseng, 2008).

A better understanding of the positioning of micro/nanomanufacturing and micro/nanofabrication within the N&N field can be gained from Fig. 3.7. The top of Fig. 3.7 shows the nanotechnology value chain and the nano-enabled product generations described in Section 3.2.4. These are underpinned by a series of 'process chains' embracing the sequence of activities involved in the design, processing, assembly, control and measurement of micro/nano-enabled products (Alting et al., 2003). For the sake of clarity, the process chain shown in Fig. 3.7 is denoted by a linear arrangement; yet, in reality it is characterized by a complex set of interplays and feedbacks, and overlapped chains. This level entails the field of nanomanufacturing. At the bottom of Fig. 3.7 the array of punctual technologies, or the scientific and technological toolbox, is found. These support the different activities of the process chains. This level is associated with micro/nanofabrication technologies. The different levels in Fig. 3.7 are highly interrelated; here, changes in a particular level imply changes in other levels.

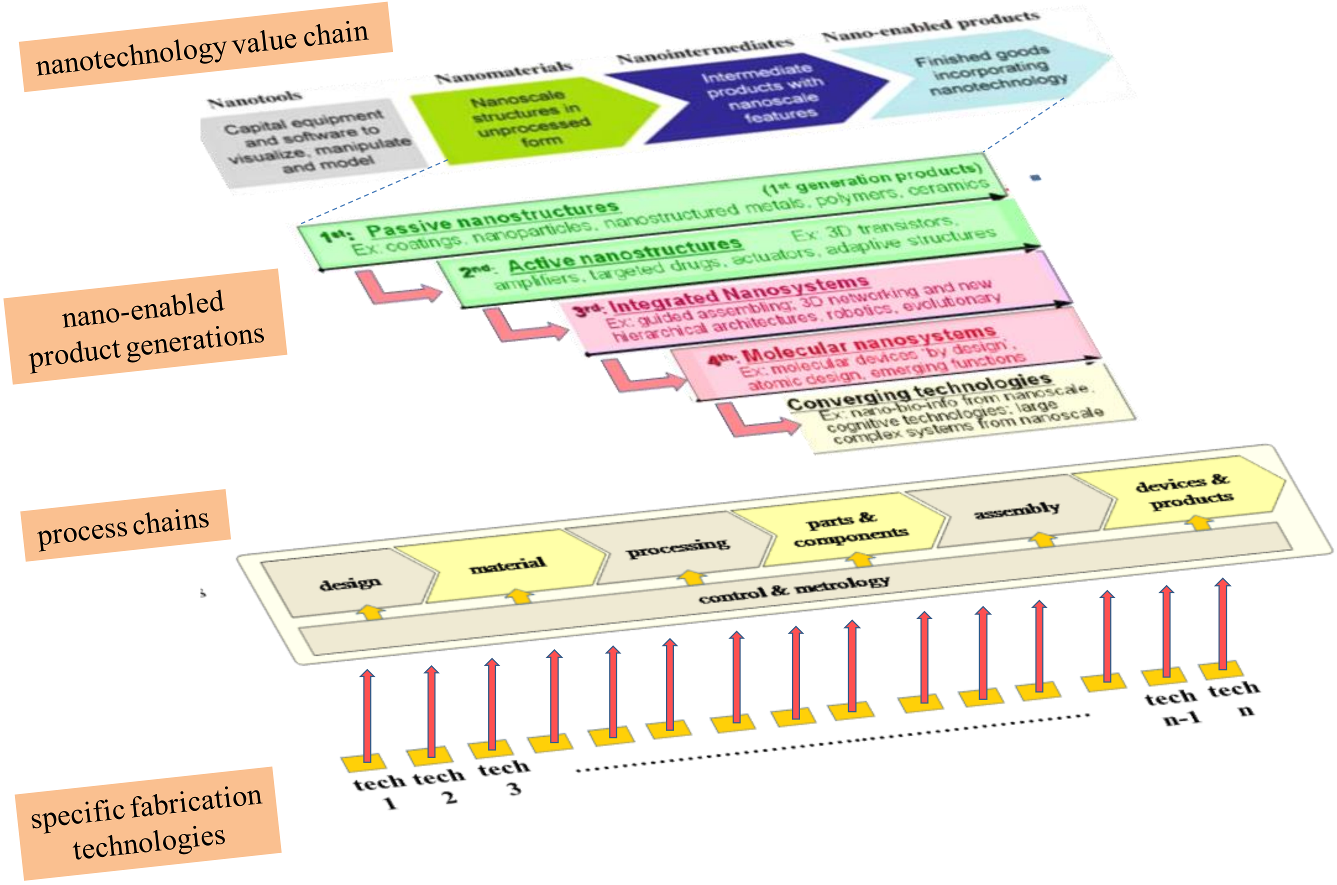


Fig. 3.7 Development and fabrication of micro/nano-enabled products (based on Alting et al., 2003; Lux Research, 2007; and Roco, 2004)

3.3.4. Micro/nano-enabled products – Microfluidic Diagnostic Technologies

The last block of the nanotechnology value chain refers to the final nano-enabled products available in the market. As described above, given the enabling properties of N&N, the outcomes of this block are reflected in a wide range of products. This study is focused on micro/nanofluidics-based point-of-care diagnostic technologies (NMDT/POC). As such, the following paragraphs provide a description of micro/nanofluidics, in-vitro diagnostics, and point-of-care technologies.

3.3.4.1. Microfluidics

Microfluidics refers to "…the science and technology of systems that process or manipulate small (10-9 to 10-18 litres) amounts of fluids, using channels with dimensions of tens to hundreds micrometres" (Whitesides, 2006). Gradually, progresses in the field of nanotechnology are moving microfluidics into nanofluidics, which is characterized by ever lower amounts of fluids in ever smaller fluidic channels. Fig. 3.8 shows the evolution of the microfluidics field over time.

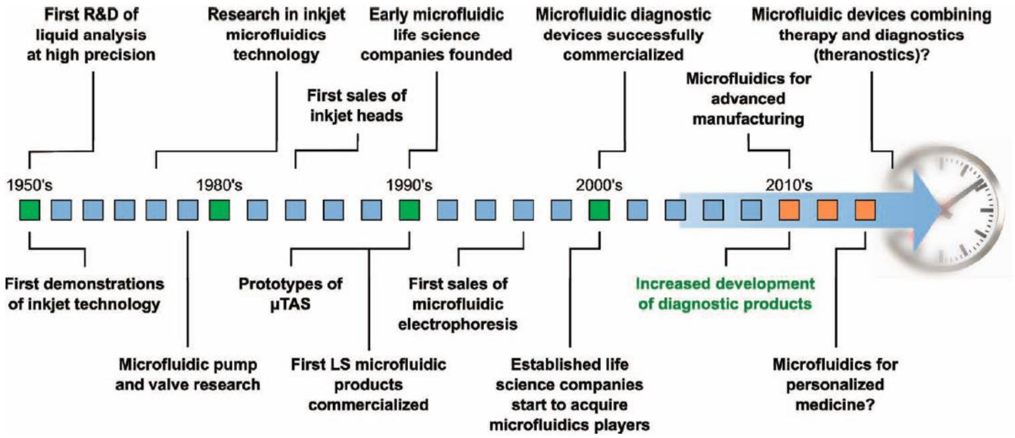


Fig. 3.8 Timeline for the development of microfluidics (Gervais et al., 2011)

The following lines rely on Gervais et al. (2011) and Whitesides (2006). The earliest attempts to dispense small amounts of fluids can be traced back as early as the 1950s with the pioneering efforts in ink-jet technology. Years later, microfluidics emerged as an analytical tool for chemistry and pharmaceutical research particularly driven by the development of the first micro-analytical device, a miniaturized gas chromatograph (GC), by S.C. Terry and researchers from Stanford University in 1979. This invention was followed several years later by the first high-pressure liquid chromatography (HPLC) column microfluidic device in 1990 by A. Manz and his colleagues at the Hitachi Central Research Laboratory. Also, the late 1980s and early 1990s saw the proliferation of efforts aimed at developing microfluidic components such as valves, mixers, reactors, separators, and pumps, particularly relying on silicon micromachining technology. The accumulated research resulted in the development of miniaturized total chemical analysis systems (micro-TAS) by A. Manz and his group at Ciba-Geigy AG (Switzerland) in 1990. In a sense, micro-TAS paved the way for the use of microfluidics as an enabling technology for the integration of multiple analytical steps into a single chip. Now, the term 'micro-TAS', although still used in the literature, has been mainly supplanted by the term 'lab-on-a-chip'. Thereafter, the mid-1990s and early 2000s saw the creation of different microfluidic life science companies such as Caliper Life Sciences, Cepheid, Agilent, etc.

Typical markets associated with microfluidics are biotechnology, drug delivery, ecological monitoring and medical applications. The main advantages of miniaturized fluid handling are: “faster reaction times, integration of multiple functions with reduced sample handling, improved reaction control, inherent scalability, reduced reagent and sample consumption and hence lower cost, and the ability to make portable systems” (Webb et al., 2009).

Fig. 3.9 shows that microfluidics represents a relatively emerging technology in terms of its recent and accelerated rates of growth in the number of scientific publications and granted patents. In Fig. 3.9, the stars in both lines depict the year when more than five publications or patents were accumulated.

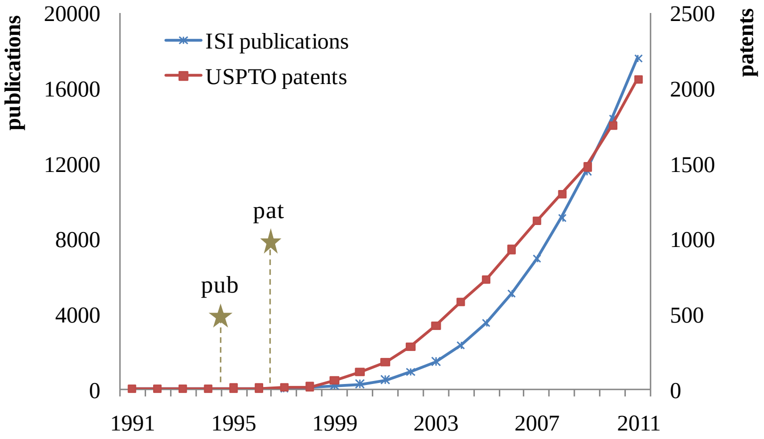


Fig. 3.9 Longitudinal evaluation of publications and patents (author’s own compilation)

A wide range of terminologies have been used in the literature for microfluidic-related devices: microchips, microarrays, biochips, nanochips, bioelectronic chips, bioMEMS, fluidic MEMS, biosensors, etc. Conceptually, there are differences among them; nevertheless, as this study is interested in the integration of multiple laboratory processes into a single chip, the remainder of this study focuses on the term ‘lab-on-a-chip’ (LOC). LOCs comprise sensors and devices integrating different functions such as handling and preparation, mixing, separation, detection, etc. into a single miniaturized device or chip (Bashir, 2004). Hence, in short, a microfluidics-based LOC is an integrated multi-functional devices handling and experimenting with minute volumes of fluids within a single chip. LOC-based innovations embed a highly interdisciplinary set of technological, scientific and operational fields – such engineering (biomedical, chemical, electrical and mechanical), chemistry, and physics, microfluidics, micro/nanofabrication, integration, materials science, detection technologies (Sia and Kricka, 2008).

In particular, highly positive expectations are being placed on the application of microfluidics/LOC technologies in the development of complex, highly miniaturized point-of-care diagnostic devices (POC). Next section touches upon In-Vitro Diagnostics and Point-of-Care technologies.

3.3.4.2. In-vitro-diagnostics (IVD) and Point-of Care

In-vitro-diagnostics (IVD) are tests conducted on samples taken from the human body, such as saliva, blood, urine, serum, nasal secretions, sweat, and cerebrospinal fluids, among others. As such, IVD spans over a wide range of diagnostic segments such as clinical chemistry, immunochemistry, hematology, microbiology, and molecular diagnostics (The Lewin Group, 2005) (Table 3.2).

Table 3.2 Market segments for In-vitro Diagnostics (The Lewin Group, 2005)

Market segment	Description
Clinical chemistry	Measurements of base compounds in the body
Immunochemistry	Match antibody-antigen response to indicate the presence or level of a protein
Hematology/Cytology	Study of the blood, blood-producing organs and cells of the body
Microbiology/Infectious diseases	Detection of disease causing agents
Molecular diagnostics	Study of the DNA and RNA to detect genetic sequences that may indicate presence or susceptibility to disease

Based on market report data (YoleDeveloppement, 2010), the In-Vitro Diagnostics market was worth US $45.5 billion in 2008 with a compounded annual growth rate of around 14%. Point-of-Care (POC), a particular market within In-Vitro Diagnostics, is characterized by being the fastest growing market segment (Melo et al., 2011). Moreover, in terms of its market volume, POC currently represents the second market for microfluidic devices (YoleDeveloppement, 2012). POC encompasses those devices performed outside a central which are easy to move into the vicinity of the patient and, if necessary, capable of being operated under field conditions without the need for highly specialized personnel (Melo et al., 2011). POC devices have also been referred in the literature as wearable, hand-held tests, and bench-top devices, among many other names. The POC market is characterized by a high fragmentation; typical POC market segments are: home tests (glucose, pregnancy, etc.), doctor office screening (cancer, cardiac markers, etc.), emergency tests, decentralized hospital tests, environment testing, forensic and military, third world infections, and agro-foods. From these, devices for glucose monitoring, blood chemistry and electrolyte, and pregnancy testing dominate the POC market. Together, these represent more than 70% of the POC market (YoleDeveloppement, 2012). Moreover, POC technologies can be applied in the four most common centralized laboratory techniques: blood chemistries, immunoassays, nucleic-acid amplification tests and flow cytometry (Yager et al., 2006).

POC devices are, by far, not new as seen in the hand-held blood glucose meters monitoring the sugar levels of diabetes patients and lateral-flow test strips for pregnancy testing. Despite this, as later chapters will show, there are plenty of additional application domains demanding fundamentally different from those provided by conventional technologies. In turn, this call for the development of novel methods and devices (Linder, 2007). This is where microfluidic technologies come into play. Particularly, these are the types of technologies that this thesis will be focusing on. As defined in the beginning of this section, these technologies will be referred in this thesis as micro/nanofluidics-based point-of-care diagnostic technologies (MNDT/POC). A typical example of MDT/POC is illustrated in Fig. 3.10.

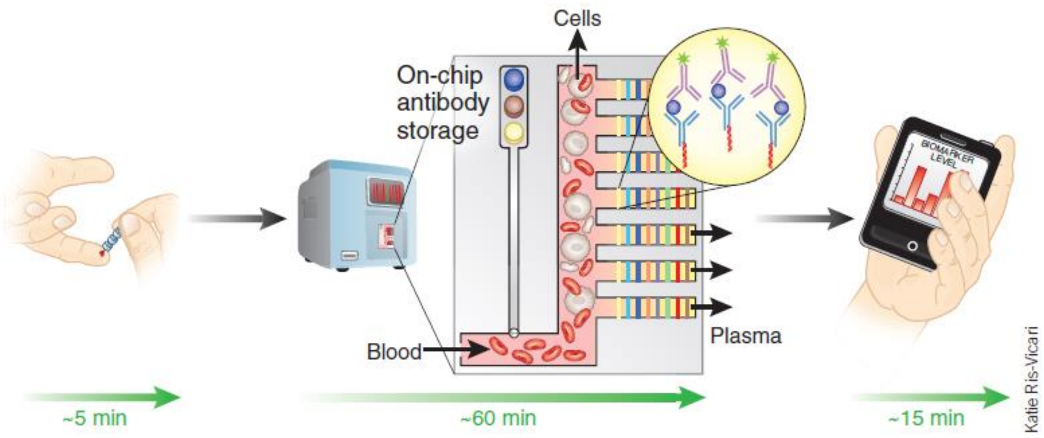


Fig. 3.10 Schematic of the workflow of potential MDT applications (Sorger, 2008)

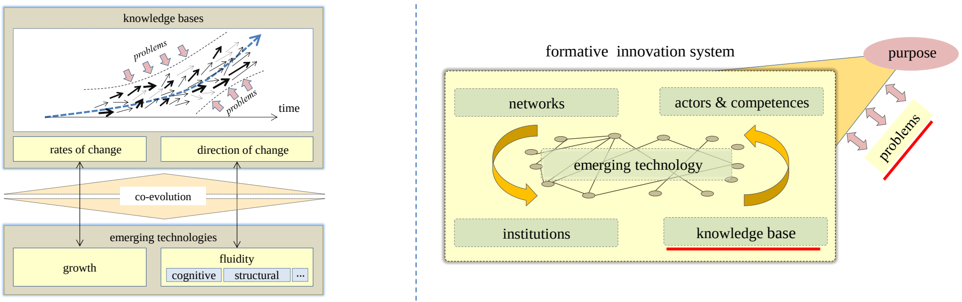
Fig. 3.10 schematically depicts the possible workflow for a certain type of microfluidic system (based on biomarker assays), as defined by Sorger (2008). This workflow runs as follows. After the introduction of the collected blood sample into the fluidic chip, the blood undergoes a separation process into cells and plasma. Multiple analytes are then captured from the plasma by patterned antibodies immobilized on the surface of the chip. After washing and introducing secondary reagents, the analyte levels can be read through the use of a hand-held device.

The reasons behind the selection of the case of MNDT/POC are three-fold. First, microfluidics in general and microfluidic diagnostics in particular are characterized by significantly high expectations in terms of market size and market growth rates (YoleDeveloppement, 2012). For some, POC is regarded as a potential killer application in the microfluidics market (Becker, 2009). Second, few business-related research has been conducted in the field of microfluidics (Becker, 2009). Third, this technology promises to revolutionize diagnostics by enabling rapid clinical tests at near-patient settings.

3.4. Summary

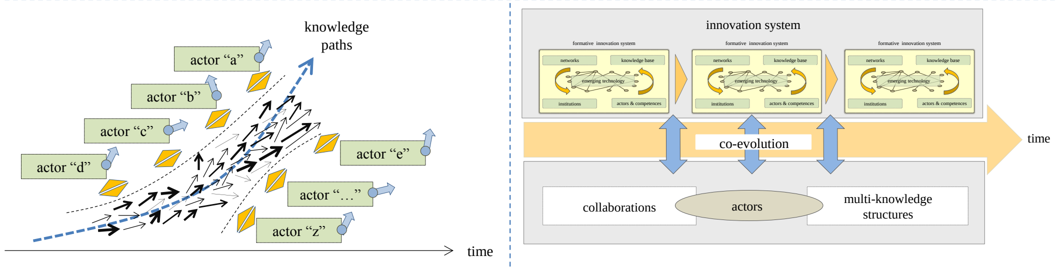
This chapter provided background information on the cases studies to be analyzed in this thesis, namely micro/nanotechnologies and micro/nano-enabled technologies. In this chapter, it was seen that micro/nanotechnologies and micro/nano-enabled technologies are denoted by different product generations and that technological change in this field appears to be taking place along the nanotechnology value chain. Particularly, as it was explained, the ‘nanotechnology value chain’ depicts the conceptual structure behind the arrangement for the subsequent chapters of this study. Relying on the nanotechnology value chain, this chapter continued with the description of the different specific technological case studies to be analyzed in the following chapters. The approach taken in this chapter consisted in selecting a representative emerging technology for each of the four building blocks of the nanotechnology chain: ZnO one-dimensional nanostructures for nanomaterials, MEMS/NEMS technologies for intermediate products, micro/nanofabrication technologies for tools and instrumentation, and microfluidic diagnostic POC devices for end products. The reasons behind the selection of each of these technologies were also discussed in this chapter.

Coupled with the discussions of the previous chapter, Fig. 3.11 relates the conceptual models described in Section 2.5 with the different specific technologies discussed in this chapter.



Micro/Nanoelectromechanical systems

Zinc Oxide one-dimensional nanostructures



Micro/nanofabrication technologies

Microfludics-based point-of-care diagnostic systems

Fig. 3.11 Allocation of technologies to each of the conceptual models

Each of these ‘conceptual model – technological case studies’ couplings will be described from Chapter 5. Finally, it should be pointed out that the contents of this chapter were mainly restricted to an overview of these technologies. More detailed information will be provided in the corresponding analytical chapters of this thesis.

4. Research Methods and Data Sources

4.1. Introduction

This chapter attempts to provide an overview of the different research methods and sources of data to be used throughout this study for answering the research questions posed in previous chapters. Section 4.2 discusses the theoretical underpinnings of the different research methods to be used in this thesis. Section 4.3 and Section 4.4 continue with the description of the bibliometric mapping and social network analysis approaches, which may be regarded as the core methods of this thesis. Section 4.5 describes additional bibliometric indicators. Finally, Section 4.6 briefly summarizes this chapter.

4.2. Bibliometrics

Bibliometrics is the main general research method underpinning the analyses of this thesis. Although bibliometric approaches have been typically associated with scientific publications (Verbeek et al., 2002), this thesis visualizes bibliometrics from a broader perspective. In line with Porter and Detampel (1995), bibliometric approaches are regarded as encompassing the use of publications, patents and/or their citations targeting the measurement and interpretation of scientific and technological advances. In broader terms, the use of bibliometric approaches is underpinned by two general assumptions (Bassecoulard and Zitt, 2004): a) publications provide a good representation of the contents of science, and b) patents embody a large part of technological information. Furthermore, it should be kept in mind that bibliometric data – scientific publications and patents – mainly depict highly codified theoretical and practical knowledge and know-how; thus, they tend to overlook tacit knowledge (Bassecoulard and Zitt, 2004). Within this backdrop, bibliometric data should be better visualized as quantitative measures defining proxies or approximations of a complex system (Tijssen et al., 2002). This is the way bibliometrics is regarded in this thesis.

Before embarking into the description of the main research methods, the rest of this sub-section touches on general information on scientific publications and patents.

4.2.1. Scientific publications

4.2.1.1. General aspects of scientific publications

Scientific publications represent one of the tangible outcomes of the scientific process. Obviously, scientific publications are not the only aspects active in the generation and dissemination of knowledge, but they are definitely crucial (Huang et al., 2011). A scientific publication refers to any written material, physical or electronic on scientific research activities (Verbeek et al., 2002), be it journal papers, conference proceedings, reviews, meeting abstracts, and book chapters, among others. Publications are composed of metadata fields, such as the title, the names of the authors and their affiliation, the date of publication, the body of the text, and the list of references. Additionally, a series of keywords or classification codes are included by the authors or indexers according to the contents of the publication; these may also include, in some cases, the use of controlled vocabulary and classification schemes. Any of the above-mentioned aspects may be used for the conduction of bibliometric analyses.

Some of the merits scientific publications are their role as powerful aids for identifying and comparing systematic features of research systems and institutions; they also provide an objective external description of scientific performance, as well as enable the dissemination of quantitative information on the scientific realm (Tijssen et al., 2002). As such, publications are regarded as a reflection of the general scientific research in a particular field (Miyazaki, 1995). Also, the shorter time lags of publications over those of patents make publications more suitable for assessing emerging technologies (Porter et al., 2002). Finally, scientific publications may perform as reliable ‘signals of scientific competence’ (Debackere et al., 1996). Conversely, publication-based bibliometric approaches have been associated with a series of drawbacks. Some of those frequently encountered in the literature are the existence of field-specific biases underlying bibliometric data such as the different publication propensities across fields, the inability of journal publications to represent the multi-dimensionality of scientific activity, and the difficulties in delineating research fields within an area or its demarcation from different areas (Moed, 2005; Schmoch and Schubert, 2009; Tijssen et al., 2002). Given the plethora of research efforts relying on publication data, it is obvious that these limitations have not prevented the widely diffusion of publication-based bibliometric approaches among the technology and innovation management community. The present thesis is not an exception.

4.2.1.2. Data sources for scientific publications

There are a wide array of data sources from which bibliographic information can be retrieved: CiteSeerX (http://citeseerx.ist.psu.edu), arXiv (http://arxiv.org), ISI/Web of Science (WoS) (http://www.isiknowledge.com) from Thomson Reuters, Engineering Village (http://www.engineeringvillage.com), Scopus (http://www.scopus.com) from Elsevier, Chemical Abstracts Service (http://www.cas.org), PubMed Medline (http://www.ncbi.nlm.nih.gov/pubmed) administered by the National Library of Medicine, and Google Scholar (http://scholar.google.com), among others. Some of these bibliographic databases are commercial, others freely available. Moreover, each of these databases is characterized by aspects such as their journal coverage, the type of metadata available, easiness-of-use of their interface, etc.

For this study, the ISI/WoS database was selected as it is readily available at the Tokyo Institute of Technology; also, it is one of the few databases providing the list of cited references from the indexed documents. The on-line version of this database is the Science Citation Index Expanded (SCIE) which includes more than 8,300 journals across 150 disciplines, as of 2011 (Thomson-Reuters, 2011). Moed (2005) provides a detailed description, in terms of a series of empirical research studies, of the properties of the ISI/WoS database. Some of the limitations that have been associated with the ISI/WoS database are indexing of a limited number of journal titles, coverage of mainly English-language titles from North America and Western Europe, the lack of citations from books and conference proceedings, as well as the discipline-dependent coverage (Moed, 2005). Despite that, ISI/WoS is, by far, the database most often used for the conduction of bibliometric methods.

4.2.2. Patents and their data sources

4.2.2.1. General aspects of patents

Similar to Debackere et al. (2002), next Griliches (1990) is quoted as he provides a clear description of the definition of a patent:

> *"A patent is a document, issued by an authorized governmental agency, granting the right to exclude anyone else from the production or use of a specific new device, apparatus, or process for a stated number of years. The grant is issued to the inventor of this device or process after an examination that focuses on both the novelty of the claimed item and its potential utility. The right embedded in the patent can be assigned by the inventor to somebody else, usually to his employer, a corporation and/or sold to or licensed for use by somebody else. This right can be enforced only by the potential threat of or an actual suit in the courts for infringement damages." (Griliches, 1990: 1662-1663).*

Hence, a patent may be defined as an intellectual property right issued by authorized bodies – national and international patent offices – that gives its owner the legal right to prevent others from using, manufacturing, selling, or importing, the property in the country concerned, for a period of up to 20 years from the filing date. As such, patents are regarded as reflections of the general technological research in a particular field. Patent analyses typically distinguish between two types of patents: granted patents and patent applications. The former embrace those filed patents that have already been granted, while the latter depict those patents, still to be granted, with a period of 18 months since their date of application. Similar to scientific publications, patent documents comprise of metadata fields, such as title, inventors and affiliation, assignee and affiliation, abstract, cited references, claims, and specifications. As may be inferred, each of these aspects may be used for the conduction of patent-based bibliometric analysis. In this regard, Tseng et al. (2011) provides a detailed description of the potential bibliometric indicators that may be derived from patent data.

Over the years, the research community has regarded patents as obvious candidates for analyzing technological change and processes of invention. As such, they have been applied for discussing R&D inputs and outputs, measuring a company's technical abilities, planning companies' strategies, and discussing market value and financial performance (Tseng et al., 2011). Nevertheless, it should be kept in mind that patents are only a partial measure of the inventive activities of organizations (Tijssen, 2001). In this regard, Table 4.1 illustrates the series of benefits and limitations associated with the use of patents.

Table 4.1 Benefits and limitations of using patent information to compare innovation rates of different sector (OECD 2008)

Benefits	Limitations
+ Patents are closely linked to inventions. + Patents cover a broad range of technologies for which few other data sources are available. + Each patent document contains detailed information on the inventive process + Patent data are quite readily available from national and regional offices + The coverage of patent data in terms of space and time is unique, extending back into the 19th century.	- Not all inventions are patented - The propensity to file patent applications differs significantly across technical fields - The value distribution of patents is highly skewed; many patents have no industrial application, whereas a few are of very high value - Differences in patent laws and practices around the world limit the comparability of patent statistics across countries - Changes in patent laws call for caution when analyzing trends over time - Patent data are complex, because they are generated by complex legal and economic processes - Patents are not always classified by economically relevant industry or product lines

From these limitations, the fact that not all inventions are patented is a major limitation. As defined by Arundel and Kabla (1998), a relatively small proportion of inventions are patented; this is highly sectoral-dependent. What is more, the economic value varies across fields (Griliches, 1990), in particular sectors such as pharmaceutical, chemicals, biotechnology, and machinery appear to be those sectors in which patents are of greatest value (Harabi, 1995). Moreover, patents may be used for different strategic reasons besides the building up of technological competences (Cohen et al., 2000). Thus, at a deeper level, holding a patent does not necessarily reflect the mastering of knowledge in a particular field of knowledge (Carlsson et al., 2002). In this regard, alternative methods of appropriation are lead-time advantages, technical complexity, high investment costs, among others. Yet, what reasons are behind organizations patenting or not patenting; here, Davis (2006) highlights that organizations take out patents as a protection against imitation, the establishment of a legal basis for cooperation, their use as strategic signals and as indicators of value. Conversely, he regards as possible reasons for not taking out patents as: problems associated with the application process, problems relating to preventing imitation, problems relating to patent infringement, patents are not suitable given nature of information concerned, and firms prefer the use of other means to appropriate value.

4.2.2.2. Data sources for patents

Patent data may be retrieved from a variety of databases. In particular, two main types of databases may be distinguished: those commercially available and those publicly available. Typical examples of the former are: LexisNexis' TotalPatent (http://www.lexisnexis.com/en-us/products/total-patent.page), Thomson Reuters software suites (Derwent, Delphion, Inspec, and MicroPatent), and PatentHunter (http://www.patenthunter.com), among others. Each of those databases varies according to aspects such as data coverage, special indexing, update frequency, search interface functionality, etc.[3]. In contrast, the latter, on the one hand, comprises the patent databases provided by the different national patent offices, such as the United States Patent and Trademark Office (USPTO: http://www.uspto.gov), European Patent Office (EPO Esp@cenet: http://www.espacenet.com), Japan Patent Office (JPO: http://www.jpo.go.jp), and World Intellectual Property Organization (WIPO: http://www.wipo.int), among others. On the other hand, a series of free patent databases provided by independent companies and individuals are also common, such as FreePatentsOnline (http://www.freepatentsonline.com), PatentStorm (http://www.patentstorm.us), and GooglePatents (http://www.google.com/patents), among others.

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[3] A comparison of the different data sources for patents can be found in the following websites:
http://piug.wildapricot.org/vendors#OnlineServices;
http://www.intellogist.com/wiki/Compare:Patent_Search_System

This study makes use of the USPTO and EPO databases. The main reason behind their selection is the readily availability of these databases. As later chapters will show, this comes with the trade-off of an exhaustive pre-processing stage. The use of the USPTO database has been common in the literature as it has been argued that the U.S. technological market depicts the most important market in the world (Pavitt, 1985; Schmoch, 2009). Moreover, given the time and costs involved in the process of patent application in the USPTO office for foreign applications, it is usually inferred that those patents are characterized by a higher quality (Vertova, 2001). Moreover, as this database was one of the first to be available electronically, its use is well-established within the research community (Schmoch, 2009). In comparison to other databases, the reasons behind the selection of the EPO database are three-fold: (a) publicly available database, (b) the possibility to take into account 'patent families', i.e. similar inventions being filed in multiple countries, and thus avoid double-counting issues, and (c) the possibility to draw patents from a multitude of patent databases, such as United States Patent Office (USPTO) in terms of patent applications and granted patents, European Patent Office (EPO), Japan Patent Office (JPO), World Patent Office (WIPO), and several domestic patent offices.

4.3. Bibliometric mapping

Bibliometric information, i.e. publications, patents, and their citations, has been regarded as an adequate source for the mapping of scientific and technological fields and sub-fields (Verbeek et al., 2002). Bibliometric mapping – also defined as science mapping, domain visualization, information/knowledge visualization, scientography – entails an attempt 'to find representations of intellectual connections within the dynamically changing system of scientific knowledge' (Cobo et al., 2011). In this thesis, 'bibliometric mapping' lies at the heart of the research methods used. For the purposes of this study, 'bibliometric mapping' refers to the mapping of both scientific publications and patents. Mapping approaches aim at displaying the *structure* and *dynamics* of scientific (or technological) research into two or three dimensions (Cobo et al., 2011; Noyons, 2001). In these maps, items – be it authors, documents, or organizations – are positioned relative to each other according to their cognitive relatedness; i.e. the closer, the more cognitively related they are (Noyons, 2001). One of the main benefits of this approach to be exploited throughout this study is the possibility to 'unravel the immense network of interrelated pieces of knowledge, and to uncover major 'hidden patterns' in the vast amount of information carried by the scientific literature' (Verbeek et al., 2002). Over time, different approaches have been developed to extract networks/maps from bibliometric data, e.g. co-word, co-authorship, bibliographic coupling, co-citation analyses, co-classification, among others (Cobo et al., 2011). A commonality among those approaches is their reliance on co-occurrence information, i.e. the number of times two elements appear together in a publication (or patent), be it words (co-words), authors (co-authorships), source articles (bibliographic couplings), and cited references (co-citations). The conduction of bibliometric mapping approaches follows, more or less, standardized steps, as defined by Börner et al. (2003) and Cobo et al. (2011). Later sections will discuss these steps in greater detail.

The rest of this section provides a more detailed description of the different bibliometric mapping methods used in this study: co-citation network analysis, co-word analysis, and co-classification analysis. Thereafter, detailed information on the research methods used to construct these bibliometric mappings will be provided.

4.3.1. Co-citation network analysis

Co-citation analysis is a citation-based technique that relies on the list of cited references, also referred as 'backward citations'. A co-citation refers to when two publications are cited together in an article, i.e. publications *C1* and *C2* are appear together in publication *P1*; conversely, bibliographic coupling which is another common citation-based technique, focuses on publications sharing common cited references, i.e. both publications *P1* and *P2* citing publication *C2* (Fig. 4.1).

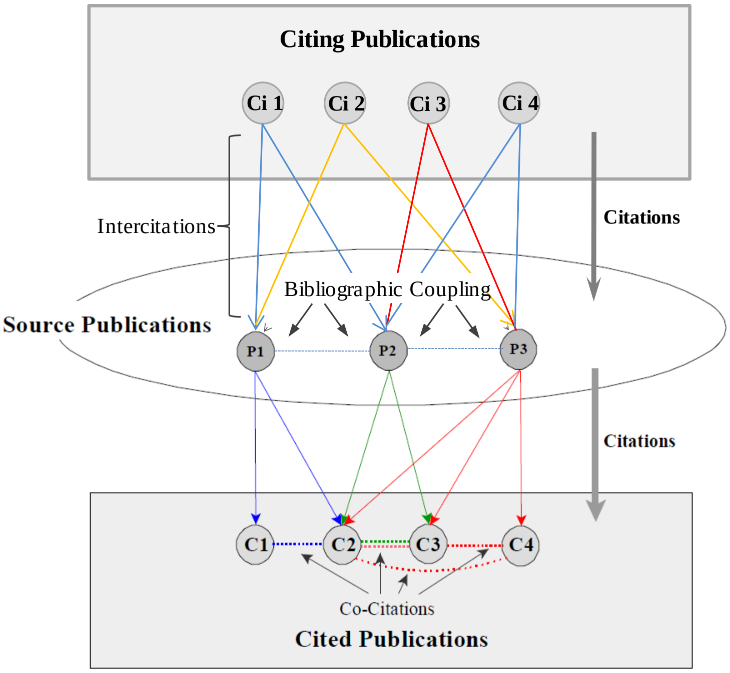

Fig. 4.1 Co-citation analysis and bibliographic coupling (adapted from (Noyons et al., 2004))

Whereas co-citation networks are visualized as knowledge bases, bibliographic coupling depicts research fronts. Compared to bibliographic coupling, co-citation analysis is more time-dependent as publications can only be cited by other researchers after publication. Moreover, as references vary over time, co-citation analysis shows dynamic characteristics. As will be seen, those properties will be exploited in this study. Besides co-citations and bibliographic coupling, an additional citation-based approach is intercitation analysis which refers to the direct citations among the source publications and those citing those publications (Fig. 4.1).

In general, cited references define the earlier publications underpinning the research of a particular author. Different perspectives on the aspects measured by cited references abound; here, Moed (2005) has compiled the views from thirteen different researchers. In this study, the list of cited references is regarded as key aspects for defining the 'socio-cognitive' location of publications; as such, they are visualized as an interpretation of the manifestation of intellectual influences impinging upon a particular research (Moed, 2005). Others have similarly stressed the cognitive connotations of cited references (Noyons, 2001; Shapira et al., 2010). As will be shown in later chapters, this study will exploit the cognitive characteristics of cited references through the use of co-citation analysis.

Co-citation analysis was pioneered simultaneously by Small (1973) and Marshakova (1973). Typically, co-citation analysis is conducted on documents (publications, but also patents), on the authors of the publications (Author Co-citation Analysis, ACA), or on journals (Journal Co-citation Analysis, JCA). From its outset, the main aim of co-citation analysis has been to dynamically model the intellectual structure underlying a particular field. This is related to the use of co-citation analysis for tracing epistemic links and the evolution of scientific and technical fields (Mina et al., 2007). The basic assumption in co-citation analysis is that publications frequently cited together are related in subject matter (Tsay et al., 2003). Additional assumptions behind co-citation analysis are as follows: (a) citation implies use, (b) citations and use are based on merit or degree of influence, (c) co-citations reflect similarity of content, merit, or influence, and (d) all citations are equal (Verbeek et al., 2002). In this case, the more frequent particular publications are co-cited, the stronger their similarity; in turn, the closer they are positioned in the map or network. Over the years, co-citation network relationships have been visualized in terms of 'intellectual bases or intellectual structures' of fields (Persson, 1994; White and McCain, 1998), 'knowledge domains' (Small and Greenlee, 1986), 'invisible colleges' (Gmür, 2003; Zuccala, 2006), 'research problem areas' (Franklin and Johnston, 1988), paradigms (Small, 2003), among others. Recently, there has been an explosion in the use of co-citation analysis for the understanding of intellectual structures of social science disciplines: strategic management (Nerur et al., 2008; Ramos-Rodriguez and Ruiz-Navarro, 2004), electronic commerce (Shiau and Dwivedi, 2012), strategic alliances (Di Guardo and Harrigan, 2011). Given the ability of co-citation analysis to reveal the knowledge underpinning a particular field, it was decided that co-citation analysis depicted the best method for the analyses to be presented in Chapter 5 and Chapter 6.

Co-citation data is not exempt of limitations; here, main drawbacks typically listed in the literature are: the focus on the first author of a paper, the inclusion of self-citations, crony citations, ceremonial citations and negative citations, exhaustive data sorting and cleaning procedures, variation of the results according to the selection criteria for co-citation relations, problems with author homonyms, among others (Hicks, 1987; MacRoberts and MacRoberts, 1996; Verbeek et al., 2002). Many of these limitations disappear with a large sample of publications as the consensus of the bulk of authors tend to prevail (Vargas-Quesada and Moya-Anegón, 2007). Conversely, one of the main advantages of co-citation approaches is the relative easiness with which they can be visualized into networks; a property to be exploited in this thesis.

4.3.2. Co-word analysis

Since the pioneering efforts by Callon et al. (1979) in the mid-1970s, co-word analysis has been regarded as a bibliometric tool capable of mapping the dynamics of the knowledge structure underlying a particular field. In this regard, Kostoff (1993) provides a historical evolution of the co-word technique. For Callon and co-workers, the rationale behind the selection of words instead of cited references relied on their doubts about the citing behavior of scientific authors (Noyons, 2001). Similar to co-citations, co-word analysis relies on co-occurrence data. As such, co-word analysis reveals the patterns of association underlying publications based on the number of times two words from titles, abstracts, or texts appear together, i.e. co-occur, in scientific publications or patents. The more frequent particular words appear together in a publication, the stronger their similarity. For Verbeek et al. (2002), those areas of strong similarity constitute ‘problem areas’ or ‘research themes’. A basic assumption underlying this type of analysis is that a research field can be characterized by a list of important keywords (Börner et al., 2003). For the nanotechnology field, co-word analysis has been used by Bhattacharya et al. (2012); Bonaccorsi and Thoma (2007); Lee and Su (2011); Lee et al. (2010) and Leydesdorff and Zhou (2007), among others. In contrast to other bibliometric methods, e.g. co-citation analysis, co-author analysis, among others, co-word analysis approaches provide a more direct access to the research topics of a field (van den Besselaar and Heimeriks, 2006). Assuming words as a representation of technical thrust areas, co-word analysis may be helpful in unraveling the interrelation and evolution of the research thrusts in a particular field (Kostoff, 1993). This is the main rationale behind the selection of the co-word analysis for Chapter 7.

Co-word and co-citation analyses are not mutually exclusive, as shown in the series of research efforts attempting to combine both approaches, such as Braam et al. (1991a, b) and van den Besselaar and Heimeriks (2006).

Finally, co-word analysis has not been exempt of criticism. Some of the typical limitations associated with this approach are: words may have other than purely descriptive purposes, words are not always unambiguous, their meaning is often context dependent, a concept may be perceived differently by different researchers, among others (Chau et al., 2006; Kostoff, 1993; Leydesdorff, 1997).

4.3.3. Co-classification analysis

Co-classification analysis: It reveals the relationships between classification categories in scientific publications or patents appearing together. For the case of scientific publications, ISI/SCI database allocates one or more journal subject categories to publications according to the nature of the contents of the journal (Moed, 2005). As of now, ISI/SCI database encompasses more than 170 different journal subject categories. Taking aggregately, journal subject categories may provide a proxy for the variety of knowledge (Porter and Rafols, 2009; Rafols et al., 2010b); however, given the journal-based and aggregate nature of their collection, the use of journal subject categories as meaningful indicators have been contested in the literature (Rafols et al., 2010b). On the other hand, for the case of patents, the International Patent Classification (IPC) is used.

4.3.4. Description of the methods used for the bibliometric mapping approaches

This section describes details on the different research methods used for the construction of the different bibliometric mapping approaches used in this thesis. For that purpose, the process flow for mapping knowledge domains discussed by Boerner et al. (2003), as shown in Fig. 4.2. Each of the blocks of the process flow in Fig. 4.2 will be discussed next.

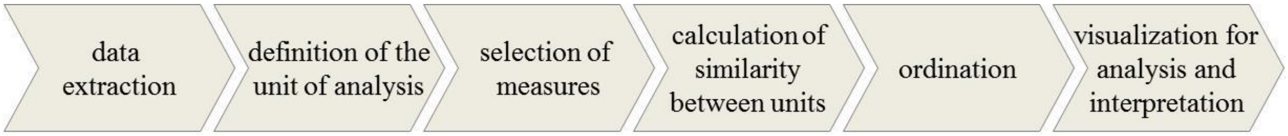

Fig. 4.2 Process flow for bibliometric mapping (Boerner et al., 2003)

Aspects regarding the data extraction, such as search strategies, data pre-processing, etc., will be dealt in the 'research methods' sections of each of the analytical chapters (Chapter 5 – Chapter 8). Similarly, the approaches used for the definition of the units of analysis and the selection of measures can be drawn from Table 4.2. This section will be focusing on the stages 'calculation of the similarity between units' and 'ordination' of the process flow shown in Fig. 4.2. The stage 'visualization for analysis and interpretation' that relies on the use of social network analysis approaches will be discussed in detail in the next section (Section 4.4).

4.3.4.1. Calculation of similarity between units – Salton's cosine similarity

Network normalization aims at providing a better visualization of the similarity structures across the data and to control for size effects. Whether normalization is necessary for co-occurrence data has been a topic of discussion in the literature (Leydesdorff and Vaughan, 2006; Waltman and Eck, 2007). Over the years, an array of similarity measures have been developed in the literature: Salton's cosine, Jaccard's Index, Equivalence Index, and Association Strength, among others (Cobo et al., 2011). From these, it was decided that the best method to adopt for this investigation was the Salton's cosine similarity measure. Its selection relied on two aspects: a) its common use in the literature for the analysis of co-occurrence data (Cobo et al., 2011), and b) the availability of this type of normalization embedded in the tech-mining software used (VantagePoint). In particular, the binary or standardized implementation of the Salton's cosine was used, which is defined as follows:

$$\mathrm{S_s(i,j)} = \frac{\mathrm{coc(i,j)}}{\sqrt{\mathrm{cit(i)} * \mathrm{cit(j)}}} \qquad [1]$$

where $S_s(i,j)$ stands for the cosine-normalized co-citation strength between cited references i and j, coc(i,j) entails the number of co-citations between cited references i and j, and cit(i) and cit (j) depict the number of citations for the cited references i and j respectively.

Another important step is the definition of the threshold for the cosine values of the normalized networks. This is a necessary step for the proper visualization of the cosine-based networks as they are often almost complete (Leydesdorff and Rafols, 2009). For Leydesdorff and Rafols (2009), the definition of the threshold cannot be set analytical. However, Egghe and Leydesdorff (2009) have recently specified an algorithm for obtaining a threshold for the cosine value expected to optimize the visualization. For the purposes of this thesis, the definition of the thresholds for the cosine values was carried out experimentally. In this approach, the changes in the visualization of the networks were observed by changing the threshold for the cosine values with the help of the software UCINET/NetDraw.

Table 4.2 Comparative table of the research methods used in the subsequent chapters of this thesis

	Chapter 5	Chapter 6	Chapter 7	Chapter 8
nanotechnology value chain block	intermediate products	nanomaterials	nanotools and instrumentation	nano-enabled products
technologies in focus	MEMS/NEMS technologies	ZnO one-dimensional nanostructures	micro/nanomanufacturing technologies	microfluidic diagnostic technologies / point-of care technologies (MDT/POC)
unit of analysis	journals	journals	terms / journals	journals / patents
level of analysis	technological field	technological field	technological field	industry level
quantitative approaches	co-citation analysis, social network analysis, general bibliometric indicators, hierarchical cluster analysis	co-citation analysis, social network analysis, hierarchical cluster analysis	co-word analysis, social network analysis, Revealed Scientific Advantages (RSA) indexes, general publication indicators, hierarchical cluster analysis	general patent indicators, general publication indicators, network analysis, hierarchical cluster analysis, classification networks
data sources	ISI/SCI database, Engineering Village database, market reports, technical publications and books, interviews, market reports, industrial exhibitions	ISI/SCI database, EPO/esp@cenet patent database, market reports, technical publications and books, interviews, industrial exhibitions, lab visits	ISI/SCI database, market reports, technical standards, technical publications and books, interviews, industry exhibitions	USPTO patents database, EPO/esp@cenet patent database, ISI/SCI database, USFDA approvals database, market reports, technical publications and books, interviews, firms’ websites, industrial exhibitions, lab visits, industry databases

The selection of the thresholds for the cosine values relied on the assessment of the changes undergone by the network visualizations. Here, care was taken that the thresholds for the cosine values were within those typically found in the literature, i.e. ≤ 0.20.

4.3.4.2. Ordination - Hierarchical cluster analysis

Cluster analysis is a multivariate statistical technique aimed at assessing and visualizing the similarity among cases (Hanneman and Riddle, 2007). In particular, cluster analysis divides a set of objects into groups, or clusters, in the sense that the objects included in one group show a great resemblance to each other (internal cohesion), but those of the different clusters will be different (external isolation) (Vargas-Quesada and Moya-Anegón, 2007). A series of methods have been developed for the definition of clusters. In this study, the similarity of a cluster vis-à-vis that of the rest of the clusters is measured through the use of the Ward’s clustering method and squared Euclidean distances. This clustering approach was selected as it has been encountered in the science mapping literature (Rafols and Meyer, 2010). In this study, the statistical software SPSS is used for the conduction of the hierarchical cluster analysis. The main outcome of the hierarchical cluster analysis is the tree-like representation dendrogram, from which it is possible to derive the number of clusters. However, the definition of the number of clusters is directly dependent on the selection of the cut-off value. For the purposes of this study, an iterative approach for the selection of the cut-off value was used. This was done as follows: first, a predetermined cut-off value of five was selected, as it appeared to be fitting suitably across the dendrograms obtained. This initial cut-off value was evaluated by assessing the cluster distribution in the networks; here, the contents of these clusters were then analyzed in order to define the cognitive plausibility of the clusters. The cut-off value was fine-tuned when discrepancies in the cognitive contents of the clusters were observed.

4.4. Social Network Analysis (SNA)

Cobo et al. (2011) defines a series of techniques for mapping and visualizing the relationships among the retrieved data. Some of the methods they define are dimensionality reduction techniques such as principal component analysis or MDS (multidimensional scaling) which are used to transform the data into a lower dimensional space; clustering algorithms for splitting the global network into different sub-networks; pathfinder networks (PF) which identify the backbone of the network; general graph mining techniques; and social network analysis (SNA). This thesis makes use of SNA approaches. The rest of this section provides an overview of the approaches and quantitative measurements used in this thesis for the analysis of networks.

4.4.1. Overview of SNA

Social Network Analysis (SNA) defines ‘a set of methods for the analysis of social structures, methods that specifically allow an investigation of the *relational* aspects of these structures’ (Scott, 2007). For a description of the historical evolution of the SNA field, the reader is referred to Scott (2007) and Borgatti et al. (2009). A key aspect of SNA is its focus not on the individuals but on the *structures*, i.e. the set of individuals and their connections (Wasserman and Faust, 2009). Thus, SNA examines the relationships between actors, be it people, groups of people, organizations, or countries, with certain type of association or interdependence among them. Examples of those relationships are financial exchange, friendship, kinship, similarity, trade relations, internet links, and disease transmission, among others (Hanneman and Riddle, 2007). As the theory behind SNA approaches is universally applicable, over the years their use has spread into a variety of disciplines including sociology, geography, linguistics, and information science, among many others. Within the field of innovation management, the use of SNA approaches has migrated from their focus on social groups into the analysis of physical entities such as publications and patents.

Within the SNA approach, networks depict the graphical representation for structuring relational data. Network data is depicted by actors or agents (nodes, points, vertices or agents) and their relations (ties, lines, or edges). Besides the relations among actors, network analysis focuses on the attributes of those relations (Hanneman and Riddle, 2007). By attributes it is meant the properties characterizing a particular network node or tie; one way of schematically visualizing attributes is by changing the colors and shapes of the nodes, or the thickness or color of the ties (Hanneman and Riddle, 2007). As will be seen, this will be used in the following chapters. For the case of bibliometric data, i.e. publications and patents, SNA approaches have intensified as reflected in the intensive efforts conducting research on ‘science mapping’, as shown by Leydesdorff et al. (2012) and Rafols and Meyer (2010). As defined by Sternitzke et al. (2008) the use of SNA approaches in patent analysis has been scarce; nevertheless, over the years the use of network approaches with patent data has increased significantly.

Networks are represented in terms of matrix data, which, in turn, allows performing mathematical operations for assessing the information on the graph. Some of these indicators are presented in the remainder of this section.

4.4.2. Visualization techniques and network indicators

4.4.2.1. Visualization techniques for networks

Different software tools can be used for visualizing network relationships. From the variety of software tools available in the market, UCINET/NetDraw was chosen[1] as it is characterized by an easy-to-use interface, as well as its capabilities are enough for the quantitative approaches necessary for this study. Regarding visualization techniques, a series of algorithms known as ‘spring embedders’ are typically used to reach a clearer arrangement of the network layout. From the algorithms available, the Kamada-Kawai algorithm built into UCINET/NetDraw was selected as it is commonly used by the research community. In particular, this algorithm attempts to minimize the energy in the system when network ties are modeled by springs. This approach results in the location of highly connected nodes closer to the center of the network.

4.4.2.2. Network structural indicators

Table 4.3 illustrates a series of indicators that will be used in the measurement of the structural properties of networks. This table also provides a description, meaning, and formula for each of these indicators.

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[1] Alternative software for visualizing networks can be found at the website of the International Network of Social Network Analysts (http://www.insna.org/software/index.html) (Hanneman and Riddle, 2007)

Table 4.3 Description of network structural indicators (Wasserman and Faust, 2009; Scott, 2007)

Indicator	Description	Meaning	Formula
Number of nodes	Total number of nodes.	Measure of the impact or significance of the nodes of the network	n n: number of nodes present
Average length	Ratio between the total number of ties and nodes.	Measure of the network coherence.	$\frac{l}{n}$ l: number of lines present n: number of nodes present [2]
Network density	Total number of ties divided by the total of possible number of ties.		$\frac{l}{n(n-1)/2}$ l: number of lines present n: number of nodes present [3]
Degree centrality (local centrality)	Number of edges incident on a node in a network.	Definition of the network predominance of a node according to its degree of *local* connectivity. It depicts the degree of participation of a node in a network.	$d(i) = \sum_{j} m_{ji}$ m_{ij}: 1 if actor *i* and actor *j* are linked [4]
Betweenness centrality	Extent to which a node lies on the shortest path (geodesic) between pairs of actors in the network.	Definition of the network predominance of a node according to its locational quality. High betweenness centrality nodes play intermediary roles; as such, they tend to be closer to the core or center of the network.	$b(i) = \sum_{j,k\neq 1} \frac{g_{jik}}{g_{jk}}$ g_{jk}: shortest path between actor *j* and actor *k* g_{jik}: shortest path between actor *j* and actor *k* containing actor *i* [5]
Closeness centrality (global centrality)	Inverse of the average shortest paths between an actor and all other actors in the network.	Definition of the network predominance of a node according to its degree of *global* connectivity. Higher closeness centrality values point to a higher influence on other actors.	$c(i) = \sum_{j=1}^{N} \frac{1}{d_{ji}}$ d_{ji}: shortest path between actor *j* and actor *i* [6]
Bonacich Eigenvector centrality	The principal eigenvector of the adjacency matrix defining the network	Definition of the network predominance of a node according to the node's degree weighted by the centrality of the nodes it is connected to.	$e_i = \lambda^{-1} \sum_{j} a_{ij}\, e_j$ λ: eigenvalue (constant) a_{ij}: 1 if actor *i* and actor *j* are linked e_j: centrality of the connecting node *j* [7]
Centralization measures (degree, betweenness, closeness)	Degree of inequality or variance in the network as a percentage of a perfect star network of the same size.	Definition of the degree to which a whole network is revolving around particular focal nodes in terms of the different centrality measures.	-

4.5. *Other bibliometric analyses and indicators*

4.5.1. Revealed Technological/Scientific Advantages (RTA/RSA)

The use of the revealed technological advantage (RTA) was pioneered by (Soete and Wyatt, 1983) and further developed by Cantwell (1989) and Patel and Pavitt (1987). The RTA index is defined as the 'country's share of patents in a particular field of technology, divided by the country's share in all patents' (OECD, 2011). Similar indicators are the specialization index, the revealed comparative advantage, among others. If publications are used instead of patents, the RTA index becomes Revealed Scientific Advantage (RSA). RSA may be used to reveal patterns of scientific specialization of a given country within a particular field. As such, RSA indexes are related to the scientific micro/nanofabrication competences of countries/regions. Quantitatively, the RSA index is estimated as follows:

$$RSA = \frac{\mathrm{P_{ij}} \,/\, \sum_{\mathrm{i}} \mathrm{P_{ij}}}{\sum_{\mathrm{j}} \mathrm{P_{ij}} \,/\, \sum_{\mathrm{ij}} \mathrm{P_{ij}}} \qquad [8]$$

where Pij defines the total of scientific publications for a country i in sector j.

Other approaches making use of RTA or RSA indexes are those by Miyazaki (1994, 1995) for the field of optoelectronics, Kumaresan and Miyazaki (1999) for the robotics field, and more recently Miyazaki and Islam (2007) and Islam and Miyazaki (2010) for the field of nanoscience and nanotechnology.

The RSA index varies around 1; thus, it is asymmetric. A simple transformation can be applied to the RSA index in order to make it symmetric around 0 and thus facilitate its graphical visualization, as follows: RSAsymmetric = (RSA – 1) / (RSA + 1). Whereas RSA index values greater than 0 denote a relative technological advantage, those below 0 show a relative technological disadvantage. In this study, RSA indices are used as a proxy for examining the specialization patterns of countries within a particular field of research.

4.5.2. Diversity indicator – Informational entropy

For the particular case of the evaluation of the scientific variety of knowledge bases, we used the informational entropy of the shares of journal subject categories allocated by the ISI/SCI database to publications. Here, entropy is defined as follows (Grupp, 1990):

$$S = -\sum_i p_i \ln p_i \tag{9}$$

where pi defines the share of proportions of SCs across a scientific field. Entropy is defined in terms of the number of scientific fields a knowledge base embeds and how intense they are (Grupp, 1990). In this study, informational entropy is used for analyzing the intensity within scientific fields.

4.6. Summary

This chapter has provided a summary of the different research methods to be used in the following chapters. More detailed information will be provided in the corresponding chapters. The remainder of this thesis will focus on the study of the four hypotheses proposed in previous chapters.

5. Rates and Directions of Change of Knowledge Bases as Proxies for Technological Emergence – The Case of MEMS/NEMS Technologies

5.1. Introduction

As previously said, emerging technologies are characterized by embracing fast recent growth rates, transitions into something new, market or economic potentials, and a significant science-driven nature (Cozzens et al., 2010). Yet, such growth and potential of change come with a price, namely the uncertainty and fluidity surrounding these technologies (Day et al., 2000; van Merkerk and van Lente, 2005). It has already been discussed that despite their appealing nature, emerging technologies have been loosely defined and operationalized (Cozzens et al., 2010). In particular, operationalization approaches based on bibliometric methods have often tended to emphasize the exponential growth and the potential impacts of emerging technologies while overlooking their inherent uncertainty and fluidity. Hence, this chapter attempts to set their sights on enhancing the operationalization of the dynamics of emerging technologies by describing a bibliometric-based approach for quantitatively interpreting technologies of an emerging nature along both dimensions vis-à-vis those of more mature technologies. As such, this chapter refers to the first hypothesis defined in Section 2.5.5.

To do so, this chapter focuses on the properties of the knowledge bases underlying technologies. In particular, the dynamics of scientific knowledge bases, in terms of their rates and directions of change, are investigated. It will be shown that the former provides insights into the patterns of growth experienced by technologies, while the latter hints at their degree of cognitive fluidity. In particular, the directions of change of the knowledge bases are related to the problems encountered by technologies throughout their evolution. As defined in Section 2.4.2., literature has highlighted the ability of problems to reflect the directions along which scientific knowledge bases are oriented (Consoli and Ramlogan, 2008; Mina, 2009). As problems demand knowledge for their solution, it is argued that the nature of the knowledge underlying technologies depicts a sort of a *‘cognitive imprint’* reflecting the types of problems confronted by technologies over time. This provides insights into the directional dynamics of knowledge bases, and, in turn, into the fluidity, in cognitive terms, of technologies.

This chapter is structured as follows. Section 5.2 provides an overview of literature on bibliometric approaches for the operationalization of emerging technologies. Section 5.3 moves on to the description of the research methods. Next, Section 5.4 presents the results of this chapter. Finally, Section 5.5 concludes with a brief summary of this chapter.

5.2. Bibliometric approaches on emerging technologies

Different methods have been used for evaluating emerging technologies. This section focuses on bibliometric approaches. Recently, Cozzens et al. (2010) highlighted the significant potential of bibliometric approaches, provided their limitations are considered, for the identification and measurement of emerging technologies. For the particular case of bibliometric approaches on emerging technologies, three main streams of research were discerned from the literature.

Given the uncertainty surrounding emerging technologies it is not surprising that a large amount of research efforts have been devoted to *technological forecasting and related areas*. Bengisu and Nekhili (2006) relied on the statistical evaluation of publication and patent data for forecasting the technological growth of a series of materials and manufacturing technologies through the use of 'S-curves'. Daim et al. (2006) combined the use of publications and patents with tools such as scenario planning, growth curves and analogies to forecast emerging technologies in the fuel cell, food safety and optical storage technological fields. More recently, Robinson et al. (2011) proposed an integrated framework for analyzing emerging technologies based on the future-oriented technology analyses (FTA) for the cases of bionanosensor and deep-brain stimulation technologies. Moreover, relying on patent data, Chen et al. (2012) identified and visualized the future technological evolution of the field of smart grid technology.

A second broader research stream has aimed at the *understanding of the properties of emerging technologies*. In particular, significant research efforts have been devoted to the newly emerging field of nanoscience and nanotechnology (N&N). Takeda et al. (2009) traced the structure and research domains in the field of nanobiotechnology through the use of scientific publications. Similarly, Lee and Su (2011) studied the scientific knowledge structure of the electrical-conducting polymer nano-composites. Bonaccorsi and Thoma (2007) and Bonaccorsi and Vargas (2010) made use of publication and patent data particularly of co-word analysis to analyze the performance of N&N inventors and to evaluate the dynamics of knowledge of the N&N field, respectively. Relying on publication data, Islam and Miyazaki (2009a) have focused on the dynamics of nanoscience fusion trajectories and conflation phenomena, as well as on the definition of nanotechnology research domains (Islam and Miyazaki, 2010).

Finally, a third stream of research has focused on *quantitatively identifying emerging technologies*. Upham and Small (2010) described the use of co-citation clusters of scientific publications combined with qualitative data to identify emerging research fronts. Shibata et al. (2010) described the detection of emerging technologies in the fields of Gallium Nitride and regenerative medicine through the use of a co-citation network clustering approach. Lee (2008) and Schiebel (2010) relied on the construction and analysis of 'co-word' networks for the identification of emerging research fields for the cases of information security technologies and optoelectronic devices, respectively. Chang et al. (2010) analyzed patents through network approaches to monitor technological trends in the field of carbon nanotube-based field emission displays.

5.3. Research Methods

Thirteen different MEMS/NEMS technologies were used in this analysis (Table 5.1).

Table 5.1 MEMS/NEMS technologies included in this analysis

Technology	Brief description and potential application domains
Accelerometers	Inertial device measuring acceleration forces.
Bio-MEMS	Biological and medical applications of MEMS. Broad encompassing field: surgical instruments, drug delivery systems, bio-sensors, pressure sensors, among others.
Gyroscopes	Sensors for measuring angular velocity. Uses in automobiles, consumer electronics, among others.
Microfluidics	Handling of fluids in MEMS. It includes: micro total analysis systems, labs on a chip, and their components such as micro-pumps, micro-valves, etc.
MOEMS displays	Micro-mirror arrays, micro-gratings, etc. for display projectors, bar code readers, etc.
MOEMS telecomm	Devices for optical fiber communications, such as optical switching units, variable optical attenuators, tunable filters, among many others.
Micro-tips (AFM)	Probes and tips for measuring the properties of surfaces with atomic force microscopes.
Power-MEMS	Includes energy-related applications for MEMS devices, such as energy scavengers, microturbines, microthrusters, microgenerators, micromotors, among others.
Pressure sensors	Main applications in automotive, industrial automation, medical, and aerospace.
Printheads	Heads for inkjet printing applications.
RF-MEMS	High-frequency circuits (radio frequency, micro- and millimeter waves), such as high-Q inductors, phase shifters, antennas, tunable capacitors and resonators, among others.
ZnO nanosensors	Use of Zinc Oxide nanostructures for sensing and actuation applications.
Carbon nanotube nanosensors	Use of carbon nanotubes for sensing and actuation applications.

The dataset comprised of scientific publications and citations – including articles, reviews and proceedings – indexed in the ISI/SCI database, published in English and up to the year 2009. For this search, the titles, abstracts and keywords of scientific publications were reviewed.

A keyword-based analysis was used to collect the publication data. The definition of the appropriate search query for each of the MEMS/NEMS technologies relied on the construction of 'technological trees' Here, Fig. 5.1 presents the technological tree built for accelerometers.

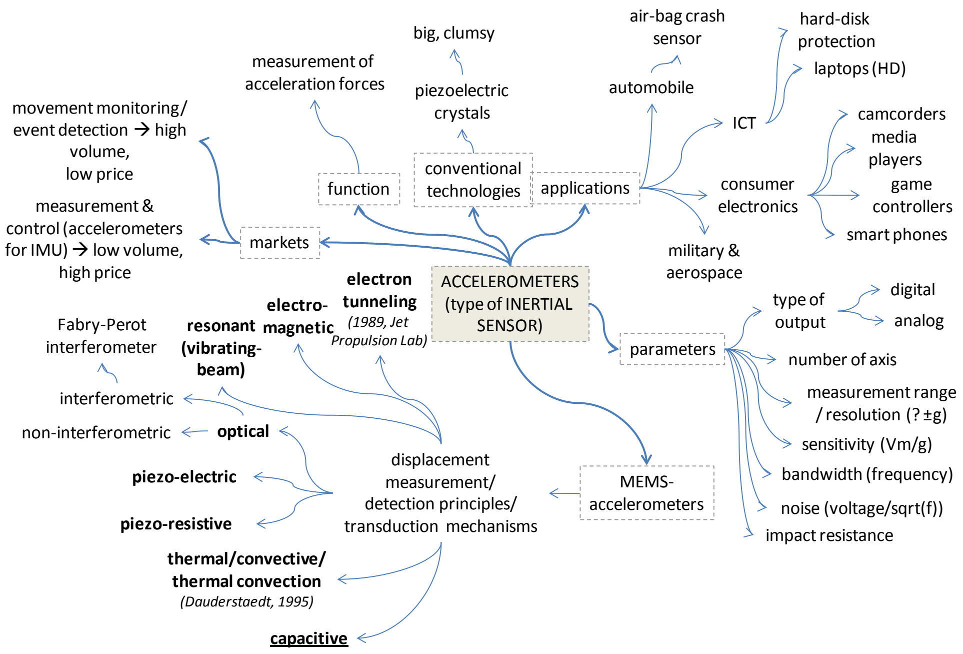


Fig. 5.1 Example of technological tree for MEMS/NEMS technology 'accelerometers'

In this regard, keywords extracted from these technological trees were combined into a series of alternative search strings until representative publications for each technological field were obtained. Here, Appendix 1 lists the different search queries used for this analysis. Given the large amount of data, the fine-tuning of the search strings consisted in sampling the total of the collected publications. For that purpose, the equation for the sample sizes corrected for finite populations was used, which is defined as follows:

$$n = \frac{z^2 Npq}{e^2(N-1) + z^2 pq}$$

where e defines the error or confidence level (e= 0.05), z defines the double-tailed standard normal z value at the error 0.05 ($z_{0.05}$= 1.96), p represents the proportion value equal to 0.05, and q equals to 1-p, thus 0.95.

The boundaries of the bibliometric search of this chapter were set at the device/product level. Given the interrelatedness among the different MEMS/NEMS technologies, in some cases this proved difficult. One example is the case of pressure sensors in bio-medical applications which can be considered as both 'pressure sensors' and as 'BIO-MEMS' devices. Furthermore, in order to rule out any biases due to the use of a single database, a complementary search was conducted in the database Engineering Village. By analyzing the ratio of publications from the ISI/SCI database over those extracted from the Engineering

Village database, it was found that the ISI/SCI vs. Engineering Village ratio reached values close to the unit across the different MEMS/NEMS technologies. This suggests the similarities in the results extracted from both databases. Nevertheless, larger differences were noticed particularly in biology-related technologies such as microfluidics which displayed ratios around 1.67. This is in line with the wider coverage of the ISI/SCI database in biology-related fields (Moed, 2005). In contrast, more engineering-oriented technologies such as gyroscopes, bio-MEMS, and print-heads displayed ratios of around 0.67.

A total of 13,393 publications were collected, from which 89,901 citing references were drawn. These citing references were restricted to articles, proceedings and reviews in any language, and published up to the year 2009; self-citations were excluded. Moreover, cited references were retrieved for some MEMS/NEMS technologies, as later sections will show. Based on the collected data, the rates and directions of change of the scientific knowledge bases underpinning MEMS/NEMS technologies were evaluated.

On the one hand, for the case of the rates of change of MEMS/NEMS knowledge bases, bibliometric parameters such as publication outputs, publication years, countries of publications, and journal subject categories (SC), among others, were extracted from the source publications and their citing papers. These parameters were further processed into eleven bibliometric indicators embracing aspects as different as the dynamism, variety, diffusion, complexity and age of scientific knowledge bases (see Section 5.1). For the particular case of the evaluation of the scientific variety of knowledge bases, the informational entropy of the shares of journal subject categories allocated by the ISI/SCI database to publications was used. In order to make the study of SCs practicable, SCs were grouped according to Porter and Rafols' classification into 21 macro-disciplines (Porter and Rafols, 2009). Subsequently, correlation and hierarchical cluster analyses were conducted on the bibliometric indicators to discern the general and specific rates of growth of MEMS/NEMS knowledge bases, respectively. For both analyses the statistical package SPSS was used.

On the other hand, for the case of the directions of change of MEMS/NEMS knowledge bases, co-citation networks were constructed and evaluated. For that purpose, cited references were collected, and subsequently cleaned and sorted by manually grouping together similar references and correcting input errors in their bibliographic information. To prevent the inclusion of random errors and size-related biases a normalized citation count of 0.6 was defined. Following, the software VantagePoint was used to construct co-occurrence matrices which depict pairwise relations between cited references. Those co-occurrence matrices were normalized with the Salton's cosine similarity measure in order to provide a better visualization of the similarity structures across the data and to control for size effects. A predetermined co-citation threshold greater or equal to 0.18, within the range of values typically used in the literature, was chosen in order to center our attention on those predominant co-citation relationships.

In a subsequent step, problems were allocated to the nodes of the co-citation networks. Those problem-attached co-citation networks were evaluated through a series of network indicators in order to assess the significance and predominance of the different problem areas within knowledge structures. Subsequently, the cognitive sub-fields, i.e. those agglomerations of highly cognitive-related nodes, underlying the MEMS/NEMS knowledge structures were discerned. This was done through the conduction of a hierarchical cluster analysis on the cosine-normalized co-citation networks through the SPSS software.

The remainder of this chapter describes the main results extracted from both analyses.

5.4. Results

5.4.1. Rates of change of scientific knowledge bases

Within this section, the general and specific rates of change experienced by the scientific knowledge bases underpinning MEMS/NEMS technologies are described. This, in turn, provides insights into the patterns of growth of technologies. The results of this section rely on a series of bibliometric indicators to be described next.

5.4.1.1. Description of the bibliometric indicators

A total of eleven bibliometric indicators for analyzing the rates of the knowledge bases for MEMS/NEMS technologies were defined:

- Dynamism of the generated knowledge *[DYN_PUB]* and the diffused knowledge *[DYN_CIT]* – These proxies define the median of the slopes of the curve of the accumulated proportions of publications and citations, respectively, for the period 2006-2009. They provide a measure of the recent speeds of growth of the generated knowledge *[DYN_PUB]* and the diffused knowledge *[DYN_CIT]*. The higher their values, the faster the speeds of growth experienced by the knowledge bases.
- Relative dynamism *[RATIO_DYNCP]* – This proxy describes the ratio of the dynamism of the diffused knowledge *[DYN_CIT]* over that of the generated knowledge *[DYN_PUB]*. Ratios higher than one imply higher relative speeds of knowledge diffusion vis-à-vis those of knowledge generation.
- Acceleration of the generated knowledge *[CHDYN_PUB]* and the diffused knowledge *[CHDYN_CIT]* – This indicator estimates the average of the ‘slopes of the slopes’ of the cumulative proportion curve of publications and citations, respectively, for the period 2006-2009. Higher acceleration values point

to more sustained recent growth for the generated *[CHDYN_PUB]* and the diffused knowledge *[CHDYN_CIT]*.

- Rate of growth of countries active in the field *[RATE_COUNTRY]* – It indicates the rates of growth in the number of countries active in the field between the periods 2002-2005 and 2006-2009. By active, it is meant those countries with at least five publications in those periods. As such, higher *[RATE_COUNTRY]* imply a growing interest and participation of countries in a particular field.
- Collaboration at the country level *[COLL_MACRO]* – This indicator estimates the proportion of papers – publications and proceedings articles – co-authored by authors from two or more different countries as a proxy for the collaboration at the country level. The higher the *[COLL_MACRO]* values, the higher degrees of collaboration in the knowledge generation.
- Collaboration at the author level *[COLL_MICRO]* – This proxy defines the proportion of papers – publications and proceeding articles – co-authored by three or more authors. It attempts to capture the degree of collaboration in the knowledge generation at the author level. Higher values point to higher levels of collaboration. A more reliable proxy for collaboration is collaboration at the organizational level; nevertheless, due to the nature of the data, collaboration at the author level was used instead.
- Year of emergence *[YEAR_EMER]* – It describes the year in which more than ten publications are accumulated for a particular field. The latter provides a proxy for the 'chronological newness' of the knowledge base. Higher years of emergence suggest 'younger' knowledge bases.

The rest of the indicators relied on the journal subject categories (SC) for both publications and their citing references.

- Scientific variety of the generated knowledge *[S_PUB]* and the diffused knowledge *[S_CIT]* – This indicator defines the entropy values of the shares of subject categories of publications and citations, respectively, for the period 2006-2009. As such, they depict the variety of the generated knowledge *[S_PUB]* and the diffused knowledge *[S_CIT]*. Higher values imply higher levels of variety.
- Relative variety *[RATIO_SCP]* – Ratio of the variety of the diffused knowledge *[S_CIT]* over that of the generated knowledge *[S_PUB]*. Ratios above one denote higher degrees of variation in the diffused knowledge relative to those of the generated knowledge.
- Potential scientific complexity *[POT_COMPL]* – It indicates the average number of journal subject categories per publication, as resulting from the ISI/SCI database, for the period 2006-2009. As such, *[POT_COMPL]* provides a rough indication of the potential complexity of a scientific field.

As may be inferred, the use of bibliometric indicators should be taken with care for they, as proxies, attempt to abstract the complexities of reality into a set of indicators.

5.4.1.2. General rates of change of MEMS/NEMS scientific knowledge bases

This section discusses the general patterns of relationship among the bibliometric indicators described above through the conduction of a correlation analysis. Table 5.2 illustrates the resulting correlation matrix.

Table 5.2 Correlation matrix

		Correlations										
	Proxies	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1)	S_PUB	1										
(2)	RATIO_SCP	-0.11	1									
(3)	DYN_PUB	-0.26	-.72**	1								
(4)	RATIO_DYNCP	-0.19	.56*	-.74**	1							
(5)	CHDYN_PUB	-0.33	-.58*	.84**	-0.55	1						
(6)	CHDYN_CIT	-0.28	-.75**	.93**	-.57*	.84**	1					
(7)	RATE_CNTRY	-0.03	-0.49	.72**	-.88**	0.51	0.50	1				
(8)	COLL_MACRO	-.58*	-0.04	0.35	0.07	0.10	0.29	0.15	1			
(9)	COLL_MICRO	-0.23	-.76**	.69**	-0.35	0.46	.69**	0.44	.62*	1		
(10)	POT_COMPL	-0.13	-.56*	.56*	-0.20	.64*	.66*	0.12	0.00	0.30	1	
(11)	YEAR_EMER	-.61*	-0.38	.79**	-0.43	.69**	.74**	0.47	.67*	.66*	0.42	1

NOTES:
- * statistically significant at the 0.05 level; ** statistically significant at the 0.01 level
- S_PUB: variety in the generated knowledge; RATIO_SCP: ratio of the variety of the diffused over the generated knowledge; DYN_PUB: speed of growth of the generated knowledge; RATIO_DYNCP: ratio of the speeds of growth of the diffused over the generated knowledge; CHDYN_PUB: acceleration of growth of the generated knowledge; CHDYN_CIT: acceleration of growth of the diffused knowledge; RATE_CNTRY: rate of growth in the number of countries active in knowledge generation; COLL_MACRO: degree of collaboration at the country level; COLL_MICRO: degree of collaboration at the author level; S_BREADTH: average number of subject categories per articles; YEAR_EMER: year of emergence;

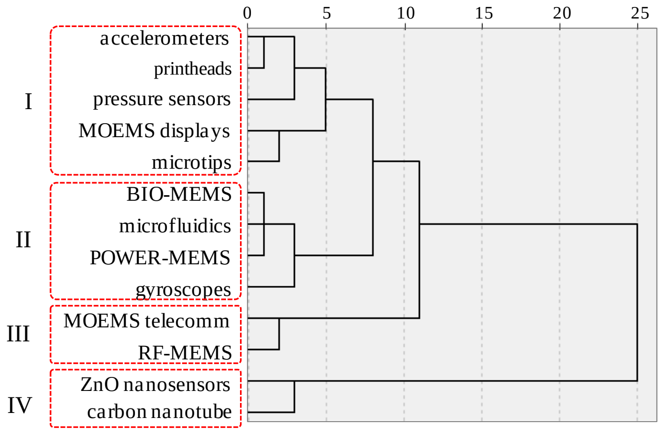
An examination of the correlation matrix of Table 5.2 reveals the following results. The variety of the generated knowledge base appears to be inversely correlated at significant levels with the year of emergence. This suggests that ‘younger’ scientific knowledge bases embrace lower levels of variety. Despite that, they show greater levels of collaboration. Formative knowledge bases in terms of their levels of diffusion are associated with higher levels of dynamism, collaboration, and potential complexity. It appears that rapid rates of growth of knowledge bases tend to be paralleled by a sustained, accelerated growth. Such significant levels of dynamism bring with it the building up of a ‘critical mass’ of actors as reflected in the greater engagement of countries and the larger degrees of collaboration. Moreover, the dynamics of the generated and diffused knowledge are highly coupled. This may be partly attributable to the high correlation typically observed between publications and citations (Moed, 2005). Finally, these results demonstrate that newer and potentially more complex knowledge bases are associated with greater levels of dynamism; what is more, newly emerging knowledge bases entail higher levels of collaboration.

These results suggest that the patterns of growth of emerging technologies, as reflected in the scientific knowledge bases, cannot be explained by chronological newness alone. Instead, it is suggested that newness, high dynamism in terms of the speeds and acceleration of growth, high levels of collaboration, potential complexity, and early knowledge diffusion go hand in hand. This is also accompanied by a narrow scientific variety.

5.4.1.3. Specific rates of change of MEMS/NEMS scientific knowledge bases

The dynamics of the scientific knowledge bases underpinning MEMS/NEMS technologies are unique; yet, they share some similarities. This section attempts to discern the groupings of similar MEMS/NEMS knowledge bases. For that purpose, a hierarchical cluster analysis based on the Ward's clustering method/squared Euclidean distances was conducted. Z-score standardized values were used to reduce the effects of the different ranges of value across the indicators.

Fig. 5.2 left presents the dendrogram resulting from the cluster analysis.



Cluster I	**Cluster II**
• accelerometers	• BIO-MEMS
• printheads	• microfluidics
• pressure sensors	• POWER-MEMS
• MOEMS displays	• gyroscopes
• microtips	

Cluster III	**Cluster IV**
• MOEMS telecomm	• ZnO nanostructures based nanosensors
• RF-MEMS	• Carbon nanotube based nanosensors

Fig. 5.2 Dendrogram and scientific knowledge bases in each cluster

Four main clusters of MEMS/NEMS scientific knowledge bases were identified. Table 5.3 presents a schematic comparison of these clusters across five groupings: variety, diffusion, dynamism, complexity, and age. The bibliometric indicators described in Section 5.1 were allocated to each of those groupings. Different symbols are allocated to Table 5.3 according to the quartile values of the cluster means.

Table 5.3 Characterization of clusters across the indicator groupings

	groupings of indicators							
	VARIETY		DIFFUSION		DYNAMISM	COMPLEXITY		AGE
Clusters	absolute	relative	rel. speed	rel. accel.		collab	pot. compl.	
CLUSTER I	+	+	+	− −	−	− −	−	− −
CLUSTER II	+ +	−	−	+	+	−	+	−
CLUSTER III	− −	+ +	+ +	−	− −	+	−	+
CLUSTER IV	− −	− −	− −	+ +	+ +	+ +	+ +	+ +

NOTES:
- rel.: relative; accel.: acceleration; collab.: collaboration; pot. compl.: potential complexity
- x < 1st quartile → − ; 1st quartile <= x < 2nd quartile → − − ; 2nd quartile <= x < 3rd quartile → + ; x > 3rd quartile → + +

In terms of performance, the data in Table 5.3 shows two extreme clusters, namely Cluster I and Cluster IV. Between those clusters, Cluster II and Cluster III fall. Following, the properties of those clusters are described. We begin with the description of these extreme clusters:

- **Cluster I** – This cluster shows moderately high levels of variety in the generated and the diffused knowledge. It is characterized by fast, yet decelerating, rates of knowledge diffusion relative to those of their knowledge generation. Its dynamism is low. It is also characterized by low levels of collaboration, as well as by low degrees of potential complexity. This cluster includes the most mature knowledge bases. From those, ‘pressure sensors’ stand out as the most mature and the least dynamic MEMS/NEMS scientific knowledge base. Despite their relative maturity, ‘inkjet printing-head’ technologies display a higher dynamism particularly driven by novel application domains in the fields of biotechnology and nanotechnology.
- **Cluster IV** – Compared to Cluster I, this cluster depicts ‘the other side of the coin’. It shows the lowest levels of variety, as well as the lowest, yet the most highly accelerating, rates of knowledge diffusion. This cluster also displays the highest dynamism and potential complexity levels, and the chronologically newest knowledge bases. It includes the nanotechnology-related scientific knowledge bases ‘carbon nanotube sensors’ and ‘ZnO nanostructured sensors’.
- **Cluster II** – In terms of their generated knowledge, this cluster displays the highest variety and relatively high speeds of growth and acceleration rates. The dynamics of the diffused knowledge are still lagging behind but about to grow given their high rates of acceleration. Despite its high variety and potential complexity, this cluster shows moderately low degrees of collaboration. Relative to the rest of MEMS/NEMS technologies, this cluster embraces slightly aged technologies. In particular, this cluster includes broad-encompassing technological domains rather than punctual technologies. Some examples are BIO-MEMS, POWER-MEMS, and microfluidics.

- **Cluster III** – This cluster shows a performance mostly opposite to that of Cluster II. Despite its moderate chronological newness, this cluster displays the lowest average levels of dynamism. It shows high levels of collaboration yet low levels of potential complexity. Their relative newness coupled with their sluggish dynamism makes the knowledge bases of this cluster to be 'stuck in the middle'. This cluster includes technologies such as 'RF-MEMS' and 'MOEMS telecommunications' which are closely related to the telecommunications 'bubble burst' of the early 2000s.

These results highlighted the 'commonalities' and differences in the patterns of growth among the different MEMS/NEMS knowledge bases. In this regard, Cluster IV appears to be in line with the patterns of growth of emerging technologies described in the previous section: newness, dynamism, complexity, scientific narrowness, and formative diffusion. As mentioned above, this cluster includes the nanotechnology-related scientific knowledge bases 'carbon nanotube sensors' and 'ZnO nanostructured sensors'.

5.4.2. Directions of change of scientific knowledge bases

This section now looks into the directions of change of the scientific knowledge bases underpinning MEMS/NEMS technologies at different levels of emergence/maturity. As previously noted, the directional dynamics of knowledge bases are closely related to the degree of cognitive fluidity inherent in technologies. Quantitatively, this section relies on the construction and evaluation of co-citation networks drawn from the cited references of scientific publications. Here, a crucial step consists in the allocation of problem areas to the nodes of those co-citation networks. Before explaining the results of this section, the 'problem space' defined for MEMS/NEMS technologies is described next.

5.4.2.1. 'Problem space' for MEMS/NEMS technologies

The 'problem space' entails the set of general problem areas confronted by the field of MEMS/NEMS technologies in terms of micro- and nano-sensors and actuators. As such, it includes applied, theoretical and technical knowledge and know-how of different natures: scientific, technological, and organizational, among others. The definition of the 'problem space' relied on the evaluation of large amounts of technical literature aimed at discerning the general problem areas being tackled by a particular technological field. The initial list of problem areas was modified according to the advice of an expert[1].

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[1] Prof. Dmitri Golberg, Principal Investigator at the International Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science (NIMS), Tsukuba, Japan.

After a series of fine-tuning loops, six general problem areas – from a scientific perspective – were defined:

- **Materials fabrication technologies -** This problem area deals with the development and understanding of process technologies aimed at the bulk fabrication of materials.
- **Micro/nanostructure fabrication technologies -** It entails research efforts dealing with the understanding, development and improvement of technologies aimed at the processing of micro/nanostructures, which are defined as those arrangements or structures with physical dimensions in the micro/nanoscale.
- **Characterization technologies -** It embraces the exploration and understanding of the fundamental properties of materials and micro/nanostructures. Examples of those properties are: optical, electrical, mechanical, and magnetic, among others.
- **Fabrication and analysis of components -** This problem area deals with the development, evaluation, and improvement of single components for micro/nanosensors and actuators. It includes components such as the circuitry, actuation parts, etc.
- **Fabrication and analysis of devices or systems -** This problem area deals with the development, evaluation, and improvement of devices or systems.
- **Design and optimization approaches -** It includes those areas entailing approaches aimed at the design or optimization of micro/nanosensors and actuator technologies.

Two additional categories were defined for some nodes: ‘general knowledge’ which includes publications describing topics of interest for the field of micro/nanosensors and actuators as a whole, and ‘literature review’ that embraces those publications assessing relevant literature in the field of MEMS/NEMS technologies.

The problem areas defined above are general and focus on issues derived from scientific publications. As such, they include basic and applied knowledge, as well as engineering know-how. Throughout their evolution, a variety of efforts are conducted to advance technologies (Nelson, 2003) which translates into the concurrent tackling of problem areas across the ‘problem space’. Despite their high levels of interrelationships and feedbacks, given the cumulative nature of knowledge it is expected these problem areas to be highly cognitive dependent. In this regard, the earliest phases of problem search and solution should be partly cleared out and a certain amount of knowledge accumulated before attempts into more complex problem areas are conducted ((Miyazaki, 1994; Nelson and Winter, 1982). It follows, from what has been said so far, that different problem areas may be visualized, from a macro perspective, as a loosely defined chain composed of upstream and downstream problem areas. These theoretical implications also apply for the analysis of the next chapter.

For the case of MEMS/NEMS technologies, such a cognitive chain may be depicted as follows. The rest of this paragraph is based on Lieber and Wang (2007). First, materials and micro/nanostructures with controlled and tunable chemical composition, structure, size, and morphology are required; they embrace the building blocks on which potential devices build upon. This, in turn, calls for the development of appropriate fabrication technologies. At the same time, efforts should be aimed at understanding the fundamental properties of the fabricated materials and micro/nanostructures through characterization approaches. The interplay between materials fabrication and fundamental characterization not only expands the basic understanding, but may also be helpful for defining potential device concepts. Subsequently, devices and their components should be developed and fabricated targeting particular application domains. Deeper understanding gives way to the conduction of approaches aiming at the optimization of devices and components.

5.4.2.2. Cognitive analyses of the knowledge structures

In the remainder of this section focuses on 'ZnO nanosensors' and 'pressure sensors' which according to the results of the previous section were characterized by the most emerging and the most mature knowledge bases in the field of MEMS/NEMS technologies, respectively. Fig. 5.3 presents the knowledge structures for both technologies as reflected in their co-citation networks. It should be remarked that the scales of both networks in Fig. 5.3 are different.

A series of attributes were allocated to both networks. The size of the nodes denotes the number of citations. The thickness of the ties depicts the co-citation strength between nodes. The color and the shape of the nodes indicate the type of problem assigned to a particular node. Here, a single 'problem area' was allocated to each node. For that purpose, the contents of each cited reference (the nodes in the networks shown in Fig. 5.3) were evaluated. The latter consisted in assessing the title, abstract, and in some cases the full text of each cited reference with the purpose of defining the problem area, from the problem areas described in Section 5.4.2.1, being tackled by a particular network node. For those cited references involving more than one problem area, the allocation of the problem area relied on the farthest stage reached along the cognitive problem chain described at the end of Section 5.4.2.1. Moreover, the networks were arranged through the 'spring-embedding' algorithm which tends to locate similarly connected nodes closer together. For the sake of clarity, node labels and single-tie nodes were removed from the network.

Two main types of indicators were proposed to evaluate the knowledge structures of Fig. 5.3 from a cognitive perspective: cognitive compositions and cognitive sub-fields. By cognitive, it is meant those processes involved in the acquisition and understanding of knowledge and problem solving.

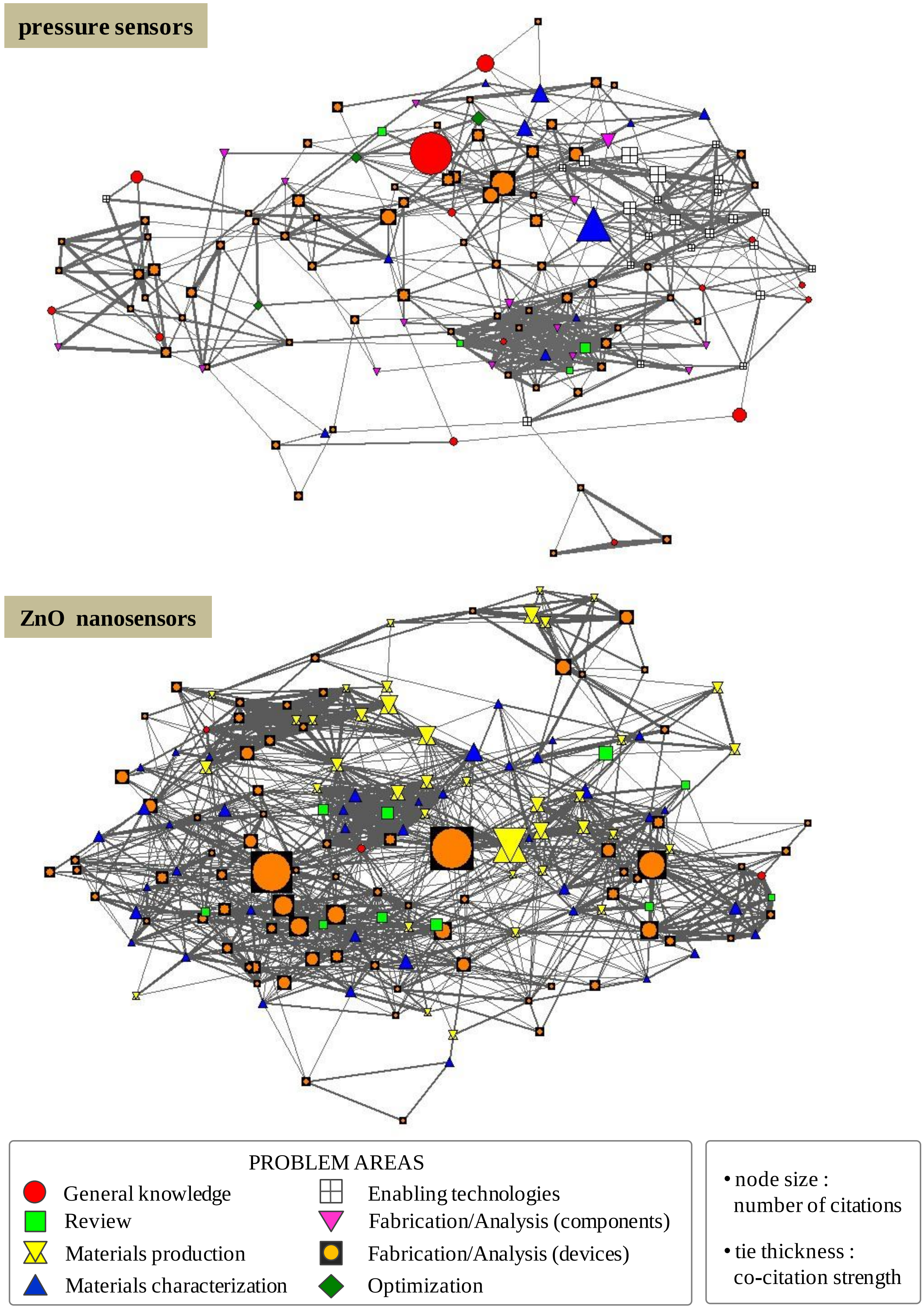

Fig. 5.3 Knowledge structures for 'pressure sensors' and 'ZnO nanosensors' (cos ≥ 0.18)

5.4.2.3. Cognitive compositions

Cognitive compositions evaluate the significance and predominance of the different problem areas in a knowledge structure. For that purpose, the distribution of the shares of nodes [No] and records [Rec], and the average normalized network centrality values [nDEG, nBET, nCLOS] across the different problem areas were estimated, as shown in Table 5.4.

Table 5.4 Cognitive compositions (cosine >= 0.18)

Problem area	Pressure sensors					ZnO nanosensors				
	No	**Rec**	**DEG**	**BET**	**CLOS**	**No**	**Rec**	**DEG**	**BET**	**CLOS**
Gnal. Knowledge	14.5%	10.0%	3.4	0.8	8.0	1.7%	2.2%	9.2	0.3	39.8
Review	2.4%	2.9%	9.4	1.2	8.4	6.2%	6.6%	7.7	0.4	41.3
Mat. Production	-	-	-	-	-	10.8%	10.9%	10.8	1.1	43.2
Fabrication tech.	14.2%	16.4%	5.8	1.6	8.3	13.3%	13.1%	8.8	1.0	40.0
Characterization tech.	11.5%	7.1%	6.9	2.4	8.3	19.8%	23.5%	8.7	0.6	41.9
Analysis of comp.	7.4%	10.7%	5.4	1.1	8.2	-	-	-	-	-
Analysis of devices	47.5%	50.0%	5.6	1.8	8.2	27.9%	26.4%	10.2	1.0	41.9
Other nanomaterials.	-	-	-	-	-	8.2%	7.6%	9.5	0.5	41.5
Conventional ZnO	-	-	-	-	-	7.7%	8.4%	8.7	0.6	41.3
Design & optimization	2.4%	2.9%	3.3	1.1	8.1	-	-	-	-	-

NOTES:
- Gnal. Knowledge: general knowledge; ma. Production: materials production technologies; Fabrication tech.: fabrication technologies for micro/nanostructures; Characterization tech.: characterization technologies for materials and micro/nanostructures; Analysis of comp.: development and evaluation of components.

Here, normalized centrality values were used in order to prevent the inclusion of any size-related bias. Following, the differences in the cognitive compositions between both MEMS/NEMS technologies are explained.

For the case of pressure sensors, the influence of ‘materials production technologies’ is nonexistent as these MEMS devices rely mostly on silicon and its compounds which have already been intensively researched for decades in the development of semiconductor devices. As MEMS fabrication methods differ slightly from those of the microelectronics industry, technologies for the fabrication of microstructures account for a sixth of the shares of nodes and citations. Also, they show a moderate predominance according to their normalized centrality values. Despite their low significance in terms of the shares of nodes and citations, characterization technologies appear to take predominant positions. Particularly, one node stands out, namely a paper by KE Petersen from IBM Research Laboratory in 1982 that stresses the suitability of the mechanical properties of silicon for the development of miniaturized, reliable and low-cost mechanical components and devices. The bulk of the knowledge structure revolves around the development and analysis of components and devices. They account for about three-fifths of the nodes and citations, as well as take relatively high predominant positions within the knowledge structure. These problem areas appear not to be solely focused on the development of new designs or application domains for pressure sensors (telemetric linkages, integrated electronics on sensors, etc.) and their components (compensation circuitry, actuation parts, etc.), but also on the improvement and optimization of their performance (noise, pressure variations and offsets, etc.), as well as the use of design and simulation approaches. This suggests the greater cognitive maturity of this knowledge structure.

The emerging knowledge structure ‘ZnO nanosensors’ shows a different picture. As it embraces a newly emerging material, the influence of the understanding and development of reliable fabrication processes for ZnO nanomaterials and nanostructures is still high. They account for a quarter of the shares of nodes and citations; in particular, ZnO nanostructures take the most predominant positions within the knowledge structure across all centrality values. Similarly, the characterization of fabricated ZnO nanomaterials and ZnO-based nanostructures take around a fourth of the shares of nodes and citations, yet it shows lower predominance levels. The influence of the development, fabrication and analysis of ‘ZnO nanosensors’ is still lagging behind; it accounts for more than a quarter of the shares of nodes and citations. Yet, their high centrality values suggest their imminent role in this knowledge structure. Here, a node stands out: a study from the Berkeley National Laboratory (USA) exploring the use of ZnO nanowires as potential room-temperature ultraviolet nano-lasers. This is the pioneering application of this field. The majority of the device-related nodes embraces early demonstrations or ‘proofs of concept’; still far from potentially commercial devices. Moreover, the influence of devices made from other nanomaterials and conventional ‘macro’ ZnO materials, each with about a tenth of the nodes and citations yet slightly predominant, suggests the partly path-dependent nature of this nanotechnology field.

In terms of the cognitive compositions, the cognitive fluidity of knowledge structures is denoted by two aspects as shown for the case of the ‘ZnO nanosensors’. First, the cognitive ‘center of gravity’ of the knowledge structure appears to be heavily tilted toward getting to grips with the earliest phases of problem search and solution, i.e. problem areas upstream. Second, the variety generated in their knowledge structures is significantly lower than that of their mature counterparts.

5.4.2.4. Cognitive sub-fields

Another way to visualize the cognitive nature of the knowledge structures is by discerning the cognitive sub-fields – the agglomerations of highly cognitive-related nodes – underlying knowledge structures. For that purpose, a hierarchical cluster analysis was conducted on the cosine-normalized co-occurrence matrices of ‘pressure sensors’ and ‘ZnO nanosensors’. As noted in Section 4.5.2.4, following

Rafols and Meyer (2010)’s approach, the Ward’s clustering method and squared Euclidean distances were used in this analysis. Fig. 5.4 presents the knowledge structures of both technologies with their clusters displayed in thick dotted lines.

The definition of those clusters was based on the evaluation of the resulting dendrograms. More detailed discussions on the methods used for the identification and definition of clusters can be found in Section 4.5.2.4. Moreover, the clusters were named according to the nature of the publications embraced by a particular cluster. The rest of this section explains the differences in the clusterings of both technologies.

First, the number of clusters of both knowledge structures differs. Whereas the knowledge structure of pressure sensors shows a more fragmented and diverse nature embracing a total of ten clusters that of ZnO nanosensors displays a compact network structure composed of fewer clusters of larger size. These differences in the number of clusters may stem from the differing cut-off values used to define the clusters from the dendrograms (Section 4.5.2.4). Nevertheless, as already noted, care was taken to select clusters in line with the contents they embed. Second, as suggested by their cognitive sub-fields, both knowledge structures appear to be driven by applications. This is not surprising, as devices depict fields of applied science. Here, this has also been observed by Rafols et al. (2010a) for the case of the field of hybrid nanomaterials. Nevertheless, the nature of the cognitive sub-fields between emerging and mature knowledge structures differs. On the one hand, the knowledge structure pressure sensors is divided into the different design principles that have been developed over the years for micro-pressure sensing, such as optical, piezoresistive, and resonant, among others, as well as special application domains, such as

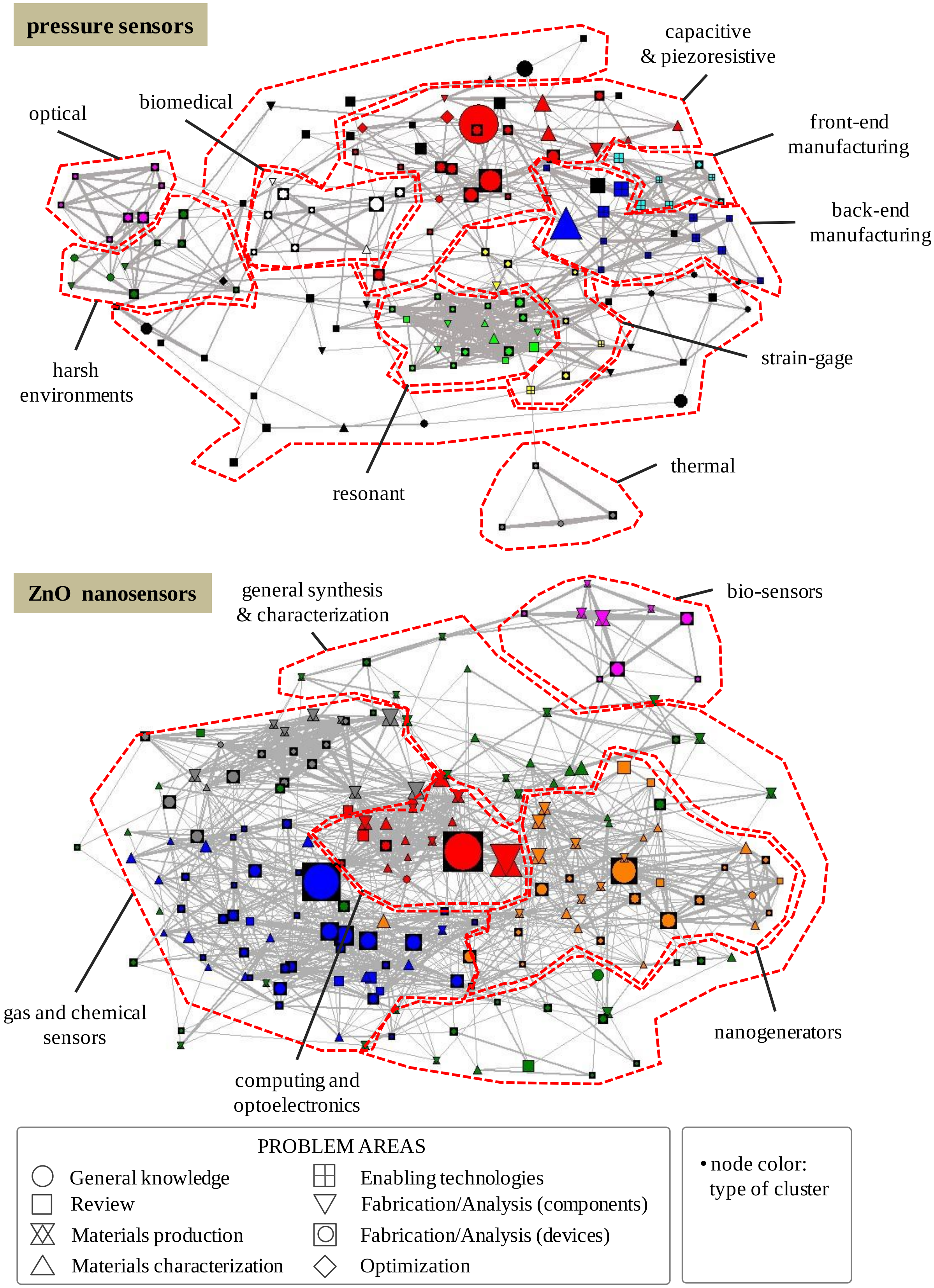

Fig. 5.4 Cluster for 'pressure sensors' and 'ZnO nanosensors' (cosine ≥ 0.18)

their use in the biomedical field or harsh environments. This greater segmentation may be attributed to their more matured nature. On the other hand, although the knowledge structure of ZnO nanosensors embraces potential application domains such as biosensors, gas and chemical sensors, and nanogenerators, it seems that those applications have not fragmented into more specific sub-domains yet, i.e. they still remain as single homogeneous groups. Third, differences can be discerned in the cluster interconnectivity for the knowledge structures. This is mostly sparse for pressure sensors, while that of ZnO nanosensors is significantly denser. Here, higher levels of cluster interconnectivity point to a greater cognitive dependence among clusters. This result must be interpreted with caution because it is derived from a visualization approach; therefore, more numerical approaches should be conducted. Nevertheless, in broader terms, these differences highlight the still formative nature of emerging knowledge structures.

5.5. Summary of the Results

This chapter has aimed at understanding the dynamics of emerging technologies by evaluating the rates and directions of change of their underpinning knowledge bases. It was inferred the rates of change of knowledge bases to be useful in discerning the patterns of growth of technologies, while the directions of change of knowledge bases appeared useful for tracing the fluidity, particularly in cognitive terms, of technologies. The directions of change of knowledge bases were related to the concept of ‘problems’. Particularly, it was argued that the nature of the knowledge underlying technologies may depict a sort of a ‘cognitive imprint’ reflecting the types of problems confronted by technologies over time. For both cases, a series of bibliometric and social network analysis methods were used. Whereas the rates of change of knowledge bases were assessed through the definition and evaluation of bibliometric indicators derived from scientific publications, their directions of change were evaluated through the construction of co-citation networks based on the list of cited references listed in the collected publications. These co-citation networks were, in turn, allocated from a series of problem areas drawn from the problem space defined for the field of micro/nanosensors and actuators. Furthermore, two main cognitive-related indicators were defined and evaluated: cognitive compositions and cognitive sub-fields. These indicators provided a proxy for the cognitive properties of the knowledge base. The empirical case of MEMS/NEMS technologies was used. This field proved useful as it involved a series of mature and emerging technologies.

In terms of the rates of change of the knowledge base, the results of this chapter showed that the patterns of growth of emerging technologies are reflected in chronologically new, highly dynamic, collaborative, and complex, yet ‘narrow’ and lowly diffused scientific knowledge bases. This result suggests that emerging technologies go beyond a mere newness and rapid growth. In particular, significant differences were observed between emerging and mature technologies at the cognitive level. The directions of change of the knowledge bases underpinning emerging technologies appear to have a strong focus on the earliest stages of problem search and solution. This was referred in this chapter by the greater tendency of the cognitive ‘center of gravity’ of knowledge bases of emerging technologies to be located in the upstream problem areas. This strongly resonates with the results of Miyazaki (1994, 1995) who in her analysis of the search trajectories in the field of optoelectronics depicted the existence of a ‘wedge-shaped pattern’ reflected in the decline of experimental papers and the increase of application-related papers. In contrast, mature technologies – in this case ‘pressure sensors’ – appeared to be entailed of more complex aspects such as design and optimization approaches. This may be attributable to a greater mastery or ‘domestication’ of the technology. Similarly, the clustering of the knowledge bases, as reflected in the cognitive sub-fields, demonstrated some differences. Furthermore, emerging knowledge structures appear to be more compact and less diverse. They also seem to be composed of fewer, larger, and more highly interconnected cognitive sub-fields. This suggests the formative nature of emerging knowledge structures. In contrast, mature knowledge structures showed a fragmented structure. It is inferred that as time passes by, a technological field is fragmented into different niche areas, each depicting technological fields by themselves. Differences in the nature of the cognitive sub-fields between mature and emerging technologies were also observed. It was shown that whereas mature technologies tend to be composed of clusters related to the particular physical phenomena underpinning devices and of a series of application domains, emerging technologies still remained as general homogenous groups of application domains.

In summary, the integration of the patterns of growth and cognitive fluidity allowed gaining deeper insights into the properties of emerging technologies. In particular, this chapter attempted to stress the crucial role of cognitive aspects in discerning technological emergence. In a sense, this chapter ‘looked back’ into the cognitive properties of the knowledge underlying technologies as a way to assess their degree of emergence.

Building on the cognitive properties of knowledge discussed in this chapter, the next chapter delves deeper into this research stream and investigates the evolutionary nature of the dynamics of an emerging nanomaterial technology, namely Zinc Oxide one-dimensional nanostructures.

6. Evolutionary Paths of Change of Emerging Nanotechnological Innovation Systems – The Case of ZnO Nanostructures

6.1. Introduction

One of the main results derived from the previous chapter was the need to look at the cognitive properties of the knowledge bases as proxies for discerning technological emergence. Building upon these cognitive properties, this chapter aims at quantitatively interpreting the nature of the paths of evolution along which emerging nanotechnological systems are channeled over time. Thus, the time variable is now included in the cognitive analysis. In particular, this chapter explores the 'evolutionary side' of change in an emerging technology. As previously noted, the case of Zinc Oxide one-dimensional nanostructures (henceforth ZnO 1D-nanostructures) is used. Evolutionary change in the nanotechnology field (N&N) may be trivial for some (Meyer, 2007); it is intuitively known and articulated, yet few research efforts have attempted to quantitatively express it for the N&N field.

Similar to the previous chapter, this chapter relates the evolution of newly emerging technologies with the building up of formative innovation systems (Jacobsson and Johnson 2000). Borrowing from Consoli and Ramlogan (2008), Metcalfe et al (2005), among others, this chapter highlights the role of 'problem sequences' as critical constructs for discerning the dynamics and directions of formative innovation systems. According to the previous authors, 'problem sequences' depict the recurrent patterns of problem search and solution confronting innovation systems throughout their evolution. In particular, this chapter revolves around the close interrelationship between problems and knowledge. Here, as problems demand knowledge for their solution, it is argued that the types of problems confronted by an innovation system, and in turn its dynamics of change, are imprinted on the nature of the knowledge bases underpinning these innovation systems. Hence, by analyzing the changes undergone by these knowledge bases over time, the dynamics of an emerging innovation system may be traced. . Given the heavily science-driven nature and the still early stages of development of newly emerging technologies in general (Cozzens et al. 2010) and N&N in particular (Bonaccorsi and Thoma 2007; Miyazaki and Islam 2007), the scientific knowledge bases expressed in scientific publications are regarded as appropriate proxies for the evaluation of emerging technologies (Porter et al. 2002). As such, this chapter corresponds to the second hypothesis enumerated in Section 2.5.5.

This chapter is organized as follows. Section 6.2 begins with a brief description of the dynamics of change of emerging nanotechnologies. This is followed by the description of the 'problem space' for nanostructures in Section 6.3. Section 6.4 continues with the definition of the research methods used. Next, Section 6.5 enumerates the results of this chapter. Finally, Section 6.6 provides a brief summary of this chapter.

6.2. Dynamics of change of emerging nanotechnologies

The dynamics of change in the field of nanoscience and nanotechnology (N&N) has drawn considerable attention from the scholarly community. Change in N&N has been depicted as discontinuous, radical, revolutionary and disruptive in nature (Shea, 2005). Such status-quo overthrowing capabilities are reflected in the different connotations used to describe change in N&N, such as 'sixth Kondratieff wave' (Wonglimpiyarat, 2005), 'Grilichesian breakthrough' (Darby and Zucker, 2003), or 'Schumpeterian wave' (Linton and Walsh, 2008), among others. At the same time, change in N&N has also been defined evolutionary and incremental in nature (Meyer, 2007; Miyazaki and Islam, 2007). As such, it is likely to be occurring along established technological trajectories and existing knowledge, as well as strongly being influenced by phenomena such as path-dependencies and lock-ins (Meyer, 2007).

Moreover, in terms of its dynamics, the N&N field is said to be quasi-exponentially growing (Roco, 2004), as well as to be punctuated by patterns such as convergence (Battard, 2011; Hacklin et al., 2009), fusion (Islam and Miyazaki, 2009b; No and Park, 2010), and conflation (Islam and Miyazaki, 2009a), among others. This chapter complements these studies by making use of 'evolutionary eyes' for approaching the dynamics of emerging technologies.

6.3. Definition of the 'Problem Space' for Nanostructures

As noted in previous sections, as innovation systems evolve, it is expected that the nature, structure, and composition of the knowledge bases underpinning these innovation systems to vary accordingly. In particular, these knowledge bases may be endowed with directionality through the manual allocation of problems to each node of the co-citation networks. Similar to the approach taken in Chapter 5, these problem areas are drawn from a 'problem space'. In contrast, the specific problem areas were fine-tuned to describe those typically encountered in the field of one-dimensional nanostructures. The definition of the 'problem space' was based on the evaluation of large amounts of technical literature coupled with the advice of an N&N expert[1]. Five main problem areas were defined:

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[1] Prof. Dmitri Golberg, Principal Investigator at the International Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science (NIMS), Tsukuba, Japan.

- **Fabrication technologies for randomly arranged nanostructures** *[Synthesis & Growth (random)]* - This problem area deals with the development, understanding and improvement of technologies for the synthetic growth and the rational design of randomly arranged, single-composition ZnO nanomaterials. It also includes the general structural evaluation of the grown nanowires in terms of their morphology, shape, composition, microstructure, defects and purity, etc.
- **Fabrication technologies for complex nanostructures** *[Synthesis & Growth (complex)]* – This problem area entails those research efforts for the understanding, development and improvement of technologies aimed at the fabrication and rational design of well oriented and aligned arrays of 1D ZnO 1D-nanostructures. It includes the synthesis of complex nanostructures, such as nanorings, nanohelixes, tetrapods, hierarchical nanostructures and heterostructures (hybrid and doped nanostructures). Similar to the previous problem area, it also embraces the general structural evaluation of the grown nanostructures.
- **Characterization technologies** *[Characterization]* – This problem area embraces the exploration and understanding of the fundamental properties of the grown nanostructures, e.g. optical, electrical, mechanical, magnetic, sensorial, emission, etc., excluding structural properties.
- **Assembly and integration technologies** *[Assembly]* – This problem area entails those activities aimed at the controlled and predictable positioning of nanostructures at multiple length scales and their integration in increasingly complex architectures, as well as their interfacing/interconnectivity with the nano-micro-macro-world.
- **Applications** - This problem area deals with the development, evaluation, and improvement of devices based on ZnO 1D nanostructures. Four main application domains were defined: computing and optoelectronics *[Applications (C&O)]*, sensors and actuators *[Applications (S&A)]*, energy-related applications *[Applications (solar)]*, and spin electronics *[Applications (spin)]*.

As may be inferred, each of the problem areas described above comprises, in turn, of a series of sub-problem areas. Besides those problem areas, two additional cognitive influences were defined: those coming from ‘macro’, conventional ZnO materials (bulk macro ZnO materials and ZnO thin-film technologies), and those from other nanomaterials besides ZnO such as Carbon nanotubes, Silicon, Tin Oxide, Gallium Nitride, etc. Both of them entail fabrication, characterization and applications related activities. Additionally, two broad categories were defined for some nodes: ‘General Knowledge’ which includes publications describing topics of interest for the field of ZnO 1D nanostructures as a whole, and ‘Literature Reviews’ embracing publications with relevant literature for this field. More detailed information on the theoretical concepts behind problem areas and the problem space is provided in Chapter 4.

As previously described, the problem space was visualized as a loosely-defined problem chain. For the case of nanomaterials, such a problem chain may be depicted as follows. The rest of this paragraph relies on Lieber and Wang (2007). First, one-dimensional nanostructures with controlled and tunable chemical composition, structure, size, and morphology are necessary. The latter demands the design and development of methods for the synthesis and growth of nanomaterials and nanostructures. Mastering fabrication technologies, in turn, calls for the evaluation and experimentation of the properties of those nanomaterials and nanostructures. For that purpose, a series of characterization instruments and methods are used. Understanding of the fabrication of nano building blocks and their properties, in turn, enable the development of nano-devices. Here, assembly technologies depict a critical input for the development of potential nano-devices as they allow the fabrication of complex and hierarchical nano-architectures. Finally, technologies for interconnecting nano-devices with the macro-world are necessary to develop truly nano-systems.

6.4. Research Methods

The dataset comprised mainly of the list of references cited by scientific publications – articles, reviews, and proceedings – indexed in the Thomson Reuters/ISI Science Citation Index Expanded database published in English and from the period 2000-2009. The year 2000 was selected as the pioneering publications of the field of ZnO nanostructures were published around that year. A keyword-based analysis focused on the publication titles was used to collect the data. Appendix 2 presents the search query used for this analysis. A total of 3,615 scientific publications were extracted, from which more than 33,147 cited references were drawn. Additionally, published patent applications up to the year 2009 were retrieved from the online European Patent Office's database esp@cenet. This database was used as it allows searching across a multitude of patent offices worldwide. By searching in the titles and abstracts of patents across a worldwide patent database, 187 patent families were collected. For that purpose, the search query presented above was partially modified to make it suitable for the search rules of the esp@cenet database.

Besides a brief longitudinal bibliometric analysis relying on the collected publications and patents, similar to the research approach of the previous chapter, the main research method of this chapter consisted in a co-citation network analysis based on the cited references drawn from scientific publications. The reasons behind the selection of the co-citation method are described in Section 4.3.1. The remainder of this section explains the construction and evaluation of these co-citation networks, as shown in Fig. 6.1.

The collected data underwent a series of cleaning and sorting procedures consisting mainly of manually grouping together similar references and correcting input errors in their bibliographic information. Two periods of analysis were defined: 2000-2004 and 2005-2009. In broader terms, it is expected the first period of time to encompass the initial efforts of the field of ZnO nanostructures, as the main building blocks of this field, ZnO nanowires and ZnO nanobelts, where discovered in this time period, 1999 and 2001, respectively. In contrast, the second period is expected to be punctuated by a greater role of applications as nanogenerators, one of the most intensively researched applications up to now, were first developed around 2006. In order to prevent the inclusion of random errors and size-related biases between the two periods of time, a standard-deviation normalized threshold on citation counts equal or greater than 0.40 was defined. After setting this threshold, we ended up with 92 and 361 cited references for the periods 2000-2004 and 2005-2009, respectively. Following, the software VantagePoint was used to construct co-occurrence matrices – pairwise relationship between cited references – for each period of time. In order to provide a better visualization of the similarity structures across the data and to control for size effects, the co-occurrence matrices were normalized with the Salton’s cosine similarity measure. A co-citation threshold greater or equal to 0.15, within the range of values typically used in the literature, was chosen in order to center our attention on the predominant co-citation relationships. Following, the similarity matrices were visualized as co-citation networks with the software UCINET/NetDraw.

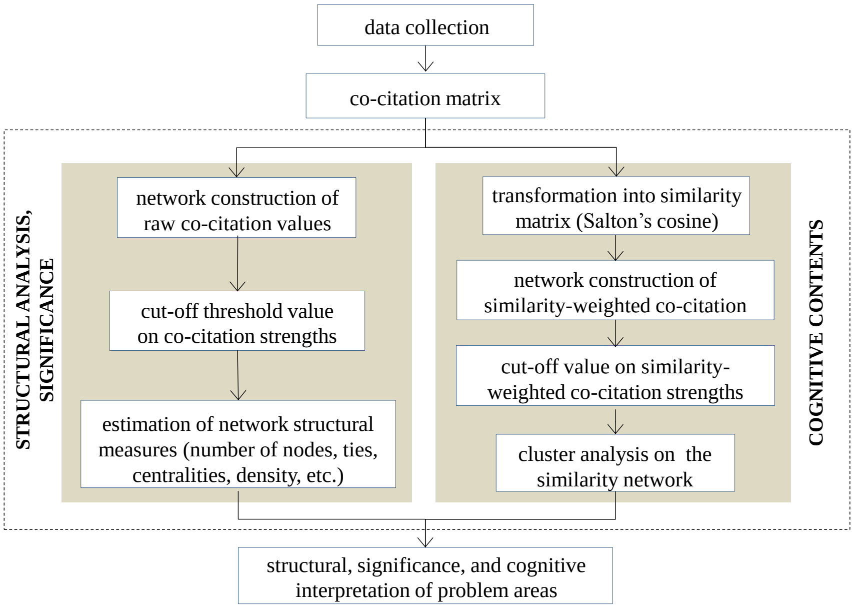


Fig. 6.1 Summary of the research methods

Next, the knowledge structures expressed in the normalized networks were evaluated structurally and cognitively (please refer to the two main divisions of Fig. 6.1). On the one hand, the structural network analysis consisted in the estimation of a series of network indicators for both knowledge structures. On the other hand, the cognitive analysis focused on the evaluation of the problem-attached co-citation networks. For that purpose, ‘problem areas’ drawn from a ‘problem space’ for ZnO 1D-nanostructures were manually allocated to each node of the co-citation networks. A series of indicators based on the problem areas: (i) ‘cognitive compositions’ measuring the significance and predominance of the different problem areas within the networks; (ii) ‘problem trajectories’ evaluating the growth rates across the different problem areas; (iii) ‘cognitive interrelationships’ indicating the extent to which the different problem areas relate to each other over time; as well as (iv) the conceptual sub-fields underlying the knowledge structures. The results of these analyses are presented in the next section.

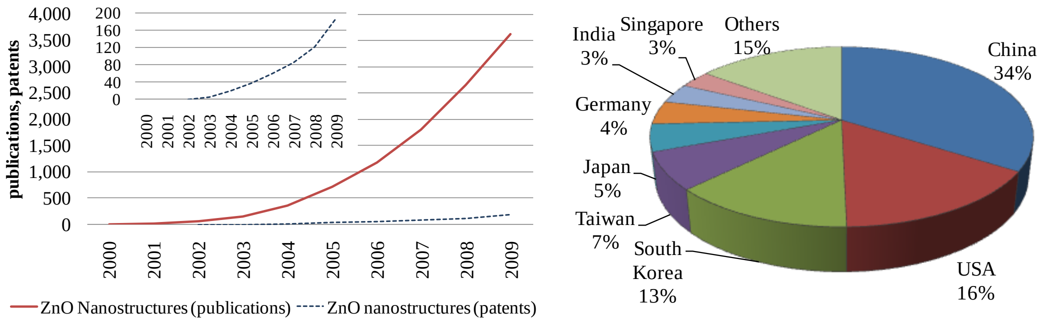
6.5. Research Results

6.5.1. General bibliometric analysis

This section provides preliminary insights into the patterns of scientific and technological change in the field of ‘ZnO 1D nanostructures’ through the analysis of publications and patents (Fig. 6.2).

a) cumulative number of publications and patents over time

b) distribution of publications by author origin



c) distribution of published patents by issuing patent office

d) distribution of published patents by field of application

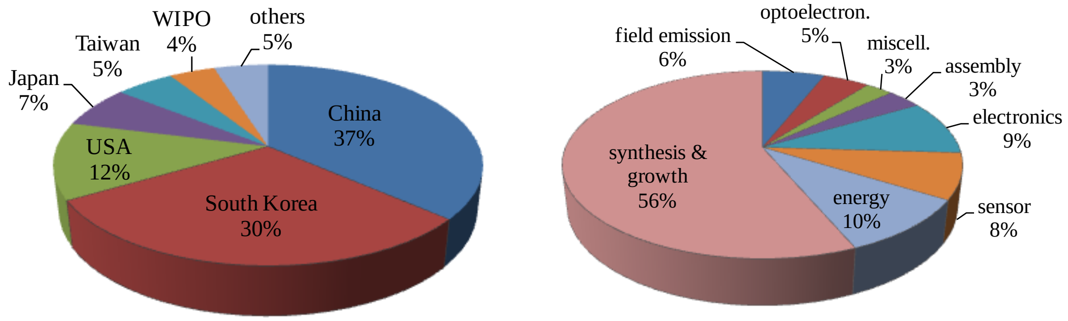


Fig. 6.2 Longitudinal bibliometric analysis on ZnO 1D nanostructures.

Fig. 6.2a demonstrates the exponential scientific and technological interests surrounding the field of ZnO 1D-nanostructures. As the number of publications significantly surpasses that of patents, it may be inferred that this field is still heavily science-driven in nature.

Fig. 6.2b and Fig. 6.2c indicate that China appears to lead this nano-field, at least in terms of the publication output, by embracing more than a third of the total of scientific publications and patents. Despite the pioneering efforts of the USA in this field particularly through the research work of the Center for Nanostructure Characterization at the Georgia Institute of Technology, the contribution of the USA in the number of publications and patents is half of that of China. Overall, these results reflect the dominant position of East Asian countries – China, Japan, South Korea, and Taiwan – in this nano-field, which embrace about 60% of the publications and 80% of the published patents. Moreover, the results of Fig. 6.2d show the heavy focus on the development of technologies for the fabrication of ZnO 1D-nanostructures, which suggest the still early stages of technological development of this nano-field. Moreover, Fig. 6.2d depicts the broad range of potential application domains embraced by this nano-field. Examples are optoelectronics (lasers, light-emitting diodes, etc.), electronics (transistors, diodes, etc.), field emission, energy-related applications (solar cells, nano-generators, etc.), and sensors (gas, humidity, biological, chemical), among others.

6.5.2. Analysis of the knowledge structures ‘ZnO 1D nanostructures’

6.5.2.1. Construction of the knowledge structures

Fig. 6.3 presents the scientific knowledge structures for the time periods 2000-2004 and 2005-2009, as reflected in their respective co-citation networks. It should be remarked that different scale sizes were used for the networks of Fig. 6.3.

A series of attributes were allocated to those networks. Here, a single ‘problem area’ was allocated to each node. For that purpose, the contents of each cited reference (the nodes in the networks shown in Fig. 6.3) were evaluated. The latter consisted in assessing the title, abstract, and in some cases the full text of each cited reference with the purpose of defining the problem area, from the problem areas described in Section 6.3, being tackled by a particular network node. For those cited references involving more than one problem area, the allocation of the problem area relied on the farthest stage reached along the cognitive problem chain described at the end of Section 6.3.The color or shape of the nodes depicts the particular type of allocated problem. The size of the nodes denotes the average number of citations. The thickness of the ties varies according to the co-citation strengths among the nodes.

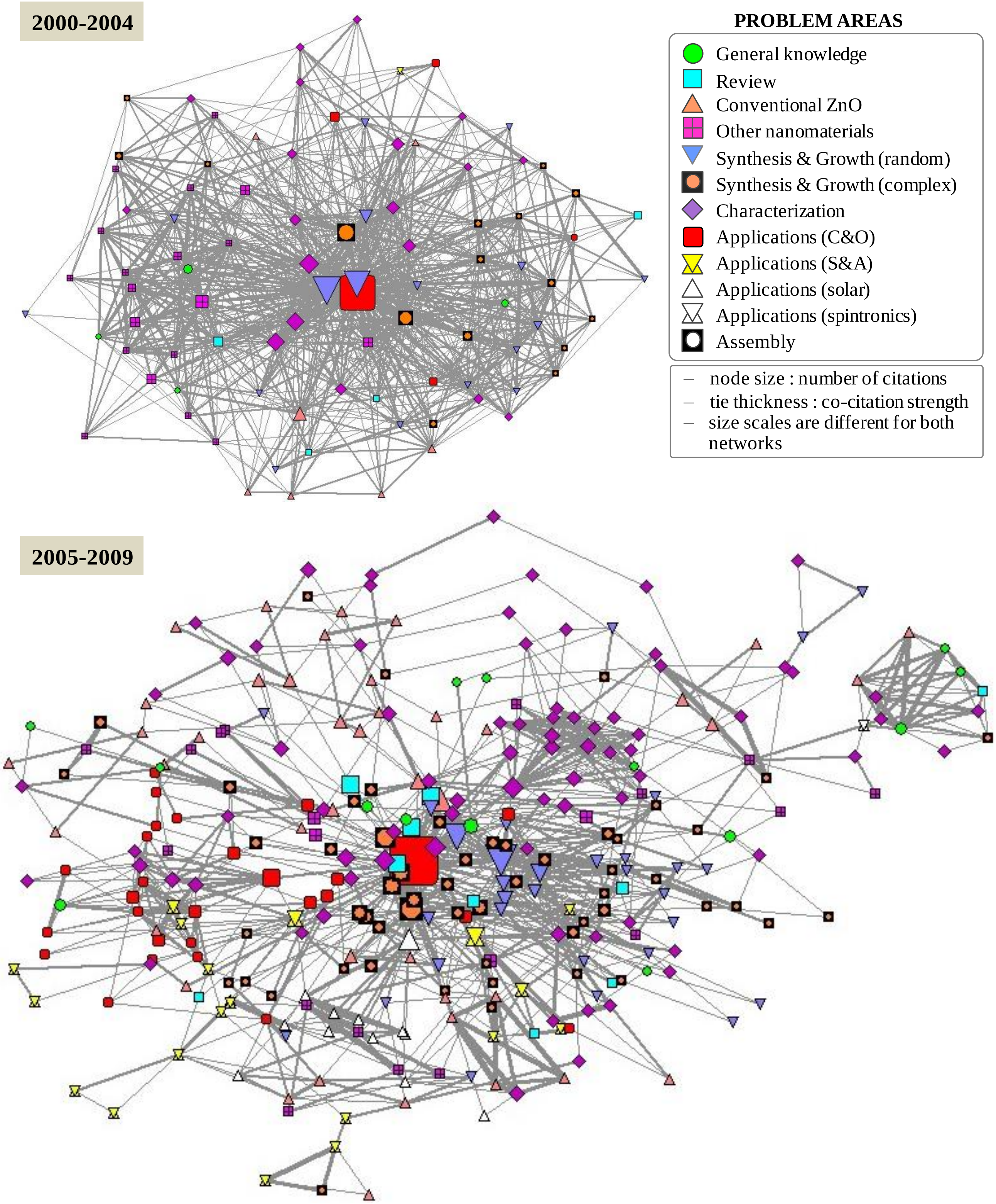


Fig. 6.3 Knowledge structures for the periods 2000-2004 and 2005-2009 (cosine ≥ 0.15)

Moreover, the network layout was arranged based on the 'spring-embedding' algorithm which tends to locate similarly connected nodes closer together. For the sake of clarity, node labels and single connected nodes were excluded from the networks. Subsequent sections rely on the networks of Fig. 6.3 for their analyses.

6.5.2.2. General structural network analysis

This section evaluates the general structural changes undergone by the knowledge structures over time. For that purpose, a series of network structural indicators were estimated (Table 6.1).

Table 6.1 General structural indicators of the knowledge structures and rates of change

Structural network aspects	2000-2004 (1)	2005-2009 (2)	Rates of change (1) vs (2)
Total number of nodes	92	361	2.9
Average number of citations	27.9	71.2	1.6
Network density	0.24	0.03	-0.9
Average weighted degree	22.2	9.9	-0.6
Average publication years	2005.6	2002.4	-
Normalized degree centrality	24.4	0.6	-1.0
Normalized betweenness centrality	0.89	0.89	0.0
Normalized closeness centrality	56.4	16.4	-0.7
Network centralization (degree)	58.2%	5.8%	-0.9
Network centralization (betweenness)	11.1%	46.0%	3.1
Network centralization (closeness)	56.6%	35.7%	-0.4

The data of Table 6.1 helps us to infer that the knowledge structure 'ZnO 1D-nanostructures' is undergoing strong structural changes. Three aspects should be highlighted. First, it is rapidly expanding as implied by the increasing number of nodes and average number of citations point. Obviously, the network connectivity has not been capable of coping with such rapid rates of growth which had resulted in lower network density and average degree values. The latter has led to a knowledge structure with less connected nodes positioned farther apart from each other, as inferred from the decreasing centrality values. Second, the knowledge structure appears to be continuously regenerating given the ever newer sources of knowledge it relies upon. Third, the increasing network centralization in terms of betweenness centrality suggests the existence of a series of focal network nodes concentrating at locations closer to the core of the network.

Overall, the results of this section denote a rapidly expanding, sparser and more fragmented knowledge structure over time. As the rest of this chapter shows, those structural changes provide only one side of the story; they are paralleled by significant cognitive changes.

6.5.2.3. Cognitive analysis of the knowledge structures

This section now looks at the cognitive changes undergone by the co-citation networks over time. Four different cognitive analyses were conducted on the networks of Fig. 2: cognitive compositions, problem trajectories, cognitive interrelationships, and conceptual sub-fields.

a) Cognitive compositions

Cognitive compositions evaluate the role of the different problem areas within a knowledge structure through the estimation of the distribution of their shares of nodes and citations, as well as normalized centrality values (Table 6.2).

Table 6.2 Co-citation networks for the field 'ZnO 1D nanostructures' 2000-2004 and 2005-2009

		2000-2004					2005-2009				
		No.	Rec.	nDEG	nBET	nCLO	No.	Rec.	nDEG	nBET	nCLO
	Conventional ZnO	7.6%	5.4%	14.6	0.2	53.2	15.0%	11.2%	0.4	0.6	15.3
	Other nanomaterials	20.7%	15.5%	21.1	0.4	55.1	6.6%	4.7%	0.4	0.6	16.5
ZnO nanostructures	General Knowledge	4.3%	3.6%	23.9	0.3	56.2	4.4%	3.8%	0.5	0.3	15.7
	Review	4.3%	3.0%	19.8	0.5	54.7	4.2%	6.9%	0.3	0.4	16.7
	Synthesis &Growth (random)	18.5%	22.3%	28.9	1.5	58.1	10.2%	13.1%	0.8	1.1	17.1
	Synthesis &Growth (complex)	17.4%	15.7%	26.6	0.9	56.8	18.3%	20.1%	0.7	0.9	17.0
	Characterization (ZnO nano)	20.7%	22.8%	25.9	0.9	56.8	23.8%	19.9%	0.6	0.6	16.2
	Assembly (ZnO nano)	-	-	-	-	-	-	-	-	-	-
	Applications (C&O)	5.4%	11.1%	29.7	2.6	59.9	8.3%	11.9%	0.8	2.3	17.2
	Applications (S&A)	1.1%	0.7%	8.8	0.1	50.8	5.3%	5.0%	0.6	1.4	16.0
	Applications (solar)	-	-	-	-	-	3.6%	3.2%	0.7	0.6	16.7
	Applications (spin)	-	-	-	-	-	0.3%	0.2%	0.6	5.9	13.9

NOTES:
No.: proportions in the number of nodes; Rec.: proportions in the number of records; nDEG: average normalized degree centrality; nBET: average normalized betweenness centrality; nCLOS: average normalized closeness centrality

Cognitive composition 2000-2004

The cognitive composition for this period is dominated by the understanding and development of synthetic methods for the growth of ZnO-based nanostructures. They account for about two-fifths of the shares of nodes and citations, as well as they are characterized by high centrality values. In particular, the most basic 1D nanostructures, i.e. randomly arranged, single-composition ZnO nanomaterials, dominate. The understanding and exploration of the properties of nanostructures through characterization approaches follows with one-fifth of the shares of nodes and citations, as well as by a moderate predominance in terms of centrality values. Application-related problem areas entail merely over 6% of the nodes yet around 12% of the citations. In particular, 'computing and optoelectronics' applications (C&O) dominate. Despite their low shares, C&O takes the most predominant role in the network in terms of their centrality values. Here, a node stands out: a study from the Berkeley National Laboratory (USA) exploring the use of ZnO nanowires as potential room-temperature ultraviolet nano-lasers, which is the pioneering application in this field. This suggests the critical role of potential applications even if still embodying 'primitive' proofs-of-concepts, besides the creation of fundamental science, as aspects driving the building up of a 'critical mass' of knowledge around emerging technological fields.

Interestingly, nanomaterials other than ZnO such as Silicon, Gallium Arsenide, Tin Oxide, and Gallium Nitride, among others, account for a fifth of the nodes and citations, which may point to the close interrelationships among the research efforts conducted across different nanomaterial contexts. In contrast, the influence of conventional ZnO materials is significantly lower. Both 'Other nanomaterials' and 'Conventional ZnO' appear to be taken peripheral positions within the network, as inferred from their relatively low centrality values.

Cognitive composition 2005-2009

In broader terms, the knowledge structure for the time period 2005-2009 displays an increasing diversity in the network in terms of its size and the nature of the knowledge it contains. In this regard, technologies for the synthetic growth of nanostructures slightly reduce their shares of nodes and citations, yet they still remain highly significant and predominant. Here, the focus of the synthetic growth methods appears to be shifting to more complex 1D-nanostructures such as doped nanostructures, heterostructures, hierarchical structures, and particularly to aligned and oriented arrays of nanostructures. These nanostructures are closer to the building blocks necessary for the development of potential nano-devices. The characterization of ZnO nanostructures increases in terms of their nodes to over one-fourth, yet slightly decreases to over one-fifth in terms of their citations. This result suggests the still strong significance of characterization approaches during this time period. Nevertheless, their predominance is still limited given their relatively lower centrality values.

Significantly higher increments are experienced by application-related problem areas. They now entail about one-fifth of the nodes and citations. C&O applications are still characterized by their predominant location within the knowledge structure; however, other applications have flourished. In particular, sensing and actuation applications (S&A) experienced strong increments in their significance and predominance in this period of time. Moreover, as assembly calls for more complex architectures, its absence in both time periods suggests the still ‘primitive’ nature of the ZnO nano-devices developed so far. Also, this period is characterized by the significant decrement of the influence of nanomaterials other than ZnO, coupled with the strengthening of conventional ‘macro’ ZnO materials. The strong influence of conventional ZnO materials suggests the partly cumulative and path-dependent nature of ZnO 1D nanostructures.

Overall, these results of this section hint at a redistribution of the cognitive contents of the knowledge structure ‘ZnO 1D nanostructures’ over time. It appears that the cognitive ‘center of gravity’ of the knowledge structure is still heavily tilted toward upstream problem areas such as the synthetic growth of ZnO nanostructures. Yet, over time a stronger emphasis is being placed on characterization and, particularly on application-related problem areas. The latter is closely in line with the findings from Miyazaki (1994) and Miyazaki (1995) for the field of optoelectronics.

b) Problem trajectories

This section now evaluates the growth rates experienced by the different problem areas over the time periods 2000-2004 and 2005-2009 in terms of nodes and citations (Table 6.3). These are referred as ‘problem trajectories’.

Table 6.3 Problem trajectories for the knowledge structure 'ZnO 1D nanostructures'

	Problem Fields	Nodes	Records
	Conventional ZnO	6.7	19.8
	Other nanomaterials	0.3	2.0
ZnO 1D nanostructures	General Knowledge	3.0	9.6
	Review	2.8	21.9
	Synthesis & Growth (random)	1.2	4.9
	Synthesis & Growth (complex)	3.1	11.8
	Characterization	3.5	7.7
	Assembly	-	-
	Applications (C&O)	5.0	9.7
	Applications (S&A)	18.0	74.3
	Applications (solar)	-	-
	Applications (other)	-	-

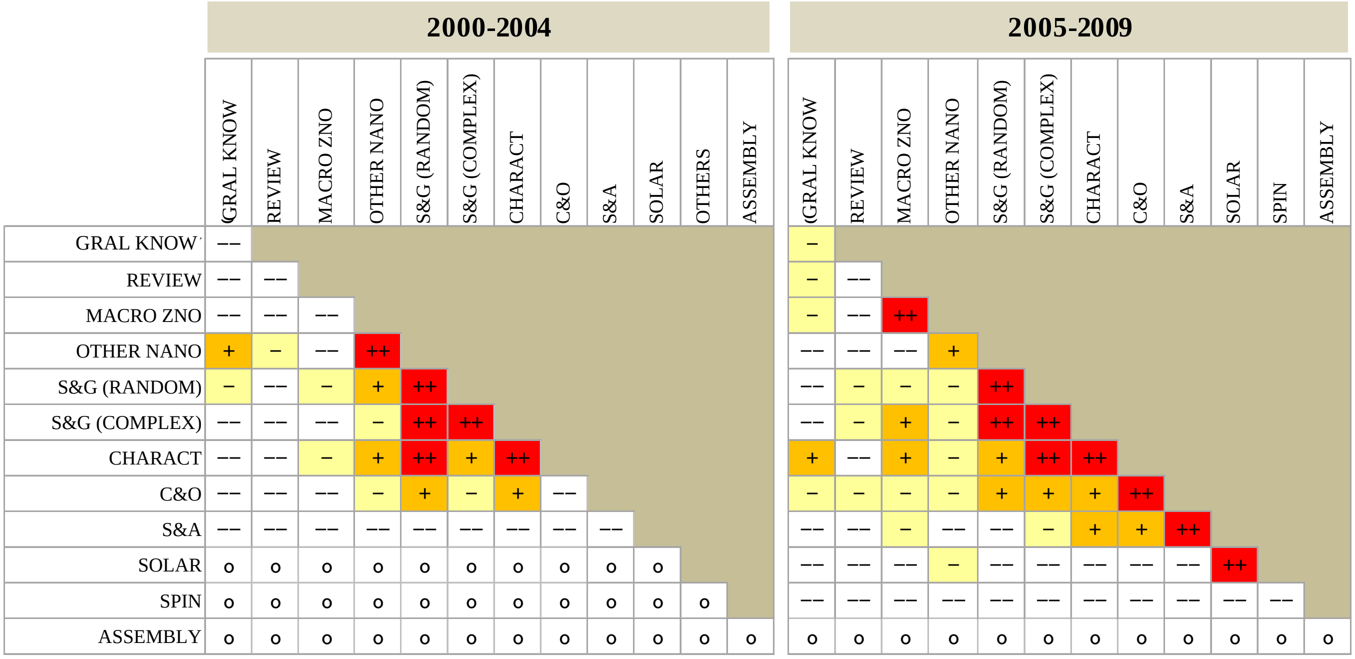
The data in Table 6.3 indicates a multi-trajectory growth across the different problem areas; yet, some of them appear to be accentuated. In support of the results presented in the previous section, the results of Table 6.3 demonstrate that a gradual shift in the cognitive stress of the knowledge structure toward downstream problem areas is under way. Here, applications related to sensors and actuators show the highest rates of growth in terms of nodes and citations, which implies their imminent emergence. Nevertheless, such transition is still paralleled by strong rates of growth in upstream problem areas. From these, particularly synthetic methods for complex nanostructures stand out. Also, significant growth rates of conventional ZnO materials are coupled with the sluggish growth of other nanomaterials besides ZnO.

The results in Table 6.3 show that upstream problem areas are not decreasing; they are still growing, and at relatively high rates. Nevertheless, downstream problem areas appear to be experiencing even stronger rates of growth.

c) Cognitive inter/intra relationships

Cognitive changes are not only reflected on the distribution of the shares of 'problem areas' across the network, but also on the extent to which the different problem areas interact to and within each other over time. This is referred in this chapter as 'cognitive inter/intra relationships'. The way to visualize these interactions is by collapsing the networks of Fig. 6.3 into single nodes based on the attribute 'problem areas'. Here, the sum of the co-occurrence strengths among the different problem areas was used. The collapsed networks were, in turn, visualized into co-occurrence matrices indicating the pairwise relations between problem areas (Fig. 6.4). A particular type of symbol (+ +, +, −, − −) was allocated to each cell of these matrices depending on their quartile values.

The main results are as follows. As inferred from the spread of the matrix cells with [+ +], the highest levels of interaction are mainly restricted to those involving a particular problem area with itself, i.e. intra relationships (matrix diagonals in Fig. 6.4). Nevertheless, for both periods of time strong interactions among synthesis & growth, characterization, and application related problem areas can also be discerned. Over time, the degree of interaction can be seen to be extending toward newer application domains. Interestingly, the interactions of conventional ZnO materials and other nanomaterials besides ZnO appear to be influential at different time periods. In this regard, whereas other nanomaterials exert an influence during the time period 2000-2004, conventional 'macro' ZnO materials are influential in the time period 2005-2009. For both cases, these interactions are limited to synthesis and growth (S&G), and characterization-related problem areas.



2000-2004

	GRAL KNOW	REVIEW	MACRO ZNO	OTHER NANO	S&G (RANDOM)	S&G (COMPLEX)	CHARACT	C&O	S&A	SOLAR	OTHERS	ASSEMBLY
GRAL KNOW	−−											
REVIEW	−−	−−										
MACRO ZNO	−−	−−	−−									
OTHER NANO	+	−	−−	++								
S&G (RANDOM)	−	−−	−	+	++							
S&G (COMPLEX)	−−	−−	−−	−	++	++						
CHARACT	−−	−−	−	+	++	+	++					
C&O	−−	−−	−−	−	+	−	+	−−				
S&A	−−	−−	−−	−−	−−	−−	−−	−−	−−			
SOLAR	o	o	o	o	o	o	o	o	o	o		
SPIN	o	o	o	o	o	o	o	o	o	o	o	
ASSEMBLY	o	o	o	o	o	o	o	o	o	o	o	o

2005-2009

	GRAL KNOW	REVIEW	MACRO ZNO	OTHER NANO	S&G (RANDOM)	S&G (COMPLEX)	CHARACT	C&O	S&A	SOLAR	SPIN	ASSEMBLY
GRAL KNOW	−											
REVIEW	−	−−										
MACRO ZNO	−	−−	++									
OTHER NANO	−−	−−	−−	+								
S&G (RANDOM)	−−	−	−	−	++							
S&G (COMPLEX)	−−	−	+	−	++	++						
CHARACT	+	−−	+	−	+	++	++					
C&O	−	−	−	−	+	+	+	++				
S&A	−−	−−	−	−−	−−	−	+	+	++			
SOLAR	−−	−−	−−	−	−−	−−	−−	−−	−−	++		
SPIN	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	−−	
ASSEMBLY	o	o	o	o	o	o	o	o	o	o	o	o

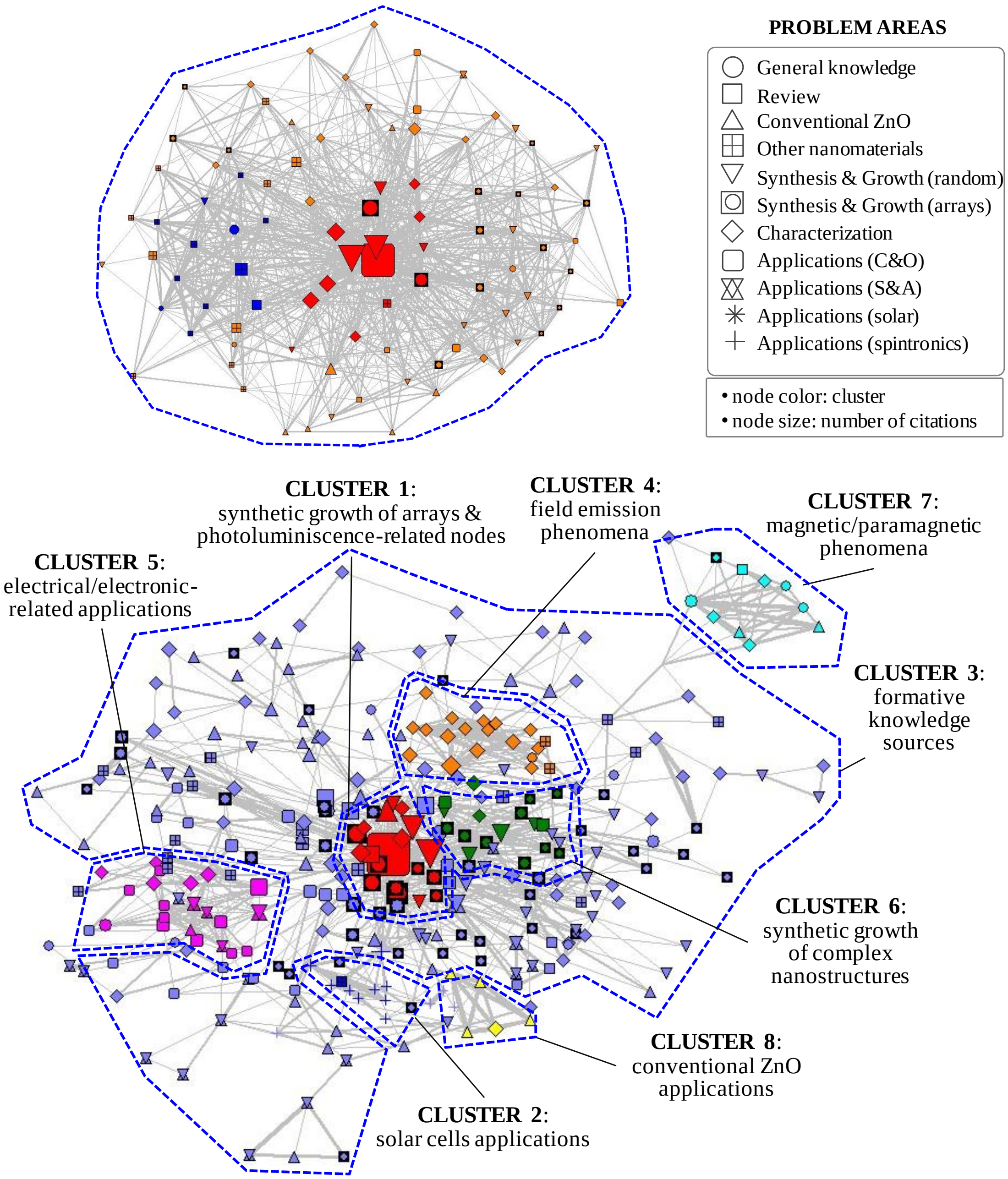
NOTES: GRAL KNOW: general knowledge; REVIEW: literature review; MACRO ZNO: conventional ZnO materials; OTHER NANO: other nanomaterials; S&G (RANDOM): synthetic growth of randomly arranged, single-composition nanostructures; S&G (COMPLEX): synthetic growth of complex nanostructures; CHARACT: characterization approaches; C&O: applications related with computing and optoelectronics; S&A: applications related with sensors and actuators; SOLAR: solar energy-related applications; SPIN: spin electronics-related applications; ASSEMBLY: assembly into more complex architectures.

Fig. 6.4 Cognitive interrelationships for the knowledge structure 'ZnO 1D nanostructures'

The next section shows that some of these interactions have led to agglomerations or clusters of highly cognitive-related nodes, which are defined in this chapter as ‘conceptual sub-fields’.

d) Conceptual sub-fields

In line with Rafols and Meyer (2010), a hierarchical cluster analysis based on the Ward’s method and squared distances was conducted to discern the conceptual sub-field underlying the knowledge structures of ZnO 1D nanostructures. The definition of the clusters relied on the evaluation of the resulting dendrograms and the schematic networks. Fig. 6.5 shows the knowledge structures of Fig. 6.3 with the identified clusters. The clusters were named according to the cognitive contents they embraced. As previously described, the entropy of the proportion of problem areas within each cluster was also estimated (Fig. 6.5, bottom). Here, higher entropy values relate to a higher number of and more intense problem areas within a particular cluster.



	2000-2004	2005-2009							
Clusters	1	1	2	3	4	5	6	7	8
General knowledge	0.04	-	-	0.04	0.05	0.05	-	0.27	-
Review	0.04	0.05	-	0.03	-	-	0.06	0.09	-
Conventional ZnO	0.08	0.05	-	0.16	-	0.05	-	0.18	0.80
Other nanomaterials	0.21	-	0.10	0.08	0.11	-	-	-	-
Synthesis & Growth (random)	0.18	0.21	-	0.11	-	-	0.24	-	-
Synthesis & Growth (complex)	0.17	0.42	-	0.18	-	-	0.53	0.09	-
Characterization	0.21	0.21	-	0.22	0.84	0.24	0.12	0.27	0.20
Assembly	-	-	-	-	-	-	-	-	-
Applications (C&O)	0.05	0.05	-	0.08	-	0.48	0.06	-	-
Applications (S&A)	0.01	-	-	0.07	-	0.19	-	-	-
Applications (solar)	-	-	0.90	0.02	-	-	-	-	-
Applications (spin)	-	-	-	-	-	-	-	0.09	-
Entropy	1.94	1.49	0.33	2.09	0.54	1.30	1.26	1.67	0.50

Fig. 6.5 Clusters for the knowledge structures 2000-2004 and 2005-2009

As shown in Fig. 6.5, the knowledge structure for the time period 2000-2004 is characterized by a compact and densely connected network. Three main clusters were discerned for this period. Nevertheless, given the high degree of interconnectivity among the different clusters we decided to regard them as a single cluster. The core of the network contains few highly significant nodes, as depicted by their sizes: a computing and optoelectronics-related node, as well as a series of synthetic growth and characterization-related nodes. For the rest of the network, different problem areas appear to be distributed at particular places across the network.

In contrast, the knowledge structure 2005-2009 appears to be fragmenting into more clearly defined clusters. A total of eight clusters were discerned. As shown in Fig. 6.5, the knowledge structure revolves around Cluster 1 which is mostly associated with the synthetic growth of ZnO nanostructured arrays. Also, this cluster contains a series of characterization and application nodes related to the evaluation of the photoluminescence properties of ZnO nanostructures and their use in potential nano-laser applications. These, as previously said, are the pioneering applications of the field of ZnO nanostructures. Also, at the center of the network are Cluster 4 and Cluster 6. Both clusters are highly focused on particular problem areas, as shown in their entropy values at the bottom of Fig. 6.5. Whereas the former centers on the evaluation of the field emission properties of ZnO nanostructures which is highly related to their use in flat panel display applications, the latter focuses on the synthetic growth of nanostructures with more complex geometries. On the periphery of the network we find Cluster 5, Cluster 2, Cluster 7, and Cluster 8. From these, Cluster 2 and Cluster 5 are the only two clusters with a relatively high proportion of application-related nodes (see table at the bottom of Fig. 6.5): Cluster 2 embracing the application of ZnO nanostructures in solar cells, and Cluster 5 related to a series of applications dealing with electric/electronic properties of ZnO nanostructures, e.g. field-effect transistors, chemical sensors, etc. In their vicinity, we find Cluster 8 which focuses on applications from conventional ZnO materials. On the other hand, Cluster 7 appears to be farther away in the periphery of the knowledge structure. This cluster deals with the evaluation of the magnetic/paramagnetic properties of ZnO nanostructures necessary for their use in spin electronics, which is an application domain still at early stages of development. Finally, Cluster 3 appears to work more as support network highly interacting with the rest of the clusters. It appears to be embracing a series of still formative node agglomerations about to become formal clusters, e.g. biosensors, nano-generators, and other sensing applications, among others.

The results of this analysis highlight the still formative nature of this knowledge structure. In this regard, the bulk of this knowledge structure appears to be still dominated by clusters mainly dealing with the understanding of methods for the synthetic growth of ZnO nanostructures. Nevertheless, over the years, application-related clusters seem to be flourishing. Most of the application-related clusters occupy largely peripheral locations and tend to focus their efforts on the understanding of properties and phenomena key for particular application domains.

6.5.3. Co-evolutionary mechanisms for the case of nanogenerators

As repeatedly stated throughout this thesis, the use of knowledge as a proxy for measuring the dynamics of emerging technologies relied on the co-evolutionary relationships between technologies and knowledge (Section 2.5.1 – 2.5.4). So far, the previous two chapters have assumed these co-evolutionary interrelationships without delving into the nature of these interrelationships. This section attempts to analyze the nature of the co-evolution between technologies and knowledge through the use of a case-study approach.

In order to continue with the technologies studied in the previous two chapters, the case study of the zinc oxide-nanostructure-based nanogenerators will be used. For the purposes of this study, a nanogenerator is defined as a device that converts mechanical energy into electric power with the use of zinc oxide (ZnO) nanowires (Wang and Song, 2006). In particular, the research efforts conducted by Prof. Zhong Lin Wang's research laboratory at the Georgia Institute of Technology will be investigated. The reasons for selecting this research lab are two-fold: first, Prof. Wang's research institute is the pioneer in the development of nanogenerators. Second, the different stages of the development of this nanodevice have been well documented by this research institute. In this regard, a series of scientific articles and books published by this research group were used for constructing this brief case study; in particular, two key sources should be mentioned: Wang (2011) which is a publicly-available book on the research of ZnO nanostructure-based nanogenerators, and Wang (2009a) which compiles a concise background about the progress of the field of ZnO nanostructures from 2001-2009[2].

This section begins with a brief description of conventional ZnO materials and ZnO nanostructures. The analysis of the co-evolutionary mechanism between technologies and knowledge for the case of ZnO nanostructures follows.

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[2] This was complemented with a brief conversation with Prof. Zhong Lin Wang on the occasion of the MANA International Symposium 2013 organized by the National Institute for Materials Science on February 27th – March 1st in Tsukuba, Japan.

6.5.3.1. Conventional Zinc Oxide

Zinc Oxide (ZnO) has been formally researched since the first quarter of the last century (Klingshirn et al., 2010); however, oldest references can be traced back as early as 1944. Over this period, research on ZnO has experienced a series of peaks of interest (Gomez and Tigli, 2013). For example, episodes of increased attention occurred during the 1950s and 1970s in topics related to the growth, doping, transport, band-structure, and luminescence of ZnO. Particularly, in the last 5 to 10 years research on ZnO has experienced a renaissance directed towards the potential use of ZnO for epitaxial layer growth, quantum wells and nanostructures (Klingshirn et al., 2010). For over a hundred of years, Zinc Oxide has been used in applications such as: facial powders, ointments, sunscreens, catalysts, lubricant additives, paint pigmentation, piezoelectric transducers, varistors, gas sensors, and transparent conducting electrodes (Jagadish and Pearton, 2006). In this regard, the first technical-use of ZnO was as detectors in build-your-own radio sets in the 1920s (Jagadish and Pearton, 2006). More advanced applications of ZnO have been high-temperature transistors, UV-light detectors, spintronics, and biosensors, among others.

6.5.3.2. Zinc Oxide nanostructures

Pioneering research efforts on Zinc Oxide one-dimensional nanostructures were conducted by Prof. Zhong Lin Wang of the School of Materials Science and Engineering at the Georgia Institute of Technology in 2001 with the discovery of ZnO nanobelts. From that on, research on ZnO nanostructures has rapidly grown, as shown in Fig. 6.6 (Gomez and Tigli, 2013).

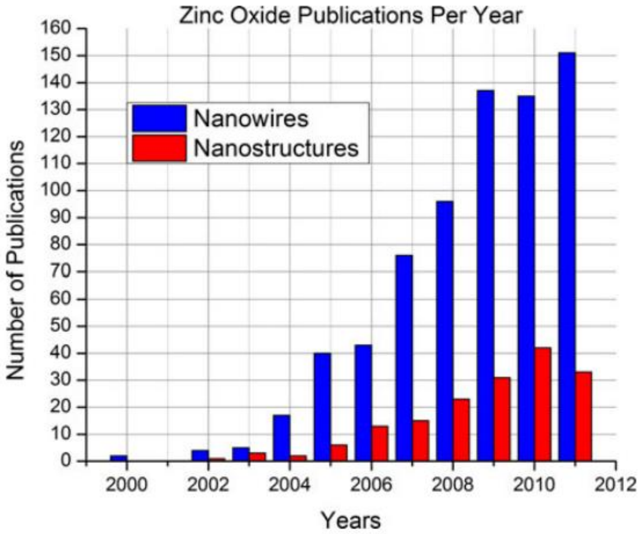

Fig. 6.6 Zinc Oxide publications over time (Gomez and Tigli, 2013)

As can be seen, up to now, thousands of scientific papers on ZnO nanostructures, particularly nanowires, have been published. As defined by Gomez and Tigli (2013), the greatest growth rates can be discerned in the mid-2000s, slowly losing momentum in the later years. Rather than a leveling off of ZnO research, this change obeys the accelerating growth experienced by other nanomaterials, particularly by graphene[3]. In terms of applications, the earliest device demonstration making use of ZnO nanowires was the room-temperature ultraviolet nanowire nanolasers, an optoelectronic device, shown by researchers from the University of California and the Lawrence Berkeley National Laboratory in 2001. As of now, this publication has received over 6,400 citations. As explained in previous chapters, this development constituted the device 'luring' more researchers into the field of ZnO nanostructures. Years later, however, optoelectronic-related applications of ZnO nanostructures have faced a series of difficulties, whereas other applications domains, such as sensors and actuators, have appeared to be more feasible. Within this context, nanogenerators has been forging ahead as one of the flagship applications within the field of ZnO nanostructures.

6.5.3.3. Co-evolutionary mechanisms: The case of nanogenerators

As described above, nanogenerators convert mechanical energy into electric energy through the use of ZnO nanostructures. The high expectations being placed on nanogenerators lie on their potential to work as energy harvesters[4] for the development of self-power nanosystems. As defined by Wang (2012), this has to do very much with the roadmap established for semiconductors by the ITRS (International Technology Roadmap for Semiconductors) in which 'more Moore'[5] is expected to be supplanted by 'more than Moore', where value is added through the functional diversification of semiconductor-based devices, e.g. addition of sensors, controllers, actuators, etc. (Arden et al., 2010).

This section will focus on the co-evolutionary relationships between technologies and knowledge for the case of ZnO-based NGs. In particular, the discussions of this section will be based on the diagram of Fig. 6.7.

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[3] Two-dimensional nanomaterial consisting of one-atom-thick sheets of carbon atoms first isolated by researchers from the University of Manchester (Great Britain) and the Institute for Microelectronics Technology (Russia) in 2004.

[4] Energy harvesting defines "the process by which energy is derived from external sources (e.g. solar power, thermal energy, wind energy, salinity gradients, and kinetic energy), captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks" (http://en.wikipedia.org/wiki/Energy_harvesting)

[5] 'More Moore' refers to the continuation of Gordon Moore's law stating that the number of components per integrated circuit should double every two years.

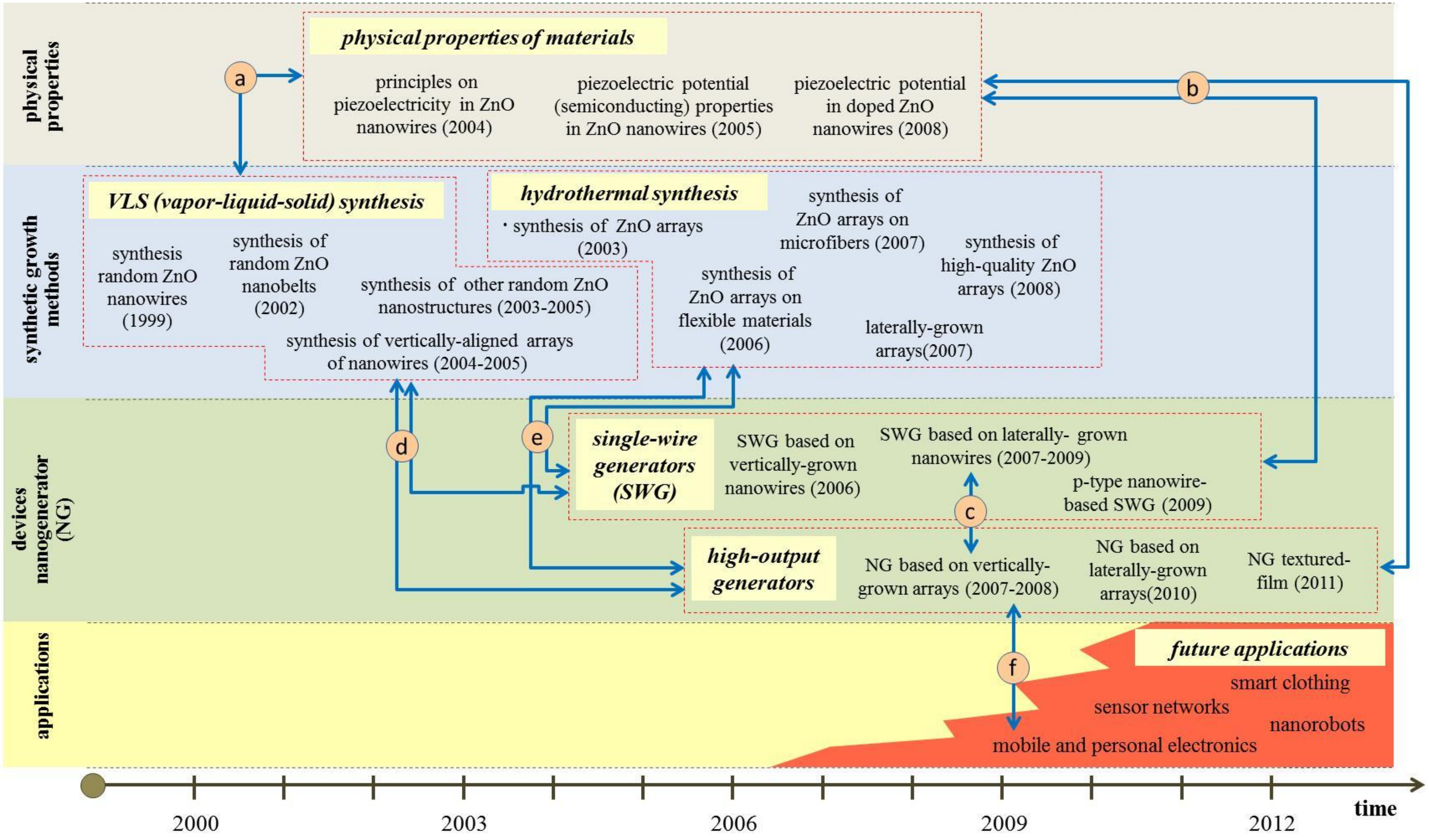

Fig. 6.7 Co-evolutionary relationships in the development of nanogenerators.

As can be seen, four main levels are defined: physical properties of nanomaterials, methods for the synthetic growth of nanostructures, devices, and application domains. The remainder of this section discusses in detail the interactions between each of these levels (arrows shown in Fig. 6.7).

As shown in Fig. 6.7 (*arrow 'a'*), the first synthesis of randomly-arranged ZnO nanostructures and aligned arrays of ZnO nanostructures during the early 2000s enabled the initial studies of the basic physical phenomena of these nanostructures. As it will be shown, changes in the understanding of the fundamental properties and the physics underlying nanostructures play a critical role in defining the potential types of devices that may be created and fabricated (Schmidt-Mende and MacManus-Driscoll, 2007; Wang, 2004) (*arrows 'b*' in Fig. 6.7). The latter is of utmost importance for nanomaterials; as the 'rules' tend to change at the nanoscale, new effects, phenomena, and properties may be discovered whose understanding could lead to the creation of novel, possibly unexpected, applications and devices (Segal, 2012). For the case of nanogenerators, the understanding of the principles behind the conversion of mechanical energy into electricity through the use of ZnO nanostructures proved to be crucial (Wang, 2009, 2012). As such, research in this field particularly centered on the piezoelectric and semiconducting properties of ZnO nanostructures. Based on Wang (2009), first observations of the higher piezoelectric properties of ZnO nanowires vis-à-vis ZnO bulk materials were conducted in 2004. This discovery drove the need to search for potential approaches for exploiting the superior piezoelectric properties of ZnO nanowires, i.e. their ability to convert mechanical energy into electricity. This began in early 2005 with the conduction of experiments on single nanowires and vertically-aligned arrays of ZnO nanowires with an atomic force microscope. At the end, these observations led to the understanding of the mechanism for nanogenerators late that year. This knowledge, in turn, allowed further experimentation with simple prototypes of nanogenerators, made of single wires or small arrays of nanowires, aimed at describing the fundamental principles behind nanogenerators. This led, at the end, to the creation of the different prototypes of nanogenerators that have been developed in the recent years (*arrow 'c'* in Fig. 6.7).

Moreover, changes in the knowledge on the synthesis of differing nanostructures allows new ideas to flourish, which at the end may lead to new devices, and in turn, to new application domains (Sahu et al., 2012; Schmidt-Mende and MacManus-Driscoll, 2007) (*arrow 'd' and 'e'* in Fig. 6.7). For the case of ZnO, due to its material properties, particularly its polar surfaces, it allows the creation of an array of structures larger than any other nanomaterial, including carbon nanotubes (Wang et al., 2004). The understanding of the control of the synthetic processes has allowed the discovery of a wide array of nanostructures, such as nanosprings, nanowires, nanobelts, nanohelixes, nanopropellers, nanonails, nanopencils, nanoflowers, tetrapod-like nanostructures, axial and radial heterostructures, hierarchical nanostructures, and doped nanostructures (Wang, 2004; Sahu et al., 2012). Typically, as described by Nightingale et al. (2008), the potential applications for many of these nanostructures may come ex-post.

Within this backdrop, knowledge on the methods for the synthetic growth of arrays of vertically (or laterally)-aligned nanowires proved crucial for nanogenerators. The latter demands, among other aspects, a thorough understanding of the impact of the different process variables (control of growth kinetics, growth temperature and chemical composition of source materials, etc.) on the properties of the grown nanostructures (size, size distribution, shape, crystal structure, defect distributions, and even surface structure), as well as on the mechanisms and kinetics of growth of nanostructures (Wang, 2004).

Continuing with the synthetic growth of nanowires, changes in the technologies available for the growth of nanostructures have impacted the fabrication and development of devices and application domains (*arrow 'd' and 'e'* in Fig. 6.7). For the case of nanogenerators, initial efforts in the growth of aligned arrays of nanowires were conducted around 2004 through the use of the vapor-liquid-solid (VLS) synthetic method (Wang, 2009). VLS is a high-temperature synthetic method for growing nanostructures first proposed in the 1960s, but used for the growth of nanowires until 1998 (Appell, 2002). This radically changed with the use of low-temperature routes, also referred as hydrothermal growth, wet chemistry or aqueous solution deposition approaches, years later. These processes are characterized by being simple, low-cost, and enabling large-scale fabrication (Gomez and Tigli, 2013; Wang, 2012). The development of low-temperature processes opened up opportunities for the creation and fabrication of novel devices and applications not possible to conduct with high-temperature processes, for example through the use of general substrates, such as plastics (Wang, 2009b). Moreover, the broader knowledge on the synthesis of arrays through hydrothermal approaches has resulted in the diversification of the types of generators that have been developed over time, such as laterally-grown nanowire-based nanogenerators and fiber-based nanogenerators. For example, the case of fiber-based nanogenerators has opened the possibility to be used as a flexible, foldable and wearable power source in smart clothing applications (Wang, 2012) (*arrow 'f'* in Fig. 6.7).

It should be remarked that development is not necessarily cascading solely from the top to the bottom of Fig. 6.7. In this regard, applications may also dictate the choice of certain fabrication approaches and the use of materials with particular properties (Gomez and Tigli, 2013). In a sense, applications may 'pull' the paths of knowledge accumulation of nanostructures toward particular directions. Furthermore, applications can also result in the improvement of manufacturing processes, which may spur further, unrelated, applications, and, in turn, trigger the development of further new structures and processes.

In summary, this section has enumerated a series of co-evolutionary aspects for the case study of nanogenerators based on ZnO nanostructures. These results have shown that the development of devices is punctuated by a complex set of feedbacks between the different blocks defined in Fig. 6.7. These feedbacks, in turn, are expected to open up new avenues for the development of novel devices and application domains. Similarly, this section has shown the co-evolving and highly cumulative nature of these feedbacks.

6.6. Summary of the Results

This chapter has sought to quantitatively interpret the evolutionary nature of change of the technological innovation systems building around an emerging technology. The empirical case of the newly emerging nanomaterial Zinc Oxide one-dimensional nanostructures was used. The research approach in this chapter integrated a series of bibliometric and social network analysis methods. Similar to Chapter 5, the nature of the knowledge on which innovation systems draw upon to innovate was used as a sort of ‘cognitive imprint’ of the problems being confronted by these innovation systems throughout their evolution. This, in turn, was expected to provide insights into the nature of the dynamics of these innovation systems, particularly that from an evolutionary nature. Bibliometrically, these ‘cognitive imprints’ were quantitatively expressed through the construction and evaluation of co-citation networks. In particular, these knowledge structures were endowed with directionality by manually allocating a particular type of problem to each node of the network. For that purpose, a series of cognitive-related indicators were evaluated: cognitive contents, cognitive trajectories, cognitive inter/intra-relationships, and cognitive sub-fields.

The findings of this chapter are summarized as follows. Structurally, the knowledge structures underpinning the emerging nanotechnological field of ‘ZnO 1D nanostructures’ appear to be rapidly expanding and dispersing. Yet, cognitively such growth is punctuated by particular patterns of change. The results of this chapter suggest that the knowledge bases underlying emerging technologies are cognitively redistributing over time. In particular, over time a gradual shift toward downstream problem areas appears to be under way. Despite the still significant growth of upstream problem areas, problem areas downstream are experiencing even stronger rates of growth. In terms of nanostructures, the focus of synthetic growth methods appears to be shifting to the synthesis and, particularly, to the characterization of more complex nanostructures such as doped nanostructures, heterostructures, hierarchical structures, as well as aligned and oriented arrays of nanostructures. These nanostructures are closer to those required by the development of nanodevices which is reflected in the greater role played by applications over time. The results of this chapter also showed that other nanomaterial contexts and conventional ‘macro’ ZnO materials are highly influential, yet at different time periods. This reflects the path-dependent and cognitive nature of this nano-field. In broader terms, the results also point to the formative nature of the knowledge structure ‘ZnO 1D nanostructures’. Conceptually, the bulk of the knowledge bases appear to be dominated by clusters related to the synthetic growth of ZnO nanostructures. Here, application-related clusters still occupy peripheral locations within the knowledge structure and mainly tend to focus on the understanding of the material properties or the physical phenomena key for particular application domains rather than on the development and design of devices. Despite the still weak influence of application-related problem areas, a single application node – room-temperature nano-laser – was characterized by a predominant location within the network. This results highlights the critical role of potential applications even if they still embody 'primitive' proofs-of-concept, which besides the creation of fundamental science, may be aspects driving the building up of a 'critical mass' of knowledge around this nanotechnological field. This has also been discussed by Rafols et al. (2010) for the case of hybrid nanomaterials. Moreover, the absence of problem areas related with more complex issues, such as the fabrication and assembly of complex nanoarchitectures and their interconnection to the macro-world, is also an indicative of the still immature nature of these knowledge structures. Summarizing, these results highlight the need for a 'critical mass' of knowledge to be available before attempts into more complex areas are conducted. Later chapters will discuss this issue in greater detail.

Another interesting result of this chapter is that two types of dynamics appear to be active in emerging technologies. Interestingly, these dynamics appear to be following different patterns of change. Structurally, they appear to be expanding and dispersing. Yet, cognitively such growth is punctuated by a series of patterns of change largely stepwise and cumulative in nature.

The results of this section have also shown that the development of devices is punctuated by a complex set of feedbacks between the different blocks defined in Fig. 6.7. These feedbacks, in turn, are expected to open up new avenues for the development of novel devices and application domains. Similarly, this section has shown the co-evolving and highly cumulative nature of these feedbacks.

In the next chapter, the focus of analysis moves on to the coupling between the paths of knowledge evolution and the nature of competence building for the case of micro/nanofabrication technologies.

7. Alignment between the Paths of Knowledge Evolution and International Patterns of Specialization – The Case of Micro/Nanofabrication Technologies

7.1. Introduction

This chapter continues with the third hypothesis enumerated in the Section 2.5.5. As mentioned in previous chapters, knowledge changes, evolves, and transforms. As a result of this, knowledge is expected to be channeled along particular paths of progress. On the same token, to be successful there is a need for actors active in a particular field, be it firms, industries, or countries, to build up competences in line to where the paths of knowledge are heading to. Within this background, this can be used for gaining insights into the dynamics of emerging technologies. This chapter aims at examining the *alignment* between the paths of knowledge evolution and the nature of the competence building of actors, i.e. countries/regions, as depicted by their patterns of specialization. Here, the case of micro/nanofabrication technologies is used.

This chapter is organized as follows. Section 7.2 defines nanofabrication and nanomanufacturing and provides a brief description of the dynamics of change visualized as alignment processes. Section 7.3 then continues with the description of the taxonomy for micro/nanofabrication technologies. Following, section 7.4 provides shortly discusses the research methods used in this chapter. Section 7.5 continues with the results of this chapter. Finally, Section 7.6 summarizes this chapter.

7.2. Some Theoretical underpinnings

7.2.1. Nanofabrication and Nanomanufacturing as Enabling Technologies

The building-up of manufacturing capabilities – process knowledge and technologies, machinery, instrumentation and tools, etc. – coming from manufacturing-related R&D is regarded as a crucial prerequisite for accruing value from the opportunities and challenges associated with N&N (Russell and Hall, 2008). Within this context, nanomanufacturing and nanofabrication play a crucial role; they are regarded as enabling technologies bridging nanoscience discoveries and the development and commercialization of micro/nano-based products (Mirkin and Tuominen, 2011; Postek and Lyons, 2007).

‘Nanomanufacturing’ and ‘nanofabrication’ have been used indiscriminately in the literature to describe the range of activities involved in the development and fabrication of nano-enabled products, yet they are conceptually different. Whereas nanomanufacturing embraces the whole range of capabilities and competences involved in the production of commercial micro/nano-enabled products, nanofabrication may be visualized as a sort of scientific and technological 'toolbox' underlying the nanomanufacturing field. As a series of predominantly micro-scaled technologies are also included in this analysis, the term micro/nanofabrication is preferred. Despite its imminent importance and the large amount of social science studies on N&N making use of bibliometric approaches – Huang et al. (2011) evaluated more than 120 different publications – few studies have attempted to approach N&N from a 'manufacturing lens'. Some exceptions are those of Invernizzi (2011), Islam (2010), and Kautt et al. (2007), among others. Furthermore, the majority of the research efforts on N&N have mainly approached this field aggregately; thus, leaving aside the understanding of the differing component technologies making up this field.

Against this background, nanomanufacturing and nanofabrication technologies may be visualized as 'bridges' connecting nanoscience discoveries and nano-based products (Postek and Lyons, 2007). Hence, they are regarded as 'enabling technologies'. Although it is difficult to discern a direct connection between enabling technologies and their applications (Fleischer et al., 2005), it is believed that progresses in nanomanufacturing/nanofabrication are expected to accelerate the development and commercialization of micro/nano-based products (Mirkin and Tuominen 2011; Postek and Lyons 2007). Accordingly, nanomanufacturing and nanofabrication have taken a predominant position within national nanotechnology programs. For example, nanomanufacturing is one of the eight 'program component areas' of the National Nanotechnology Initiative (NNI) (Roco, 2011b). For the case of the European Union, nanomanufacturing is represented in the '7th Framework Programme' in the form of the sub-European Technology Platform (sub-ETP) for Micro- and NanoManufacturing (MINAM) of the ETP 'MANUFUTURE' (Woegerer and Wolfgang, 2008), among others.

7.2.2. Dynamics in terms of re-alignment processes

By considering nanofabrication and nanomanufacturing as aspects 'creatively destroying old methods of manufacturing' (Romig Jr et al., 2007), it is inferred that this new paradigm demands different requirements at the national level. Following Vertova (2001), the latter may involve changes in the incentive structures, technological and scientific knowledge, and organizational and managerial skills, among others. Some of these changes may be revolutionary, others more evolutionary in nature (Romig Jr et al., 2007). Nevertheless, at the bottom, the grasping of opportunities arising from new technologies calls for the institutional restructuring of the economies and societies of countries (Vertova, 2001). The latter is visualized in this chapter as readjustments involving the (mis) alignment process taking place along different dimensions (technological, scientific, institutional, etc.). This chapter particularly focuses on the scientific (mis) alignment occurring in the field of micro/nanofabrication technologies across relevant countries/regions. This is investigated in this chapter by relating the way this field is changing as reflected in the dynamics of the paths of knowledge evolution and the nature of the engagement of relevant actors in this field as revealed by their patterns of scientific specialization which are, in turn, expected to be related to their scientific competence building.

7.3. Taxonomy for nanofabrication/nanomanufacturing techs

A key aspect for the use of any bibliometric method is the delimitation of the boundaries within which the field of interest falls; this study is not an exception. In particular, for the case of interdisciplinary and emergent fields, i.e. in process of definition or formation, such as micro/nanofabrication technologies the latter proves to be a daunting task. In this chapter, the field of relevant micro/nanofabrication technologies was divided into ten main taxonomy groupings, as demonstrated in Table 7.1.

This taxonomy is based upon Kautt et al. (2007)'s classification of micro/nanofabrication technologies for their study on the evaluation of nano-oriented competence research centers. In this chapter, this classification was partly modified in order to better differentiate those technologies relying on a common set of capabilities in terms of the underlying fabrication principles or phenomena, type of machinery and equipment used, etc. As the micro- and nano-worlds are intimately intertwined, micro nanofabrication technologies were also included. In a subsequent step, the range of component technologies within each of the micro/nanofabrication taxonomy groupings was described. The modifications made to the taxonomy and the characterization of each of the taxonomy groupings relied on the exhausting examination of books, technical handbooks, scientific publications, technological roadmaps, on-line information, and technical standards, among others. Particular interest was taken on the way micro/nanofabrication technologies were classified in these sources of information. In order to assure the collection of publications relevant to the field of micro/nanofabrication technologies, keywords related to process technologies were used; thus, for example, instead of using specific nanomaterials labels (nanocrystals, nanowires, nanotubes, etc.) concepts such as synthesis, self-assembly, etc. were defined. Moreover, the plausibility of the proposed taxonomy was verified through the advice from two nanotechnology experts. Some caveats apply for the proposed taxonomy (Kautt et al., 2007): only relevant technologies were used, those technologies were allocated according to their most representative category, standard terminology was used, as well as the different taxonomy groupings may overlap.

Table 7.1 Taxonomy groupings defined for micro/nanofabrication technologies

Micro/nano-manufacturing categories	Brief description	Examples
Synthetic growth of nanostructures	It encompasses those technologies used in the synthetic growth of nanostructures (nanowires, nanotubes, quantum dots, quantum wires, etc.); it excludes self-assembly	Chemical vapor deposition, spray pyrolysis, electrodeposition, vapor-liquid-solid methods, etc.
Thin-film deposition	It embraces those technologies aimed at depositing thin films of materials on substrates.	Chemical vapor deposition, physical vapor deposition, sol-gel methods, atomic layer deposition, etc.
Micro/nanostructuring technologies	It involves those technologies related with the general structuring of materials, mainly through lithographic and etching methods.	Deep ultraviolet lithography, mask-less lithography, wet etching, dry etching, focused ion beam (FIB), laser writing, etc.
Micro/nanomechanical technologies	This category encompasses those technologies derived from the traditional mechanical methods for material removal.	Ultra-precision machining, micro-milling, electric discharge machining (EDM), laser micromachining, etc.
MEMS process technologies	It embraces those technologies involved in the production of microelectromechanical structures, devices, and systems.	Surface micromachining, bulk micromachining, bonding methods, packaging and integration processes, etc.
Replication micro/nano-technologies	This category embraces those process technologies characterized by the ability to manufacture micro/nano-enabled products in large volumes.	Soft lithography, nanoimprint, roll-to-roll processes, micro-injection technologies, etc.
Self-assembly and nanomanipulation	It encompasses those processes for making ensembles of nanostructures by autonomous organization. It also included nanomanipulation-related issues.	Self-assembly, layer-by-layer methods, biofunctionalization, nanomanipulation, etc.
Other nanofabrication technologies	It includes additional nanofabrication processes, mainly based on the use of scanning probe microscopy	Deep pen nanolithography, scanning probe microscopy-based lithography, etc.
Modeling & simulation	This grouping involves computational methods used to theoretically model and simulate the behavior of materials, devices or systems at the nanoscale	Finite element analysis, molecular dynamics, atomic simulations, Monte Carlo simulations, etc.
Characterization (micro/nanometrology)	It encompasses those technologies used in the evaluation of the physical, chemical, biological and technological properties of nano-based products.	Transmission electron microscopy (TEM), scanning electron microscopy (SEM), atomic force microscopy (AFM), etc.

7.4. Research Methods

The dataset comprised of scientific publications – articles and proceedings – indexed in the ISI/SCI database published in English from the years 1993 to 2010. This period was selected as the ISI/SCI database included abstracts and keywords from 1991 onwards. Three main six-year-periods of analysis were defined: 1993-1998, 1999-2004, and 2005-2010. A keyword-based analysis was used to retrieve the publication data. For that purpose, search queries were defined for each of the taxonomy groupings described in Table 7.1. These search queries consisted of both broad-encompassing and specific technical terms related to the component technologies of the taxonomy groupings shown in Table 7.1. Here,

Appendix 3 defines the different search queries used for this analysis. As some of the technologies included in our analysis are not exclusive of the N&N field, they were delimited by a series of N&N-related terms as defined by Porter et al. (2008). This prevented the inclusion of terms unrelated to the N&N field. The search strategy was restricted to the titles of scientific publications, as we attempted to focus on the most relevant hits for each fabrication technology. A total of 59,346 scientific publications were collected.

Besides the conduction of a conventional longitudinal bibliometric approach on the collected publications, two main bibliometric methods were used. First, a co-word analysis on the keywords listed by the authors was used to evaluate the paths of knowledge evolution. Second, 'Revealed Scientific Advantage' (RSA) indexes were evaluated to reveal the patterns of specialization on micro/nanofabrication technologies for the relevant countries/regions. The remainder of this section briefly describes both research methods.

7.4.1. Co-word analysis

The methodology of analysis used for the co-word analysis is as follows. First, the original list of keywords – those assigned by the authors and the KeywordPlus[1] keywords assigned by the ISI/SCI database – from the publications collected for each of the micro/nanofabrication taxonomy groupings.

In a subsequent step, this list underwent a series of cleaning and sorting procedures consisting mainly of manually grouping together similar keywords. In order to prevent the inclusion of random errors and to control for size effects, a pre-determined threshold value was set on the number of times a particular keyword appears. A threshold greater or equal to ten records was used in this study. This threshold was predetermined after a series of fine-tuning loops. Co-occurrence matrices, depicting pairwise relations among keywords, were constructed for the time periods 1993-1998 and 2005-2010 through the use of the tech-mining software VantagePoint. Taking into account that the early 1990s saw the emergence of carbon nanotubes, it is expected the first period to embrace the beginning of the nanotechnology boom. In contrast, as the second period is depicted by stronger efforts in the development of nanofabrication processes aimed at the large-volume production of nanostructures, it is expected replication processes, such as roll-to-roll approaches, to play a role. These periods were selected to reflect extreme 'snapshots' in the evolution of knowledge on micro/nanofabrication technologies. The construction of these general networks was done as follows. For that purpose, the co-occurrence matrices constructed for each of the ten different micro/nanofabrication taxonomy groupings were summed up to

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[1] KeywordPlus are automatically assigned by the ISI/SCI database based on the titles of the references listed in a particular scientific publication.

give way to aggregate co-occurrence matrices for each of the time periods. In order to provide a better visualization and to control for size effects, those co-occurrence matrices were normalized with the Salton's cosine similarity measure. A co-citation threshold greater or equal to 0.07 was chosen in order to center our attention on those predominant co-word relationships. Similar to the previous chapters, the cosine-normalized matrices were visualized as networks with the software UCINET and NetDraw (Borgatti et al., 2002). Using this software, the predominance of the keywords within each knowledge structure was evaluated through the estimation of network centrality measures and the inter/intrarelationships among keyword nodes. For the particular case of the latter analysis, seven technological categorizations were assigned to the keyword nodes (Table 7.2).

Table 7.2 Technological categorizations assigned to co-word networks

Categorization	Brief description	Examples of keywords
Materials	It encompasses keywords dealing with materials-related aspects	Nanostructures, nanoclusters, hybrid materials, gold nanoparticles, graphene, carbon nanotubes, silicon and compounds, etc.
Bottom-up	It includes keywords related to bottom-up approaches	Colloids, self-assembly, sol-gel, self-assembled monolayers, chemical synthesis, etc.
Top-down	It includes keywords related to top-down approaches	Deep reaction ion etching, micromachining, nanolithography, focused ion beam, etc.
Characterization	It entails keywords dealing with characterization methods and instrumentation	Optical, thermal, magnetic, mechanical, electric, etc. properties; instrumentation (AFM, XPS, SEM, TEM, etc.), etc.; and simulation and modeling approaches.
Bio	It includes keywords related with the bio-field	DNA, molecular applications, proteins, biocompatibility, molecular applications, etc.
Devices	It encompasses keywords dealing with micro/nano-enabled devices or systems	sensors, MEMS, solar cells, MOEMS, optical tweezers, fiber optics, fuel cells, gas sensors, optical components, etc.
Others	It entails general keywords not possible to allocate to any of the previous categorizations	Dispersion, bandgaps, stability, bonding, interface, phases, surfactant, etc.

The technological categorizations of Table 7.2 were defined after reviewing the totality of keywords collected in this study. In this regard, the rationales behind the selection of the technological categorizations rely on the general classification schemes that have been typically used for micro/nanofabrication technologies (Kautt et al., 2007). Thereafter, keywords were allocated to each of the technological categorizations. Despite its general nature, as it will be seen, this technological classification will provide a useful way to evaluate the interrelationships active in the networks.

7.4.2. Revealed Scientific Advantage (RSA)

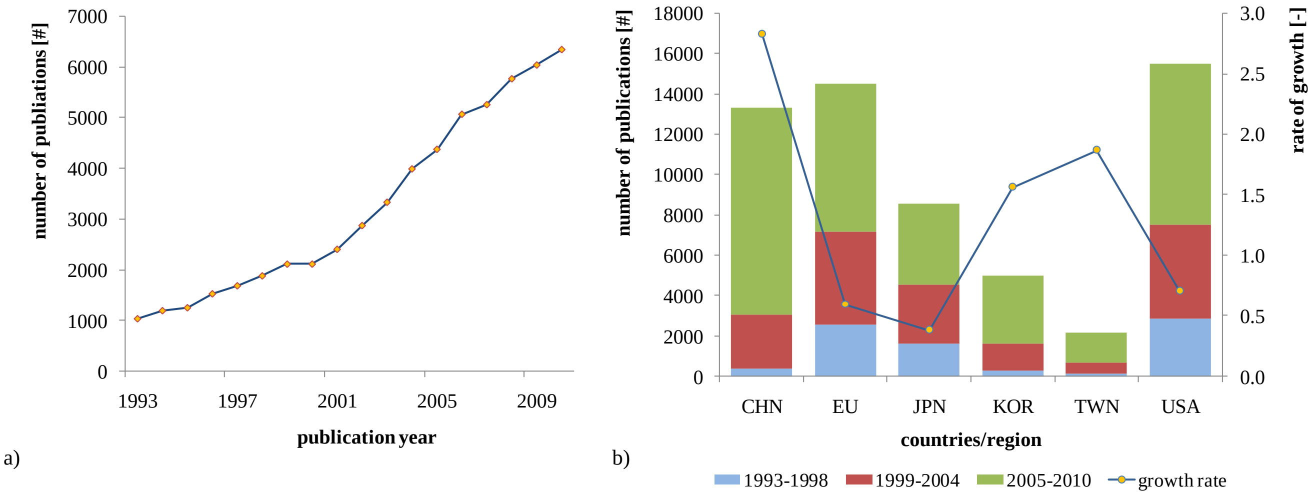
After the extraction and cleaning of the scientific publications collected for each taxonomy groupings, Revealed Scientific Advantage (RSA) indexes were evaluated. More detailed information on the Revealed Scientific Advantage indicators is given in Section 4.4.1. Besides the calculation and evaluation of the RSA indexes, the different micro/nanofabrication taxonomy groupings underwent a hierarchical cluster analysis in order to discern similar patterns of specialization across the countries/regions under analysis. The countries/regions included in this analysis are: the United States, the European Union (EU), Japan, China, South Korea, and Taiwan. For the case of the EU, the following countries were included: Germany, France, United Kingdom, Italy, Spain, the Netherlands, Belgium, and Sweden. These countries were selected based on their predominant role in the field of micro/nanofabrication technologies.

7.5. Research Results

Three main analyses will be described in the remainder of this chapter: a longitudinal bibliometric analysis, the evaluation of the paths of knowledge through co-word networks, and the analysis of the patterns of micro/nanofabrication specialization across countries through the evaluation of the Revealed Scientific Advantage (RSA) indexes. These analyses will be described in the remainder of this chapter.

7.5.1. Longitudinal bibliometric analysis

This section provides a brief longitudinal analysis based on the scientific publications for micro/nanofabrication technologies (Fig. 7.1). Fig. 7.1a indicates that the number of publications on micro/nanofabrication technologies has steadily increased over time. Particularly, from the early 2000s a stronger growth can be observed. This result should be taken with care as it is influenced by the overall increment of publications added to the ISI/SCI database over the years.



* *CHN: China; EU: European Union; JPN: Japan; KOR: South Korea, TWN: Taiwan; USA: United States*

Fig. 7.1 a) Cumulative output of publications, b) Publication outcomes and growth rates across countries

Nevertheless, as indicated in Fig. 7.1b major differences exist in the distribution of the publication output across relevant countries/regions. The results of Fig. 7.1b give a familiar picture for Nanoscience & Nanotechnology (N&N)-related studies, namely the predominant role of the United States, the EU and Japan, and the recent significant efforts experienced by China. In terms of publication output, South Korea and Taiwan appear to be playing a secondary role. In this regard, it should be pointed out that these results solely consider the outcome of publications in terms of their quantity not their quality. The line chart superimposed in Fig. 7.1b suggests that all countries/regions are experiencing positive rates of growth between the periods 1999-2004 and 2005-2010; however, these values differ and significantly. In particular, emerging East Asian countries – South Korea, Taiwan, and particularly mainland China – are characterized by significantly stronger growth rates vis-à-vis those of the traditionally incumbent nations in the N&N field. This result suggests the nature of those countries as emerging nations in the micro/nanofabrication field. This is closely in line with the findings of the study of the nanotechnology research domains conducted by Islam and Miyazaki (2010).

Following Islam and Miyazaki (2010), Fig. 7.2 relates the recent rates of growth experienced by the taxonomy groupings between the periods 1999-2004 and 2005-2010 (y-axis) and the shares of publications for the latter period (x-axis).

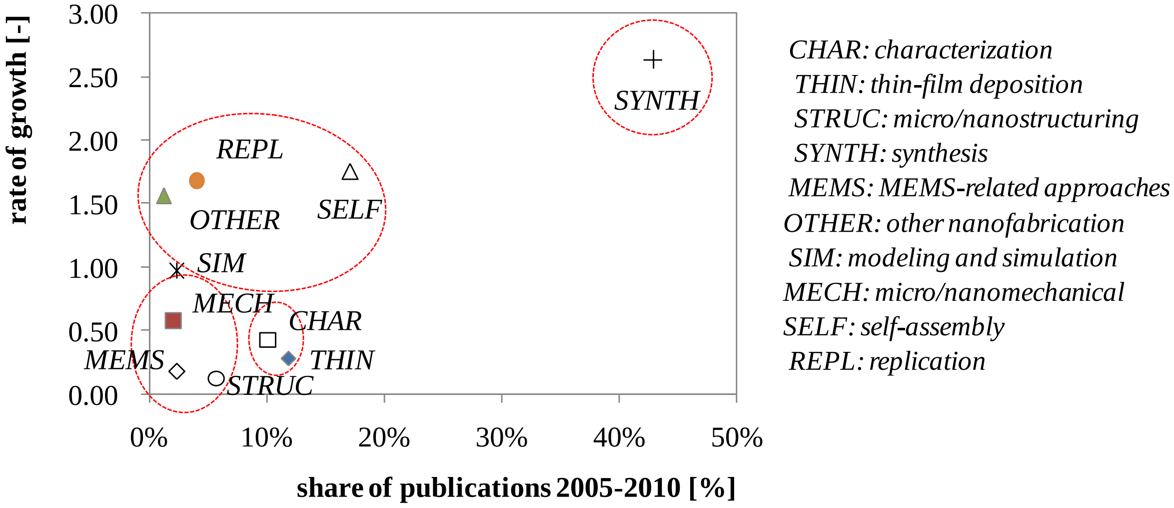


Fig. 7.2 Rates of growth vs. shares of publication for the different micro/nanofabrication technologies

The results of Fig. 7.2 are described as follows. First, techniques for the synthetic growth of nanostructures [SYNTH] entail the largest share of the total of publications as well as experience the highest rates of growth. This may be attributable to the still predominant role of technologies at the bottom end of the nanotechnology value chain. Second, other nano-related technologies – micro/nano-replication technologies [REPL], other nanofabrication technologies [OTHER], self-assembly [SELF], and to a less degree modeling and simulation techniques [SIM] – are characterized by similarly high rates of growth, albeit at still lower shares of publications. This suggests the emerging properties and the imminent potential of these technologies in the future. Following, characterization-related methods [CHAR] and deposition technologies [THIN] entail significant shares but relatively lower rates of growth. Finally, micro/nano mechanical technologies [MECH], MEMS-related processes [MEMS], and micro/nano structuring technologies [STRUC] are located at the left/bottom region of figure, i.e. low publication shares and low rates of growth. Given their nature as extensions of the traditional microelectronics-based technologies, and their inherently maturity, those technologies appear to be the least attractive for the scientific community.

Summarizing, this section presented a general description of the field ‘micro/nanofabrication technologies’. It was observed that this field is growing, yet such growth is not uniformly distributed across countries. As pointed out, differences in the shares and rates of growth of publications were also observed across micro/nanofabrication technologies. Next section now moves on to the description of the way these technologies have evolved and have interrelated over time.

7.5.2. Paths of evolution of micro/nanofabrication scientific knowledge

As already known, knowledge building around the field of micro/nanofabrication is evolving, changing, and transforming over time at specific rates and following particular paths of growth. Within this context, this section attempts to discern the nature of those dynamics through the construction and evaluation of co-word networks. As previously noted, two extreme periods of time were selected for this analysis: 1993-1998 and 2005-2010. Fig. 7.3 presents the co-word networks constructed for both time periods.

Similar to the networks of the previous chapters, a series of attributes were allocated to both networks. The size of the nodes denotes the number of records. The thickness of the ties varies according to the co-occurrence strengths among the keyword nodes. The color or shape of the nodes depicts the particular type of technological categorization assigned to a particular keyword node (please refer to Table 7.2). It should be remarked that the size scales of both networks in Fig. 7.3 are different.

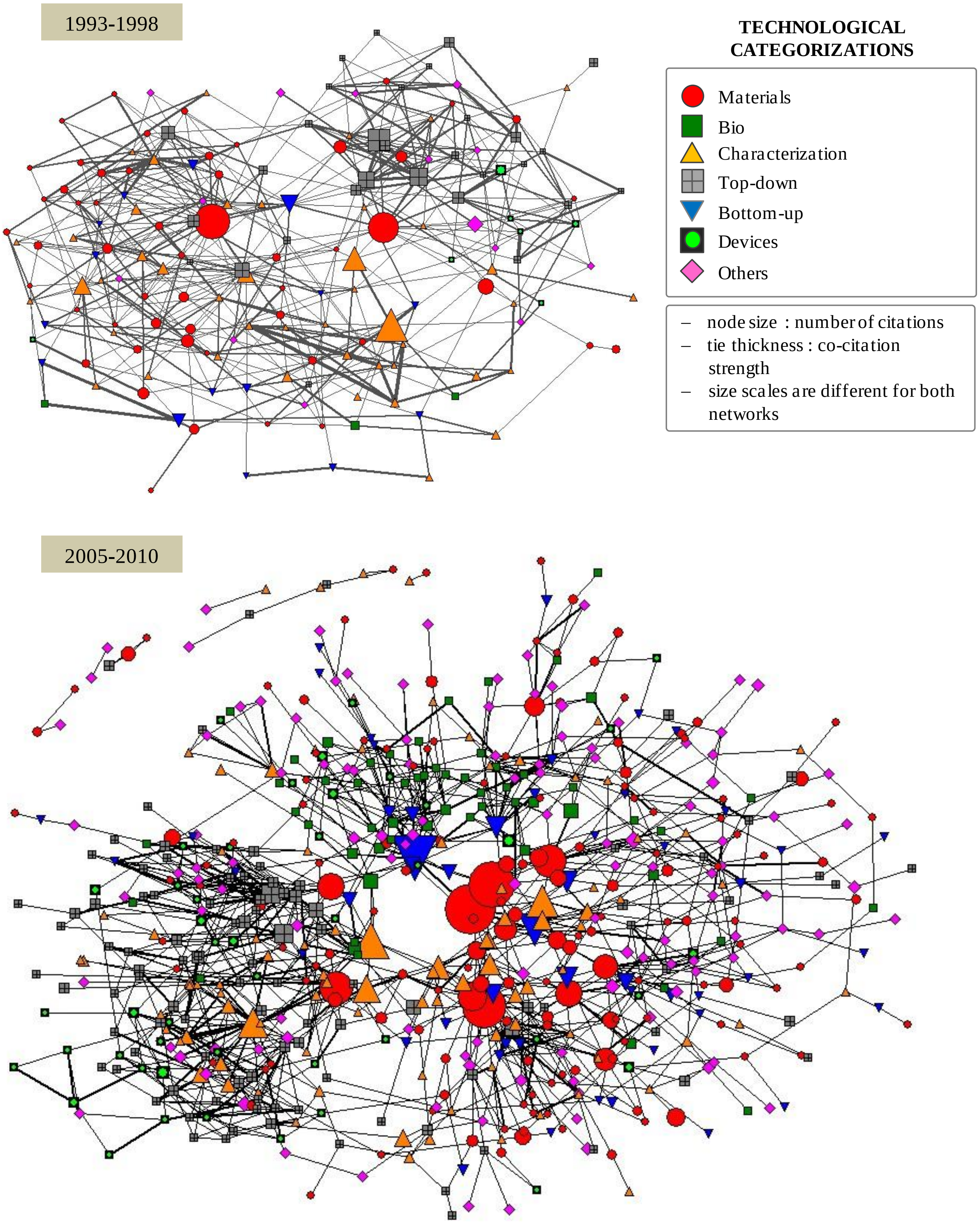


Fig. 7.3 Co-word networks for the periods 1993-1998 and 2005-2010

Moreover, the layouts of the networks were arranged based on the ‘spring-embedding’ algorithm which tends to locate similarly connected nodes closer together. For the sake of clarity, node labels were removed from the networks.

Fig. 7.3 demonstrates the accelerating rates of growth experienced by the knowledge structure ‘micro/nanofabrication technologies’ over the years. This is reflected in the sharp increment in the number of keyword nodes for this field which have increased from 165 to 625 over the time periods 1993-1998 and 2005-2010. This has not only resulted in a knowledge structure of an increasing size, but also, and most importantly, in a greater diversity (Bonaccorsi and Thoma, 2007). Two main analyses were conducted in the networks of Fig. 7.3: the definition of predominant keywords and the evaluation of the interrelationships among keywords. Both analyses are described in the remainder of this section.

7.5.2.1. Predominant keyword nodes

The areas of knowledge emphasized in the knowledge structures of Fig. 7.3 can be discerned through the evaluation of the predominant keyword nodes. For the purposes of this chapter, the predominance of the network nodes of Fig. 7.3 was based on the estimation of their normalized centrality values of nodes: degree, betweenness, and closeness. Here, the higher the centrality of a particular network node, the more predominant its location within the network. The nature of such predominance varies according to the type of network centrality value. Here, Table 4.2 provides a detailed discussion on the different network centrality values. Table 7.3 lists the top-15 predominant keyword nodes across the different centrality values for both knowledge structures.

Overall, the results of Table 7.3 suggest that over time a shift has taken place in the nature of the knowledge predominant in the knowledge structure: from the traditional microfabrication-related technologies to the more recent nano-related technologies. As indicated in the top-15 keywords for the period 1993-1998, concepts such as reactive ion etching, plasmas, plasma processing/deposition, etching in general, micromachining, dry etching, etc. are predominant. These keywords are closely associated with the traditional, top-down, silicon micromachining technologies derived from the field of microelectronics. In contrast, the top-15 keywords for the period 2005-2010 appear to be heavily rooted in the nano-domain. They include keywords such as nanoindentation, replication technologies such as nanoimprint and layer-by-layer processes, and technologies for the fabrication of nanostructures/nanomaterials such as self-assembly and chemical synthesis, as well as nanolithography which is an extension into the nanoscale of traditional silicon-based microtechnologies. Furthermore, over time the knowledge structure appears to be dealing with a wider array of phenomena going beyond surface characterization to include optical, ferroelectric, elastic properties. Similarly, a broader range of materials are predominant. Here, the predominance of silicon and traditional thin film materials (tantalum, yttrium and titanium, and their components) during the period 1993-1998 gives way to nanoparticles, nanostructures, carbon nanotubes, polymers, mesoporous materials, zinc and compounds, and bio-materials such as DNA and myoglobin during the period 2005-2010.

Table 7.3 Top-ten of keywords for different centrality values, 1993-1998 and 2005-2010

1993-1998

Degree centrality	Betweenness centrality	Closeness centrality
RIE reactive ion etching	CVD chemical vapor deposition	CVD chemical vapor deposition
thin films	silicon and compounds	thin films
plasmas	thin films	X-ray photoemission spectroscopy
ferroelectric phenomena	AFM atomic force microscopy	silicon and compounds
etching	X-ray photoemission spectroscopy	plasmas
silicon and compounds	Raman scattering spectroscopy	Raman scattering spectroscopy
AFM atomic force microscopy	RIE reactive ion etching	surface characterization
MOCVD metalorganic CVD	plasmas	AFM atomic force microscopy
nanoindentation	MOCVD metalorganic CVD	MOCVD metalorganic CVD
CVD chemical vapor deposition	surface characterization	plasma processing/deposition
micromachining	plasma processing/deposition	RIE reactive ion etching
Raman scattering spectroscopy	block copolymers	dry etching
deposition methods	tantalum and compounds	photoluminiscence
resist materials	titanium and compounds	yttrium and compounds
hardness	crystals/crystalline	defect

2005-2010

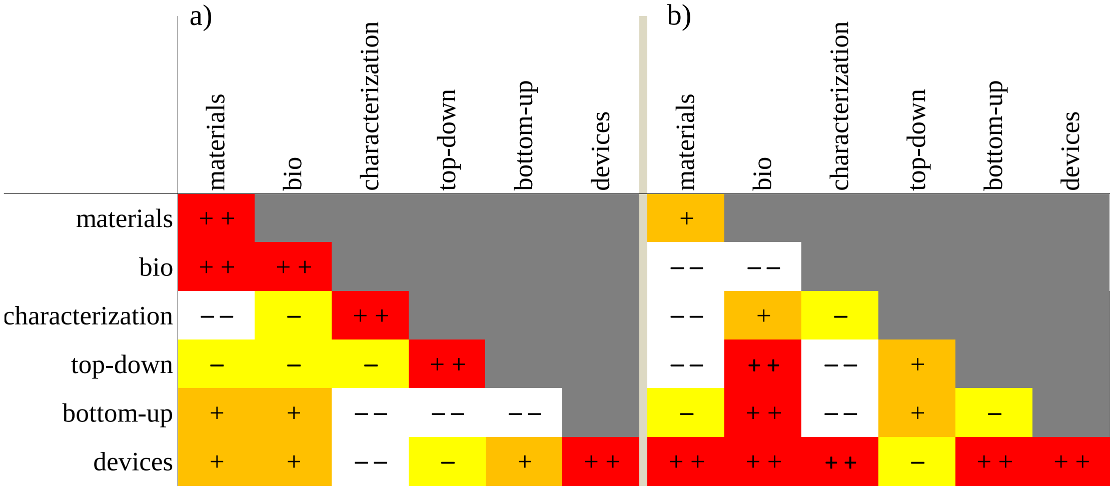
Degree centrality	Betweenness centrality	Closeness centrality
nanoindentation	self-assembly	self-assembly
nanoimprint lithography	polymers	nanostructures
self-assembly	nanoparticles	nanoparticles
LBL layer-by-layer	thin films	X-ray photoemission spectroscopy
thin films	LBL layer-by-layer	semiconductor materials
tool condition/monitoring	AFM atomic force microscopy	chemical synthesis
nanolithography	Nanostructures	optical properties
direct electrochemistry	X -ray photoemission spectroscopy	AFM atomic force microscopy
ferroelectric properties	chemical synthesis	polymers
chemical synthesis	zinc and compounds	transmission electron microscopy
nanopatterns	carbon nanotubes	thin film
mesoporous materials	nanoindentation	DNA
myoglobin	nanoimprint lithography	zinc and compounds
elastic properties	transmission electron microscopy	X-ray diffraction/scatter./ reflection
carbon nanotubes	mesoporous materials	pulsed laser deposition

For both time periods, instrumentation such as atomic force microscopy, transmission electron microscopy, X-ray photoemission spectroscopy, among others, appear to play central positions. Their predominance, particularly in terms of their betweenness centrality values, point to the intermediary, connecting role typically associated with N&N instrumentation and related technologies (Meyer, 2007).

Another way to analyze the paths of knowledge evolution is through the study of the interrelationships within the network nodes. Given the large number of keyword nodes, the analysis of the node interrelationships is futile. Instead, a plausible way is through the evaluation of the node interrelationships at the level of the technological categorizations.

7.5.2.2. Inter/intra-relationships among the keyword nodes

This section aims at unraveling the patterns of interaction among keywords. This is done by evaluating the degree of interaction of the network nodes at their level of technological categorizations (color and shape of nodes in the networks of Fig. 7.3). Analytically, the latter consisted in collapsing the nodes of both co-word networks into networks composed of nodes based on their allocated technological categorizations, i.e. 6x6 matrices comprising the interrelationships between technological categorizations (excluding the categorization 'Others'). For the construction of the collapsed network, the sum of the interactions between and within the different technological categorizations was used. Moreover, the collapsed networks for both time periods were visualized as co-occurrence matrices (Fig. 7.4). The analysis of this section centered on the changes undergone by those matrices over time in terms of their absolute differences and the rates of change between both matrices, Fig. 7.4a and 7.4b respectively.



a)

	materials	bio	characterization	top-down	bottom-up	devices
materials	+ +					
bio	+ +	+ +				
characterization	− −	−	+ +			
top-down	−	−	−	+ +		
bottom-up	+	+	− −	− −	− −	
devices	+	+	− −	−	+	+ +

b)

	materials	bio	characterization	top-down	bottom-up	devices
materials	+					
bio	− −	− −				
characterization	− −	+	−			
top-down	− −	+ +	− −	+		
bottom-up	−	+ +	− −	+	−	
devices	+ +	+ +	+ +	−	+ +	+ +

NOTE: (− −): x < 3th quartile; (−): 3th quartile ≤ x < 2nd quartile; (+): 2nd quartile ≤ x < 1st quartile; (+ +): x ≥ 1st quartile

Fig. 7.4 Inter/intra-relationships among the keyword categories in terms of differences in absolute values (a) and rates of change (b).

Each of the cells of the co-occurrence matrices in Fig. 7.4 was assigned a particular symbol, [+ +], [+], [−], [− −], according to their quartile values (see legend Fig.7.4, bottom). Regarding the changes in terms of the absolute difference values (Fig. 5b), these results suggest that the bulk of the interactions has been mainly restricted to intra-relationships within each of the technological categorizations (diagonal in Fig. 7.4a). Yet, interactions among different technological categorization can be observed. Particularly, Fig. 7.4a also denotes that 'materials' are experiencing the greatest changes of interaction with the rest of the technological categorizations. This may be attributable to their central position within the knowledge structures of Fig. 7.3. On the one hand, 'top-down approaches' are characterized by sluggish changes of interaction across categorizations over time. In contrast, 'bottom-up approaches', 'bio' and 'devices' are denoted by increasing interaction levels among each other, which may be an indication of their importance in the networks. By focusing on the rates of change, Fig. 7.4b provides a complementing interpretation. It allows discerning imminent interactions, i.e. those growing yet still limited in number. The data in Fig. 7.4b denotes the strong interaction of 'bio' and 'devices' with the rest of the technological categorizations. Particularly imminent interactions were discerned for 'bottom-up' and 'bio', as well as for 'top-down' and 'bio'. Interestingly, 'top-down' and 'bottom-up' approaches appear to be moderately interacting over time. This result is in line with the convergence or synthesis between 'bottom-up' and 'top-down' approaches previously highlighted in the literature (Brousseau et al., 2010; Whatmore, 2001).

In summary, the results of this section depict a rapidly increasing and diversifying knowledge structure for 'micro/nanofabrication technologies'. It is not surprising, that, over the years, nano-related knowledge has taken a predominant position within the knowledge structure. Nevertheless, the latter is far from entailing a mere transition from micro into nano domains. Instead, it was shown that the paths of knowledge evolution on micro/nanofabrication are diverse, entailing the study of multiple phenomena, multiple materials, as well as by the integration of knowledge of a differing nature: bio, top-down, bottom-up, and devices, among others. As will be seen, in the next section, those trends exert a crucial influence on the micro/nanofabrication competence building processes of countries/regions as inferred from their patterns of specialization.

7.5.3. Patterns of micro/nanofabrication technological specialization across countries

This section now turns to the study of the patterns of specialization in micro/nanofabrication technologies followed by relevant countries/regions. For the purposes of this chapter, the patterns of specialization across countries are regarded as proxies for the nature of the competence building of countries. Fig. 7.5 describes the general profiles of specialization and significance for the micro/nanofabrication field as a whole. For each micro/nanofabrication taxonomy grouping, following Patel and Pavitt (1987) Fig. 7.5 relates the symmetric revealed scientific advantage (RSA) indexes along the y-axis with the shares of publications along the x-axis for each country/region across the extreme time periods 1995-2000 and 2005-2010. A similar analysis has been previously conducted by Kumaresan and Miyazaki (1999) for the case of the robotics industry. Whereas the former depicts the changes in the relative specialization of a given country/region within a particular micro/nanofabrication field, the latter entails the bulk significance given by a country/region to a particular micro/nanofabrication field. Three areas are highlighted in each of those graphs, as depicted in the legend of Fig. 7.5: symmetric RSA index values greater or equal than 0.20, shares of publication greater or equal than the average value across countries, and the area overlapping both regions in a darker color. Moreover, the nodes for both periods are connected by an arrow indicating the direction of change. In a sense, Fig. 7.5 portrays the dynamics of specialization and significance for the micro/nanofabrication field.

From the results of Fig. 7.5, four different trends can be drawn. First, in line with the results of the previous sections, nano-related technologies such as ‘micro/nano-replication methods’, ‘other nanofabrication technologies’ and ‘self-assembly’, as well as ‘modeling and simulation techniques’, and ‘characterization’ are denoted by positive changes in specialization and significance across countries/regions. Second, despite the large publication shares of the synthetic methods for the fabrication of nanostructures appear to be experiencing negative changes in the degree of specialization for the majority of countries/regions. This may be related to the lower attractiveness of synthetic methods relative to the rest of micro/nanotechnologies. Third, technologies such as ‘thin film deposition’ and ‘micro/nanomechanical technologies’ are denoted by negative trends in terms of their specialization and significance across countries. Finally, despite their decreasing publication shares, technologies such as ‘MEMS technologies’ and ‘micro/nanostructuring technologies’ show moderate levels of specialization across regions/countries, which denotes that they are still on the interest of researchers. Compared to the results of the diagram in Fig. 7.2 the inclusion of the symmetric Revealed Scientific Advantages (RSA) provided a slightly different perspective.

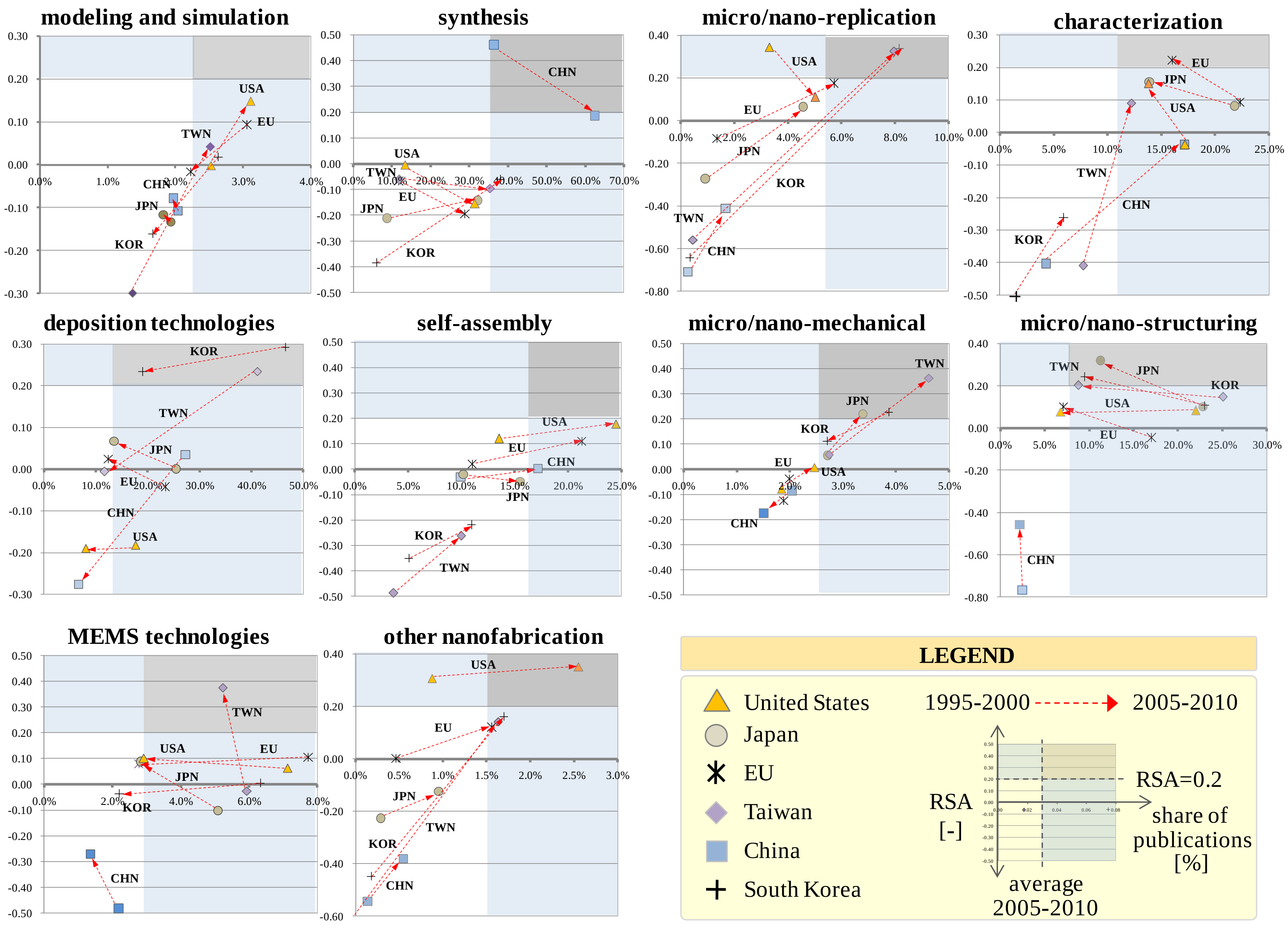
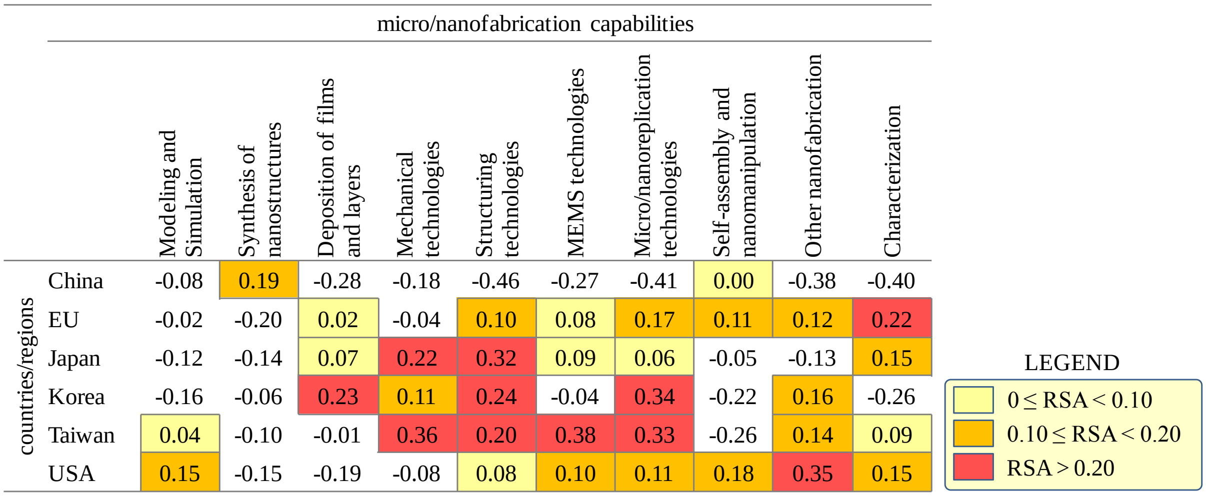


Fig. 7.5 Profiles of specialization and importance for the field of micro/nanofabrication technologies

By analyzing the results of Fig. 7.5, it is inferred that some countries/regions appear to be following similar patterns of specialization. This can be qualitatively observed in Table 7.4 which summarizes the symmetric RSA indexes for the different countries/regions across the array of micro/nanofabrication technologies for the period 2005-2010. In Table 7.4, symmetric RSA index values equal or greater than 0 were highlighted with different shadings according to the legend shown at the bottom of this table. As previously mentioned, symmetric RSA indexes closer to one depict greater degrees of specialization of a country in a particular technological field, and thus in a greater competence building.



	micro/nanofabrication capabilities									
countries/regions	Modeling and Simulation	Synthesis of nanostructures	Deposition of films and layers	Mechanical technologies	Structuring technologies	MEMS technologies	Micro/nanoreplication technologies	Self-assembly and nanomanipulation	Other nanofabrication	Characterization
China	-0.08	0.19	-0.28	-0.18	-0.46	-0.27	-0.41	0.00	-0.38	-0.40
EU	-0.02	-0.20	0.02	-0.04	0.10	0.08	0.17	0.11	0.12	0.22
Japan	-0.12	-0.14	0.07	0.22	0.32	0.09	0.06	-0.05	-0.13	0.15
Korea	-0.16	-0.06	0.23	0.11	0.24	-0.04	0.34	-0.22	0.16	-0.26
Taiwan	0.04	-0.10	-0.01	0.36	0.20	0.38	0.33	-0.26	0.14	0.09
USA	0.15	-0.15	-0.19	-0.08	0.08	0.10	0.11	0.18	0.35	0.15

LEGEND

🟨 0 ≤ RSA < 0.10

🟧 0.10 ≤ RSA < 0.20

🟥 RSA > 0.20

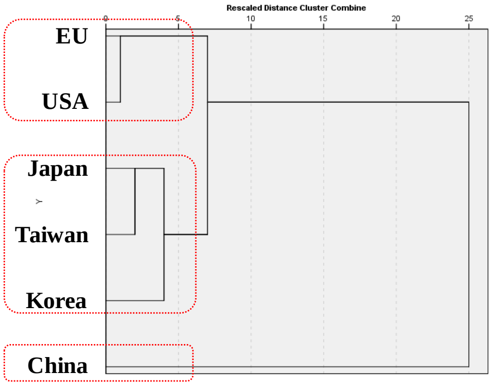
Table 7.4 Symmetric RSA indexes for the period 2005-2010 for the countries/regions of interest

In a subsequent step, the similarities in the patterns of micro/nanofabrication specialization were quantitatively assessed through the conduction of a hierarchical cluster analysis of the symmetric RSA indexes across countries/regions. Here, Ward's clustering method and squared Euclidean distances were used. Section 4.5.2.4 provides further information on hierarchical clustering techniques. From Table 7.4 some patterns may be discerned, which can be better highlighted through the evaluation of a dendrogram (Fig. 7.6). As shown in Fig. 7.6a, three main clusters of countries/regions were discerned. These clusters were then characterized through the definition of a typology consisting of three main measures, as depicted in Fig. 7.6b:

- **Breadth**, which defines the number of micro/nanofabrication taxonomy groupings embraced by a particular country/region. Breadth of the knowledge base was measured through the number of micro/nanofabrication technologies with positive symmetric RSA values as well as by the type of these technologies.

- **Intensity**, which entails the strength of the degree of specialization of countries/regions across their array of micro/nanofabrication technologies. Intensity was measured in terms of the levels of the symmetric RSA values across the different micro/nanofabrication technologies.
- **Nature**, which depicts the type of knowledge embraced by the different countries/regions. This was qualitatively evaluated by analyzing the micro/nanofabrication technologies specialized by the different countries.

a) Dendrogram



b) Characterization

	scientific specialization		
	breadth	intensity	nature
Cluster I (EU, USA)	high	mid	micro/nano; top-down/bottom-up
Cluster II (Japan, Taiwan, South Korea)	mid	high	micro; top-down
Cluster III (China)	low	mid	synthesis

Fig. 7.6 Dendrogram and typology derived from the cluster analysis

Following, the general properties of each of those clusters are briefly defined based on the typology presented in Fig. 7.6b.

a) **Cluster I** – The United States and the European Union (EU) are characterized by more or less well-proportioned mid-intensity levels across a wide range of micro/nanofabrication technologies. They appear to embrace the full spectrum of micro/nanofabrication technologies: from predominantly micro-scaled to predominantly nano-scaled technologies, as well as both top-down and bottom-up approaches. The case of the US is not surprising as plenty of literature sources have highlighted their leading position in the N&N field (Huang et al., 2011). On the other hand, the broad nature of the capabilities of the EU on micro/nanofabrication technologies, also defined in WTEC (2000), may be attributable to the array of differing countries embracing this block; each with their own set of competences and capabilities.

b) **Cluster II** – Japan, South Korea, and Taiwan depict narrower specialization profiles than those of the United States and the European Union. In particular, these countries appear to be significantly emphasizing micro/nanofabrication technologies derived from traditional miniaturization technologies, i.e. semiconductor-based processing technologies and mainly top-down approaches.

This may be attributable to the traditional strength of those countries on microelectronics. For the particular case of Japan, many researchers have defined the deep roots of Japanese research in mechatronics as well, i.e. the combination of mechanical and electronics capabilities (Howe et al., 2003). In this regard, Kanama and Kondo (2007) have highlighted the focus of N&N research in Japan on extensions of traditional miniaturization technologies, e.g. nano-lithographic processes. Their study identified the leading role of Japanese N&N research in top-down technologies vis-à-vis the United States; however, they found the lagging position of Japan in nano-bio bottom-up approaches. From a more aggregate perspective, the latter has also been evidenced in Islam and Miyazaki (2010) who highlighted the lower performance of these East Asian countries in the nanobiotechnology research domain.

c) **Cluster III** – The case of China is unique. China appears to be following a trajectory heavily concentrated on technologies for the synthetic growth of nanostructures. Here, Bhattacharya et al. (2012), Shapira and Wang (2009), among others have highlighted China's biased nano-research efforts in the lower end of the nanotechnology value chain.

In summary, the results of this section evaluated the differences in the patterns of specialization on micro/nanofabrication technologies across countries/regions. Despite the inherent differences among different countries/regions, similarities in the breadth, intensity and nature of their patterns of specializations were observed.

7.6. Summary of the Results

This chapter set its sights on the study of the dynamics of emerging technologies through the examination of the paths of knowledge evolution and the patterns of scientific specialization across countries. The former consisted in the conduction of a co-word analysis, whereas the latter in the evaluation of the Revealed Scientific Advantage (RSA) indicators. In particular, the scientific alignment between both aspects was referred as a crucial aspect for grasping the opportunities of new technologies.

It was observed that the field of micro/nanofabrication technologies is growing, yet such growth is not uniformly distributed across countries. Similarly, differences in the shares and rates of growth of publications were also observed across technologies. This analysis showed that the knowledge structure underpinning micro/nanofabrication is characterized by an increasing size and diversification. Over the years, nano-related knowledge has taken a predominant position within the knowledge structure. As observed in the results of this chapter, the latter is far from entailing a mere transition from micro into nano domains. Instead, it was shown that the paths of knowledge on micro/nanofabrication are diverse, entailing the study of multiple phenomena, multiple materials, as well as by the integration of knowledge of a differing nature: bio, top-down, and bottom-up, among others. As later sections will show, these results are closely associated to the need to build a broad knowledge base on micro/nanofabrication technologies. Here, it is expected this need for more diverse knowledge bases to increase as transitions into new nano-enabled product generations ensue: active nanostructures, integrated nanosystems, and eventually molecular nanosystems (The reader is referred to Section 3.2.4.1 for a greater discussion on these nano-enabled product generations).

On the other hand, the patterns of competence building were evaluated through the evaluation of the degrees of specialization of countries. For that purpose, a typology consisting of three global indicators was defined: breadth, intensity, and nature of the micro/nanofabrication technology knowledge bases of countries. Building upon on this typology, three clusters of countries/regions were defined. These results revealed that an alignment between the nature of the paths of knowledge evolution and the way countries build their competences in this field could only be observed for the case of the United States and the European Union as a whole. This result suggests the difficulties in building micro/nanofabrication competences for countries. Later sections will denote the highly dependent nature of nano-related competences on long-term capital investments and scientific capabilities, but also on the creation of new workforce and productions methods.

In the next chapter, the dynamics of emerging innovation systems are evaluated by tracing the patterns of change undergone by the actors and their knowledge networks being built over time. Here, the empirical case of micro/nanofluidic-based point-of-care diagnostic systems is discussed.

8. Changes in the Actors and their Knowledge Networks as Reflections of the Dynamics of Emerging Innovation Systems – The Case of Microfluidic-based POC Diagnostic Devices

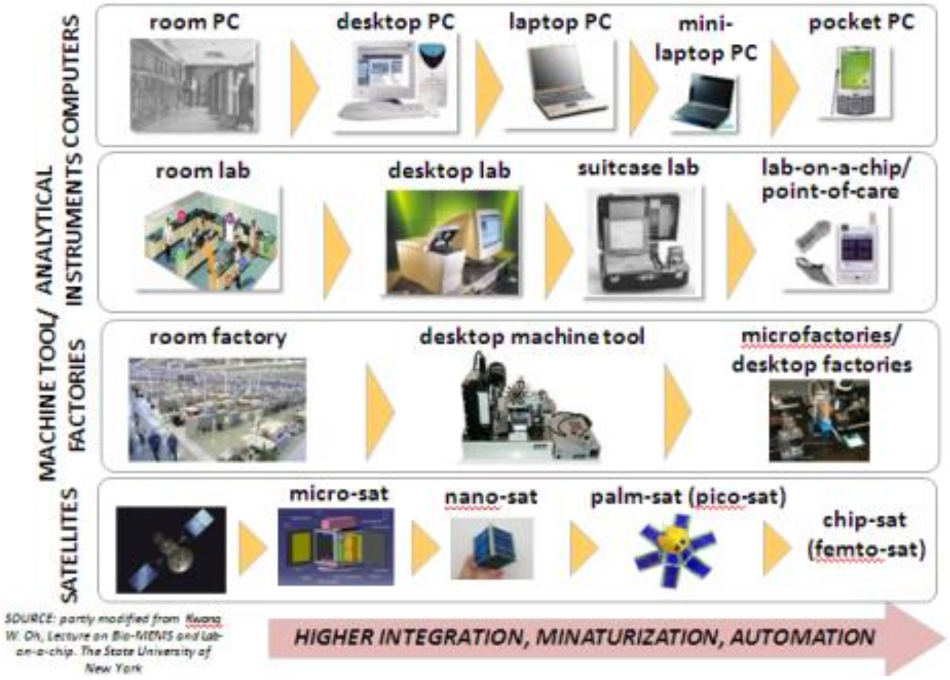
This chapter now turns to the characterization of the dynamics of an emerging innovation system. Previous studies have highlighted the possibility to visualize formative innovation systems as niches, which refer to the ‘brewing’ spaces for emerging technologies (see Section 2.4.1). This chapter revolves around the case study of micro/nanofluidic-based point-of-care diagnostic systems (henceforth MNDT/POC), which comprise portable or hand-held in-vitro diagnostic devices based on micro/nanofluidic technologies (see Section 3.3.4). This chapter comprises the fourth hypothesis described in Section 2.5.5, namely: ‘the evolution of formative innovation systems can be inferred from the changes experienced by the actors, and the knowledge networks, physical and cognitive, built by these actors’. For doing so, a niche is visualized as a technological innovation system, which, in turn, can be further described as a network. Two main analytical blocks are discussed. First, the MNDT/POC field is characterized as a whole, including devices, systems, components, and methods. The latter sets the ground for the second analysis that focuses on the particular case of MNDT/POC technologies as end-product systems (henceforth MNDT/POC systems). This analysis emphasizes the changes undergone by the actors active in this field and the knowledge networks – physical and cognitive – being built.

This chapter is structured as follows. Section 8.1 takes a step back to visualize MNDT/POC, from a broader perspective, as transitions toward miniaturization. This section also defines an analytical way to approach the study of the MNDT/POC field. Subsequently, Section 8.2 provides a description of the research methods and sources of data used. Section 8.3 continues with the discussion of the results and findings of this study. Finally, Section 8.4 summarizes the main results.

8.1. *MNDT/POC technologies visualized as transitions*

This section takes a step backward to visualize NMDT/POC technologies from a broader perspective. In particular, this section starts from the premise that NMDT/POC technologies embrace a technological transition, i.e. a transition toward miniaturization. By miniaturization, it is meant “the process of making something very small using modern technology” (Cambridge Dictionary, 2012) or “to make or construct (something, esp. electronic equipment) on a very small scale; reduce in size” (Collins

Dictionary, 2012). A well-known example of a miniaturization trajectory is Moore's law[1] which has driven for over forty-five years the transistor density in integrated circuits for the semiconductor industry. Miniaturization has been actively pursued, particularly since the development of the transistor in the early 1950s and the integrated circuits in the late 1950s. Currently, the proliferation of small technologies – micro- and nanotechnologies - have gradually expanded the impact of miniaturization beyond consumer electronics (e.g. computers, telephones, radios, etc.) into more non-traditional application domains, such as satellite technologies (nanosatellites, picosatellites, etc.), microfactories, and point-of-care diagnostic systems (Fig. 8.1).



SOURCE: partly modified from Kwang W. Oh, Lecture on Bio-MEMS and Lab-on-a-chip. The State University of New York

Fig. 8.1 Non-traditional miniaturization transitions

The remainder of this section discusses in greater detail the visualization of point-of-care diagnostic devices as transitions toward miniaturization.

As previously noted, in-vitro diagnostics (IVD) tests are an integral part of the health care system. Such tests play a central role in all aspects of patient care, including the diagnosis of disease, the monitoring progression of therapy, as well as the screening for health and infection. Historically, diagnostics has been conducted by professional laboratorians in centralized, consolidated laboratory facilities in which highly productive, highly automated, and centralized equipment is the rule (Zaninotto

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[1] Moore's law is term coined by Intel's founder Gordon Moore the number of components that could be incorporated per integrated circuit would increase exponentially over time" (ITRS, 2010).

and Plebani, 2010). Centralized laboratories are generally equipped with large, expensive and complex analyzers with very high throughput capabilities that are usually modularly arranged, in which each module performs a single analytical step. These modules are then robotically interconnected to provide full automation. Despite the existence of analyzers in single units, they still require a significant amount of laboratory space. In contrast, point-of-care-testing (POC) defines highly-portable, miniaturized in-vitro diagnostics (IVD) testing devices which can be easily transported into the vicinity of patients, physician-offices, home end-users, populations in remote or rural areas, emergency rooms, etc. (Holland and Kiechle, 2005). As can be inferred, centralized testing and POC depict differing approaches for conducting the same function: to clinically diagnose a fluid sample taken from a human. As described in Section 3.3.4, POC itself is not new as seen in the now widely diffused cases of glucose tests (diabetes) and pregnancy lateral flow tests (paper strips). The growth of new POC technologies is being particularly enabled by the development of innovative technologies such as lab-on-a-chip (LOC)[2]. These technologies have the potential to make an impact in clinical testing by Chin et al. (2012): (a) the detection of low concentrations of the target, (b) the quantification of the results, i.e. not qualitative results, (c) the possibility to simultaneously conduct multiple measurements (multiplexing), and (d) the possibility to simplify currently complex testing such as nucleic-acid testing (also referred as molecular diagnostics).

Compared to their centralized testing counterpart, the advantages of POC devices are: lower costs through lower input consumption and waste levels, handheld portability, faster results, on-site testing for user convenience, automated operation, automated data management and transfer, increased safety and reliability, and suitability for unskilled users with no sample preparation. Following Sahal (1985), miniaturized products are visualized to comprise drastic changes of a morphological, functional and structural nature. Nevertheless, in some case, the impact of miniaturized technologies such as POC involves more disruptive and far-reaching effects. Some of these are the transformation of current systems, value chains, and business models as they enable a broader accessibility and availability into the 'hands of many'. As defined by Chin et al. (2007), POC devices "*empower* health-care workers and patients with important health-related information in even the most remote settings" (emphasis added). Gaster et al. (2011) adds "just as miniaturization of computers, which once filled large rooms, into the microprocessor revolutionized the computer industry, miniaturization of medical diagnostic tools has the potential to restructure our healthcare system in a similar fashion". Gaster et al. (2011) continue: "… change the medical practice of medicine by providing society with a new medical infrastructure: one that allows individuals to literally take health care into their own hands". These aspects point to the 'hidden' dynamics stemming from these technologies. Within this context, for some, POC comprises a paradigm

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[2] LOAC technology aims to bring together the different steps in a laboratory setting onto one chip through the use of micro/nanofluidic technologies.

change, i.e. a different, novel way of ‘doing things’. However, as any emerging technology their benefits still have to live up their promises.

From what has said so far, how to conceptually approach this situation? It is assumed that the combined innovation systems approached discussed at the end of Section 2.4.1 may provide some answers. Building upon that, MNDT/POC technologies are regarded as a niche brewing within a more coherent and established structure, namely centralized laboratories. As such, centralized laboratories exemplify the regime. Both of which, niche and regime, are contained within a higher level system referred to health-care system (Fig. 8.2). This is a rather simplified view; however, it will suffice for the purposes of this chapter. In reality, a wide range of POC application domains exists. Given the maturity of some of these application domains, they may be even considered a regime. Entities, be it niches or regimes, are highly interactive as they partially share common interests, and even system components (institutions, actors, networks). As pointed out by Markard and Truffer (2008), niches may be in connection with other regimes of complementary or competitive nature, other niches of complementary or competitive nature, and with the landscape. In this chapter, the niche MNDT/POC technologies is conceptualized as a formative TIS, and even further as a as a networks (Piterou and Steward, 2011; Steward et al., 2008).

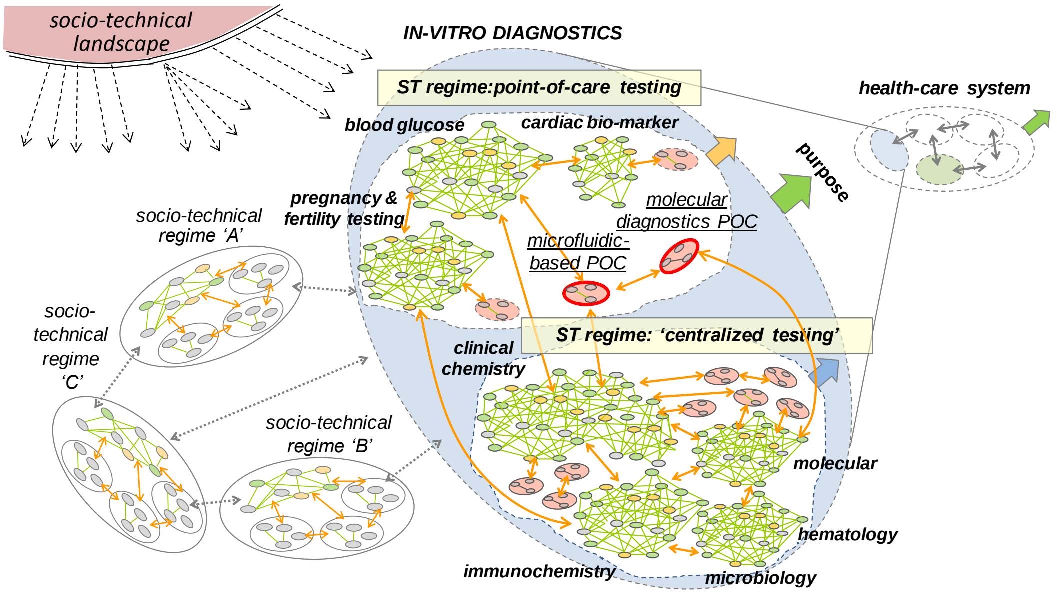

Fig. 8.2 Conceptual visualization MNDT/POC technologies

Summarizing what has been said, it is possible to visualize the innovation systems building around emerging technologies as niches, which may, in turn, be conceptualized as networks The remainder of this chapter attempts to couple the dynamics of this niche by tracing the changes in the actors and the knowledge networks being built. Before that, a general characterization of the MNDT/POC field is presented.

8.2. Research Methods and Data Sources

This chapter comprises two main analyses. The first analysis presents a general characterization of the field MNDT/POC technologies derived from publication and patent data. By focusing on MNDT/POC technologies as end-product systems, the second analysis pays attention to the changes undergone by the actors participating in this technological field and the knowledge networks they build. The remainder of this section describes the research methods and data sources for both analyses.

8.2.1.1. General characterization: 'MNDT/POC technologies'

The general characterization of MNDT/POC technologies relied on patent and publication data.

For the case of patent data, this was extracted from the United States Patent and Trademark Office (USPTO) database. The selection of the USPTO database relied on the possibility to search across all patent sections. A keyword-based search was used to identify relevant patents. Given the fact that patents are usually described in abstract terms and in order to embrace as much of the technological field as possible, a broad search query was used. Besides limiting this search to diagnostics and micro/nanofluidics-related keywords, a series of synonyms for point-of-care (e.g. near-patient, in-the-field, on-site, point-of-use, point-of-need, bedside, etc.) and portable (e.g. palm-sized, hand-carried, hand-held, pocket-size, mobile, benchtop, implantable, etc.) typically encountered in the technical literature were used. The search query was further enhanced by including the titles, abstracts, claims and specifications of patents. For this analysis, granted patents up to 2011 were included. Moreover, patents related to high-throughput applications and lateral-flow tests were excluded as, although they are closely related to MNDT/POC technologies, they are not relevant for this analysis. Appendix 4 presents the search query used for this analysis. The initial number of collected patents was 2,813. These patents were downloaded from the USPTO database website through the use of the Mozilla Firefox add-on 'DownThemAll'. This data was converted into text (.txt extension) through the software TextForever, and subsequently imported into the software VantagePoint for pre-processing. The pre-processing stage consisted mainly in the exhaustive reading each of the collected patents with the purpose of identifying those patents related to the field of MNDT/POC technologies. Some examples of excerpts from the patents included in this analysis are:

- “…Therefore, the invention can be popularized to ***point-of-care*** or **home-care** purposes...”
- “to be sufficiently miniaturized so as to be easily transportable and even made **handheld**…”
- “The present invention very advantageously elevates DMF to compatibility with diverse applications ranging from laboratory analyses to ***point-of-care*** diagnostics...”
- “This simplicity can allow microfluidic systems described herein to be used by untrained users, such as those in ***point-of-care*** settings...”
- “Embodiments of the invention may be used to provide rapid and ***point-of-care*** testing,..”
- “…they provide a framework for offering inexpensive portable "***Point-of-Care***" (POC) systems...”

After these pre-processing procedures, a total of 331 patents were collected. For these patents, meta-data such as assignee organization, issued data, application data, cited references (patent and non-patent), and patent classification indexes (IPC) were extracted.

By making use of a largely similar approach, publication data was extracted from the ISI/SCI database. All languages and types of publications up to the year 2011 were included. At the end, a total of 612 scientific publications were collected from which meta-data such as organization name, publication year, and cited references, were extracted.

8.2.1.2. Specific analysis: ‘MNDT/POC systems’

As previously noted, this analysis examines the changes in the role of actors and their knowledge networks for the case of the field MNDT/POC systems. By MNDT/POC systems, it is meant integrated micro/nanofluidic-based point-of-care devices. Here, Fig. 8.3 presents a series of MNDT/POC systems developed by firms to be analyzed in later sections. As may be inferred, MNDT/POC systems comprise complex products in which a wide range of technological and scientific fields converge.

The first and most important step in this analysis consisted in defining the list of firms active in the field of MNDT/POC systems. For that purpose, besides the results from the previous analysis, additional sources were reviewed, such as publicly available overviews from market reports (e.g. Yole Developpement (Yole, 2012)), technical publications (Chin et al., 2012; Haber, 2006), and on-line resources (e.g. pointofcare.net, ‘list of microfluidics research groups’, and fluidicmems.com). After a series of examination cycles, a total of 78 firms were discerned.

Subsequently, a series of data were collected for each of these firms. This data was restricted to the period of time between 1999 to September 2012. Two periods of time were defined: 1999-2005 and 2006-2012. The first period of time refers to the initial stages of the MNDT/POC field, while the second the period of time is depicted by the development of more complex application domains, such as molecular diagnostics. Following, the general properties of these data sources will be described:

Fig. 8.3 Examples of MNDT/POC systems

a) Patents

Patent applications assigned to these firms were drawn from the European Patent Office (EPO) database ‘esp@cenet’. In comparison to other databases, the reasons behind the selection of the EPO database are three-fold: (a) publicly available database, (b) the possibility to take into account ‘patent families’, i.e. similar inventions being filed in multiple countries, and thus avoid double-counting issues, and (c) the possibility to draw patents from a multitude of patent databases, such as United States Patent Office (USPTO) in terms of patent applications and granted patents, European Patent Office (EPO), Japan Patent Office (JPO), World Patent Office (WIPO), and several domestic patent offices. The ability to cover several patent offices proved important for this analysis as firms tend to make use of alternative ways to file a patent, as later sections will discuss. The main types of information extracted from the collected patents were their allocated IPC classification indexes and the year of application.

b) Scientific publications

Publications authored or co-authored by the sample of firms were extracted from the ISI/SCI database. Here, care was taken to include name variants of firms in order to embrace the totality of publications published by each firm. From these publications, 'Research Areas'[3] and publication years were collected. Compared to journal subject categories which are journal based, the ISI/SCI database has recently allocated 'Research Areas' to each publication according to the contents of the article. All document types – meeting abstracts, article, letter, proceedings – were included in this analysis.

c) Pre-market notification 510(k) from the U.S. Food and Drug Administration (US FDA)

Medical device manufacturers are compelled to notify their corresponding regulatory authorities their intent to commercialize medical devices, be it first introductions or reintroductions of significantly modified medical devices. The main purpose of these pre-market approval mechanisms is to ensure the conformity in terms of safety, quality and effectiveness of a particular in-vitro diagnostics device to the requirements of the corresponding country's regulatory authority. As patents cannot infer much about the final product as most of them may never reach the market (Griliches, 1990), pre-market notifications 510(k) from the U.S. FDA are regarded as proxies for product innovation knowledge. Information on the 510(k) approvals were drawn from the '510(k) Premarket Notification' database publicly available on-line from the US FDA homepage[4]. Basically, the decision date and the regulation number were extracted from this database. In this regard, the regulation number defines the classification regulation of a particular device according to their intended use. As this thesis focuses on IVD products, pre-market notifications 510(k) were restricted to those related to cleared/approved IVD products.

d) General Company Information

General information on the firms such as the number of employees, the year of foundation, type of organization, current firm's status, and the location of the headquarters were extracted from a series of publicly-available websites: Bloomberg BusinessWeek (http://investing.businessweek.com), the on-line sales intelligence company InsideView (http://www.insideview.com), Elsevier Business Intelligence (http://www.elsevierbi.com) which is an on-line provider of data and analysis on the Healthcare sector, companies' official homepages, and in some cases from the company's profiles on LinkedIn

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[3] http://images.webofknowledge.com/WOKRS58B4/help/WOS/hp_research_areas_easca.html
[4] http://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfPMN/pmn.cfm

(http://www.linkedin.com). Additionally, the Elsevier Business Intelligence database was used for extracting the type of industry or industries and therapeutic areas in which a particular firm is active.

e) R&D Collaborations

Data on the R&D collaborations was drawn from the on-line Elsevier Business Intelligence (http://www.elsevierbi.com), the news releases posted by the firms on their official homepages, as well as publicly available on-line databases on press releases and news, such as PRNewswire (http://www.prnewswire.com/). It should be noted that this data was restricted to those firms for which this information was available.

8.3. Research Findings

8.3.1. General Analysis

Fig. 8.4 presents a series of bibliometric indicators extracted from the collected patents and publications related to the MNDT/POC field as a whole. Following, a series of implications drawn from Fig. 8.4 are discussed.

As seen in Fig. 8.4a, similar to the rest of the technological fields analyzed in the previous chapters, MNDT/POC technologies appear to be experiencing an increasing scientific and technological interest as inferred from the growing number of publications and patents over time. As shown in Fig. 8.4b, this is accompanied by an increasing number of new organizations entering the field, particularly for the latest time period (2008-2011).

Regarding the country of origin, in terms of the location of their headquarters, of the organizations active technologically and scientifically in this field (Fig. 8.4c and Fig. 8.4d, respectively), it can be seen that the United States (U.S.) dominate this field with almost three-quarters of the patents and two-fifths of the publications. In contrast to the highly concentrated geographical distribution of patents, scientific publications show a higher dispersion across countries. This may be attributed to the relative ‘easiness’, compared to the filing and granting of a patent, of a scientific publication.

In terms of the types of organizations technologically and scientifically active in this field, as shown in Fig. 8.4e, it is not surprising that small and medium enterprises (SME) dominate this field[5]. This is in line with the traditional visualization of small firms as crucial organizations for the dynamics of new technological fields. Later sections will discuss that this partially reflects the realities of this field.

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[5] For this analysis, firms with less than 250 employees were regarded as SMEs.

Furthermore, as may be expected, firms dominate patenting and universities / public research organizations (PRO) dominate the publishing of scientific papers (Fig. 8.4f). Over the three periods of time shown in Fig. 8.4f, this pattern of specialization appears to be reinforced. Nevertheless, the proportion of universities/PRO actively patenting and that of firms actively publishing appear to be high, around 30% and 10% respectively. Among other aspects, this result reflects the greater scientific weight of the MNDT/POC field. Another way to assess the scientific ‘basedness’ of the field consists in evaluating the proportion of publications cited by patents (Schmoch, 1993). From the collected patents, it was found that over 80% of the patents listed at least one publication in their list of references. What is more, by analyzing the ratio of the cited publications over the cited patents for the collected patents over time, as shown in Fig. 8.4g, it can be seen that the average of this ratio oscillates around 0.6 over the three periods of time. This may suggest the high influence of science in these patents. As may be expected, the influence of cited patents in scientific publications is minimal as it reaches 1.3%.

Regarding the levels of collaboration, not shown in Fig. 8.4, the proportion of patents with more than one assignee organization compared to the co-authorship of publications by more than one organization is significantly lower, namely 5.5% against 49.9%. This result may be attributed to the different nature of both types of bibliometric data. As patents comprise a private right, their tendency to be shared among different organization is significantly lower. This result prevents the use of patents as reliable proxies for analyzing collaboration networks.

As illustrated in Fig. 8.4h, the collected patents comprise technologies across the value chain of MNDT/POC technologies. Fig. 8.4h shows that the collected patents are comprised of devices (around 45%), systems (around 25%), single components including fluidic connectors, actuators, pumps, compounds, micro-mixers, materials, etc. (around 25%), and methods such as manufacturing, detection and calibration methods (around 5%).

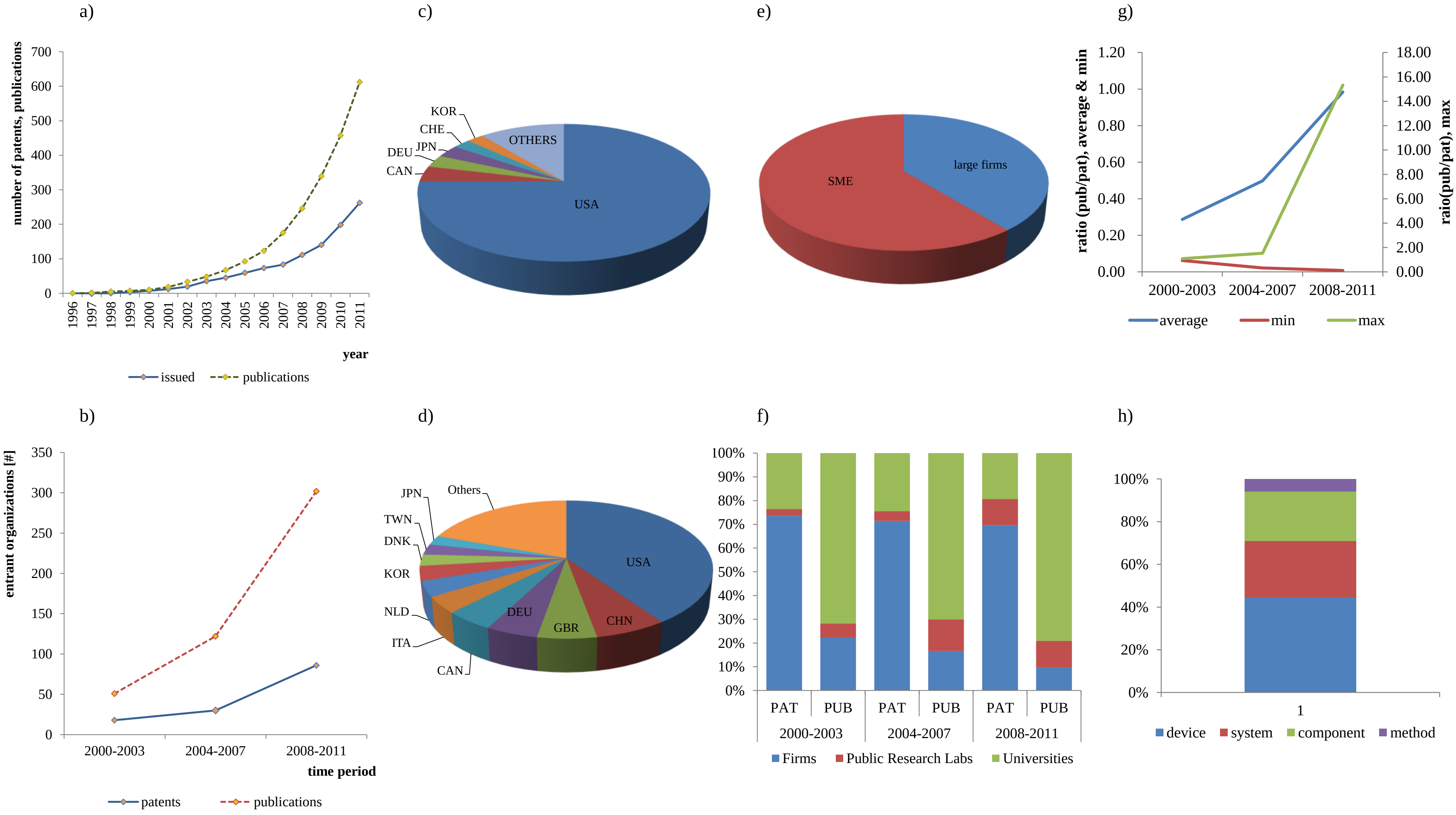

Fig. 8.4 Bibliometric indicators extracted from the collected patents and publications

Finally, Table 8.1 presents the top-ten scientific and technological topics stressed in the MNDT/POC field as reflected in the collected publications and patents, respectively.

Table 8.1 Top-ten of scientific and technological topics stressed for the MNDT/POC field

Subject categories	Count	Proportion	Growth rate
Nanoscience & Nanotechnology	211	15.5%	4.3
Chemistry, Analytical	190	14.0%	3.1
Biochemical Research Methods	154	11.3%	4.5
Chemistry, Multidisciplinary	114	8.4%	6.5
Instruments & Instrumentation	69	5.1%	4.7
Electrochemistry	58	4.3%	4.3
Biotechnology & Applied Microbiology	51	3.8%	3.1
Engineering, Electrical & Electronic	45	3.3%	1.9
Biophysics	43	3.2%	6.6
Materials Science, Multidisciplinary	43	3.2%	2.6

IPC index	Description	Count	Proportion	Growth rate
G01N 33	Investigating or analysing materials by specific methods not covered by groups	85	10.7%	3.8
C12M 1	Apparatus for enzymology or microbiology	61	7.7%	4.7
G01N 21	Investigating or analysing materials by the use of optical means	60	7.6%	0.8
B01L 3	Containers or dishes for laboratory use	54	6.8%	0.6
C12Q 1	Measuring or testing processes involving enzymes or micro-organisms; Compositions therefor; Processes of preparing such compositions	46	5.8%	2.7
G01N 27	Investigating or analysing materials by the use of electric, electro-chemical, or magnetic means	43	5.4%	0.7
G01N 1	Sampling; Preparing specimens for investigation	32	4.0%	2.2
G01N 15	Investigating characteristics of particles; Investigating permeability, pore-volume or surface-area of porous materials	27	3.4%	0.7
C12M 3	Tissue, human, animal or plant cell, or virus culture apparatus	25	3.2%	-
G01N 31	Investigating or analysing non-biological materials by the use of the chemical methods specified in the subgroups; Apparatus specially adapted for such methods	16	2.0%	1.3

For the former, journal subject categories were evaluated; for the latter, IPC classification indexes were used. For the case of subject categories, Table 8.1 highlights the significant influence of nano-related knowledge on this field. The rest of the scientific topics are dominated by chemistry and life sciences-related fields. From the total of topics only two – ‘Engineering, Electric & Electronic’ and ‘Materials Science, Multidisciplinary’ – are characterized by an engineering content. For the case of IPC indexes, the GO1N (investigating or analyzing materials by determining their chemical or physical properties) category across a wide array of main groups dominates. This is not surprising given the general role of MNDT/POC systems as measuring and instrumentation tools. Here, the list of IPCs at the bottom of Table 8.1 displays a wide range of measuring principles, such as optical, through enzymes or microorganisms, electric, electrochemical, magnetic, and chemical, among others.

Summarizing, building on patent and publication data, this section has attempted to provide general insights into the MNDT/POC field as a whole. By focusing on MNDT/POC in terms of systems, next section sets its sights on the study of the changes experienced by actors and the knowledge networks they build.

8.3.2. Specific Analysis

As previously said, this analysis aims at unraveling the evolution of firms active in the field of MNDT/POC and the changes undergone by their knowledge networks over time. It is believed that these changes may be related to the dynamics of emerging innovation systems. The remainder of this chapter revolves around the different data collected for the firms participating in the field of MNDT/POC systems.

8.3.2.1. General Characteristics: Nature, Geography, Industry and Therapeutic Focus

Table 8.2 presents the distribution of the total of firms by their size. Similar to the previous section, the results of Table 8.2 show that almost three-quarters of the firms comprise SMEs. The median year of foundation of these SMEs is 2004, which points to the relative immaturity of the majority of the firms. In contrast, large firms show median years of foundation equal to 1986, i.e. 18 years older than SMEs.

Table 8.2 Type and median years of foundation for the total of firms

Type of firm	Count	Median year of foundation
Large firms	20 (25.6%)	1986
SME	58 (74.4%)	2004

In order to better understand these SMEs, their origin was evaluated through a web search (Table 8.3). Following Libaers et al. (2006), three main categories of SMEs were defined:

- University spin-out companies, which refer to those firms spun out from universities or public research organizations.

- Corporate spin-outs, which refer to those firms created by large established firms.
- New technology-based firms, which refer to those firms founded by non-university affiliated entrepreneurs.

Table 8.3 Origin of SMEs and their performance

Origin of SME	Count	Average Patents	Average Publications	Average approvals
Corporate spin-out firms	7 (12.1%)	6.1 (13.1%)	27.3 (21.2%)	0.1 (2.3%)
New technology-based firms	24 (41.4%)	5.2 (37.9%)	10.8 (28.6%)	1.2 (67.4%)
University spin-out firms	27 (46.5%)	5.9 (49.0%)	16.8 (50.2%)	0.5 (30.3%)

As illustrated in Table 8.3, around three-fifths of the SMEs originated as spin-outs. The majority of them, with a ratio of almost 4:1, have been the result of entrepreneurial action from universities. As discussed by Libaers et al. (2006), university spin-outs are the most important technological transfer available for universities (Fernández-Ribas, 2010). Two-fifths have been set as new technology-based firms. It should be highlighted that despite their independent nature, the origin of new technology-based firms may be, in one way or another, connected to universities or firms. In particular, Fernández-Ribas (2010) have pointed out the likelihood for universities to transfer inventions to the private sector through licensing schemes. Table 8.3 also shows the average of patents, publications and approvals collected for each type of SME. As shown in Table 8.3, spin-outs from firms appear to be characterized by the largest average of patents and publications, yet they display the lowest average of approvals. New technology-based firms are characterized by a more balanced performance.

Firms constantly change, they may go bankrupt, they may join forces through joint-ventures, or they may be acquired through merger and acquisition (M&A) mechanisms. For the latter case, Table 8.4 shows that over 17% of the SMEs have been acquired by other firms. In terms of their performance, M&A show slightly higher performance levels than those of independent SMEs, particularly in terms of publication and approvals; however, these differences are almost negligible.

Table 8.4 Comparison between M&A and independent firms

Type of firm	Count	Patents	Publications	USFDA approvals
M&A	10 (17.2%)	4.0 (12.2%)	16.1 (17.8%)	0.9 (20.9%)
SME	48 (82.8%)	6.0 (87.7%)	15.5 (82.2%)	0.7 (79.1%)

Previous sections have stressed the crucial role of SMEs for the development of the MNDT/POC field. Nevertheless, when the origin of these SMEs is taken into account (e.g. SMEs spun off from firms, SMEs acquired by large firms), it is seen that the influence of large firms increases to almost 48.5% of the total of firms. This result suggests the greater influence of large firms in the evolution of new technologies. However, this influence appears to be more indirect as large-firm-related SMEs are largely independent and detached from the typical 'environment' surrounding large firms.

Table 8.5 present the proportion of firms without patents, publications, or USFDA approvals. As shown in Table 8.5, four-fifths of the SMEs have no approvals, which suggest the still incapability of the SMEs under analysis to bring MNDT/POC systems into the market.

Table 8.5 Percentage of firms without patents, publications, or approvals

	Patents	Publications	USFDA approvals
Firms without a document	6.9%	31.0%	82.8%

Similar to the results of the previous analysis, the distribution of the firms across countries shows a markedly geographic concentration in the United States (Table 8.6). Here, it can be seen that the United States dominates across the number of firms, patents, publications, and approvals. The rest of the countries show negligible contributions to this field; exceptions are Great Britain, Norway, and Sweden.

Table 8.6 Geographic distribution of firms and their output performance

Country	Count of firms (%)	Count of patents	Count of publications	Count of approvals
United States	33 (57.9%)	550 (58.6%)	226 (64.4%)	34 (79.1%)
Great Britain	7 (12.3%)	100 (10.6%)	24 (6.8%)	1 (2.3%)
Canada	3 (5.3%)	31 (3.3%)	6 (1.7%)	5 (11.6%)
Australia	2 (3.5%)	9 (1.0%)	0 (0%)	0 (0%)
Denmark	2 (3.5%)	21 (2.2%)	0 (0%)	0 (0%)
Norway	2 (3.5%)	63 (6.7%)	58 (16.5%)	3 (7.0%)
Sweden	2 (3.5%)	116 (12.4%)	29 (8.3%)	0 (0%)
Others	6 (10.8%)	49 (5.2%)	8 (2.3%)	0 (0%)

Interestingly, the analysis of the geographical distribution of American firms shows a large concentration in two U.S. states: California and Massachusetts, which have been traditionally characterized by their highly active Life Science agglomerations, Silicon Valley and Route 128 respectively (Table 8.7).

Table 8.7 Geographical distribution of American firms

U.S. state /region	Count (%)	U.S. state /region	Count (%)
California	9 (27.3%)	North Carolina	2 (6.1%)
Massachusetts	8 (24.2%)	Washington	2 (6.1%)
Illinois	2 (6.1%)	Other, West	3 (9.1%)
Maryland	2 (6.1%)	Other, Midwest	1 (3.0%)

In Fig. 8.5, the total of firms collected in this analysis, SMEs and large firms included in the Healthcare database ‘Elsevier Business Intelligence’ are evaluated in terms of their industry and their therapeutic area.

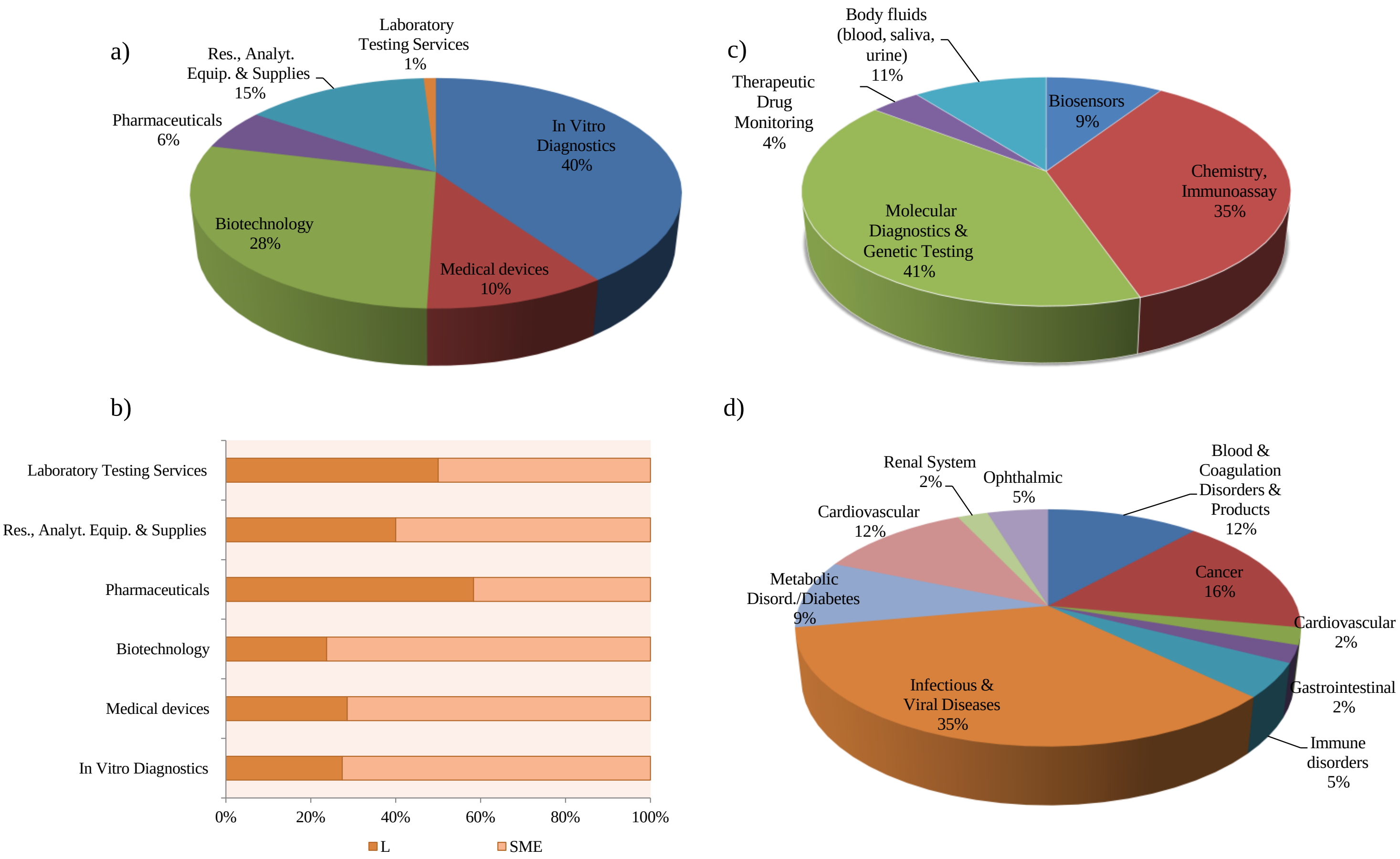

Fig. 8.5 Industries and therapeutic areas for MNDT/POC firms

As shown in Fig. 8.5a, firms appear to be active across a broad range of industries within the Life Sciences field, such as Biotechnology, Medical Devices, and, as expected, In Vitro Diagnostics dominate.

Fig. 8.5b shows that these industry segments are particularly dominated by SMEs. In contrast, pharmaceutical and research and analysis equipment tend to be dominated by larger firms. Regarding the in vitro diagnostics fields being focused by the firms in the sample, Fig. 8.5c shows that ‘Chemistry, Immunoassay’ and ‘Molecular Diagnostic & Genetic Testing’ are predominant. For the case of the therapeutic areas being tackled by these firms, as shown in Fig. 8.5d ten different areas were observed. From these, ‘Infectious & Viral Diseases’, ‘Cancer’, ‘Blood and Coagulation Disorders’, and ‘Cardiovascular Diseases’ show the largest influence. As previously noted, this analysis was restricted to firms indexed in the Elsevier Business Intelligence database. If firms not indexed in this database are included, the range of industries expands to seemingly unrelated industrial fields such as electronics, semiconductors, electric and machinery, etc. This may be the reflection of the high degree of expectation surrounding this field.

Finally, Table 8.8 displays the patent office in which the application was first filed. It can be seen that the majority of the firms made use of the USPTO, which may not be surprising given the overrepresentation of American firms in the sample. Nevertheless, a similarly large share of patent applications was filed at WIPO, and to a much lesser degree at the EPO. Literature has typically highlighted the advantages of WIPO, in terms of the lower costs and the larger windows of time (priority intervals), particularly for SMEs. Thus, for analytical purposes, it is inferred that the use of several patent offices, at least for emerging technological fields, appears to be a necessity.

Table 8.8 Patent office of the original filing office

U.S. state /region	Count (%)	U.S. state /region	Count (%)
United States Patent Office (USPTO)	413 (42.8%)	Domestic, Europe	40 (4.1%)
World Patent Organization (WIPO)	361 (37.4%)	Domestic, Oceania	24 (2.5%)
European Patent Office (EPO)	42 (4.4%)	Domestic, America	9 (0.9%)
Domestic, Asia	68 (7.0%)	Domestic, Africa	8 (0.8%)

8.3.2.2. Mapping the Dynamics of the Physical Knowledge Networks

This section discusses the dynamics of the physical knowledge networks. As these networks imply an interaction between different organizations, they are regarded as physical. In particular, this section focuses on R&D collaborations. In line with M’Chirgui (2009), this thesis regards the dynamics of the physical knowledge networks as important aspects for understanding the structure and changes of emerging innovation systems.

For that purpose, R&D collaboration arrangements were collected for the SME firms active in the field of MNDT/POC systems. Besides the name of the partner organizations, the nature of this collaboration was characterized through two attributes. First, the size of the partner organizations collaborating with the MNDT/POC SMEs was classified into the following categories: large firms, SME firms, public research organizations, and universities. Second, the industries in which the collaborating firms are mostly active were divided into eight different classes: pharmaceutical, in vitro diagnostics, medical devices, biotechnology, test services/instrumentation, electronics/semiconductors, health care services, and others.

Fig. 8.6 shows the evolution of the physical knowledge networks over three time periods: 1999-2005, 2006-2012, and 1999-2012. Each network comprises of two modes, i.e. types of nodes: one mode comprising the SMEs active in the MNDT/POC field, and another mode comprising their partnering organizations. According to the type of partnering organization, as shown at the bottom of Fig. 8.6, a particular color and shape of node was used in these networks. The remainder of this section discusses some results drawn from the networks of Fig. 8.6.

In broader terms, the networks of Fig. 8.6 reflect an increasing building of R&D collaborations over time. However, given the sparse nature of these networks, it is inferred that the MNDT/POC SMEs appear to be building their own networks of collaboration partners. Despite this, few intermediary organizations, or bridges, appear to be indirectly linking the collaboration networks of MNDT/POC SMEs. In this regard, the results of Table 8.9 show that the majority of these firms comprise large firms, particularly pharmaceutical firms. Despite that, this phenomenon appears to be increasing over the years.

Table 8.9 Number of intermediary organizations linking the collaboration networks of MNDT/POC SMEs

Partnering organization	*1999-2012*	*1999-2005*	*2006-2012*
Large firms	11	2	9
SME firms	1	0	1
Public Research Organizations	0	0	0
University	2	0	2
Total of bridges	14	2	12
Ratio from the total of linkages	0.09	0.05	0.11

From the total of M&A, 10 in total, took place in the period 2006-2012.

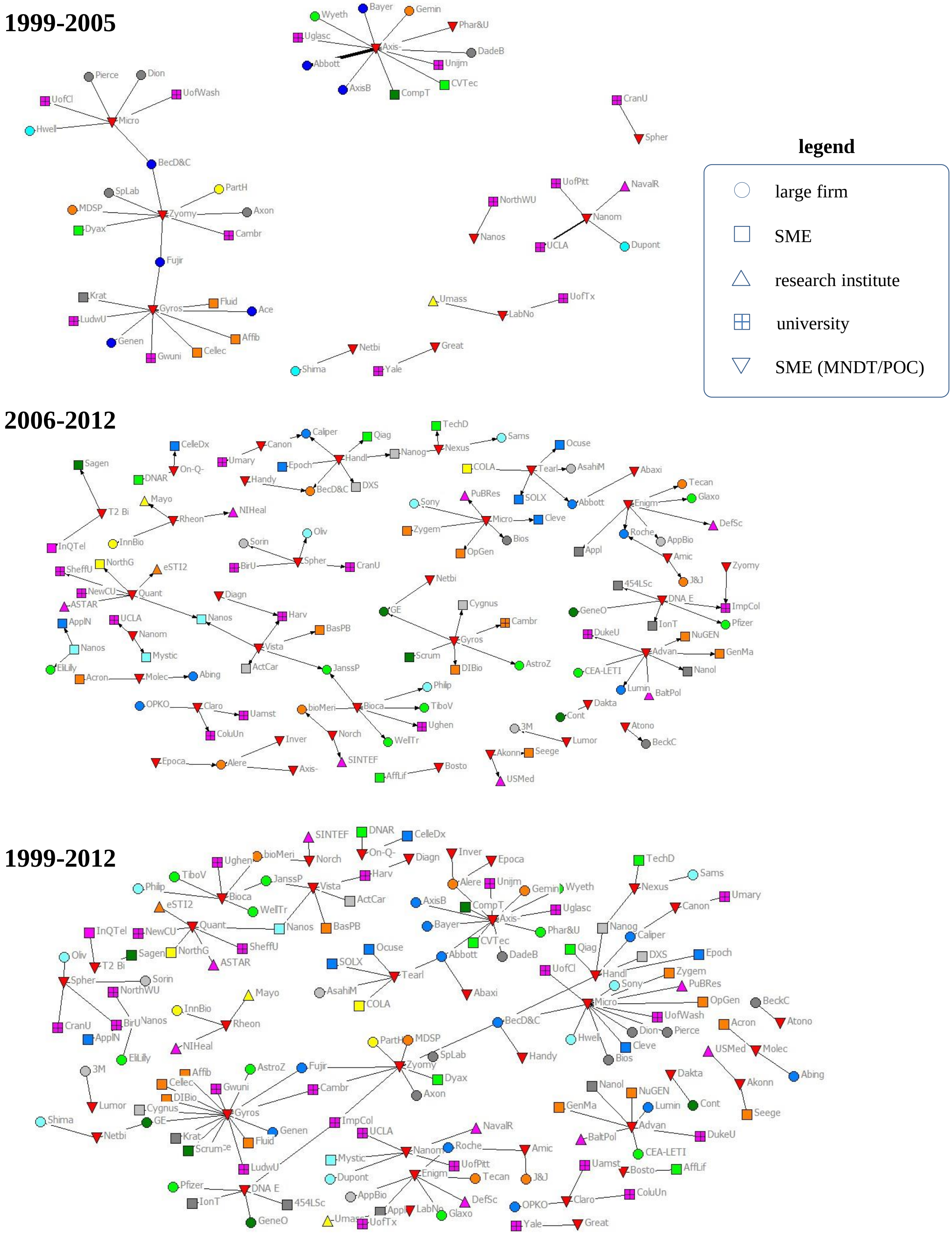

Fig. 8.6 Evolution of the physical knowledge networks over three time periods

Table 8.10 presents the total count and distribution of the types of firms, in terms of their size, for the networks over the time periods 1999-2005 and 2006-2012. As shown in Table 8.10, large firms comprise the largest share of partner firms for the MNDT/POC-related SMEs; however, their share appears to be slightly decreasing over time. Such high shares may suggest the important influence of large firms in the formation of the knowledge networks of highly emerging SMEs. The imminent potential of SME firms and public research organizations is reflected in their strongest rates of growth. From these, SMEs are also characterized by significant shares. Interestingly, the influence of universities appears to remain stable, in absolute terms, over the years; yet, in terms of their shares a sharp decline can be observed. This may suggest the more technological nature of the R&D collaborations being built by MNDT/POC SMEs.

Table 8.10 Overview of the type of organizations by size over time

Size	Total	[A] 1999-2005	[B] 2006-2012	Rate of change [A] vs. [B]
	Count (%)	*Count (%)*	*Count (%)*	
Large firms	73 (45.9%)	25 (51.0%)	48 (43.6%)	0.9
SME firms	46 (28.9%)	8 (16.3%)	38 (34.5%)	3.8
Public Research Organizations	11 (6.9%)	2 (4.1%)	9 (8.2%)	3.5
University	29 (18.2%)	14 (28.6%)	15 (13.6%)	0.1

The results of Table 8.11 display the industries in which firms collaborating with MNDT/POC SMEs are active. This table excludes universities and public research organizations.

Table 8.11 Overview of the type of organizations by nature over time

Industry	Total	[A] 1999-2005	[B] 2006-2012	Rate of change [A] vs. [B]
	Count (%)	Count (%)	Count (%)	
Pharmaceutical	18 (14.9%)	4 (11.8%)	14 (16.1%)	2.5
In Vitro Diagnostics	30 (24.8%)	12 (35.3%)	18 (20.7%)	0.5
Medical devices	11 (9.1%)	6 (17.6%)	11 (12.6%)	0.8
Biotechnology	26 (21.5%)	6 (17.6%)	20 (23.0%)	2.3
Test Services/Instrumentation	12 (9.9%)	3 (8.8%)	6 (6.9%)	1.0
Electronics/semiconductors	12 (9.9%)	2 (5.9%)	9 (10.3%)	3.5
Health care	6 (5.0%)	1 (2.9%)	4 (4.6%)	3.0
Others	6 (5.0%)	0 (0%)	5 (5.7%)	-

First, the results of Table 8.11 reflect the diversity of the firms with which the MNDT/POC SMEs build partnerships. In absolute numbers, all the industrial fields appear to be growing; however, some interesting patterns can be discerned. Here, the partnering with companies outside the ‘In Vitro Diagnostics’ field appears to be accentuated over time, such as pharmaceuticals, biotechnology, health care, and even electronics & semiconductors. This may be attributed to the need of these firms to leverage resources from a broader scope of fields.

8.3.2.3. Mapping the Dynamics of the Cognitive Knowledge Networks

This section now turns to the analysis of the cognitive knowledge networks building among actors. In contrast to the physical knowledge networks, cognitive knowledge networks do not imply a direct connection between firms. Instead, a cognitive linkage is built when firms share knowledge – scientific, technological or market related – of a similar nature. Hence, the higher the amount of knowledge being shared by two firms, the higher their cognitive similarity. In this section, it is argued that tracing the changes experienced by this cognitive similarity may be useful for discerning the dynamics of emerging technologies.

Bibliometrically, the latter is captured through the construction of networks based on the publications, patents and USFDA approvals collected by the firms under study. Specifically, the IPC classification codes from patents, research areas from publications, and regulation numbers from USFDA approvals were used. Based on this data, two-mode networks[1] were built in which one mode is depicted by the MNDT/POC SME firms under study and the other mode the IPCs, research areas and regulation numbers collected for the MNDT/POC SME firms. Here, the latter outgrow from the former. These networks are referred to as cognitive knowledge networks. Provided the limitations of bibliometric data are considered, this network integrates the knowledge being produced within a particular field across scientific, technological and innovative domains. Fig. 8.7 shows the cognitive knowledge networks constructed for the MNDT/POC field for the periods 1999-2005 and 2006-2012.

In the network of Fig. 8.7, MNDT/POC SME firms’ nodes (red squares with lines inside) closer to each other denote similar cognitive profiles according to their IPCs (blue squares), research areas (orange triangles), and USFDA approvals (green circles). In particular, nodes closer to the center depict the ‘core’ nodes, whereas the nodes located outside the networks comprise peripheral nodes. At first sight, over time the knowledge produced in this field appears to be expanding and increasing their interconnectivity.

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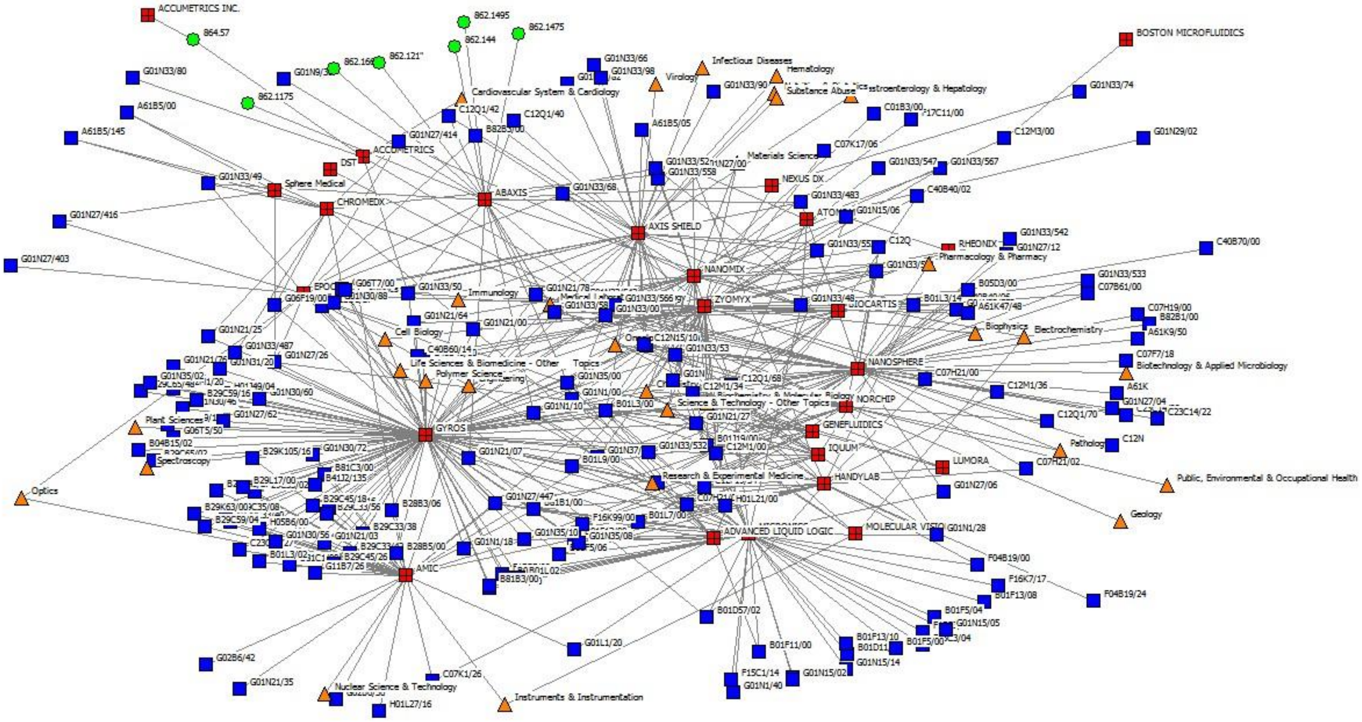
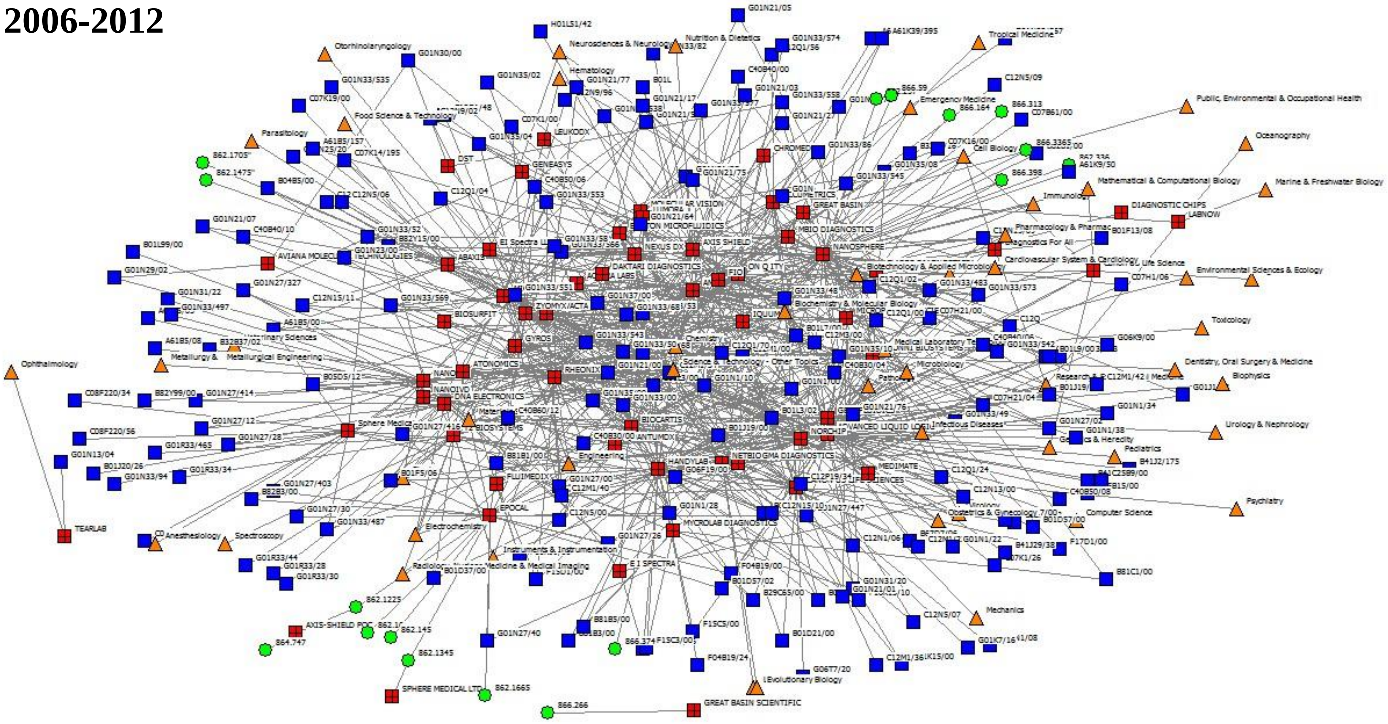
[1] Two-mode networks with two sets of nodes and ties are only established between nodes belonging to different sets.

1999-2005



2006-2012



legend

🟦	IPC numbers	●	USFDA regulation numbers	▲	ISI/SCI research areas	🟥	MNDT/POC SME firms

Fig. 8.7 One-mode network for the periods of time 1999-2005 and 2006-2012

This is reflected in Table 8.12, which presents the number of patents, research areas, and USFDA approvals over time. The results of Table 8.12 denote the predominance of technological dominance; nevertheless, they are coupled with greater rates of change in the scientific and market domains.

Table 8.12 Diversity of the cognitive networks over time

	[A] 1999-2005	[B] 2006-2012	Rate of change [A] vs. [B]
	Count (%)	Count (%)	
USFDA regulation number	10 (2.1%)	19 (3.2%)	0.9
Patents	441 (91.3%)	515 (87.9%)	0.2
Research areas	32 (6.6%)	52 (8.9%)	0.6

A different visualization of the networks of Fig. 8.7 can be found in Fig. 8.8. The networks of Fig. 8.8 present a transformation of the two-mode networks of Fig. 8.7 into one-mode networks. In the networks of Fig. 8.8, the MNDT/POC SMEs nodes were removed to leave a network directly connecting IPCs, research areas, and USFDA regulation numbers. In order to improve their visualization, the networks shown in Fig. 8.8 were standard-deviation normalized, and their isolated and one-degree nodes excluded. One-degree nodes were removed from the networks of Fig. 8.8. As may be inferred, the networks of Fig. 8.8 provide an easier to grasp visualization of the cognitive knowledge networks. In broader terms, it can be seen that the networks point to a denser interaction among the different types of knowledge. As shown in Table 8.13a, the bulk of the interactions are located within technological knowledge and the interaction between technological and scientific knowledge. Nevertheless, Table 8.13 shows that, in terms of its rates of change, the interactions between market knowledge and technological and scientific knowledge are characterized by the strongest rates of growth.

Table 8.13 Inter/intra-relationships among the different types of knowledge in absolute values (a) and in rates of change (b)

	a)			b)		
	APP	IPC	RES	APP	IPC	RES
Approvals [APP]	−−			+		
Patents' IPCs [IPC]	−	++		++	−−	
Research Areas [RES]	−−	++	+	++	−−	−

Note: Allocation of the different symbols [- -, -, +, + +] according to their quartile values.

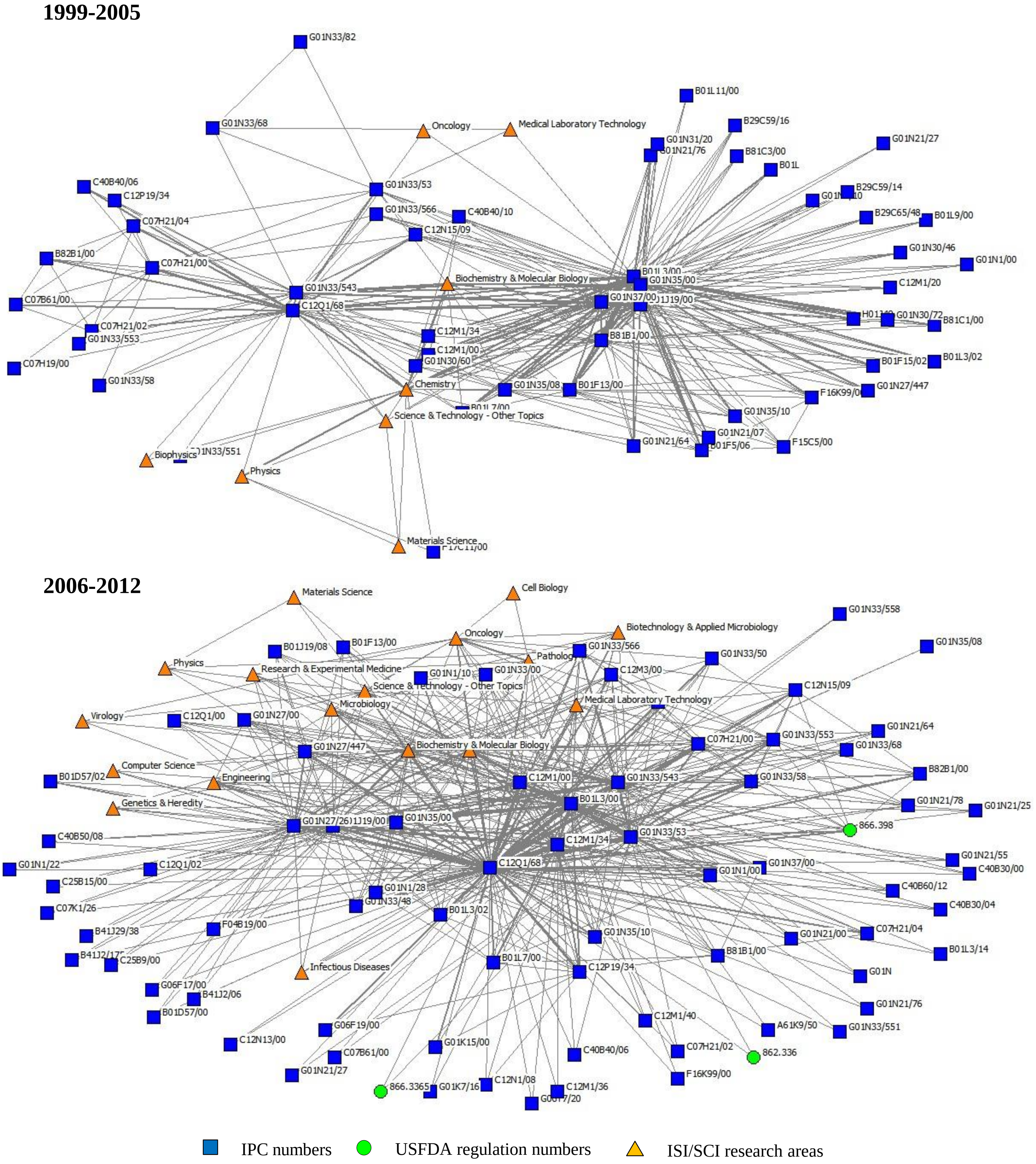


Fig. 8.8 One-mode network for the periods of time 1999-2005 and 2006-2012

The predominance of the different network nodes in Fig. 8.8 can be calculated through the measurement of their centrality measurements: degree, closeness and betweenness centralities. As previously noted, the higher the centrality of a particular node, the higher is its predominance in the network. Here, Table 8.14 presents the top fifteen of the network nodes for the two periods of time.

Table 8.14 Top-fifteen IPC-Research Areas-Regulation numbers for the two time periods

1999-2005

	Degree centrality	Closeness centrality	Betweenness centrality
1	B01L3/00	B01L3/00	B01L3/00
2	G01N35/00	G01N35/00	G01N35/00
3	B01J19/00	G01N33/543	B01J19/00
4	G01N37/00	C12Q1/68	G01N37/00
5	G01N33/543	B01J19/00	G01N33/543
6	B81B1/00	G01N37/00	C12Q1/68
7	C12Q1/68	Chemistry	B81B1/00
8	Chemistry	G01N33/53	Chemistry
9	B01F13/00	B81B1/00	B01F13/00
10	Biochemistry & Mol. Biology	B01F13/00	Biochemistry & Mol. Biology
11	G01N35/08	C07H21/00	G01N35/08
12	C07H21/00	Science & Tech - Other Topics	G01N33/53
13	G01N33/53	G01N35/08	C12M1/00
14	B01L7/00	Physics	B01L7/00
15	C12M1/00	G01N33/68	C12M1/34

2006-2012

	Degree centrality	Closeness centrality	Betweenness centrality
1	C12Q1/68	C12Q1/68	C12Q1/68
2	B01L3/00	B01L3/00	B01L3/00
3	C12M1/34	C12M1/34	C12M1/34
4	G01N33/543	G01N33/543	B01J19/00
5	B01J19/00	B01J19/00	G01N33/543
6	G01N33/53	G01N33/53	G01N33/53
7	G01N27/26	G01N27/26	G01N27/26
8	Chemistry	Chemistry	Chemistry
9	C12M1/00	C12M1/00	C12M1/00
10	Biochemistry & Mol. Biology	Pathology	Biochemistry & Mol. Biology
11	Science & Tech - Other Topics	Oncology	Science & Tech - Other Topics
12	C07H21/00	Science & Tech - Other Topics	C07H21/00
13	Oncology	Biochemistry & Mol.Biology	Oncology
14	G01N35/00	C12P19/34	Pathology
15	G01N27/447	Physics	G01N35/00

In broader terms, both time periods appear to be dominated by, more or less, similar IPCs and Research Areas. Nevertheless, the second time period is characterized by the greater impact of scientific knowledge as seen in the greater number of research areas included. In particular, molecular testing-related knowledge appears to be forging ahead over time.

8.4. Summary of the Results

This chapter investigated the possibility to infer the evolution of emerging innovation systems through the study of the changes undergone by the actors and the knowledge networks being built. This chapter began by taking a step back to visualize MNDT/POC technologies from a broader perspective as transitions toward miniaturization. This was followed by a general characterization of the field of MNDT/POC technologies based on publication and patent data. It was found that this field follows the typical patterns of emerging technologies: increasing scientific and technological growth rates, large number of new entrants, domination by small and medium enterprises (less than 250 employees), and a heavy scientific weight, among others. In particular, a high geographical concentration in the United States was observed.

The next analyses continued with the study of MNDT/POC technologies, but particularly focusing on MNDT/POC systems. By considering the origin of the SMEs active in this field, the greater influence of large firms on the evolution of new technologies was observed. This influence appears to be of a more indirect nature as large firm-related SMEs were found to be largely independent and detached from the typical 'environment' surrounding large firms. Similar to the previous analysis, a large geographical concentration in the United States was observed. This geographical concentration extended to U.S. cities that are particularly characterized by strong Life Sciences clusters, namely California and Massachusetts. In terms of industries and therapeutic areas, this technological field displayed a large segmentation. Interestingly, most of the firms (around 83%) had no USFDA approvals, which suggests the still difficulty for the MNDT/POC SMEs to bring products into the market.

This chapter then moved on to the analysis of the evolution of the physical knowledge networks. Besides their rapid growth over time, a sparse network structure was observed in which SMEs active in the field of MNDT/POC systems appear to be building their own networks of collaboration partners. Despite this, few intermediary organizations, or bridges, appeared to be linking the collaboration networks of different MNDT/POC SMEs. The majority of these firms comprised large firms active in the field of pharmaceuticals. In terms of the types of firms partnering with MNDT/POC-related SMEs, the largest share was taken by large firms, although SMEs and public research organizations appear to be significantly flourishing over time. It was also seen that the type of partner organization was broadening to other fields within the Life Sciences sectors, but also to seemingly unrelated fields, such as electronics and semiconductors.

The last analysis consisted in tracing the evolution of the knowledge being produced by the MNDT/POC SMEs combining scientific, technological and innovative competences as reflected in their IPC numbers, USFDA approvals, and ISI/SCI research areas.

9. Conclusions and Implications

In broader terms, this thesis has set its sights on qualitative evaluating the dynamics of emerging technologies and the ways for measuring these processes. At its heart, this thesis highlighted the crucial role played by the changes, growth and transformation of knowledge in the understanding of the dynamics of evolution of emerging technologies. Hence, much of what has been done throughout this thesis has to do with 'translating' the dynamics of emerging technologies into the 'language of knowledge'. In other words, knowledge, visualized as knowledge structures, was used as a proxy for assessing the dynamics of emerging technologies. As discussed in previous chapters, the latter built up on the co-evolutionary relationships between technology and knowledge structures.

This thesis made use of an integrated framework comprised of four different perspectives for visualizing the dynamics of emerging technologies. Each of these different perspectives consisted in the definition of a hypothesis, which was, in turn, visualized in terms of a conceptual model. The empirical cases of micro/nanotechnologies and micro/nano-enabled technologies were used. In particular, these technologies were visualized in this study from the perspective of the nanotechnology value chain framework (LuxResearch, 2007) into four main blocks: materials, intermediates, end-products, and tools and instrumentation. The methodological approach followed in this thesis consisted in selecting representative emerging technologies along the different blocks of the nanotechnology value chain.

The analyses of this thesis began with the evaluation of the dynamics of technological emergence through the study of the changes undergone by the knowledge bases underpinning these technologies for the empirical case of MEMS/NEMS technologies. The analysis moved on to the case of Zinc Oxide nanostructures with the investigation of the evolutionary dynamics of emerging technological systems through the evaluation of the cognitive properties of their knowledge bases. The analyses of this thesis continued with the empirical case of micro/nanofabrication technologies which focused on the study of the interrelationships between the paths of knowledge evolution and the way actors cope with these changes as inferred from their patterns of specialization. Finally, the empirical case of the end-product micro/nanofluidic-based point-of-care diagnostic systems was used to investigate the dynamics of emerging innovation systems through the study of the patterns of change undergone by the actors and the knowledge networks being built.

As shown throughout these studies, each of the analyses described above was accompanied by an intensive use of quantitative approaches. For that purpose, conventional bibliometric mapping methods – co-word, co-citation, and co-classification networks – were integrated with other quantitative methods and theoretical concepts to come up with plausible and novel research methods for the study of the hypotheses stated at the outset of this thesis.

The remainder of this chapter presents the series of findings, implications, and directions for future research derived from the results of this thesis.

9.1. Findings of this thesis

The main findings of this thesis are described in this section.

Dynamics of emerging technologies in cognitive terms

This study has shown that the patterns of growth of technologies provide only ‘one side of the story’ of their dynamics; in this regard, the crucial complementing role of the cognitive fluidity was highlighted. By evaluating the nature of the knowledge underpinning technologies, it was possible to approach the dynamics of emerging technologies from a cognitive perspective. Despite the significant opportunities and interests surrounding nanotechnology fields, it was found that the composition of their knowledge structures appeared to be heavily tilted toward the earliest phases of problem search and solution (upstream problem areas). In this regard, downstream problem areas, such as those related to applications, appeared to be still playing a secondary role. Furthermore, a cognitive redistribution of the knowledge structures underlying emerging technologies was observed over time; here, despite the still significant growth experienced by upstream problem areas, problem areas downstream are characterized by even stronger rates of growth. In broader terms, these results strongly resonate with Miyazaki (1994, 1995) who discussed the formation of a wedge-shaped pattern as experimental papers gave way to practical applications over time on her study competence building for optoelectronics firms. Moreover, the empirical results indicated that two types of dynamics, structural and cognitive, appeared to be playing a role in technologies of an emerging nature. Interestingly, these dynamics appeared to be following different patterns of change. Structurally, emerging technologies follow high and accelerate rates of change; yet, cognitively, they appear to be largely stepwise and cumulative in nature. This is defined as the first paradox of emerging technologies. By analyzing the cognitive interrelationships within the emerging knowledge structures, a series of differences were observed. Here, not only the number of cognitive clusters of emerging technologies differed, but also, and most importantly, the nature of these cognitive clusters varied. In particular, given their immaturity, the cognitive clusters of emerging technologies appear to be dominated by clusters related to the synthetic growth of ZnO nanostructures. Here, application-related clusters still occupy peripheral locations within the knowledge structure and mainly tend to focus on the understanding of the material properties or the principles key for particular application domains rather than on the development and design of devices. Despite the still weak influence of application-related problem areas, a single application node – room-temperature nano-laser – was characterized by a predominant location within the network. This was defined as the second paradox from emerging technologies. These results highlight the critical role of potential applications even if they still embody ‘primitive’ proofs-of-concept, which besides the creation of fundamental science, may be aspects driving the building up of a ‘critical mass’ of knowledge around this nanotechnological field. This, regardless of the science-driven nature typically associated with nanostructure-related fields. Here, Rafols et al. (2010) has discussed similar observations for the case of hybrid nanomaterials. This is not surprising as nano-enabled technologies are believed to encompass fields of applied science. Nevertheless, what is important for this research is the role that applications play. It may be inferred that potential application domains play the role of harbinger events for the accelerated accumulation of knowledge, which may spill over to other application and scientific-orientated domains. Next section will discuss this in further detail. Moreover, the role of conventional materials and other nanomaterials was observed for the case of nanostructures and nano-enabled devices. Interestingly, they appeared to exert their influence at different time periods.

Co-evolutionary mechanisms between technology and knowledge

By focusing on the case study of ZnO-nanostructure-based nanogenerators, the results of this thesis showed the closely intertwined relationships between the understanding on the physical properties of nanostructures, their synthetic growth methods, and devices and application domains. It was shown that feedbacks between these blocks opened up new research avenues, which in turn, may result in novel devices and application domains. In a sense, the results of this case-study indicated that not only knowledge impacts technology, but also the other way around applies.

Tying up the results of this and the previous findings, the dynamics of emerging technologies may be reflected into macro- and micro-levels. Whereas the former is characterized by being highly cognitively and loosely linear in nature, the latter is denoted by non-linear feedbacks and interactions across the different problem areas. It is still to be seen if such mechanisms may be represented in terms of an autopoietic system (Lucio-Arias and Leydesdorff, 2011; Maturana, 2000).

Breadth and convergence of micro/nanofabrication knowledge structures

For the specific case of the field of micro/nanofabrication technologies, it was observed the knowledge structures of this field were experiencing a rapid growth, yet not at a uniformly distributed growth across countries. Similarly, differences in the shares and rates of growth of publications were also observed across technologies. It was also shown that the knowledge structures underpinning micro/nanofabrication technologies are characterized by an increasing size and diversification. As may be inferred, over the years, nano-related knowledge has taken a predominant position within the knowledge structure. As observed in the empirical results of this thesis, the latter is far from entailing a mere transition from micro into nano domains. Instead, the results of this thesis indicated that the paths of knowledge on micro/nanofabrication are diverse; they entail the study of multiple phenomena, multiple materials, as well as by the integration of knowledge of a differing nature: bio, top-down, and bottom-up, among others. This result is in line with Brousseau et al. (2010) who highlighted that there is no single technology that will prevail to meet the increasing demand for micro/nano-products. In particular, these results indicated the converging nature of these different types of knowledge. The simultaneously broadening and converging nature of the knowledge underpinning micro/nanofabrication technologies depicts the third paradox of emerging technologies.

Alignment between paths of knowledge evolution and patterns of specialization

The patterns of competence building were evaluated through the evaluation of the degrees of specialization across countries reflected in the symmetric RSA values. For that purpose, a typology consisting of three global indicators was defined: breadth, intensity, and nature of the micro/nanofabrication technology knowledge bases of countries. Building upon on this typology, three clusters of countries/regions were defined. By comparing the paths of knowledge evolution of the field of micro/nanofabrication technologies and the patterns of specialization of countries, it was observed that an alignment could only be found for the cases of the United States and the European Union as a whole. Of course, these results do not mean that the rest of countries are merely overlooking the paths of knowledge evolution. However, they do tell a lot about the areas of specialization stressed by particular countries.

Impact of miniaturization transitions

Through the case of the micro/nanofluidic point-of-care diagnostic technologies, this thesis has been able to discern a pattern of change enabled by small technologies, i.e. micro- and nanotechnologies. The results of this thesis show that in some cases the changes induced by miniaturization go beyond mere technological aspects to embrace broad-encompassing transformations. These, in turn, have the potential to displace and to redefine established paradigms, regimes, organizational and business models, and even patterns of human behavior and lifestyle. The thesis does not claim the novelty of these trends, as seen for the case of computers and other consumer electronics devices; instead, through the conduction of this study, it was realized that small technologies are expanding these miniaturization tends into a series of non-conventional application domains. Here, small satellite technologies, micro-factories, point-of-care diagnostics devices were enumerated. After reviewing these examples, these appeared to comprise of the following properties:

- Improved levels of portability, mobility, and even wearability, implantability, etc. bringing about about phenomena such as ubiquitousness, 'walking architectures', 'vanishing products', among others.
- The move from centralized and isolated to decentralized and distributed business models.
- The influence of the miniaturized artifact is not limited to its own system and those systems directly surrounding the artifacts such as complementary and competitive systems, but also those systems located higher-above the hierarchy of systems.
- The transition from technological concentration and technocracy to technological empowerment and democratization of innovation Gershenfeld (2005); Mitchell (2004).
- Translation of capabilities downstream the supply chain, even up to the end-users. These changes the context in which the artifact is employed from producers to consumers, also defined as 'personalization' or 'consumerization' (Gershenfeld, 2005). This can also be found in the case of the miniaturization of the personal computer. Here, the translation of artifacts previously 'in the hands of few' producers to the 'hands of many' implies radical, paradigm-breaking changes shaking, in its entirety, current definitions of the value and the ways it is captured and exploited.

Role of large firms in emerging technological fields

Literature has typically stressed the crucial role that small and medium enterprises (SMEs) played in the development of new technologies; and thus, partially ignoring the role of large firms due to their alleged inflexibility. The results of this thesis have found that the role of large firms should not be overlooked. For the case of micro/nanofluidic point-of-care diagnostic technologies, large firms did not only comprise a large share of the total of firms active in this technological field if the origin of the SMEs is considered, but also they appeared to have actively participated in the construction of linkages in the physical knowledge networks. These results run counter to research streams differentiating the contributions of large firms and SMEs into dichotomies. In contrast, the results of this thesis portray a more balanced role between these types of firms.

9.2. Implications of the thesis

‘Looking back’ to trace the level of technological emergence

The evidence from this study suggests the possibility to look at emerging technologies from ‘cognitive eyes’ as a way to gain deeper insights into their dynamics of change. It is believed that approaching emerging technologies from a cognitive perspective provides a complementing approach for understanding technological emergence. Much of what was done consisted in ‘looking back’ at the properties of the knowledge bases underpinning technologies as a potential way for discerning technological emergence. This was done in this thesis by analyzing the contents embedded in the knowledge structure in terms of problem areas, how fast they grow, how they interrelate with each other, and how they are cognitively clustered.

Knowledge accumulation

The results of this study indicate that knowledge accumulation appears to play a crucial role in the dynamics of emerging nanotechnologies. This is reflected in a progressive redefinition as more knowledge is gathered and previously insurmountable paths are cleared out. This is very much in line with the results of Mina (2009), Consoli and Ramlogan (2008), Metcalfe et al. (2005), who have observed similar phenomena in the field of medicine. In this regard, it seems that a ‘critical mass’ of knowledge needs to be available before attempts into more complex areas are conducted. As previously said, this does not comprise a linear process, but rather a highly cognitively dependent one. This result is closely in line with Nightingale et al. (2008)’s argument that without such knowledge ‘innovations simply do not occur, even if there is very clear demand’.

For the case of ZnO nanostructures, despite the well-known potential application domains, these appear to be far from crystallizing into marketable devices and systems as knowledge on the synthetic growth and assembly methods for complex nano-architectures, nano-macro interconnections, among others, is still in formation. Among other aspects, this is due to the disruptive fabrication methods and working principles/phenomena underlying nanostructures and nano-devices. As pointed out in this thesis, this knowledge accumulation is not solely restricted to knowledge particularly related to the nanomaterial under study, as it was shown in this thesis knowledge from other nanomaterial domains and conventional macro-materials proved to have a significant influence on the knowledge structure. Knowledge accumulation, paraphrasing Miyazaki (1994) for the case of competence building, is “a long, cumulative process characterized by trial and error and experimentation”. The latter provides a glimpse into the difficulties encountered by specific nanotechnology fields in bringing forward nanostructures and nano-enabled devices.

The role of variety in emerging technologies

In general, therefore, it seems that variety was a common aspect found throughout the case studies. This was particularly so for the case of ZnO nanostructures which were characterized by the synthesis of a wide array of morphologies, shapes, compositions, chemical compositions, etc., such as nano-belts, nano-wires, nano-tubes, nano-rings, nano-helixes, hierarchical structures, and heterostructures, among many others. Rather than a well-directed search, this wide-ranged search appears to be aimed at enhancing the current stock of nano building blocks, but also of devices and applications, through experimentation. This also lied at the heart of the co-evolutionary relationships analyzed in this study. The advantages of this variety lie in the possibility for some of these nanostructures to cascade down the problem space and to end-up as applications. In this regard, it has already been noted that many of the applications of nanomaterials may come *ex-post* (Nightingale et al., 2008). The stimulation of variety should take placed across and within problem areas to give way to interplays and feedbacks, which, in turn, may lead to the necessary knowledge for the development of potential nanodevices and nanosystems. As variety increases, the chances of defining new avenues for development increase. This is closely related to the higher chances for recombinations to take place as variety increases. Finally, this variety should be the result of the uncertainty and fluidity associated with emerging technologies.

The role of applications in emerging technologies

This result highlights the critical role of potential applications even if they still embody ‘primitive’ proofs-of-concept, which besides the creation of fundamental science, may be aspects driving the building up a critical mass of knowledge around this nanotechnological field. This fact can be clearly demonstrated in ZnO nanostructures with the case of room-temperature ultraviolet nanolaser presented by researchers of the University of California and Lawrence Berkeley National Laboratory in the USA. Despite the still immature and raw nature of this device at the moment of its development, it appears that after that many researchers ‘jumped on the bandwagon’ of ZnO nanostructures. Similar phenomena have been observed by Pearton (2007) for the case of nanomaterials, Cahn (2003) for conventional materials, and more generally by Linden and Fenn (2003) with their ‘hype model’. Continuing with the case of ZnO nanostructure-based nanolasers, researchers did not only focus on optoelectronic devices such as lasers, but slowly diverged into other, more feasible, research avenues, such as sensors and actuators. It may be inferred that once potential application domains materialize, even as raw or primitive proofs of concept, play the role of harbinger events for the accelerated accumulation of knowledge, which may spill over to other application and scientific-orientated domains. Knowing ex-ante which application will flourish is impossible: here, Segal (2012) has recalled Kroemer’s Lemma of New Technology, which states that the primary application of a new technology is one created by the technology itself. An additional implication is the critical role of demand-based approaches for stimulating technological change in nanotechnological fields.

The role of problem-based approaches

Given the distinct nature of emerging technologies, the findings of this thesis indicate that there is a need to design policies adequate with the characteristics of these technologies. As previously discussed, approaching emerging technologies from a cognitive perspective may provide some answers. In particular, it is believed that visualizing technologies from a problem-based perspective may be useful for these purposes. As described in previous chapters, problem-based thinking in technological change is far from new; however, it has been experienced a renaissance due to the work of researchers from Manchester University. The analysis and visualization of technologies through the composition and changes of their ‘problem spaces’ could bring valuable information on the dynamics of emerging technologies.

The building of nano-competences

Given the inherent properties of the N&N field, the building of competences in this field is highly dependent on long-term capital investments and scientific capabilities, but also on more higher-level aspects such as the creation of new workforce and production methods, as defined by Invernizzi (2011), OECD (2010), and Romig Jr. et al. (2007). Similarly, fabrication and manufacturing capabilities are crucial but not sufficient for the successful development of nano-enabled products. In this regard, Roco (2001) has highlighted the need to couple manufacturing capabilities with the establishment of markets or users in the short/long term. In this case, an additional challenge, thus, consists in manufacturing of nano-enabled products ‘in market appropriate quantities in a reliable, repeatable, economical and commercially viable manner’ (Postek and Lyons, 2007). Recently, a survey conducted by the OECD has highlighted the crucial role of process scalability (OECD, 2010).

Based on the results of this thesis, it is expected that the increasing trends in size and diversity to be more predominant, as transitions into new nano-enabled product generations ensue: active nanostructures, integrated nanosystems, and eventually molecular nanosystems. As these transitions are expected to come with the need for an even greater mastering of multiple materials, multiple scales (macro-micro-nano), as well as knowledge of a multiple nature (top-down, bottom-up, bio, etc.). This, in turn, calls for a wide micro/nanofabrication ‘toolbox’. Although a clear one-to-one relationship between micro/nanofabrication technologies and N&N applications is difficult to establish, the benefits of a wide micro/nanofabrication ‘toolbox’ appear to be as follows. First, a wide range of micro/nanofabrication technologies increases the chances for ‘recombinations to take place – convergence, synthesis, hybrization, etc. – resulting not only in innovative processing technologies but most importantly in technological product paradigms transcending industries (Kautt et al, 2007). Second, the broader is the ‘toolbox’ on hand, the higher is the ‘absorptive capacity’ of countries.

Return of industrialization to advanced economies?

Given the alleged calls for the ‘de-industrialization’ of advanced economies, the results of this thesis reposition the crucial role of manufacturing in general and micro/nanofabrication in particular for accruing value from the opportunities and challenges arising from the field of nanotechnologies. In this regard, this field has the potential to radically redefine the contributions of manufacturing-related competences/capabilities to the economic growth of countries: from its alleged demise and declining value-added contributions to its role as a VRIN resource (valuable, rare, inimitable, and non-sustitutable) driving innovation and technological change of countries Benedettini et al. (2009); Pilat et al. (2006).

Network technologies enabled by small technologies

Miniaturized products tend to network, to distribute, to decentralize, and to fragment. Here, coupled with the accelerated advances in communication technologies (e.g. wireless networks, internet, etc.) are shifting the 'center of gravity' of miniaturized artifacts towards higher degrees of openness, based on Tushman and Rosenkopf (1992)’s product classification. As shown in Fig. 9.1, nanotechnology-based miniaturized devices and products appear to be depicting a new product classification, in between closed and open assembled systems. This brings with it a series of properties for miniaturized devices/products by small technologies. Their 'openness' has resulted, among other aspects, in an increasing number of interdependencies and organizations active in the generation, commercialization and diffusion of miniaturized artifacts, a higher (spatial) dispersion of components, increasing importance of network interactions among and within subsystems and those among systems embedded in miniaturized artifacts, multiple dimensions of merit, higher levels of complexity, etc. They can be regarded as 'network technologies' (Rip, 1995) which refers to those technologies "technologies that are networks themselves, or artifacts that require networks in order to function".

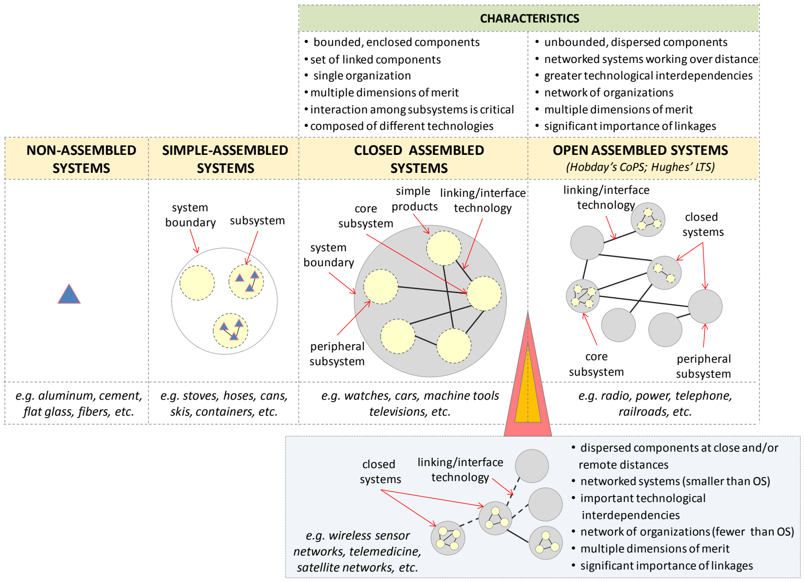


Fig. 9.1 Product classification adapted from Tushman and Rosenkopf (1992)

History repeating – Insights for nanomaterials from silicon

Much of what has been shown strongly resonate with a recent contribution from Segal (2012) who discusses the lessons that researchers of new nanomaterials, in his case graphene, may learn from the history of silicon. This is not to say that nanomaterials will follow the path of silicon, but instead that crucial lessons and insights on what to expect from nanomaterials may be learned from the study of the history of silicon. Nevertheless, given the heterogeneity and complexity inherent in nanomaterials, it is expected for them to follow more complicated and highly intertwined stories.

9.3. Future Research Directions

Based on the main findings and limitations of this thesis, this final section discusses some future research directions in the study of the dynamics of emerging technologies.

Given the heterogeneity inherent in nanotechnologies, it would be impossible to cover in one study the whole range of nanotechnologies at the level of detail conducted in this thesis. In this study, it has been attempted to cope with this heterogeneity by selecting representative emerging technologies across the nanotechnology value chain. Despite these efforts, further experimental efforts are required to complement the analyses presented in this thesis. It is believed that it is necessary to investigate additional cases of emerging technologies within the field of micro/nanotechnologies and micro/nano-enabled technologies. Furthermore, as previously discussed, this thesis has attempted to understand the dynamics of emerging technologies by understanding the way knowledge evolves, changes, and transforms, it would be interesting to investigate the dynamics of emerging technologies through the use of additional conceptual ‘proxies’ besides knowledge. In terms of methodological approaches, considerably more work will need to be done to complement the use of publications and patents with additional sources of information. Similarly, it would be interesting to approach the automation of the different bibliometric methods used. It is believed that such automation may allow them to go beyond mere research tools to potential tools in the processes of policy making. Moreover, further work needs to be done to delve deeper into the ‘hows’ behind emerging technologies, i.e. the ‘emergence’ of emerging technologies.

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Appendix 1

TS=((accelerometer* OR acceleration SAME sensor* OR acceleration SAME transducer* OR inertial-measurement-unit* OR ((inertial-sensor* OR inertial-micro-sensor*) NOT (gyroscope* OR microgyroscope*))) AND (micromachin* OR micro-machin* OR microoptoelectromechanical OR micro-opto-electromechanical OR micro-optoelectromechanical OR microfabricat* OR micro-fabricated OR microsystem* OR micro-system* OR MEMS OR MOEMS OR NEMS OR CMOS-process* OR micro-electro-mechanical OR microelectromechanic* OR nanoelectromechanic* OR micromechanical OR micro-mechanical OR micro-electromechanical OR microoptomechanic* OR micro-optomechanical OR DRIE OR LIGA OR (silicon SAME (packag* OR (etch* NOT etchant*))))) NOT TI=(gyroscop* OR micro-gyroscop*) ////////// TS=(((micro SAME accelerometer* OR nano-accelerometer* OR micro SAME acceleration-sensor* OR micro SAME acceleration-transducer* OR microaccelerometer* OR nanoaccelerometer*) SAME silicon) OR silicon SAME accelerometer*) NOT TI=(gyroscop* OR micro-gyroscop*)

TS=(((bioengineer* OR biotech* OR biological OR medical OR medicine OR biomedical OR biomedicine OR health-care OR life-sciences) SAME (micromachin* OR micro-machin* OR nanomachin* OR nano-machin* OR micromanufactur* OR micro-manufactur* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microsystem* OR nanosystem* OR MEMS OR NEMS OR CMOS-process* OR LIGA OR DRIE OR deep-reactive-ion-etch* OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical)) NOT (medical-equipment-management-system* OR microfluidic* OR micro-fluidic* OR nanofluidic* OR nano-fluidic* OR ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*))))

TS=(((((surgical OR surgery) SAME (instrument* OR equipment* OR device* OR component* OR system* OR tool* OR sensor*))) AND (micromachin* OR micro-machin* OR nanomachin* OR nano-machin* OR micromanufactur* OR micro-manufactur* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microsystem* OR nanosystem* OR MEMS OR NEMS OR CMOS-process* OR LIGA OR DRIE OR deep-reactive-ion-etch* OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical)) NOT (medical-equipment-management-system* OR microfluidic* OR micro-fluidic* OR nanofluidic* OR nano-fluidic* OR ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*))))

TS=(((catheter* OR stent* OR guidewire* OR minimally-invasiv* OR pacemaker* OR (capsul* SAME endoscop*)) AND (micromachin* OR micro-machin* OR nanomachin* OR nano-machin* OR micromanufactur* OR micro-manufactur* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microsystem* OR nanosystem* OR MEMS OR NEMS OR CMOS-process* OR LIGA OR DRIE OR deep-reactive-ion-etch* OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical)) NOT (medical-equipment-management-system* OR microfluidic* OR micro-fluidic* OR nanofluidic* OR nano-fluidic* OR ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*))))

TS=((((drug-delivery OR microneedle* OR micro-needle*) AND (micromachin* OR micro-machin* OR nanomachin* OR nano-machin* OR micromanufactur* OR micro-manufactur* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microsystem* OR nanosystem* OR MEMS OR NEMS OR CMOS-process* OR LIGA OR DRIE OR deep-reactive-ion-etch* OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical)) NOT (medical-equipment-management-system* OR microfluidic* OR micro-fluidic* OR nanofluidic* OR nano-fluidic* OR ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*)))))

TS=(((biosensor* OR bio-sensor* OR biochip* OR bio-sensing OR bio-chip* OR bio-microchip* OR bioassay* OR bio-assay* OR immunoassay* OR immuno-assay* OR immunosensor*) AND (micromachin* OR micro-machin* OR nanomachin* OR nano-machin* OR micromanufact* OR micro-manufactur* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microsystem* OR nanosystem* OR MEMS OR NEMS OR bioMEMS OR bioNEMS OR CMOS OR LIGA OR DRIE OR deep-reactive-ion-etch* OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical)) NOT (microfluidic* OR micro-fluidic* OR nanofluidic* OR nano-fluidic* OR ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*))))

TS=((biomicroelectromechanic* OR bio-microelectromechanic* OR bio-micro-electromechanic* OR bionanoelectromechanic* OR biomedical-microelectromechanic* OR biotech-microelectromechanic* OR biotechnology-microelectromechanic* OR bio-nanoelectromechanic* OR bio-nano-electromechanic* OR biological-nanoelectromechanic* OR biomedical-nanoelectromechanic* OR biotechnology-nanoelectromechanic* OR biotech-nanoelectromechanic* OR bioMEMS OR bio-MEMS OR bioNEMS OR bio-NEMS) NOT (medical-equipment-management-system* OR microfluidic* OR micro-fluidic* or nanofluidic* OR nano-fluidic* OR ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*))))

TS=(((biochemical-sensor OR biochemical-sensors OR biological-sensor OR biological-sensors) AND (micromachin* OR micro-machin* OR nanomachin* OR nano-machin* OR micromanufact* OR micro-manufactur* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microsystem* OR nanosystem* OR MEMS OR NEMS OR bioMEMS OR bioNEMS OR CMOS OR LIGA OR DRIE OR deep-reactive-ion-etch* OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical)) NOT (microfluidic* OR micro-fluidic* OR nanofluidic* OR nano-fluidic* OR ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*))))

TS=((chemical-sensor OR chemical-sensors OR electrochemical-sensor OR electrochemical-sensors OR dielectric-sensor* OR dielectric-spectroscopic-senso*) AND (bioengineer* OR biotech* OR biological OR medical OR medicine OR biomedical OR biomedicine OR health-care OR life-sciences) AND (micromachin* OR micro-machin* OR nanomachin* OR nano-machin* OR micromanufact* OR micro-manufactur* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microsystem* OR nanosystem* OR MEMS OR NEMS OR CMOS OR LIGA OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical)) NOT TS=(microfluidic* OR micro-fluidic* OR nanofluidic* OR nano-fluidic* OR ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*)))

TS=(((neural SAME prosthes* OR neural SAME probe* OR neural SAME implant* OR neuro* SAME prosthes* OR neuro* SAME probe* OR neuro* SAME implant*) AND (micromachin* OR micro-machin* OR nanomachin* OR nano-machin* OR micromanufact* OR micro-manufactur* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microsystem* OR nanosystem* OR MEMS OR NEMS OR CMOS-process* OR bioMEMS OR bioNEMS OR CMOS-process* OR LIGA OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical)) NOT (microfluidic* OR nanofluidic* OR ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*)))) TS=(((cochlea* SAME prosthes* OR cochlea* SAME implant* OR retinal SAME implant* OR retinal SAME prosthes* OR vision SAME prosthes* OR vision SAME implant* OR implantabl*) AND (micromachin* OR micro-machin* OR nanomachin* OR nano-machin* OR micromanufact* OR micro-manufactur* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microsystem* OR nanosystem* OR MEMS OR NEMS OR CMOS-process* OR bioMEMS OR bioNEMS OR CMOS-process* OR LIGA OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR micromechanical OR micro-mechanical OR nanomechanical)) NOT (medical-equipment-management-system* OR microfluidic* OR micro-fluidic* OR nanofluidic* OR nano-fluidic* ((DNA OR RNA OR protein*) SAME (microarray* OR micro-array*))))
TS=(((gyroscope* OR inertial-measurement-unit* OR ((inertial-sensor* OR inertial-micro-sensor*) NOT (accelerometer* OR microaccelerometer*))) AND (micromachin* OR micro-machin* OR microoptoelectromechanical OR micro-opto-electromechanical OR micro-optoelectromechanical OR microfabricat* OR micro-fabricated OR microsystem* OR micro-system* OR MEMS OR MOEMS OR NEMS OR CMOS SAME process* OR micro-electro-mechanical OR microelectromechanic* OR nanoelectromechanic* OR micromechanical OR micro-mechanical OR micro-electromechanical OR microoptomechanic* OR LIGA OR micro-optomechanical OR IC SAME process* OR IC SAME technolog* OR etch* OR ((polysilicon OR silicon) AND packag*))) OR (polysilicon OR silicon) SAME gyroscope* OR ((silicon OR polysilicon) AND (micro-gyroscope* OR nano-gyroscope*))) NOT TI=(ring-laser OR fiber-optic-gyroscope* OR optical-fiber* OR fiber-optic*) TS=((yaw-rate OR gyrometer* OR angular-rate-sensor* OR gyro OR gyros OR microgyro OR microgyros) AND (micromachin* OR micro-machin* OR microoptoelectromechanical OR micro-opto-electromechanical OR micro-optoelectromechanical OR microfabricat* OR micro-fabricated OR microsystem* OR micro-system* OR MEMS OR MOEMS OR NEMS OR CMOS SAME process* OR micro-electro-mechanical OR microelectromechanic* OR nanoelectromechanic* OR micromechanical OR micro-mechanical OR micro-electromechanical OR microoptomechanic* OR micro-optomechanical OR LIGA OR IC SAME process* OR IC SAME technolog* OR etch* OR ((polysilicon OR silicon) AND packag*))) NOT TI=(ring-laser OR fiber-optic-gyroscope* OR optical-fiber* OR fiber-optic*)
TI=(((device* OR system* OR part OR parts OR component* OR platform* OR sensor* OR chip* OR microchip* OR transducer*) SAME (microfluidic* OR nanofluidic* OR micro-fluidic* OR nano-fluidic*)) OR ((total-analytical-system* OR total-analysis-system* OR chemical-analysis-system* OR chemical-analytical-system*) SAME (mini* OR micro* OR mu-tas OR microtas OR micro-tas)) OR lab-on-a-chip* OR labchip* OR lab-chip* OR chip-lab* OR lab-on-chip* OR (LOC SAME (microfluidic* OR nanofluidic* OR micro-fluidic* OR nano-fluidic*)))
TS=((photonic SAME MEMS OR optic* SAME MEMS OR optic* SAME NEMS OR MOEMS OR NOEMS OR microoptoelectromechanic* OR micro-opto-electro-mechanical OR micro-optoelectromechanical OR nanooptoelectromechanic* OR nano-opto-electro-mechanical OR nano-

optoelectromechanical OR optical-microsystem* OR optical-nanosystem* OR optical-micromachine* OR optical-nanomachin* OR opto-MEMS OR optoMEMS OR opto-NEMS OR optoNEMS OR optical-microelectromechanical OR opto-microelectromechanical OR optomicroelectromechanic* OR DRIE OR LIGA) AND (telecom* OR optic* SAME transmission* OR broadband OR communication* SAME optic* OR network* SAME optic* OR optic* SAME signal*))

TS=((((optic* SAME filter*) SAME tunable) OR optical-switch* OR optic-switch* OR optic* SAME crossconect* OR optic* SAME cross-connect* OR optic* SAME microswitch* OR optic* SAME micro-switch*) AND (telecom* OR optic* SAME transmission* OR broadband OR communication* SAME optic* OR network* SAME optic* OR optic* SAME signal*) AND (micromachin* OR micro-machined OR micro-machining OR nanomachin* OR nano-machined OR nano-machining OR MOEMS OR MEMS OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR nano-electro-mechanical OR microoptoelectromechanical OR micro-optoelectromechanical OR micro-opto-electromechanical OR microoptomechanic* OR micro-optomechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical OR LIGA OR DRIE OR deep-reactive-ion-etch* OR MUMPS))

TS=((optic* SAME add/drop-multiplexer* OR optic* SAME add/drop-multiplexing OR wavelength-selective-switch* OR wavelength-selective-crossconnect*) AND (micromachin* OR micro-machined OR micro-machining OR nanomachin* OR nano-machined OR nano-machining OR MOEMS OR MEMS OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR nano-electro-mechanical OR microoptoelectromechanical OR micro-optoelectromechanical OR micro-opto-electromechanical OR microoptomechanic* OR micro-optomechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical OR deep-reactive-ion-etch* OR MUMPS OR DRIE OR LIGA))

TS=((vertical-cavity-surface-emitting-laser* OR tunable-laser* OR external-cavity-diode-laser*) AND (micromachin* OR micro-machined OR micro-machining OR nanomachin* OR nano-machined OR nano-machining OR MOEMS OR MEMS OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR nano-electro-mechanical OR microoptoelectromechanical OR micro-optoelectromechanical OR micro-opto-electromechanical OR microoptomechanic* OR micro-optomechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical OR deep-reactive-ion-etch* OR DRIE OR LIGA OR MUMPS))

TS=((((optic* SAME transmitter*) SAME tunable) OR ((optic* SAME attenuator*) SAME variable)) AND (micromachin* OR micro-machined OR micro-machining OR nanomachin* OR nano-machined OR nano-machining OR MOEMS OR MEMS OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR nano-electro-mechanical OR microoptoelectromechanical OR micro-optoelectromechanical OR micro-opto-electromechanical OR microoptomechanic* OR micro-optomechanical OR micromechanical OR micro-mechanical OR nanomechanical OR nano-mechanical OR deep-reactive-ion-etch* OR MUMPS OR DRIE OR LIGA))

TS=(((micromirror* OR micro-mirror OR micro-mirrors OR nanomirror* OR nano-mirror OR nano-mirrors) AND (telecom* OR optic* SAME transmission* OR broadband OR communication* SAME optic* OR network* SAME optic* OR optic* SAME signal* OR fiber* SAME optic*)) AND (micromachin* OR micro-machined OR micro-machining OR nanomachin* OR nano-machined OR nano-machining OR MOEMS OR MEMS OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR nano-electro-mechanical OR microoptoelectromechanical OR micro-optoelectromechanical OR micro-opto-

electromechanical OR microoptomechanic* OR micro-optomechanical OR deep-reactive-ion-etching OR MUMPS OR LIGA OR DRIE)) TS=((optical SAME amplifier* OR optical SAME equalizer* OR optical SAME waveguide* OR spectral-equalizer* OR optic* SAME transform-spectrometer*) AND (telecom* OR optic* SAME transmission* OR broadband OR communication* OR network* SAME optic* OR optic* SAME signal* OR fiber* SAME optic*) AND (micromachin* OR micro-machined OR micro-machining OR nanomachin* OR nano-machined OR nano-machining OR MOEMS OR MEMS OR micro-electromechanical OR microelectromechanical OR micro-electro-mechanical OR nanoelectromechanical OR nano-electromechanical OR nano-electro-mechanical OR microoptoelectromechanical OR micro-optoelectromechanical OR micro-opto-electromechanical OR microoptomechanic* OR micro-optomechanical OR deep-reactive-ion-etching OR MUMPS OR LIGA OR DRIE))
TS=((((harvesting OR scavenging OR harvester* OR scavenger*) SAME (energy OR power)) AND (MEMS OR NEMS OR micromachine* OR micromachining OR micro-machin* OR micromechanical OR micro-mechanical OR micromachining OR micro-machining OR nanomachined OR nano-machined OR nanomachining OR nano-machining OR microfabricated OR micro-fabricated OR microfabrication OR micro-fabrication OR microelectromechanic* OR nanoelectromechanic* OR micro-electro-mechanical OR nano-electro-mechanical OR microsystem* OR micro-system* OR LIGA OR microtech* OR nanotech* OR micro-tech* OR nano-tech* OR DRIE OR deep-reactive-ion-etch* OR MUMPS OR LIGA))) NOT TS=(radical-scavenging) TS=((micro-turbo-pump* OR microturbine* OR micro-turbine* OR micro-gas-turbine* OR microthruster* OR micro-thruster* OR micro-propulsion OR miniature-propulsion OR micro-energy-converter* OR micro-power-converter* OR micro-energy-generator* OR micro-power-generator* OR micro-energy-storage OR micro-power-source* OR micro-cooler*) AND (MEMS OR NEMS OR micromachine* OR micromachining OR micro-machin* OR micromechanical OR micro-mechanical OR micromachining OR micro-machining OR nanomachined OR nano-machined OR nanomachining OR nano-machining OR microfabricated OR micro-fabricated OR microfabrication OR micro-fabrication OR microelectromechanic* OR nanoelectromechanic* OR micro-electro-mechanical OR nano-electro-mechanical OR microsystem* OR micro-system* OR LIGA OR microtech* OR nanotech* OR micro-tech* OR nano-tech* OR DRIE OR deep-reactive-ion-etch* OR MUMPS)) TS=((micro-converter* OR micro-generator* OR micro-harvester* OR fuel-reformer*) AND (energy OR power) AND (MEMS OR NEMS OR micromachine* OR micromachining OR micro-machin* OR micromechanical OR micro-mechanical OR micromachining OR micro-machining OR nanomachined OR nano-machined OR nanomachining OR nano-machining OR microfabricated OR micro-fabricated OR microfabrication OR micro-fabrication OR microelectromechanic* OR nanoelectromechanic* OR micro-electro-mechanical OR nano-electro-mechanical OR microsystem* OR micro-system* OR LIGA OR microtech* OR nanotech* OR micro-tech* OR nano-tech* OR DRIE OR deep-reactive-ion-etch* OR MUMPS)) TS=((micropropulsion OR micro-propulsion OR micro-turbomachinery OR microturbomachinery OR microturbomachine* OR micro-turbomachin* OR microbatter* OR micro-batter* OR micro-heat-exchanger* ((microreactor* OR micro-reactor*) AND fuel*) OR micro-heat-engine*) AND (MEMS OR NEMS OR micromachine* OR micromachined OR micro-machined OR micromechanical OR micro-mechanical OR micromachining OR micro-machining OR nanomachin* OR nano-machin* OR microfabricat* OR micro-fabricat* OR microelectromechanic* OR nanoelectromechanic* OR micro-electro-mechanical OR nano-electro-mechanical OR microsystem* OR micro-system OR micro-systems OR LIGA OR micromechanical OR micro-mechanical OR microtech* OR nanotech* OR micro-tech* OR nano-tech* OR DRIE OR deep-reactive-ion-etch* OR MUMPS OR LIGA))

TS=((microfuelcell* OR micro-fuelcell* OR micro-fuel-cell OR micro-fuel-cells OR miniature-fuel-cell* OR miniature-fuelcell* OR mini-fuel-cell* OR mini-fuelcell* OR micro-thermophotovoltaic*) AND (MEMS OR NEMS OR micromachine* OR micromachined OR micro-machined OR micromachining OR micro-machining OR nanomachined OR nano-machined OR nanomachining OR nano-machining OR microfabricated OR micro-fabricated OR microfabrication OR micro-fabrication OR microelectromechanic* OR nanoelectromechanic* OR micro-electro-mechanical OR nano-electro-mechanical OR microsystem* OR micro-system OR micro-systems OR LIGA OR micro-mechanical OR micromechanical OR microtech* OR nanotech* OR micro-tech* OR nano-tech* OR DRIE OR deep-reactive-ion-etch* OR MUMPS)) TS=((micro-engine* OR micro-motor* OR micromotor* OR micro-solar-cell* OR miniature-solar-cell* OR mini-solar-cell* OR micro-photovoltaic-cell* OR miniature-photovoltaic-cell* OR mini-photovoltaic-cell* OR microcombustion OR micro-combustion OR microcombustor* OR micro-combustor*) AND (MEMS OR NEMS OR micromachine* OR micromachined OR micro-machined OR micromachining OR micro-machining OR nanomachined OR nano-machined OR nanomachining OR nano-machining OR microfabricated OR micro-fabricated OR microfabrication OR micro-fabrication OR microelectromechanic* OR nanoelectromechanic* OR micro-electro-mechanical OR nano-electro-mechanical OR microsystem* OR micro-system OR micro-systems OR LIGA OR micro-mechanical OR micromechanical OR microtech* OR nanotech* OR micro-tech* OR nano-tech* OR DRIE OR deep-reactive-ion-etch* OR MUMPS)) TS=((power-microelectromechanical OR (power-MEMS NOT low-power-MEMS) OR energy-microelectromechanical OR energy-MEMS)
TS=(((pressure-sensor* OR pressure-transducer* OR pressure-sensing) AND (micromachin* OR micro-machined OR micro-machining OR nanomachin* OR nano-machined OR nano-machining OR MEMS OR NEMS OR CMOS SAME process* OR microfabricat* OR micro-fabricated OR microsystem* OR micro-system* OR nanofabricat* OR micro-electro-mechanical OR nano-electro-mechanical OR microelectromechanic* OR nanoelectromechanic* OR micromechanical OR micro-mechanical OR micro-electromechanical OR nano-electromechanical OR IC SAME process* OR IC SAME technolog* OR LIGA OR DRIE OR microoptomechanic* OR micro-optomechanical OR MOEMS OR microoptoelectromechanical OR micro-opto-electromechanical OR micro-optoelectromechanical OR (silicon AND (packag* OR bonding)) OR (silicon-diaphragm OR silicon-diaphragms OR silicon-membrane OR silicon-membranes))) OR (silicon-pressure-sensor* OR silicon-pressure-transducer* OR (silicon AND (pressure-microsensor* OR pressure-micro-sensor* OR micro-pressure-sensor*)))) TS=((((pressure SAME sensor*) OR (pressure SAME sensing) OR (pressure SAME transducer*)) SAME (piezoresist* OR capacit* OR piezoelectr* OR optical OR quantum-tunneling)) AND (micromachin* OR micro-machined OR micro-machining OR nanomachin* OR nano-machined OR nano-machining OR MEMS OR NEMS OR CMOS SAME process* OR microfabricat* OR micro-fabricated OR microsystem* OR micro-system* OR nanofabricat* OR micro-electro-mechanical OR nano-electro-mechanical OR microelectromechanic* OR nanoelectromechanic* OR micromechanical OR micro-mechanical OR micro-electromechanical OR nano-electromechanical OR etch* OR (silicon AND (packag* OR bonding)) OR (silicon-diaphragm OR silicon-diaphragms OR silicon-membrane OR silicon-membranes))) TS=((silicon SAME (pressure-microsensor* OR pressure-micro-sensor* OR micro-pressure-sensor*)))

TS=((((inkjet* OR ink-jet*) SAME (head* OR printhead* OR printerhead* OR printinghead*)) OR (((inkjet* OR ink-jet*) SAME nozzle*) AND (print* OR direct-writ*)) OR (((inkjet* OR ink-jet*) SAME dispenser*) AND (print* OR direct-writ*)) OR (((inkjet* OR ink-jet*) SAME actuator*) AND (print* OR direct-writ*)) OR (((inkjet* OR ink-jet*) SAME chip*) AND (print* OR direct-writ*))) NOT (read/write OR R/W or magnetic near/0 head or magnetic near/0 heads or (hard-disk AND head*))) TS=((printhead* OR printerhead* OR printinghead* OR ((inkjet* OR ink-jet*) SAME nozzle*) OR ((inkjet* OR ink-jet*) SAME dispenser*) OR ((inkjet* OR ink-jet*) SAME actuator*) OR ((inkjet* OR ink-jet*) SAME chip*)) AND (MEMS OR NEMS OR micromachine* OR micromachined OR micro-machined OR micromachining OR micro-machining OR nanomachine* OR nano-machine* OR nanomachining OR nano-machining OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat* OR microelectromechanic* OR nanoelectromechanic* OR micro-electro-mechanical OR nano-electro-mechanical OR microsystem* OR micro-system* OR nanosystem* OR nano-system* OR LIGA OR DRIE OR deep-reactive-ion-etch* OR micro-mechanical OR micromechanical OR nanomechanical OR nano-mechanical OR microtech* OR nanotech* OR micro-tech* OR nano-tech*))
TS=((carbon) SAME (nanowire* OR nanotube* OR nanobelt* OR nanorod* OR nanoribbon* OR nano-wire* OR nano-belt* OR nano-rod* OR nano-tube* OR nano-ribbon*) SAME (sensor* OR sensing OR biosensor* OR nanosensor* OR nanosensing OR biosensing OR actuator* OR nanoactuator* OR resonator* OR nanoresonator* OR nanooscillator* OR transducer* OR nanotransducer* OR nanodetect* OR nanorelay* OR nanoswitch* OR NEMS OR nanoelectromechanical OR nano-electromechanical OR electromechanical OR nanodevice* OR nano-device*))
TS=((ZnO OR zinc-oxide*) SAME (nanowire* OR nanotube* OR nanobelt* OR nanorod* OR nanoribbon* OR nano-wire* OR nano-belt* OR nano-rod* OR nano-tube* OR nano-ribbon*) SAME (sensor* OR sensing OR biosensor* OR nanosensor* OR nanosensing OR biosensing OR actuator* OR nanoactuator* OR nanoactuating OR detector* OR nanodetector* OR nanodetecting OR nanogenerator* OR harvest* OR nanoharvest* OR scaveng* OR nanoscanveng* OR nanoswitch* OR nanorelay* OR resonator* OR nanoresonator* OR nanooscillator* OR nanoswitch* OR transducer OR transducers OR nanotransduc* OR NEMS OR nanoelectromechanical OR nano-electromechanical OR electromechanical OR nanodevice* OR nano-device*))

Appendix 2

TI=((nanowire* OR nanobelt* OR nanorod* OR nano-wire* OR nano-belt* OR nano-rod* OR nanotube* OR nano-tube*) SAME (ZnO OR zinc-oxide*))

Appendix 3

TI=((ultraviolet OR x-ray OR projection OR interferometric OR maskless OR beam OR interference OR immersion OR phase-shift* OR e-beam OR laser-scanning) NEAR/3 (photolithograph* OR lithograph* OR microlithograph* OR nanolithograph* OR nanopatterning OR nanowriting)) TI=(((direct* OR proton OR atom* OR laser OR ion OR electron) NEAR/3 beam) NEAR/3 (photolithograph* OR lithograph* OR microlithograph* OR nanolithograph* OR nanopatterning OR nanowriting)) TI=(((wet OR dry OR isotropic OR anisotropic OR ion-beam OR plasma OR magnetron-ion OR DRIE OR RIE OR deep-reactive OR reactive OR “high aspect ratio”) NEAR/3 etching) OR ((focused-ion-beam OR FIB) NEAR/3 (machin* OR micromachin* OR nanomachin*)) OR ion-milling)
TI=(((bulk OR surface OR silicon) NEAR/3 (micromachin* OR nanomachin* OR micro-machin* OR nano-machin* OR microfabricat* OR micro-fabricat* OR nanofabricat* OR nano-fabricat*)) OR (LIGA AND (micro* OR nano*)) OR EFAB OR HARPSS OR HEXSIL OR HARMST OR (MEMS AND MUMPS) OR ((multi-user) AND MUMPS) OR (MEMS AND SUMMIT)) TI=((anodic OR fusion OR epoxy OR solder OR thermal-compression OR thermo-compression OR thermocompression OR reactive OR eutectic OR direct OR flip-chip) NEAR/3 bonding) TI=(system-on-chip* OR system-in-package* OR (3D NEAR/2 packaging) OR three-dimensional NEAR/2 integrated-packaging OR (3D NEAR/2 stacking) OR monolithic-integration)
TI=((dip-pen OR DPN OR atom-force-microscop* OR AFM OR scanning-probe-microscop* OR SPM OR scanning-tunneling-microscop* OR STM OR scanning-near-field-microscop* OR SNP OR near-field-scanning-microscop* OR NSOM OR scanning-near-field-microscop* OR SNOM OR scanning-electrochemical-microscop* OR SECM OR magnetic-force-microscop* OR MFM OR nanosphere* OR nano-sphere* OR 2-photon OR two-photon OR colloidal OR block-copolymer* OR diblock-copolymer* OR nanocasting OR inkjet OR ink-jet) NEAR/3 (lithograph* OR nanolithograph* OR nano-lithograph* OR direct-writ* OR nano-patterning)) TI=(magnetolithograph* OR nanostereolithograph* OR nanoskiving OR nanoshaving OR nano-shaving OR nanografting OR nano-grafting OR molecular-ruler* OR on-wire lithograph* OR edge-lithograph* OR chemical-lithograph*)
TI=((deposit* OR synthesis) NEAR/5 (thin-film OR thin-films OR multilayer OR multilayers OR multi-layer OR multi-layers OR epilayer OR epilayers OR epi-layer OR epi-layers OR monolayer OR monolayers OR mono-layer OR mono-layers)) TI=((molecular-beam-epitaxy OR sputtering OR spin-coating OR laser-ablation) NEAR/5 (thin-film OR thin-films OR multilayer OR multilayers OR multi-layer OR multi-layers OR epilayer OR epilayers OR epi-layer OR epi-layers)) TI=(sol-gel NEAR/5 (via OR prepar* OR grow*) NEAR/5 (thin-film OR thin-films OR multilayer OR multilayers OR multi-layer OR multi-layers OR epilayer OR epilayers OR epi-layer OR epi-layers))
TI=((self-assembly OR selfassembly OR self-assembling OR selfassembling OR ((direct* OR guid* OR templat*) NEAR/3 (assembly OR assembling)) OR layer-by-layer) AND (monolayer* OR mono-layer* OR film* OR quantum* OR multilayer* OR multi-layer* OR array* OR molecul* OR polymer* OR co-polymer* OR copolymer* OR mater* OR biolog* OR supramolecul* OR nano* OR colloid* OR micelle* OR DNA OR protein*)) TI=(DNA origami) TI=((biofunctionalization OR biofunctionalisation OR functionalization OR functionalisation) AND (nano*)) TI=((atomic-force OR AFM OR scanning-probe OR SPM OR scanning-tunneling OR STM OR

scanning-near-field OR scanning-nearfield OR SNP OR near-field scanning-optical OR NSOM) AND (manipulat*)) TI=(((((laser OR magnetic OR nano OR optical) NEAR/3 tweezer*) OR optical-trap*) AND (monolayer* OR mono-layer* OR film* OR quantum* OR multilayer* OR multi-layer* OR array* OR molecul* OR polymer* OR co-polymer* OR copolymer* OR mater* OR bio* OR supramolecul* OR nano* OR micro* OR colloid* OR micelle* OR DNA OR protein*)) OR nanomanipulat* OR nano-manipulat* OR micromanipulat* OR micro-manipulat* OR nanopositioning OR nano-positioning)
TI=(nanopolish* OR nano-polish* OR nanolapp* OR nano-lapp* OR nanogrind* OR nano-grind* OR nanoturning OR nano-turning OR nanocutting OR nano-cutting OR nanodrilling OR nano-drilling OR ((ultraprecis* OR ultra-precis* OR precis*) NEAR/5 (grinding OR turning OR milling OR drilling OR lapping OR polishing OR cutting OR machining)) OR diamond-turning OR diamond-grinding OR diamond-machining OR (ELID AND grind*)) TI=(microgrinding OR microcutting OR microdrilling OR micromilling OR micropolishing OR microlapping OR microEDM OR microelectrodischarge-machin* OR microelectricdischarge-machin* OR microstereolithograph* OR microforming OR microECM OR microelectrochemical-machin* OR microturning OR fused-deposition-model* OR 3D-lithograph* OR 3D-microlithograph* OR ((laser OR electrodischarge) NEAR/1 (micromachin* OR nanomachin* OR nanofabricat* OR microfabricat* OR micro-machin* OR nano-machin* OR nano-fabricat* OR micro-fabricat*))) TI=(micro-grinding OR micro-cutting OR micro-drilling OR micro-milling OR micro-lapping OR micro-polishing OR micro-EDM OR micro-electrodischarge-machin* OR micro-electro-discharge-machin* OR micro-electricdischarge-machin* OR micro-electric-discharge-machin* OR micro-stereolithograph* OR micro-forming OR micro-ECM OR micro-electrochemical-machin* OR micro-electro-chemical-machin* OR micro-turning OR fused-deposition-model* OR 3D-lithograph* OR 3D-microlithograph* OR ((laser OR electrodischarge) NEAR/1 (micromachin* OR nanomachin* OR nanofabricat* OR microfabricat* OR micro-machin* OR nano-machin* OR nano-fabricat* OR micro-fabricat*)))
TI=((soft OR nanoimprint* OR nano-imprint* OR imprint* OR decal-transfer* OR (edge NEAR/2 (transfer OR spread*)) OR capillary-force OR nanostencil OR nano-stencil OR replica-mold* OR (micromold* NEAR/2 in-capillarit*) OR (solvent-assisted NEAR/2 micromold*) OR ((microtransfer OR micro-transfer) NEAR/2 mold*)) NEAR/3 (photolithogtaph* OR lithograph* OR nanolithography* OR patterning OR nanopatterning)) TI=(((microcontact OR micro-contact OR nanocontact OR nano-contact OR nanotransfer OR nano-transfer) NEAR/3 print*) OR ((hot OR nano) NEAR/3 emboss*) OR nanoemboss* OR micro-stamp* OR microstamp* OR (roll-to-roll)) TI= (((micro OR nano) NEAR/3 (injection-mold*)) OR microcast* OR micro-cast* OR ((nanocasting OR nano-casting) NOT (mesopor* OR meso-por*)) OR nanomold* OR nano-mold* OR transfer-print* OR nanotransfer-print* OR ((microdisplacement OR (micro-displacement)) NEAR/2 print*) OR micromolding OR micro-molding OR replica-molding)
TI=(((scanning-probe-microscop* OR (SPM AND microscop*) OR atomic-force-microscop* OR (AFM AND microscop*) OR scanning-electron-microscop* OR (SEM AND microscop*) OR transmission-electron-microscop* OR (TEM AND microscop*) OR x-ray-photoelectron-spectroscop* OR (XPS AND spectroscop*) OR scanning-auger-electron-spectroscop* OR (AES AND spectroscop*) OR secondary-ion-mass-spectroscop* OR (SIMS AND spectroscop*) OR energy-dispersive-x-ray OR (EDX NEAR/2 analysis) OR electron-energy-loss-spectroscop* OR (EELS AND spectroscop*) OR fourier-transport-infrared-spectroscop* OR (FTIS AND spectroscop*) OR nano-indentat* OR nanoindentat* OR picoindentat* OR pico-indentat* OR nano-tribolog* OR nanotribolog* OR dynamic-light-scatter* OR (DLS AND scatter*)) AND (monolayer* OR mono-layer* OR film* OR quantum* OR multilayer* OR multi-layer* OR co-polymer* OR copolymer* OR supramolecul* OR supra-molecul* OR nano* OR colloid* OR micelle* OR DNA OR protein*)) NOT (manipulat* OR nanomanipulat* OR lithograph* OR

nanolithograph* OR nano-lithograph* OR direct-writ* OR nano-patterning)) TI=(((small-angle-x-ray-scatter* OR SAXS OR SRSAXS OR photon-correlation-spectroscop* OR (PCS AND spectroscop*) OR scanning-mobility-particle-sizer* OR (SMPS AND sizer*) OR scanning-ion-conductance-microscop* OR tip-enhanced-raman-spectroscop* OR (TERS AND spectroscop*) OR total-internal-reflection-fluorescence-microscop* OR scanning-near-field-microscop* OR confocal-fluorescence-microscop* OR coupled-plasma-atomic-emission-microscop* OR X-ray-fluorescence-spectroscop* OR TXRF OR ultraviolet-photoelectron-spectroscop* OR (UPS AND spectroscop*) OR x-ray-photoelectron-spectroscop* OR (XPS AND spectroscop*) OR fourier-transform-infrared-spectroscop* OR nanoscratching OR nano-scratching) AND (monolayer* OR mono-layer* OR film* OR quantum* OR multilayer* OR multi-layer* OR co-polymer* OR copolymer* OR supramolecul* OR supra-molecul* OR nano* OR colloid* OR micelle* OR DNA OR protein*)) NOT (manipulat* OR nanomanipulat* OR lithograph* OR nanolithograph* OR nano-lithograph* OR direct-writ* OR nano-patterning))
TI=(((molecular-dynamic* OR monte-carlo) AND simulation) OR ((FEM OR FEA OR finite-element) NEAR/3 (analys* OR model* OR simulation OR method* OR approach* OR stud*)) OR quantum-chemical-calculation OR molecular-mechanics OR ab-initio-quantum-mechanic* OR time-dependent-density-functional OR spin-dependent-density-functional OR atomistic-simulation OR atomistic-modeling OR (computational NEAR/3 fluid-dynamic*) OR multi-scale-model*) AND (monolayer* OR mono-layer* OR thin-film* OR multilayer* OR multi-layer* OR epilayer* OR epi-layer* OR co-polymer* OR copolymer* OR supramolecul* OR molecule* OR nano* OR colloid* OR micelle* OR quantum-dot* OR quantum-wire* OR graphene OR fullerene))

Appendix 4

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ttl/(microfluidic$ or nanofluidic$ or lab-chip or lab-chips) and spec/(point-of-care or "point of care")
abst/(microfluidic$ or  nanofluidic$  or lab-chip or lab-chips) and spec/(point-of-care or "point of care")
aclm/(microfluidic$ or  nanofluidic$  or lab-chip or lab-chips) and spec/(point-of-care or "point of care")
spec/(microfluidic$ or  nanofluidic$  or lab-chip or lab-chips) and (point-of-care or "point of care")
ttl/("lab chip" or "lab chips" or lab-on-a-chip or labs-on-a-chip or "lab on a chip" or "labs on a chip" or fluidic$) and spec/(point-of-care or "point of care")
abst/("lab chip" or "lab chips" or lab-on-a-chip or labs-on-a-chip or "lab on a chip" or "labs on a chip" or fluidic$) and spec/(point-of-care or "point of care")
aclm/("lab chip" or "lab chips" or lab-on-a-chip or labs-on-a-chip or "lab on a chip" or "labs on a chip" or fluidic$) and spec/(point-of-care or "point of care")
spec/(("lab chip" or "lab chips" or lab-on-a-chip or labs-on-a-chip or "lab on a chip" or "labs on a chip" or fluidic$) and (point-of-care or "point of care"))
ttl/(point-of-care or "point of care") or abst/(point-of-care or "point of care") or aclm/(point-of-care or "point of care")
ttl/(microfluidic$ or nanofluidic$ or lab-chip or lab-chips) and spec/diagnostic$
abst/(microfluidic$ or nanofluidic$ or lab-chip or lab-chips) and spec/diagnostic$
aclm/(microfluidic$ or nanofluidic$ or lab-chip or lab-chips) and spec/diagnostic$
ttl/("lab chip" or "lab chips" or lab-on-a-chip or labs-on-a-chip or "lab on a chip" or "labs on a chip" or fluidic$) and spec/(diagnostic$)
abst/("lab chip" or "lab chips" or lab-on-a-chip or labs-on-a-chip or "lab on a chip" or "labs on a chip" or fluidic$) and spec/(diagnostic$)
aclm/("lab chip" or "lab chips" or lab-on-a-chip or labs-on-a-chip or "lab on a chip" or "labs on a chip") and spec/(diagnostic$)
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