European Journal of Scientific Research
ISSN 1450-216X Vol.68 No.4 (2012), pp. 616-635

http://www.europeanjournalofscientificresearch.com

Methods of Assessing the Evolution of Science: A Review

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Abstract

Interest in the characterization and evolution of science has sparked a vast amount of literature. The manner in which this field of knowledge is depicted is highly diversified, giving rise to different styles of reporting the history of science. Notwithstanding the relevance of the subject for a broader understanding of how knowledge is produced, certified and appropriated, a simple and informative framework is missing. Proposing a simple categorization of the methods for assessing the evolution of science, our study highlights the changing process of scientific traditions, portraying the evolution of science as shifting towards hybrid and quantitative methodologies, namely those based on bibliometric techniques, as they arguably rely less on the judgments and perceptions of researchers, and have a higher degree of certainty.

Keywords: Science of science; research methodology; bibliometrics

1. Introduction

The assessment of the roots and influence of a scientific field of research has gained greater relevance over the last few years. Indeed, interest in this matter pervades a variety of fields of thought (e.g., sociology, Merton, 1979; philosophy, Popper, 1979; economics, Buchanan and Vanberg, 1995; psychology, Klahr, 2002; Du and Teixeira, 2011; entrepreneurship, Teixeira, 2011).

The study of the structuring of scientific domains and of scientific activity is open to a variety of conceptualizations, methodologies and interpretations (Börner et al., 2003). This diversity has contributed to both a wealth of research in different branches of science and the complexity in which this topic is shrouded. Indeed, researchers have explored how science has been evolving and taking shape in very different ways (Leydesdorff, 2001; Lucio-Arias and Leydesdorff, 2007).

The evolution of science stimulates reflections on intellectual history and is a never-ending field of research as there are many perspectives through which it is possible to grasp some measure of its dynamics.

Several studies which deal with the methodology of the sciences barely serve the purpose of envisaging the different forms that shape much of the scientific literature and the way in which its content is structured in order to portray the evolution of scientific fields (Börner and Scharnhorst, 2009). Moreover, the different characteristics of disciplinary discourses and different practices of science emerging in the socio-cognitive space are worth taking account of, namely those related to historiographic approaches (Kragh, 1989).

The present paper intends to shed light on the matter and provide a categorization of the main conceptions in literature, which aim to depict the evolution of science. To do so, it sets aside the detailed portrayal of the different research strategies, and grasps the hermeneutics of the literature on the evolution of science, in order to find patterns in the discursive nature of historical writings, and in the figures of speech by which historians of science seek to portray this evolution. The gathering of evidence for this exercise was complex due to the wide variety of existing conceptualizations in this area, even when dismissing philosophical underpinnings and the debate on similarities and differences in ontology, epistemology and methodology.

The next section provides a review of the literature on the assessment and measurement of the evolution of scientific fields in a coherent framework, detailing first the qualitative approaches (Section 2.1), the quantitative approaches (Section 2.2), and finally the hybrid approaches (Section 2.3). In the Conclusion (Section 3), we summarize the main points and paths for research in this domain.

2. Portraying the Evolution of a Scientific Area: a Proposal of Categorization

Many authors have focused on how the growth of science should be assessed, whether on the basis of more traditional, qualitative approaches, without models (e.g., Merton, 1979; Popper, 1979; Kuhn, 1996; Van Fraassen 1996; Mulkay et al., 1975; Gilbert, 1978; Van Raan, 2000), more quantitative approaches using scientometric models (e.g., Price, 1965) namely resorting to mathematical models (e.g., Scharnhorst, 2001), or both (hybrid approaches).

2.1. Qualitative-Based Approaches

Qualitative-based approaches stand in contrast to the quantitative scientific view where the researchers distance themselves from the subject matter in order to maintain objectivity. From an extensive and in-depth survey of the relevant literature, we portray the evolution of scientific knowledge understood as the writing of concepts, into five different yet not mutually exclusive categories (cf. Table 1): 1) biographical histories; 2) historical accounts; 3) field studies; 4) historical views of concepts within a discipline; and 5) challenging histories.

Some authors have organized the diversity of forms of qualitative research in fairly distinct ways but without specifying the approaches used to portray the evolution of science. For instance, Creswell (1998) identified five “traditions” in qualitative research – biography, phenomenology, grounded theory, ethnography and case study. A different approach by Mayr (1982) clearly classified five modes of depicting the evolution of science (referring to biology in particular) as lexicographic histories, chronological histories, biographical histories, cultural and sociological histories and problematic histories.

We also found that different disciplines have developed different procedures and strategies to depict the evolution of science. Another dimension has to do with the purpose of the inquiry these histories portray, whether it be descriptive, exploratory, explanatory (Yin, 2009) or interpretative (so far, another kind of explanation, as Neuman (2003) has shown). Besides, there is no standard format for reporting research; many forms of writing assume narrative types which in turn may have interrelated dimensions, such as the ontological, public, conceptual and meta-narratives (Somers, 1994). The definition of narrative itself is also highly problematic (Gabriel, 2008), involving temporal chains of interrelated events and requiring sequencing. It holds that, for example, we may have a chronological narrative which matches any of Mayr’s typifications and not only chronological histories. Finally, most of the histories of science combine aspects from different methodologies, making it difficult to clearly conceptualize the different categories to reveal the evolution of science.

Table 1: Evolution of science: summary of qualitative approaches

Methods	Main characteristics, strategy and scientific attitude	Studies
Biographical histories	They show the progress or the changing paradigm through the work and/or life of relevant scientists	Cummins (1978); Mayumi and Gowdi (1999)
Historical accounts	Descriptive approaches which are often conducted only at a cognitive level with discursive methods to develop the history of the roots of a discipline	Peci and Vieira (2009); Benjamin (2007); Faber et al.(1995); Christensen (1989, 2001)
Field studies	Qualitative studies based on different methodologies, namely historical case studies, experimentation, field observations, or interviewing researchers from that field of research	Hopwood (1987); Irwin (2000); Jensen (2005); Røpke (2004; 2005)
Historical views of concepts within a discipline	Deeper understanding of disciplinary knowledge by analyzing key concepts historically	Saracevic (1975); Khondker (2004); Archambault and Larivière (2009); Hjørland (2010); Becker (2003) Hubaceka and van den Bergh, 2006 Gómez-Baggethun, (2010)
Challenging histories	Development of new theories based on a better understanding of the fundamental interconnectedness between concepts and systems. It is an opening to a new and unattainable way of thinking about a certain issue up to that time	Mayr (1982); Chen (2003; 2005); Kuhn (1996); Costanza et al. (1997)

Biographical Histories

Understood here as scientific biographies, biographical histories show the progress or the changing paradigm through the work and life of relevant scientists (Kragh, 1989; Denzin, 1989), comprising a recurrent approach to deliver science content. The discourse aims to portray life paths while placing more emphasis on the scientist's contributions. For Denzin (1989), gathering and interpreting qualitative data on humans is essentially subjective; thus, developing knowledge in a particular field based on biographies is necessarily shaped by the perceptions of the researcher when interpreting data in accordance with their own legacy of meanings. Consequently, the biography may distort events, conflate findings, and misinterpret controversies; but this strategy represents different facets of the scientists' lives and scientific research, besides being a way of clarifying the purposes of scientific work, around which a good understanding of science can be organized (Edge, 1979). Although sharing some affinities with case studies (Nilsen and Brannen, 2010), we identified biographies as an autonomous and valuable source of insight to understand the background and evolution of science and an alternative perspective to portray the development of scientific progress within a discipline. They further highlight the nature of scientific work and the processes of science, focusing on the formative experiences that shaped the scientists' lives.

The Intellectual Legacies in Modern Economics edited by Steven G. Medema (an Elgar Reference Collection) and the study of Mayumi and Gowdi (1999) on the work and contribution of Nicholas Gerogescu-Roegen to economics are both representative of such an approach. Another example is Joseph Charles Arthur's contribution to a broader understanding of phanerogamic plants, plant diseases, their control and life cycles, as well as the systematics of the rust fungi as highlighted by Cummins (1978).

This approach draws on ways of conducting research that are also applied in other qualitative research, such as analysis of archive documents, personal documentary sources, and life history interviews (Denzin, 1989). The biography strategy also entails different methods, even quantitative or mixed methods (Nilsen and Brannen, 2010), although Creswell (1998) includes these biographical histories under qualitative research (together with phenomenology, grounded theory, ethnography and case study research types).

Historical Accounts

Historical accounts generally involve descriptive, exploratory or explanatory approaches, which are often conducted only at a cognitive level with discursive methods to develop the history of the roots of a discipline. Sometimes this is integrated in a chronological history – in the field of ecological economics, the studies of Christensen (1989, 2001) and Cleveland (1999) stand as paradigmatic examples. There are also several studies from other scientific fields on the boundary work developed within the sociology of science, using this conceptual framework to analyze the formation of the field – for instance, the historical perspective of genetics in the USA, from the late 19th to early 20th century by Peci and Vieira (2009); the book by Benjamin (2007) discussing both the science and the practice of psychology, which provides an historical and disciplinary context for this field; or the research of Kevles (1995) about the coming of age of physics and the institutional history of science in America.

These historical accounts may be undertaken through different strategies, namely historical-comparative research, attending to the similarities and differences between one's current study and other studies in the field (Neuman, 2003). This is sensitive to historical and cultural contexts, being appropriate when addressing important societal questions, the development of relevant social changes (which also applies to the history of disciplines), when reinterpreting data or challenging previous explanations. According to Neuman (2003), this method, which may employ quantitative data to supplement qualitative data and analysis, contributes to reinforcing conceptualization and theory building. In this framework, what the researcher is doing is coming closer to the past, to different cultural contexts, in order to better understand the fundamental questions of the phenomena under analysis, which generally leads to the definition of new subjects, new concepts and new perspectives in historical studies. In this perspective, science is seen as embedded in and dependent on its supporting social context, but detached in its practices from the influence of that context. All these historical accounts of science normally support established beliefs and are not provocative; moreover, some of them validate the internalism-externalism debate in the history of science (Shapin, 1992).

Field studies

Field studies are a style of writing that prioritizes and relies on close and intensive observation in the gathering of information and insights; potentially, it may well apply to any of the other research methods.

These studies imply reading, watching and hearing selectively, capturing in the field the development of the discipline or at least a particular project or matter within the field. It grounds and contextualizes the activities that the researcher observes and can take different configurations which may overlap, namely: 1) historical case studies such as research into particular events, achievements or developments (e.g., Irwin, 2000, with his historical perspective of the teaching and learning of science, and Ohly (2002), who developed a case study on the history of molecular genetics); 2) experimenting, which consists of conducting experiments under controlled conditions (e.g., Jensen, 2005), although the concept of experiment is tackled differently across the diverse disciplines; 3) field observation (e.g., Latour and Woolgar, 1986); or 4) interviewing scientists from that field of research, to provide information subsequently transformed into useful knowledge for scientific processing. The work of Røpke (2005), drawing on discourse analysis and the voices of professional insiders, illustrates the latter (interviewing): based on interviews with experts on ecological economics, the author has put forward an early history of modern ecological economics and trends in the development of ecological economics (from the late 1980s to the early 2000s). The analysis is thus enriched by hindsight interviews with the scientists.

The observation of research in progress, such as lab meetings and notes, presentations or paper drafts, may comprise the most direct way of studying the evolution of science (Latour and Woolgar, 1986), since they can significantly inform on the development of a scientific field. Observational data represent firsthand contact with the phenomenon of interest, rather than a secondhand version obtained in an interview. However, this is time-consuming, besides requiring permission and trust from the scientists, to enable the observer to analyze the ongoing research, as he/she investigates the researcher within his/her real-life context. From yet another perspective, Fujigaki (1998) believed that, with regard to field observation, the focus would be better placed on publications, since laboratory discussions are not based on the scientist's finished work, subject to scrutiny, and cannot therefore provide a concrete description of their findings. Furthermore, the observer would generally have to know much of the field to determine the main aspects, problems and solutions to be developed (Neuman, 2003). The studies by Dunbar and Baker (1994) and Dunbar and Blanchette (2001) illustrate this approach (field observation) in what concerns the study of science in action.

Historical Views of Concepts within a Discipline

The historical views of concepts within a discipline rely on existing historical documents, which are broad and diverse in nature as a source of research information, but keen attention is paid to a relevant concept or key idea within a discipline, or even crossing its scientific boundaries. The account focuses selectively on a relevant subject of the scientific domain which is extensively analyzed, highlighting its historical development and its contribution to the discipline's progress, adding depth and richness to it. This conception has generated a large amount of literature enabling us to understand conceptual change and progress (e.g., Stigler, 1992; Hjørland, 2010).

As our understanding of the world is mediated by concepts and by means of tracing the roots of concepts, scientists can bring new insights and enhance understanding about that field of study. How scientific concepts evolve and can be used and expanded to answer fundamental questions within a discipline, how they can be tackled to theorize the world, their effectiveness in that context, are topics of research brought into play to develop new knowledge within a scientific field. Different methodologies are feasible to analyze qualitatively the evolution of concepts, whether they are field analysis, case studies or historical narratives, among others.

Challenging histories

Challenging histories draw their meaning from Mayr's (1982) significance of problematic histories, but may well go beyond them, as they include the development of new theories or concepts in the historical account, based on a better understanding of the fundamental interconnectedness between concepts and systems (e.g., Costanza et al., 1997). The theoretical approach is built from new theories and methods focused on solving problems of contradiction, misunderstanding, and/or misrecognition of previous theoretical approaches, apart from contesting previous interpretations of phenomena, in epistemological and/or methodological terms. Histories of a discipline in this context may be provocative and written in such a way as to justify revolutions – e.g., a change in paradigm – in the field or at least the emergence of a specialty within a field (Lepenies and Weingart, 1983).

2.2. Quantitative-Based Approaches

Studies grounded in quantitative approaches, where representativeness and reliability are important issues when interpreting the data, reflect the philosophy of positivism, closer to the perspective of the natural scientist. Indeed, the adoption of these methods makes implicit assumptions about the nature of science (Edge, 1979). Researchers continue to place strong emphasis on these approaches as they enable a better understanding of phenomena and inferences about broader contexts beyond those being studied can be drawn (Neuman, 2003; Denzin, 2009). Quantitative research is objective, with a higher degree of certainty, beyond the subjectivity inherent to qualitative studies in the social sciences, as it is beaconed by quantitative data, although reflecting somehow the perceptions of authors.

A critical issue in the quantitative study of science is measurement, namely, what to measure and how to measure the phenomena under study (Thackray 1977; Geisler, 2000). This question is challenging, as science may be viewed from more than one approach. Godin (2007:692) analyzes the emergence of statistics on science and arguments that the measurement of science came into sight due to the interest in "great men, heredity and eugenics" and that the statistics were concerned with measuring the size of the scientific community and their contribution to civilization.

There is no straightforward path of analysis and what is measured depends on what is looked at (Thackray 1977) and how it is tackled, since scientific disciplines shape the perception of the object under study. Such an endeavor involves critical aspects in the social sciences – such as choosing the most appropriate measurement instruments, developing conceptual constructs and modeling – given that the phenomena are more often than not unquantifiable, complex and dynamic. Moreover, researchers have to be especially careful with sampling in order to avoid bias. This applies to studies on the evolution of science where it becomes crucial to grasp a variety of happenings and to sort out the particular occurrences that are worthy of measurement and from there, through conceptual constructs, describe and capture the critical aspects of that evolution. It is generally accepted that publications, patents and citations accomplish these aims, even though their limitations, represent a valuable source of information for building R&D indicators, for mapping scientific fields and for assessing the performance of researchers (Geisler, 2000; Verbeek et al., 2002; Moed, 2005; De Bellis, 2009).

The results of scientific research reported in written form, such as articles, monographs, books, and proceedings from conferences, in short, bibliographic outcomes, are increasingly used to measure innovative activity and are the most successful method of knowledge transfer (Geisler, 2000), apart from performing particular functions in the research process (Garfield, 1970). Citation patterns are useful heuristic tools for the historian and provide a valid and valuable way of investigating historical dependencies (Garfield et al., 1964). These citations form a visible network linking scientific documents which can be analyzed towards a better understanding of how knowledge is constructed, connected and validated (De Bellis, 2009). Moreover, they can also bring into focus anomalies in the history of scientific development (Garfield, 1970). In short, the quality of scientists' outputs can be assessed by indexing citations of this output in other scientists' publications – shaping the interacting networks of authors and publications that illustrate current knowledge in the field – while the quantity of scientific activity is measured by counting the publications in scientific journals, books and other research supports.

The growing interest in the historical and social dynamics of science in a determined pursuit of depth and detail, allied to the increasing acceptance of bibliometric data for the quantitative study of disciplinary fields, brought to light a new area of research, known as Bibliometrics.

Bibliometrics includes "all quantitative aspects and models of science communication, storage, dissemination, and retrieval of scientific information" (Glänzel and Schoepflin, 1994: 382). The terminology related with "Bibliometrics" is not consensual in the literature, since terms such as bibliometrics, informetrics, scientometrics, technometrics and librametrics are used either as perfect synonyms (Glänzel and Schoepflin, 1994) or with different and clear distinctions amongst them. Additional terms for the same research area – communication phenomena – but taking Web information as the unit of analysis, include webometrics, netometrics, cybermetrics, and it becomes a complicated task to precisely determine the boundaries between them (De Bellis, 2009).

When it comes to portraying the history of science, bibliometrics, although first and foremost ahistorical, can be combined with historical knowledge of disciplinary activities, sociological theories of group formation and communication theories in order to study the social system of scientific knowledge production and development in a more objective way. The increasing importance accorded to the matter justifies the name historical bibliometrics, that is, a "bibliometric study of periodicals and books published in the framework of time and space" (Hérubel, 1999: 382). Kragh (1989) called it 'scientometric historiography', one of the eight approaches to the historical study of sciences mentioned previously in the introduction, but both names are synonyms as they have the same endeavor in view. This kind of historiography provides philosophers and sociologists with an accurate perspective to fully examine the meanders of science.

Bibliometric methods are an instrument to measure scientific activity that rely less on the judgments and perceptions of researchers (Geisler, 2000; Verbeek et al. 2002; Moed, 2005; De Bellis, 2009). Measurement is not based on the event measured; hence there is relative objectivity, as the researcher does not intrude in the research context. It has the additional advantage of being an unobtrusive technique of measuring, since the counting of words, publications and citations is done in arrears, based on archival data. It is a "postfactum peer review in a quantitative mode" (Geisler, 2000: 155).

To put it briefly, quantitative methods for analyzing the roots, influence and autonomy of disciplines such as the bibliometrics method, bring objectivity and formalism to the analysis, reducing the level of bias inherent to alternative approaches, such as surveys of experts (Di Stefano et al., 2010). Nevertheless, some authors argue that although bibliometrics provides relevant tools for theory development, they are not substitutes for more traditional uses of sociological methods in the theory process (Denzin, 2009).

When considering the way the scientific community analyzes the evolution/characterization of science based on quantitative approaches, bibliometrics has indeed been the privileged method, which in turn makes use of a wide range of methods and statistical analysis. In a different approach to the subject, we can find – although not matching perfectly as no one-to-one category is found – biographical histories, field studies, historical views of concepts and even challenging histories depicted with quantitative and mixed methods.

The geohistorical study of the rise of modern science by means of spatial analysis put forward by Taylor et al. (2007), using as datasets biographies of famous scientists, is an illustration of biographical histories drawing on quantitative methods. Additional references of this strategy include the study of Tony Van Raan's influence and the authors who have influenced his work by Garfield et al. (2010), a nontraditional autobiography, a kind of "workgraphy" of the author's involvement in chemical information systems, amongst many other examples in the literature. In the case of field studies, quantitative studies are also worthwhile, namely in the experimental context. Computational models of concept formation, such as those produced by Hovland and Hunt (1960) and Gooding (1990), may well illustrate the theory of scientific progress by means of simulating these processes and re-performing discoveries. These models replicate the key steps (following the same path) in the cognitive process of scientists as they made significant discoveries. These models go beyond the historical accounts mentioned previously in the qualitative context although they use the same kind of information. Historical views of concepts within a discipline through the lens of bibliometrics can be found in Verbeke et al. (1998), among others.

Nevertheless, as the level of analysis in the this section focuses on the structure, dynamics and patterns of published research by means of quantitative methods, the portrayal of scientific evolution is conducted quite differently from the qualitative approaches. Thus, we find that the historiographic reports based on the bibliometrics approach do not match any of the five aforementioned categories, mainly in what concerns the rhetoric and hermeneutics of these discourses. The scientific community's structures, relations and outcomes have comprised the data source for developing these kinds of studies, i.e., scientific journals, still the main outcome of science. These, and with increasing importance, the web and other sources of information, have been mined for authorship, institutional affiliation, and intellectual influence in order to reveal the essence of scientific knowledge.

By thoroughly analyzing a wide range of bibliometric historiographic studies, we identified three main broad approaches (cf. Table 2): 1) historical approaches based on citations; 2) historical approaches based on (key)words; and 3) visualization methods.

Historical Approaches Based on (co-)Word Analysis

Co-word analysis was first proposed by Small (1973) and Small and Griffith (1974) and later, some attempts to improve the methods for co-word analysis have been proposed in the literature by other authors (e.g., Callon et al. 1983; Leydesdorff, 1997; 1998).

The most widespread technique for bibliometric text mining is co-word analysis, which involves co-word extraction, co-word classification and clustering and visual display. This technique is one of the processes included in the broad method of content analysis or lexical methods, together with

KDD (knowledge discovery in databases), DT (database tomography) and TDM (textual data mining). Co-word analysis encompasses various methods for extracting knowledge from the distribution of keywords in the full text of scientific articles.

Table 2: Evolution of science: summary of quantitative approaches ('scientometric historiography')

Methods		**Main characteristics, strategy and scientific attitude**	**Studies**
Historical approaches based on *(key)words*	Cited references or/and general **keyword**	Explaining the rationale for creating HistCite; historiographic account of a topic and its relation to understanding scientific paradigms.	Garfield et al. (2003)
	Publication analysis and **keywords**	Analyzing the characteristics of research activities, trends in publication patterns and research hotspots.	Huang and Ho (2011); Luzadis et al (2010)
Historical approaches based on *citations*	Historical accounts and **citation** networks	Using citation data for constructing historical maps. Comparing historian's account of events and the citational relationship between these events	Garfield et al. (1964)
	Historical methods and **citation** analysis	Analysis of historical research searching for significant associations between two literature sets retrieved with different methods.	Hurt (1983)
	Ranked **citation index** of the work of influent authors as an indicator of the growth of the field	Historiographic account of quantitative studies of science and the role of D.J.D. Price as "father of scientometrics" and of D. Bernal. The subsequent influence of the journal Scientometrics on the expansion of the field using HistCite software	Garfield (2009)
	The average **citations**	Analyzing the development of a scientific field; researching the autonomy of a scientific field; appraising the influence of articles in selected journals	Tempest (2008); Costanza et al. (2004); Ma and Stern (2006)
	Aggregated journal-journal **citations**	Describing a scientific field as a set of journals in order to explore its development using factor analysis methodology	Besselaar and Leydesdorff (1996)
Visualization methods	Co-citation **maps** for different slices of time	Finding ways to graphically show the evolution of historical connections in a field	Small (1973)
	Visualizations studies using citation analysis	Perceiving topical or intellectual structures of a knowledge domain, through its citation paths	Garfield et al. (2002)
	Integrative citation-based **visualization** approach	Demonstrating the potential of information visualization as a means of tracking the development of scientific debates and the shifts in paradigms.	Chen et al. (2002)
	Collective networks of discourse (using co-citation) with the themes as nodes (**visualization study**)	Identifying rapidly changing specialties (microevolutions) and testing Khun's assertion of scientific revolutions (macroevolutions)	Small (2003)
	Mapping and citation network analysis (**visualization study**)	Investigating the process of creation and transfer of knowledge through publications. Unraveling the patterns behind a set of publications representing the core of a field.	Calero-Medina and Noyons (2008)
	Journal citation patterns (**visualization study**)	Mapping the structure and evolution of chemistry research and the growth, distribution and knowledge flows between chemistry, biology, biochemistry and bioengineering	Boyack et al.(2009)

It is concerned with the content of the outputs of science, which means that the full text itself and its proxy, such as titles, abstract, and keywords, can be analyzed and measured as an alternative to citations. The principle behind the method of co-words is that scientific work may be reduced to a specific set of words that compose it and appear together (Small, 1973). Indeed, scientific texts share ideas, concepts, vocabulary, building relationships among them. The more words appear together, the more they have meaning in that scientific context. The notions of centrality and density are worthwhile as they can highlight the morphology of the network, permitting in turn a dynamic study of the scientific domain. Each theme can be matched to different actors, including researchers, industries, countries, and laboratories, all responsible for the production of knowledge, clarifying the scientific network through simplified representations of their relationships.

This methodology enables the discovery of disciplinary patterns, the emergence of subfields, the delineation of scientific domains (De Bellis, 2009), since the keywords are supposed to express scientific findings. These keywords have two main characteristics: they represent concepts and ideas the author had in mind when he/she wrote the article, and as such, they are descriptors of the field being analyzed. Furthermore, they are the key players in the process of transmitting scientific knowledge, so they co-occur in other texts which portray similar findings (Geisler, 2000).

Co-word analysis advocates argue that this methodology is more comprehensive and is based on fewer theoretical assumptions than citation analysis (Callon et al., 1983). However, Leydesdorff (1997: 418) contends that “words and co-words cannot map the development of the sciences” because language is too lively, words are not specific enough, and do have a plurality of meanings in different contexts. Moreover, among other weaknesses, this method cannot make use of the full text of articles and fails, therefore, to capture the rationale of the author (Geisler, 2000). Indeed, as Leydesdorff and Welbers (2011:14) argue: “the measurement of the dynamics of meaning is still in its infancy”. Despite its disadvantages, co-word-analysis has many advantages and supplements citation analysis, allowing for a more in-depth analysis of patterns and relations. It can better tackle the dynamics of disciplines and dynamic comparisons across disciplines, namely the sharing of concepts and methods.

The literature provides extensive research applying this methodology to portray the evolution of science (Garfield et al., 1964; Garfield et al., 2003), to analyze the characteristics of research activities and trends in publication patterns (Huang and Ho, 2011), and to describe the networks of interaction between researchers (Callon et al., 1991), amongst other purposes.

Based on co-word analysis, a number of techniques have been proposed to create maps (e.g., Braam et al., 1991) in order to better analyze the intellectual structure of a given scientific field.

Co-word analysis is considered as the technical implementation of the actor-network theory or sociology of translation, where the focus is on the power and organization regulating social interactions (De Bellis, 2009). Indeed, the network approach is a research tool built up on insights from social anthropology and methodological underpinnings from sociometry (Wellman, 1983), which aims to describe social structures in terms of networks and to interpreting the behavior of actors according to their varying positions within those social structures. In this network, the authors cooperate actively and reinforce their position based both on the relationships they uphold with other authors and their aptitude to hold strategic positions. Some relations in this network are stronger and more successful than others and they are constantly being constructed, deconstructed and rebuilt, expressing the authors’ strategy. The relations involve not only people – the authors – but also signals that refer to concepts or themes expressed by words written in scientific communication. In this framework, knowledge represents a particular type resulting from the authors’ strategies. The intellectual structure of a scientific field may be studied on the basis of the semantic networks that people build together, giving rise to invisible colleges within a research domain, thus helping to reflect the essential patterns of science (Di Stefano et al., 2010). Network science has also been used as a tool to measure the progress and evolution of a field (Verbeek et al., 2002), to visualize knowledge domains (Börner et al., 2003), and to analyze the structural influence of journals (Baumgartner and Pieters, 2003). To extract these problematic networks from the textual rhetoric is the focus of co-word analysis.

Historical Approaches Based on Citation Analyses

Much work on portraying the evolution of science applies the aforementioned process of citation analysis, in which the publications cited in the literature are analyzed by statistical methods after being sorted and classified (Tempest, 2008). Bibliometric methods are mostly based on citation and authorship analysis but they also encompass various empirical methods, such as co-citation analysis (Small, 1973), citation content analysis and citation context analysis (e.g., Small, 1982) and co-authorship analysis (Wagner and Leydesdorff, 2003), along with bibliographic coupling (Kessler, 1963).

Citation data is used in a variety of ways whether to analyze cognitive and/or social structures by co-citation analyses or to analyze some aspects of citing articles, namely subject breath, affiliation, transdisciplinary nature, as well as the context of references by citation context analysis (Moed, 2005). Citation is intended to be a social reward (De Bellis, 2009) and a conceptual symbol whose significance is conditioned to the cognitive processes entailed in the production of written discourse (Small, 1987). The identification of concepts and their relations based on citations and references is independent of language and changing terminology (Leydesdorff, 1997), which safeguards the objectivity of the research.

The use of citation analyses in the studies on the history of science is based on the structure of the scientific process where authors documenting their findings refer to previous studies on the same subject. Hence, citations reflect the genealogical connections between the author's ideas (De Bellis, 2009) and "create a new representation of science where the realist and the constructivist perspective alternate" (Wouters, 1998: 237). Citations reflect the (perceived) dependence of authors on previous work; therefore, science can be understood as a chronological sequence of occurrences or scientific developments, each one matched a specific time, author and publication. When analyzing the network that emerges from this behavior of citing, historical research may underpin the history of science, as citations link previous ideas, concepts, theories, and these connections are both internal to each scientific field and transversal to diverse areas of knowledge.

As highlighted by Garfield et al. (2003), this analysis brings to light the intellectual influence so clearly that the information in a set of scientific publications is enough to recapture the historiographic structure of the field. This method depends on the frequency distribution of citations and bibliographic references in documents. This type of analysis is applicable to scientific literature regardless of the domain, as it disregards the content of the articles to concentrate on the characteristics that emerge from the process of citation. The statistical treatment of the data in order to recognize the patterns contribute to the validity of the results of the citation analysis (Wouters, 1998). The journals are on the whole the unit of analysis that enable a better understanding of the organization of sciences at an aggregate level (Leydesdorff, 2001), as they are widely acknowledged as the major network of communication.

Apart from the basic act of citation analysis in counting of the number of citations, there are also some methodological options within the scope of citation analysis, such as citation counting (e.g., Costanza et al., 2004; Ma and Stern, 2006, in the field of Ecological Economics, Tempest, 2008, in the field of microbiology), bibliographic coupling (Kessler, 1963), author co-citation analysis (White and Griffith, 1981), and context analysis (Small, 1982).

The study of citation patterns is useful in analyzing the developments of scientific knowledge, the historical study of science and technology, information search and retrieval (Osareh, 1996), in identifying and mapping research fronts (Garfield, 1994) as well as scientific domains (Börner et al., 2003). Citation analysis has also played a key role in mapping scientific domains (Samoylenko et al., 2006) and in analyzing the social characteristics of highly cited scientists, given that such knowledge is meant to enhance the understanding of the conditions which foster highly cited work (e.g., Parker et al., 2010, in environmental science and ecology). In short, citation analysis is meaningful for the historiography of the sciences (Garfield et al., 1964; Garfield, 2004)

Finally, the study of citations patterns using factor analysis to identify groups that reveal similar choices has been developed to highlight the role of social processes and scientific communities underlying the growth of scientific knowledge (White and Griffith, 1981; Börner et al., 2003), and to describe a scientific field through an aggregated journal-journal citation analysis (Teixeira, 2011).

Visualization Approaches

Visualization studies focus on the mapping and creation of road maps for science and technology in order to envision scientific results (Geisler, 2000). These maps, portraying graphically quantitative information, allow us to understand and communicate the changing structure of science and technology and the dynamics of their boundaries.

Scientists have begun to employ an ingenious blend of symbols, colors, graphics, algorithms and interplay, altering the way we perceive and experience space and time in order to clarify the disarray that emerges from our ability to generate information.

Although the scope of visualization studies is much broader than the study of the Science and Technology (S&T) domains, as there is a whole range of issues that increasingly rely on visualization and geospatial analysis to address complex problems (Friendly, 2007), our approach here focuses on mapping history and the characterization of science. Research in knowledge domain visualization has focused on the statistical patterns of citation networks, co-authorship networks and the identification of research fronts (Samoylenko et al. 2006).

The advances in information visualization have highlighted pathways in the evolution of scientific knowledge, in short, scientific visualization. Although each mapping process is a crosscut perspective, the comparison of network maps for different time periods inform us about the dynamic aspects of scientific evolution within the disciplinary field or within some of its specialties. For instance, Boyack et al. (2005) mapped the backbone of science; Estabrooks et al. (2008) mapped the historical development of knowledge use as a field and identified the changing intellectual structure of its scientific domains; and Ponzi (2002) studied the intellectual structure and interdisciplinary breadth of knowledge management.

These maps are generally interpretations of word co-occurrence data matrices as they are believed to represent the structure and the evolution of a scientific field (Geisler, 2000), enabling researchers to explore the dominance, distribution, and interrelations of topics, since prominent semantic structures emerge from patterns of word-frequency distribution in a set of scientific publications. Visualization methods have been applied at an accelerated rate, across a wider range of disciplines and to an ever-growing variety of issues and data structures. To name a few, Chen et al. (2002) studied the movement of paradigms with integrative citation-based visualization, Small (1973) applied co-citation maps to different slices of time showing the evolution of historical connections in a field, and Small (2003) identified rapidly changing specialties and tested Khun's assertion of scientific revolutions. Boyack et al. (2009) mapped the structure and the evolution of chemistry research and the growth, distribution and knowledge flows between chemistry, biology, biochemistry and bioengineering based on journal citation patterns, while Calero-Medina and Noyons (2008), through mapping and citation network analysis, disentangled the patterns behind a set of publications representing the core of the absorptive capacity field. Small and Griffith (1974) and Garfield et al. (2002) also mapped scientific domains.

In short, visualization provides a way to perceive the elements underlying a complex structure, to find answers to questions, highlight relations, and even apprehend outcomes which would not be so readily seen otherwise (Eick, 1994).

2.3. Hybrid Approaches

By hybrid approaches we consider the merging of strategies in studying a research field which may be based on distinct quantitative approaches, distinct qualitative approaches or a mix of quantitative and qualitative approaches. This merging might improve the effectiveness of the conducted study as it offers a valuable support for further and more in-depth exploration of the scientific field.

A combination of strategies in the study of the same discipline or, as it is often referred to, the triangulated perspective (Denzin 2009), which has been extensively advocated in the literature (Neuman, 2003; Tashakkori and Teddlie, 2010; Denzin, 2009). Nevertheless, some authors (e.g., Gilbert, 1978) hold that triangulation often creates more problems than it removes when the findings of different approaches diverge.

With regard to the mixed use of quantitative and qualitative approaches, most scholars restrict their work to one of these perspectives (Leydesdorff and Wouters, 1996) but there are various studies illustrating this triangulation. In particular, we have the examples of Garfield et al.'s (1964) comparison between an historian's account of events (a book by Isaac Asimov, "The Genetic Code"), and the citational relationship between these events in relation to the discovery of the DNA code. These authors conclude that there is a high degree of coincidence between the two approaches, strengthening the historical account.

Another perspective is that put forward by Buter et al. (2006), who have combined bibliometric and concept mapping, this way improving the mapping of science fields.

Trying to close the aforementioned gap between the sociology of science and scientometrics (Leydesdorff and Wouters, 1996; Van den Besselaar, 2000), the work of Gläser and Laudel (2001) is noteworthy. These authors discussed in detail the methodological problems of integrating scientometric methods into qualitative studies. They tried to demonstrate how sociological theory and scientometric methods could be integrated and how these methods could contribute to causal sociological explanations.

There is also increased interest in combining different quantitative methods across a variety of research problems in science studies, leading to greater clarity of findings and explanations. To name a few, this strategy can be illustrated with Braam et al. (1991), who provide a wealth of information about the development of a scientific field, combining co-citation and word analyses. Noyons et al. (1999) joined mapping with evaluative bibliometric analysis, investigating in detail the performance in a research field, and Calero-Medina and Noyons (2008) merged mapping and citation network analysis to untangle the patterns behind a set of publications representing a field in science studies.

More recently, Guo et al. (2011) compared the performance of three bibliometric indicators in identifying emerging research areas. The mix of citation analysis and co-word analysis is common in the literature as it improves the performance of bibliometric methods and allows for the emergence of a structure of networking, thus providing a more consistent portrayal of the universe of knowledge (Braam et al., 1991). The effectiveness improvement in the bibliometric mapping of scientific fields is also well illustrated by Glenisson et al.'s (2005) study that combined full-text analysis and traditional bibliometric methods with the nuances of qualitative analysis. By providing an additional understanding and clearer insights on the subject, the hybrid approach seem to be a useful way of increasing both the breadth and the width of the study of scientific foundation of the disciplines of science.

3. Discussion and Conclusions

The history of science is dominated by the history of academic research but science is not only about producing knowledge but also practical, technologically-oriented activity (Etzkowitz and Leydesdorff, 1998; Leydesdorf and Meyer, 2003). It shows that we are moving from pure science (knowledge in itself, driven by its own internal logics) to strategic science (for whom, is it worthwhile?) (Irvine and Martin 1984), where the emphasis on knowledge is shifting to an emphasis on relevance, it is being converted from mode 1 to mode 2 of knowledge production (Gibbons et al. 1994; Etzkowitz and Leydesdorff, 1998; Leydesdorf and Meyer, 2003).

Since science must be fully integrated with broad societal needs, it is essential to understand the forms of producing, certifying and appropriating knowledge from a social and political perspective. If science is to play a role in society, one needs to analyze its dynamics, its scientific community, its boundaries and evolution. Grasping the historical background is important to highlight the controversies between different schools of thoughts (Mayr, 1982), as well as to trace trends and developments in scientific disciplines (Acedo et al., 2006). To this end, different criteria and procedures which define the historiographic methods or approaches have been proposed in the literature, whether they are qualitative, quantitative, or both.

Although there are many excellent studies on the matter (e.g., Mayr, 1982; Mulkay et al., 1975; Kragh, 1989; Van Fraassen 1996; Börner and Scharnhorst, 2009), these contributions have not been organized in an integrated manner, as they appear isolated and spread over different disciplines. The majority of these studies follow different paths to tackle the issue, either focusing on the evolution of theories in the different fields of knowledge, or on the paradigms that guide scientific activities, relating them to the issues they intend to portray, or even leading to different interpretations on the production and progress of scientific knowledge.

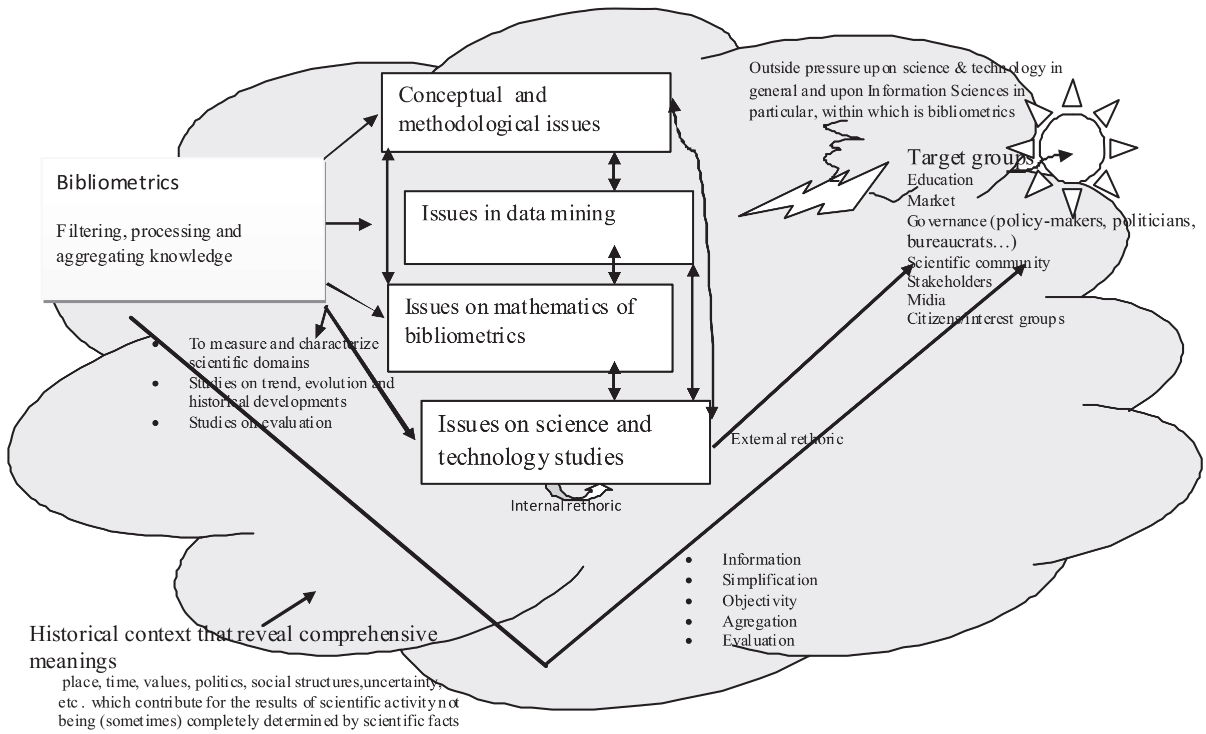
The present article intended to propose a simple taxonomy which embraces and categorizes the different approaches to the evolution of scientific domains and their characterization. A contextual analysis of the literature was conducted, so as to ascertain the specific motivations, language and discursive forms authors employ when portraying and characterizing the evolution of the different scientific fields. Our proposal categorizes the distinct contributions into three main approaches: qualitative, comprising five different conceptions: 1) biographical histories; 2) historical accounts; 3) field studies; 4) historical views of concepts within a discipline; and 5) challenging histories; quantitative, with three main broad conceptions: 1) historical approaches based on citations; 2) historical approaches based on keywords; and 3) visualization methods; and the hybrid. Each has its role in the complex process of knowledge diffusion.

Focusing of the relative strengths/weaknesses of quantitative and qualitative approaches, we might point that the use of quantitative methods when analyzing the roots, the influence and the autonomy of disciplines brings objectivity and formalism to the analysis, reducing the level of bias inherent to qualitative approaches, since the author has to place distance between him/herself and the subject matter. In the case of qualitative approaches, they tend to operate in the sphere of values, beliefs and choices, and consequently, tend to be context-dependent (Morgan, 2007). They, nevertheless, contribute to a great extent to the construction of meaning in the study of science.

Quantitative analysis is held as neutral regarding any particular theory or set of values, and thus, more trustworthy. It has, however, the disadvantage of destroying evidence from individual variations which may be relevant in the constitution of the scientific field (Edge, 1979). In contrast, qualitative analysis, although better exploring the depth, complexity and richness of phenomena by investigating the structural connections rooted in philosophical, sociological and cultural grounds, fails to make us understand the changing structure of science, the dynamics of its boundaries, the emergence of research fronts and invisible colleges. In brief, it fails to find the objective patterns of the emergence and evolution of knowledge, due to the natural difficulty in retrieving information from disorderliness, as well as having to marshal and compare a huge amount of science output data.

Bibliometric techniques, which are increasingly being use to assess and analyze science in a variety of research fields with different purposes and scopes, are squarely placed within quantitative analyses. Bibliometrics techniques are powerful enough to enable dynamic comparisons across disciplines, the mapping of scientific disciplines, the possibility of tracing long-term developments of the field, of finding expert authors in a research field and/or organizations, appraising the prestige of articles, evaluating the scientific component of knowledge creation, portraying the evolution of scientific fields, etc. (see Figure 1).

Figure 1: Relevant relations to characterize the dynamics of the scientific and societal workplace



Data from the outputs of science have been applied to appraise indices of progress in a field, the emergence of new research topics, the evolution of new disciplines (Leydesdorff, 2001), and to point out the common topical characteristics of documents and their authors. In addition, they have been used to uncover otherwise hidden knowledge structures of a discipline and its users, such as invisible colleges (e.g., Crane, 1972; Price, 1986). Indeed, scientometric studies have persistently stressed the importance of “research fronts” or “invisible colleges” for sustained growth in mature sciences. These colleges are strongly connected core groups in a specialty or discipline who do research on highly innovative and fundamental issues, and frequently lead and signal where the larger scientific field is moving (Crane, 1972).

These methods, whether mixed or independent, examine the data to find information patterns, by analyzing reference and citation patterns or/and word use frequencies, combined with statistical analysis. There are multiple contexts where citation analysis can lead to a more complete picture of disciplinary formation and evolution than traditional qualitative methods, but the literature falls short of putting forward a clear and comprehensive theory of citation (Leydesdorff, 1998), although some advances have been made in this field (Moed, 2005). Visualization (dynamic) or information design (fixed visual forms, like graphics, diagrams, etc.) help to clarify complex data or highlight relationships in this context, justifying the widespread use of these tools (one or the other, or both) in almost all bibliometric studies.

A majority of the authors/researchers are placed along the subjective-objective continuum according to their ethos, their perspectives, and their educational background, in addition to external societal and political interests. This means that once more we cannot ignore the role of context within which science is produced, where the results of scientific activity (most of the time) are not completely determined by scientific facts (Ravetz, 1990).

In portraying the history of science authors have increasingly relied in quantitative methods, such as bibliometrics. Such methods minimize – although they do not override – the role of context. This means that qualitative methods have to play the role of enhancing the historical interpretations/explanations in terms of frames of theoretical reference. Since not all disciplines work according to the same ethos and principles, the portrayal of knowledge varies according to epistemological choices, the nature of sponsors, the social modes of control and the institutional frameworks which define what is relevant and appropriate. Even in quantitative methods the discursive interplay of authors has to be constrained to this context, and the discourse has to be biased towards certain choices and values as opposed to others.

As information is conditioned to the ends and can be sized in different ways, the target audience of bibliometric studies (cf. Figure 1) – as for all sciences generally – is relevant for the overall shaping of the strategies and the mode of inquiry.

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