CARLOS III UNIVERSITY OF MADRID

ANALYSIS AND VISUALIZATION OF NETWORKS APPLIED TO THE STUDY OF SCIENTIFIC COLLABORATION IN RESEARCH GROUPS

CARLOS III UNIVERSITY OF MADRID

(ISI, Web of Science, 1990-2004)

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Ph. D. Thesis from the Department of Library and Information Science

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December 2007

How to cite this document:

Perianes-Rodríguez, A. *Analysis and Visualization of Networks Applied to the Study of Scientific Collaboration in Research Groups: Carlos III University of Madrid (ISI, Web of Science, 1990-2004)*. Carlos Olmeda-Gómez and Félix Moya-Anegón (dir.). [PhD Dissertation]. Madrid: Carlos III University, 2007. ISBN: 978-84-690-8819-7

Carlos III University of Madrid

ISBN: 978-84-690-8819-7

Nemo solus satis sapit

"No one by himself knows enough"

(*Miles Gloriosus, III, iii, 885*, Titus Maccius Plautus)

ABSTRACT

1. BACKGROUND

In recent years, spectacular advances have taken place in the scientific field of structural studies. This has made network theory an emerging area of interdisciplinary research, geared towards developing theories and techniques to increase existing knowledge of biological, technological and academic networks and, in general, of complex systems (Börner K et al., 2007). All this has been made possible through the convergence of several parallel developments. These include computerized data acquisition and manipulation, which have simplified the use of large databases and have prompted the appearance of myriad real-world network topologies, and the increase in computing power, which has facilitated the exploration of networks with millions of nodes (Albert R y Barabási AL, 2002).

These studies have their origins in such disciplines as discrete mathematics and graph theory, mathematical sociology, group psychology and biology, but also in bibliometrics, informetrics and cybermetrics, and most recently in physics. Network studies comprise multiple approaches, which focus on describing and analyzing their properties, investigating their modelling and dynamics and establishing new techniques to visualize them. Their sphere of analysis encompasses problems stemming from the existence of social, biological, information and technological networks, such as communication systems (the Internet, telephone networks), transport infrastructure (roads, railways and airlines), biological systems (protein interaction, DNA, epidemic patterns) and a wide range of social interaction structures, including collaboration networks among scientists (Donetti L y Muñoz MA, 2004).

This final area has proven to be of great interest for more than just bibliometrics, as its characteristics (publicly accessible data in the form of a social network) make it an especially attractive proposition for understanding the topology and the dynamic laws that govern complex networks (Barabási AL et al., 2002).

However, even though from a physics standpoint the findings of these studies, which focus on large networks and on establishing universalities relating to both their topology and to the dynamics that govern their evolution, might facilitate analysis and decision making in their own right, networks cannot be characterized only by their topology. Their information dynamics, or, in other words, the information flows that take place within them, must also be analyzed. In particular, the different degrees of intensity in their relationships are instrumental to improving the understanding of social systems, in the same way that traffic flows in communications or transport infrastructures are essential to fully describing these types of networks (Barrat A et al., 2004), (Matia K et al., 2005).

The properties of collaboration networks are not unique, although they do have certain features that make them special, such as the dynamics of their evolution. Data on scientific collaboration not only make it possible to visualize the network, but also to establish the time frames in which nodes and links appear in it, which is essential to revealing evolutionary dynamics.

The structure and evolution of scientific development can be captured from two different perspectives: the descriptive model, whose aim is to define the main traits of a set of usually static data, and the process model, which tries to determine temporary mechanisms and dynamics through the use of real-world networks, such as co-authorship networks (Börner K et al., 2004). This thesis studies collaboration networks, going beyond the use of tabular data to extract indicators, which serve only as a starting point for a quantitative analysis of the cooperative links between partners. As the aim is to obtain information from the regularity of relationships among a large number of actors, a more refined analysis is needed, which is only possible through graphic representations that provide an overview of these link patterns through the application of sophisticated data analysis techniques (Luukkonen T et al., 1993).

From this perspective, networking among scientists, in which the links grow out of co-authorship of one or more documents, is often more real from a social network standpoint than institutional networking. This is because the former, which constitutes the largest social network analyzed to date, truly reflects professional interaction among scientists. (Newman MEJ, 2001b), (Newman MEJ, 2001a). While similar to citation and co-citation networks, collaboration networks involve much stronger social ties. Citations imply no acquaintance among authors and may extend over time, whereas co-authorships entail a temporary relationship between colleagues that fall within the scope of social network analysis (Liu X et al., 2005).

The application of network theory to the study of scientific collaboration is based on the understanding of science as a self-organized system in which collaborators and the research site are selected by the researchers themselves rather than through institutional or national incentives or those of any other nature. There is no authority whatsoever in the world scientific community responsible for arbitrating or resolving possible disputes that may arise during the exchanges that may arise within it (Podolny JM y Page KL, 1998). Co-authorship will be discussed from the standpoint of its use in establishing communication networks, showing that this indicator is apt for analyzing cooperative flows (Wagner CS y Leydesdorff L, 2005).

In short, scientific collaboration analyzed from the perspective of network theory is a key phenomenon in research practice. Although collaboration has always been common in science, a significant change is presently underway. In traditional knowledge production, the disciplinary order is clear, the communication is formal and the work is managed through a hierarchical division of tasks (Gibbons M et al., 1997), (Gibbons M, 1997). New research practices, on the other hand, are characterized by interdisciplinarity, growing interaction among institutions and individuals, and more flexible ways of organizing scientific work (Sandström U, 1998). Therefore, in most disciplines, it is very difficult to produce scientific results individually. The chapter devoted to research groups discusses how these groups and the networks of researchers comprising them have become the main creators and producers of knowledge at the present time.

2. MOTIVATION AND JUSTIFICATION

From the perspective of Library Science and Documentation, little research has yet been conducted on scientific networking and its possible uses in ascertaining the composition of research groups, the differences in associations between specialities or departments, and the different policies that may be followed in this regard, depending on the institution or the domain analyzed. Traditionally, most studies on scientific collaboration have been geared to analyzing output, be it international or domestic, of a given scientific discipline or a research institution. Studies on smaller units such as departments or research groups are less common (Bordons M et al., 1995a), (Bordons M y Zulueta MA, 1997), (Molina JL et al., 2000), (Molina JL et al., 2002), (Zulueta MA et al., 1999), (Zulueta MA y Bordons M, 1999).

This thesis focuses on a specific facet of scientific communication networks, namely scientific co-authorship networks, based on the premise that scientific communication is the essence of research, and research is only known as such when it has been analyzed and accepted by the scientific community, which gives it the status of a social activity (Meadows AJ, 1998). The use of the term “scientific communication”, therefore, means deliberately limiting considerations on communication to a specific group of individuals (authors directly involved in the creation of original research work): those engaging in a well-defined activity and having very specific objectives (Borgman CL, 2000), (Borgman CL y Furner J, 2003).

Therefore, from the perspective of Library Science and Documentation, a need has arisen for research focusing on how co-authorship networks can represent a new information system, built on the distributed organization of knowledge stored in hundreds of thousands of documents signed by millions of authors, as an interface for accessing and retrieving information. To this end, the analysis of internal relationships and of the different topologies of these new information systems is necessary. The concept of distributed organization is particularly relevant in analyzing collaboration in this context, as there is no single factor that explains its increase in modern science. As noted above, the international scientific community has no guiding or governing authority, nor is there a clear power device that unequivocally explains this increase. Hence collaboration may be inextricably linked to local interactions among scientists (Wagner CS y Leydesdorff L, 2005).

These new information systems are based on visualization tools developed from graphic representations that maximize human understanding and communication through the choice of the appropriate encoding techniques. Although maps and scientific diagrams have been used for thousands of years, today's sophisticated processes and computer-assisted tools can explore information, providing a better understanding of data, patterns and trends, and facilitating decision making. The chapter devoted to information visualization discusses the ability of the human brain to comprehend and retain visualizations more quickly than any form of written text. This ability, together with the power of visual representations have to trigger instant recognition and the increasing need to generate and study data differing in size and nature, is what has made information visualization a key area in data representation today (Chen C y Lobo N, 2005).

The visualizations resulting from the analysis of co-authorship-based scientific collaboration, in the form of networks of individuals whose respective positions reveal their inter-relationships, would be very useful for different types of users. The latter range from the authors themselves to research or scientific policy managers, and include the citizens of a society that is becoming increasingly aware of the importance of science and technology in everyday life. These visualizations are able to describe and explain historic and/or contemporary research structures, as well as the direction of communication in the domain selected, and identify the most relevant documents in a search for specific information (Borgman CL y Furner J, 2003).

In light of the foregoing, more detail is needed about what happens at the micro level, and how that activity contributes to the formation of socio-cognitive macrostructures. Such detail would provide a better understanding of their formation, development, evolution, dynamics and implications—providing, in short, an overall idea of a complex and dynamic process (Harsanyi MA, 1993), (Bozeman B y Corley E, 2004), (Melin G, 2000), (Sandström U, 1998).

3. OBJECTIVES

The main objective of this thesis is to establish a theoretical and methodological framework with which to identify, characterize and interpret research groups using empirical analysis, through the examination and visualization of scientific networking based on co-authorship papers. The findings obtained will contribute to a better understanding of network dynamics and of how they affect network topology and the internal structure of links among such research groups, and by extension, how they affect the higher-level administrative units of which they form a part. To this end, this thesis will try to achieve four specific objectives:

a) To establish a methodology that facilitates microanalysis of the internal dynamics of research in scientific organizations, at the department and research group levels (Bordons M et al., 2004), (CINDOC, 2006), (Melin G, 2000), (Moya-Anegón F, 2006).

b) To model and characterize co-authorship networks by calculating indicators of the properties of nodes and links that describe sizes and neighbourhoods in subgraphs, as well as to obtain comprehensive measurements that statistically characterize the structure of network interconnections as a whole (Barabási AL et al., 2002), (Börner K et al., 2007), (Newman MEJ, 2004a).

c) To create specialized network-based visualizations, including diagrams of nodes and links, that can be used as interfaces to retrieve information. These interfaces provide data on the element matrices and on the values of their attributes in a clear, easily understood, explanatory and interactive way. They facilitate an understanding of the structural context represented, transmitting detailed information to the user about a variety of aspects relating to scientific collaboration and its evolution over time, such as administrative position, gender, speciality areas of research and the internal and external association patterns among authors (Chen C y Paul RJ, 2001), (Genest C y Thibault C, 2001), (Latour B, 1998), (Melin G y Persson O, 1996), (Morris MA y Yen GG, 2004), (Shneiderman B, 1996), (Tufte ER, 1997), (Tufte ER, 1995), (Tufte ER, 1991).

d) To develop synthetic, hybrid indicators in pursuit of convergence of the bibliometric and structural approaches, and complement the traditional simple indicators normally used in analyzing scientific collaboration (Mählck P y Persson O, 2000), (Zitt M, 2006).

4. INFORMATION SOURCES

Scientific collaboration has been dealt with as a research subject in several disciplines: documentation, psychology, management, computer science, sociology, research policy, physics, mathematics, social sciences and philosophy. In some cases, specialized communities have even sprung up in collaboration-related areas, such as, for example, scientometric studies to analyze cooperation patterns through quantitative methods, such as co-authorship (Sonnenwald DH, 2007). All of these papers can be found in such journals as *Scientometrics*, *Journal of the American Society for Information Science and Technology* (JASIST), *Information Processing and Management* (IPM), *Research Policy*, *Research Evaluation*, *Journal of Documentation*, *Journal of Information Science*, *Social Studies of Science* and the *Annual Review of Information Science and Technology* (ARIST). They are also in conference communications, such as those of the *International Society for Scientometrics and Informetrics* (ISSI) and the *Conference on Multidisciplinary Information Sciences and Technologies* (INSTAC).

The literature consulted on network theory and structural analysis includes monographs and manuals, as well as papers published in such periodicals as *Complexity*, *Physica A*, *Physical Review E*, *Proceedings of the National Academy of Sciences of the United States of America* (PNAS), *Nature*, *Science* and *Social Networks*.

The bibliography on information visualization and the use of computer tools to improve communication among researchers included a variety of monographs and periodicals published by the Institute of Electrical and Electronics Engineers (IEEE), such as *IEEE Computer*, *IEEE Multimedia* and I*EEE Computer Graphics and Applications*, as well as conference communications. Among the most prominent are the communications published by the Association for Computer Machinery

(ACM) in connection with ACM SIGMOD, *ACM Transactions on Information Systems* and *ACM Transactions on Computer-Human Interaction*.

5. STRUCTURE OF THE THESIS

The thesis is divided into three parts: the theoretical part, in which the background and status of the issue are addressed; the practical part, in which the main results are extracted; and the analytical part, which includes discussion, conclusions and future lines of research.

The theoretical part comprises four chapters:

CHAPTER 2. SCIENTIFIC COLLABORATION

Science is now no longer a solitary pursuit, but has become a group activity. From the very outset, collaboration has been intrinsic to scientific activity, one that goes beyond the growing specialization described by Beaver and Rosen in one of the most ambitious studies on this subject (Beaver D y Rosen R, 1978), (Beaver D y Rosen R, 1979). Collaboration is a complex development, a way to exchange information, to work together, to use resources rationally and to perpetuate communities of scientists and technologists (Maltrás B et al., 1995). All of these reasons taken together, or any combination thereof, make collaboration more a necessity than a choice.

An abundance of literature on scientific collaboration began to appear beginning in the 1970s. British researchers Katz and Martin classified these papers into four different categories: one for papers focusing on how collaboration is measured; a second for papers analyzing the factors that favour scientific collaboration; a third for papers exploring the communication function and the effects of physical and social proximity, especially as they relate to collaboration; and lastly, a category for studies that analyze the effects of collaboration on research output and impact (Katz JS y Martin BR, 1997).

Interaction among scientists has been the essence of scientific practice for some time. Many of the stages of the research process are associated with a great many communication activities, such as discussion among scientists or the reading and writing of articles. However, scientists not only communicate their results amongst themselves, but actually co-produce research. In essence, they communicate and cooperate. Thus, collaboration is an intense form of interaction that makes effective communication possible and involves allocation of skills, responsibilities and resources.

A review of the spectacular increase in co-authored papers among scientists and research institutions would readily lead to the assumption that collaboration is a prerequisite of modern science and that the essential production unit is the network of scientists who interact to produce new knowledge (Melin G y Persson O, 1996). This intense interaction can take on several forms: scientific projects and publications, research contracts, informal contacts, patents, training through courses and seminars, Ph.D. thesis direction, consulting, researcher exchanges and mobility or participation on scientific committees (Vidal J y Villarroel R, 1995).

As noted earlier, and I will come back to this issue later, research collaboration is assumed to be desirable and an approach that should be encouraged and stimulated. Numerous initiatives along these lines have been taken to develop and increase cooperation among researchers. Policies directed to improving the connection between science and technology through scientific collaboration between sectors, primarily between universities and industry has also been established. Many governments, keen on increasing their researchers' level of international involvement, finance their activity in the belief that this will mean a cost savings as well as other benefits.

This enthusiasm for collaboration and policies to promote it, more political than scientific, is based on a series of implicit assumptions (Katz JS y Martin BR, 1997):

1) That the concept of scientific collaboration is known and understood.
2) That it is a single phenomenon, whether collaboration takes place among scientists, groups, institutions, sectors or nations.
3) That we can somehow measure collaboration and determine whether it changes as a result of certain policies.
4) That the more intense the collaboration, the greater are the advances in knowledge, the better the use of the results and the greater the preparation to face scientific challenges.

But are these assumptions really valid? In order to find out, this chapter will be devoted to a detailed analysis of the notion of collaboration, its nature, its participants, the reasons behind it, the methods for measuring it, its advantages and drawbacks, and its implications for scientific policy and for inter-disciplinary relationships.

CHAPTER 3. RESEARCH GROUPS

Scientific creation is influenced by a variety of factors, both individual (age, psychological characteristics, prior knowledge and so on) and structural (research funding, institutional context, organization and so on). As mentioned, the most significant evidence of the trend towards the transformation of scientific research is the increasingly important role played by research groups, which are acquiring special relevance as opposed to the individual work patterns that predominated in earlier periods (Bordons M y Gómez I, 2000), (Seglen PO y Aksnes DW, 2000).

This chapter contains a discussion on the definition of research groups, the new forms of research that determine its advent, the internal structures adopted to address scientific problems, the methodology available to determine group size, and the future challenges that the expansion of this entity will pose.

CHAPTER 4. VISUALIZING INFORMATION

The study of scientific disciplines encompasses several types of quantitative analysis whose aim is to determine the most relevant features of science and technology, which, as complex and heterogeneous knowledge systems, have a variety of fields of activity characterized by a multitude of interrelated aspects.

The exploration of the social and cognitive networks of scientific interrelationships is crucial to the study of knowledge structures in research work. The use of methods based on count data from scientific publications (frequency of co-occurrence of citations, authors, words or classification codes) or similar procedures yields indicators that help to discern the internal structure of disciplines, the relationships among scientists and the research fronts where work is underway.

Graphic representations (science maps, or "scientograms") showing the most significant traits of relational structures, revealing both cognitive (thematic relationships) and social links, are used to this end. Science maps are two- or three-dimensional representations that facilitate understanding of the structure analyzed through symbols that reflect real-world categories or aspects, which act in much the same way as cities on a conventional geographic map.

The relative positions of the elements and their links offer a vision that is precise and easy to grasp, making it possible, for example, to identify the central and peripheral research fields in a discipline, or the relationships that are established among the scientists contributing to a certain field of knowledge.

Network analyses make a graphic description of the entire structure of interdisciplinary links among fields possible. This particular type of content analysis not only reveals the central disciplines, but also shows the most important contributions (scientific or technological) from other areas. Science maps both clarify the underlying structure of the relationship network and shed light on less evident links. They can also provide information about static aspects of the structure, such as, for example, how a research programme has contributed to increasing the level of interdisciplinarity in a certain field, or to what other fields the discipline being analyzed is closely related. Map series also provide information about the directions in which the network is growing and how it is evolving, thus facilitating identification of emerging research specialities.

These quantitative studies have been relaunched in recent years because of the significant growth of scientific research and the attendant increase in public spending on these budget items. This has meant that political authorities require understandable and well structured information that enables them to evaluate research activities and identify the most noteworthy scientific developments.

This chapter takes a closer look at the concepts of visualization and visualizing information as a prerequisite to the application of visualization techniques aimed at representing scientific information (Moya-Anegón F et al., 2004), (Moya-Anegón F et al., 2005b).

CHAPTER 5. NETWORK THEORY

Despite its long existence and international acceptance, network theory and analysis is a practically unknown approach in Documentation, both theoretically and methodologically speaking. Fortunately, this trend is changing, inasmuch as network theory and analysis may mean a quantitative and qualitative leap forward in the representation and analysis of the structure of all types of scientific domains, whether geographic, thematic or institutional (Vargas-Quesada B y Moya-Anegón F, 2007).

Subjects dealt with throughout this chapter include different views of network theory from such disciplines as sociology, psychology, mathematics, biology, physics and anthropology; it also addresses real-world network types, their mathematical properties and the processes governing their evolution.

Based on his exploration of the social structures emerging from among the different domains of human activity and experience, Manuel Castells, one of Spain's most reputed sociologists, has concluded that the predominant functions and processes in the information era are organized in the form of networks. These networks constitute a new social morphology and the dissemination of networking logic substantially modifies the operations and outcomes of production processes, experience, power and culture. Although social organization in network form is neither new nor exclusive to today's world, the new information technology paradigm is established on a solid base that facilitates its expansion and influence in the social structure as a whole. The result is a network society characterized by the pre-eminence of social morphology over social action, in which networks are open, infinitely expandable structures, integrating new nodes as communicating facilities allow, provided that communication codes are shared (Castells M, 1998).

The vision of real-world networks from the perspective of physics concurs with the aforementioned. Today's is a world of networks, which are also one of the pillars on which the current era of economic, political and cultural globalization is built (Dorogovtsev SN y Mendes JFF, 2003).

This is a revolutionary period in the study of networks. Networks are everywhere. They surround individuals, who form a part of them, sometimes as nodes (in our relationships with family or friends) and on occasion as links (flowing between stations or airports as users). Communication networks, the World Wide Web, the Internet, the human genome, chemical reaction networks, catalytic networks, metabolic reaction networks, protein networks, neural networks, arterial networks, transport networks, river systems, ecosystems and food chains, social networks, scientific collaboration networks, terrorist networks, telephone and postal networks, citation networks in scientific literature, electric power networks, and even the language that is used to conduct this research is a network, made up of words linked by syntactic and semantic relationships (Barabási AL y Bonabeau E, 2003), (Barrat A et al., 2004), (Börner K et al., 2005).

Progress in this discipline is taking place so quickly that for some authors, a new science based on a new concept, and even on a new philosophy, that of the "small world", is emerging (Milgram S, 1967). Old ideas from mathematics, statistics, physics, biology and computer science can be applied in a new way to real, evolving networks (Dorogovtsev SN y Mendes JFF, 2003).

However, one should no lose sight of the fact that the extraordinary advances that have taken place in recent years in the study and analysis of complex networks have been made possible by a number of parallel developments. First of all, with computerized data acquisition and handling, large databases can be managed, leading to the emergence of different real network topologies. Secondly, the increase in computing power has made it possible to explore networks with millions of nodes. Thirdly, there is the slow but sure breakdown of boundaries between disciplines. This can be seen by researchers because of their ability to access and use databases that facilitate an understanding of the generic properties of complex networks (Albert R y Barabási AL, 2002).

The practical part encompasses the next three chapters.

CHAPTER 6. MATERIALS

Most bibliometric indicators are compiled at the national level (Gómez I et al., 2005), (Moya-Anegón F, 2004a), (Moya-Anegón F, 2005a), (Moya-Anegón F, 2006). These indicators reflect the data of the actors in the system. National collaboration is analyzed and the numbers of citations obtained by articles published in the country, region or subject area are tallied (CINDOC, 2004), (Guerrero-Bote VP y Moya-Anegón F, 2005), (Moya-Anegón F, 2004b), (Moya-Anegón F, 2005b), (Moya-Anegón F, 2005c), (Olmeda Gómez C et al., 2007). Analyses regularly reporting on indicators that examine the internal dynamics of national science systems with data disaggregated by institutions or departments are less frequent, however, even though they are necessary, for they can be used to examine such dynamics in detail (CINDOC, 2006), (Moya-Anegón F et al., 2005a).

The section dealing with measuring cooperation establishes the fact that scientific articles contain valuable information that can be processed and statistically analyzed (Price DJ, 1969), (Ziman JM, 1969). There is a consensus that a count of scientific production in the form of articles is a basic indicator for representing publicly accessible knowledge. A detailed study of their contents provides information on impact (understood as a measure of visibility) and collaboration, as they include the links that exist between the people, institutions and nations involved in their publication. Bibliometric indicators can also reveal the movements of authors from one institution to another, and inter-organizational bonding. Such ties can be plotted on maps showing research-related knowledge flows.

However, they cannot capture all of the characteristics of a society's knowledge production. They capture the significance of the written record of formal scientific communication, encoded knowledge, but not in its entirety. Moreover, they better capture the results of institutions, which, like universities, have incentives to publish (Olmeda Gómez C et al., 2006).

This chapter addresses the origin of the secondary data source chosen, its limitations, the operations necessary to minimize its disadvantages and the final encoding of the database, from which the analytical part of this thesis is covered.

CHAPTER 7. METHODOLOGY.

This chapter devoted to methodological issues contains an overview of a variety of methodologies used to date for different research objectives, whose convergence is not only possible but necessary for the subject at hand: the development of science maps, the visualization of scientific domains and network theory.

The development of information technologies and communications and the increasingly refined techniques for processing and representing information have blurred the boundaries between these three areas.

The following is a simplified compilation of the different procedures proposed by each of them:

The first methodology describes the analytical process for creating science maps. The original version was intended for the development of this type of map based on an analysis of author co-citations, but it can be extrapolated to any analysis based on co-occurrences (McCain KW, 1990):

- Sample selection: the analysis begins with the selection of the sample and the preparation of the database where all of the information necessary to define the academic landscape to be represented is stored.

- Frequency count: this is the step prior to creating the raw data matrix. In this stage, all papers containing at least one reference in which pairs of elements co-occur (authors, journal titles, thematic categories, etc.) are counted.

- Creation of the raw data matrix: reflects all the data from the counts of pairs of elements. It is characterized by its symmetry, as it has the same number of rows and columns.

- Matrix conversion and normalization: prior to obtaining the results, a series of operations are performed on the raw data matrix. These often include normalization through procedures such as the Pearson correlation or the cosine function, and treatment of the main diagonal.

- Multivariate analysis: once the data from the matrix have been normalized, they can be used as proximity values between elements. The greater the correlation, the greater the similarity between them. The techniques used to exploit proximity data include: cluster analysis, multidimensional scaling (MDS) and factor analysis.

- Interpretation and validation of results: this is the final stage of the process, in which the relationships between the elements and the groupings obtained in the multivariate analysis stage are established. Next, results are validated by consulting specialists or through statistical validation.

The second methodology focuses on the process that the design of a network study should follow. Although originally applied to social networks, as in the previous case, it can be extended to any network study, of whatsoever type (Marsden PV, 1990):

- Level of analysis: this makes it possible to obtain data to represent the links between the elements in the community studied.

- Analysis limits: the set of units to be included in the study is determined in this stage. This is especially important in network analyses, which focus on the explicit interdependencies between units. Omitting elements that should form a part of the analysis or setting arbitrary limits may produce misleading or incorrect results.

- Network sample: the proposed methods include a complete list of all the constituent nodes, or random procedures to select only some of them.

- Data source: among the methods used to obtain data are surveys and questionnaires, social experiments, files and databases.

- Data quality: when data is gathered through surveys, certain processes must be performed to ensure the quality of the data obtained and reduce subjectivity.

- Interpretation: the interpretation of the results should be based on measurements of the network itself, such as its size, data regarding node centrality and network centralization, and the size of the links.

The third methodology includes the steps necessary to obtain domain visualization tools (Börner K et al., 2003):

- Data extraction: from information on journal articles included in databases (*ISI*, *Inspec*, *Medline*), from patents, monographs, research projects, etc.

- Unit of analysis: this should be selected depending on the research question to be solved, the most prominent being journal, author, term and classification code.

- Unit of measurement: closely related to and dependent upon the previous stage. It involves selecting the measurements whose occurrences or co-occurrences help obtain the matrices that underlie and give meaning to subsequent visualizations.

- Spatial reduction: this, with connectionist techniques and networks obtained through pruning with the Pathfinder algorithm, completes the list of tools proposed by McCain (self-organized maps).

- Information visualization: the design of the data visualizations obtained should use techniques that enable the user to interact with the maps through filters, panoramic views, zoom or distortions that facilitate searches in the new informational domains.

Science maps are ideal tools for learning about and better understanding the details of associations and flows in scientific communication based on research results, in the same way that maps in the real world familiarize users with their environment and help identify their exact location and surrounds. Full information on surroundings helps predict or anticipate future changes, especially changes in the immediate environment (Boyack KW et al., 2005).

The aim of disciplinary maps is to help researchers become more familiar with their work context, enabling them to navigate and move around in it. As most scientific institutions are organized into departments, extracting disciplinary maps of these administrative research units (together with the respective authors) is the main objective of this thesis.

Having discussed the aforementioned methods, some of whose aspects are partially applicable to the work proposed, one must now be formulated that will encompass the three preceding approaches. To this end, a new, convergent methodology is proposed.

CHAPTER 8. RESULTS

In this chapter devoted to the results obtained, the methodology described in the previous chapter is empirically applied to achieve the proposed objectives. The aim is to describe collaboration patterns in the departments analyzed from a kaleidoscopic perspective, including international, national and departmental cooperation. Collaboration activity in the latter area is broken down into several categories: interdepartmental, subject area, author's gender and actors' hierarchical status. Finally, the evolution of the topological and structural patterns of the networks as a whole was determined, and the popularity and prestige of the most noteworthy nodes in each department were analyzed.

The information gathered about departmental collaboration at UC3M, i.e., the data subset extracted from the database created as described in chapter 6, sheds light on work habits, the importance of geographic proximity, the influence of national and international collaboration on output and impact, women's status in institutional research, group formation along speciality lines and their makeup based on the hierarchical status of their members. It also contributes to establishing possible variations in collaboration patterns, depending on the scientific discipline described.

Finally, the analytical part comprises the last two chapters:

CHAPTER 9. DISCUSSION

This chapter, which deals with the analytical aspects of the results, focuses on a detailed examination of each of the facets of cooperation discussed in the previous chapter, the summary and explanation of the findings and the recommendations arising from their analysis.

CHAPTER 10. CONCLUSIONS AND FUTURE STUDIES

6. CONCLUSIONS

A methodology developed for the convergent use of scientific map formulation, the visualization of scientific domains and network theory was applied to a case study of Carlos III University, and its scalability and robustness were verified. “Scalability” refers to its applicability to a set of data, regardless of size. The only limitation in this regard is the physical space available on a computer screen to show a large number of nodes and/or links. In this case, the solution would be to use schematization algorithms. “Robustness” refers to the validity of the results obtained once the matrix data are transformed into information networks. Their accuracy is confirmed both by the opinion of the experts consulted, and by the similarity of the research subjects based on the categories to which the bibliographic references contained in the papers analyzed are assigned.

One small drawback was encountered, which is not attributable to the methodology itself, but to the nature of the data used. In the chapter on material, the databases used were exhaustively analyzed. However, despite their potential and suitability for this type of research, they indisputably pose problems that they are not wholly representative in two respects: in light of the small number of journals they included in the databases, and the accuracy in light of the many problems surrounding the normalization of both individual and institutional data.

These were resolved using techniques that ensured their consistency. Thus, the methodology is also sound in this regard, and the higher the quality of the data used in applying it, the more reliable, representative and accurate it will be.

The inclusion of new collections of data from other databases on scientific papers, such as Scopus, or on other types of documents (conference proceedings, monographs, patents, research projects, researcher mobility, research contracts, technical reports, etc.), will serve to improve the results and further establish the solvency of the method proposed.

The conclusions on the modelling and characterization of the co-authorship networks must be vertically subdivided into the three levels of analysis proposed: individuals, groups and departments.

- Individuals: the development of new convergence indicators has made it possible to discover link patterns between actors, invaluable in understanding the individual scope of the issue. The new formulas for characterizing researchers seem to be valid and effective assessment instruments for identifying excellent authors, i.e., not only the most productive or visible ones, but those who are able to pool their efforts and work in communities. Their excellence is based on both their individual worth and their ability to teamwork with partners, with whom they can generate new, high-quality scientific, technical and/or technological knowledge and obtain additional resources that ensure that further research can be conducted.

  The positions of individuals and their distinguishing characteristics could, then, be determined, through indicators identifying the leading and most prestigious professors, as well as the intermediaries. This information could then be used to compare time frames and departments. The establishment of the relationships within the co-authorship networks for the two periods analyzed revealed the collaboration patterns followed by the actors concerned to achieve recognition for their ideas among their colleagues.

These tools are sensitive to traditional indicators but also to the new demands of modern science as a self-organized system of interactions among individuals. They provide information about researchers' environments and about the way they behave in it (always cooperating with the same colleagues within the same lines of research, or working with new scientific partners to seek new challenges, for example). In this new panorama, it is no longer enough to *have* (papers published or cited); rather, it is necessary to *be*, from the perspective of the "*connecto ergo sum*" so aptly coined by Björneborn (Björneborn L, 2004).

The results obtained emphasize the new concept of science and research, and give the necessary prominence to the degree of cooperation among researchers, until now ignored. They also reliably confirm the importance of collaboration in the management of science and technology policies.

A unique feature of the resulting visualizations is that the egocentric network of each of the participating nodes can be accessed. This development not only identifies all of an author's partners, but also denotes the strength (the darker and thicker the line, the stronger the link) and diversity of the links, the latter in the form of a ratio depending on the typology of cases in each partition.

- Groups: with this thesis research groups can be feasibly identified on the basis of their choice of co-authorship links. The group to which authors are assigned is established according to the similarity in their choice of collaborators. Factor analysis, used for this purpose, yields results from which each group's communication structure within its department can be characterized. The result is a set of research-based communities, each of which shares research guidelines and objectives that distinguish it from other groups.

The subsequent identification and pooling of groups according to their common characteristics, in this case subject category, provide intellectual snapshots or cognitive organizational charts for the various departments studied. The aim of this instrument is to detail authors' specialities and their evolution, as a way to initially assess their research.

In addition, the differences in magnitude of the links represented can be used to descend to a deeper level in the concept of "research team", understood as a nuclear subset identified through nodal groupings with very intense relationships, as an instrument that distinguishes the nature of inter-group relationships.

- Departments: the findings at this level led to the observation and analysis of the departmental structure with an unusual degree of detail in the various facets and perspectives suggested by the literature on this subject: specialities, gender, hierarchical status and intra- and inter-institutional relationships. The inclusion of up to twelve one-dimensional indicators combines the (structural) process facet with the (bibliometric) descriptive aspect to enhance the information content. This facilitates the understanding of the details of associations and communication flows among researchers and managers, enabling them to discover, as exceptional observers, the reality of their working context, which they themselves have built.

In this regard, collaboration with other institutions (Spanish or foreign) does not ensure the greater visibility expected from the results of the research. Therefore, partners should be chosen not because of proximity (geographic, political, social, cultural or any other type), which would augur easy understanding, but because of interests, abilities and needs that contribute to solving common problems. In other words, this choice should be based on cognitive proximity, which involves greater effort, but also generates greater benefits. In short, it is a question of achieving dialogue between groups, institutions, countries and disciplines to advance scientific knowledge.

The limited inter-departmental cooperation highlights two different but closely related issues. The first is the importance of external intellectual capital in departments' scientific production. On occasion, it even takes precedence over internal intellectual capital. The second, a derivative of the first, denotes severe internal communication problems within the institution. This makes it necessary to develop mechanisms that ensure the effective transmission of the contents of the organization's research work and skills, and any of their most outstanding features that may be of interest and use to the rest of the university community.

Besides, the cases of female and younger researcher representation are similar. Their moderate increase (in production, visibility and centrality) should not prevent the implementation of plans to recruit research staff who combine both quantity and quality, and for the development of professional careers based on merit and individual capabilities.

From a purely structural standpoint, the institution's "youth" has facilitated the observation of the development and evolution of co-authorship networks. In their emergent stage, which coincides with the first period analyzed, such networks are characterized by the predominance of groups in the form of factions, coalitions and rings lacking in any interconnections. In the second period, however, the networks reach some degree of consolidation, the intensity of which depends on departmental maturity and the scientific environment. This stage is characterized by an increase in the number of actors and weak links that connect communities, making up larger components.

Substructures in the form of a distributed network have been shown to be more efficient than star networks, as will be emphasized below in the discussion on complete networks. The distinguishing characteristic of the latter is that they are governed from a central node whose role is to control and manage information, around which the links with the rest of the participants are established; there are no other connections in the network (Goyal S y Vega-Redondo F, 2005). In network theory, this is known as a structural hole, or the type of inter-group relationship that acts as a barrier (control) for information flows, affording one or a series of actors an advantageous and prominent structural position (Burt RS, 2001). Compared to these, distributed networks are characterized by sharing control among their members and the predominance of reciprocal connections. In such structures information flows are homogenized and shared, facilitating the integration of the actors in the different groups, and generating non-redundant structures that add information and are better adapted to obtaining new knowledge.

There is a final, conclusive, horizontal level that summarizes the departmental level and relates the networks analyzed as a whole. From this perspective, this thesis corroborates, in the first place, the widespread idea, generally accepted by the international scientific community, that it confers positive effects on scientific collaboration and believes that it improves productivity and visibility, as observed in the case at hand.

Secondly, this thesis contributes to characterizing the networks that make up co-authorship relationships. Although working at the micro level of the scientific structure, with small- and medium-sized networks, is regarded as a handicap by many researchers, the distributions of degree obtained are similar to the archetypal structure of scale-free networks taken from the analysis of much larger real-world networks.

Thirdly, as far as network analysis is concerned, this thesis reveals the influence of network structure and cohesion and their effect on basic bibliometric indicators. The analysis of the values of these representations makes it possible to study network “efficiency”, understood as the comparison of results on the basis of the predominant structural configuration. Centralized structures with fewer components are more efficient than decentralized ones formed by the concurrence of isolated groups. A paradigmatic case of the effects of structural configuration on efficiency is the evolution of the Mathematics Department’s network, whose centralized composition was changed to a structure based on unconnected groups, resulting in a clear decrease in both productivity and visibility.

The visualization tools developed based on the premises expressed in the chapter on information visualization represent space-time solutions to a variety of propositions. These include the non-distortion of the original data (thanks to the scant density in the resulting medium-sized networks it was unnecessary to apply schematization or simplification algorithms, offering an unaltered view of the underlying reality of the data used); the coherent presentation of a large amount of information in as little space as possible (thanks to spring-embedder algorithms); and the ability to compare different types of indicators (bibliometric and/or structural). However, among the qualities most appreciated by users are their interactive capabilities (visual aids such as the different colours and sizes of nodes and links, option buttons to change the visualization perspective, the ability to hide data to make it easier to obtain information, and the ability to move around and navigate using the zoom feature).

These are, therefore, tools that go beyond mere graphic representation to become knowledge instruments able to reflect the evolution of collaboration analyzed over time based on their own protagonists, emphasizing the often-expressed idea of science as a social system in which scientists exchange ideas, experiences, questions and solutions. Even though this evolution is static and historic, the observation of its trends over time is an invaluable tool for predictions and forecasts, in much the same way as weather maps are.

Finally, the increase in scientific cooperation is the best indication of how difficult it has become for an individual scientist to have all the knowledge, techniques, skills and ability to use the tools required for carrying out quality scientific work. Therefore, researchers are moving further and further away from individuality to move closer to a model in which the research plays the lead role, relegating the scientist to the background.

In this new interdisciplinary, multidisciplinary, transdisciplinary work environment, it is as difficult to divide the whole of the research into disciplinary parts as it is to try and do the same with the authorship of the documents. The shift towards the new paradigm predicted by Gibbons means not only changing the locations where the new science takes place and how it is created, but also changing the way it is understood. This should undoubtedly include the way research is assigned to those responsible for creating it. As group work has been proven to be is the basic and essential way in which scientific studies are conducted, why keep dividing up the authorship of these studies as if they were a cake? The subject (disciplinary) assignment of papers should be as indivisible as their authorship.

Attendant upon this is the proven validity of scientific collaboration *per se*, which is ratified by such illustrative examples as the most recent calls for research projects at the regional (Comunidad de Madrid, 2005), national (Ministerio de Educación y Ciencia, 2006) and European (Unión Europea, 2006) levels, in which the concurrence of several research groups in each of the proposals presented becomes strictly necessary.

Finally, this dissertation has verified the fact that analyses at the lowest level of the scientific structure, despite their comparatively smaller volume of data, can obtain relevant results able to corroborate scientific observations and ideas resulting from the analysis of macro datasets on collaboration (national or international). It is, therefore, evident that, even though the normalization effort at this level is greater than that which is necessary in other, the results are broken down to a further extent; or to put it another way, they contain more relevant and detailed information. Some authors criticize this type of analysis because of its lack of statistical significance. On the contrary, it is an ideal formula for detecting peculiarities and for trying to explain and understand possible deviations from the norm that would otherwise remain totally hidden in higher-level studies. In short, understanding science in its broadest sense involves the type of scrutiny afforded by micro-analysis.

7. FUTURE STUDIES

RESEARCH GROUPS

This thesis presents a methodology appropriate for the analysis of research groups, and its potential has been proven in the analysis and visualization of departmental collaboration networks and for the identification of research groups and specialities. However, one immediate objective focuses on comparing these “real” units, based on common scientific work in the form of publications, to the “official” structures reflected in UC3M’s first Catalogue of Research Groups.

NETWORK ANALYSIS

This dissertation has identified some of the underlying factors that explain different network configurations, the position of the groups in the network, the internal communication structure of these groups, and the position of the different authors within their group and in relation to the other actors in the overall network. However, there are other unknowns that must be explained: how do the group’s diversity and heterogeneity affect its creativity, cohesion, cooperation and decision making? What type of internal relationships may be associated with encouraging group work? Does the density of links between a group and its environment influence its development? Are there structural positions that bring greater benefits, forming strategic connections?

From another standpoint, the thesis shows co-authorship network structures that can be divided into the following types, depending on their cohesion: distributed networks, independent networks and networks with structural holes. The identification and analysis of these structures may serve as a basis for ascertaining whether composition is a decisive factor that affects the success of group research.

INFORMATION VISUALIZATION

Other, more ambitious, medium-term objectives include the construction of visualizations with a higher degree of interactivity, enabling users to navigate through map systems on different sublevels. Starting with macrodomains (countries or geopolitical regions), with these systems users could descend to the level of mesodomains (regions, sectors, disciplines, institutions), which in turn would lead to microdomains such as the ones represented here. The *modus* *operandi* is similar to the procedures deployed by the Atlas of Science's co-citation maps (Grupo SCImago, 2004).

The main difficulty lies in the normalization and control of the enormous volume of authors participating in thousands of papers, which increase in number with each higher level. However, the practice of standardizing the names of both individuals and institutions, which is becoming increasingly widespread among scientists (the IRALIS initiative (IraLIS, 2007) is a good example), as well as algorithmic advances in identifying and correcting these problems, are working to the advantage of researchers in the field.

DEVELOPING NEW INDICATORS

The introduction of new bibliometric and, especially, structural indicators as ideal information complements for the development of an on-line information recovery system will also be very important. The exploration of these innovative representations from a structural analysis standpoint, expanding the battery of centrality indicators with others for cohesion and even probabilistic methods for predicting network evolution, constitutes a line of research with good prospects and promising results.

EVOLUTION OF NETWORKS

Lastly, an equally exciting line of research is the development of interactive maps that incorporate time information. These break the mould of static, unchanging representations by using animation that enables the user to observe network formation and evolution processes.

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