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Bibliometric mapping as a science policy and research management tool

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Part I Evolution of Science Maps

1 Introduction

When apples are ripe, they fall readily

(Sir Francis Galton 1822-1911)

The above quotation was used by Price (1963) to illustrate the fact that scientific innovations or discoveries mostly arise from ongoing developments, rather than pop up by surprise. In the same way, the developments presented in this book spring from several developments in the recent past. These developments concern cultural changes and technological opportunities.

Ziman (1994) argues that science has reached a steady state. By this he means that the proportional investment in scientific research has remained for a longer period of time at a similar level (average percentage of the gross national product). At the same time a tendency towards improving the quality (in all its aspects) of scientific research is being pursued. The societal relevance has become an important issue for funding scientific research since the seventies. Furthermore, evaluation of scientific research has become a major issue for science policy. Scientific groups are being evaluated by peers (visitations) in order to assess the emphasis and impact of their activities. More and more these judgements by peers get accompanied by bibliometric evaluation: *what do scientists publish and to what extent is this appreciated by the scientific community?*

As a result of this intended efficiency of scientific research, the exponential growth of science is still going on, in spite of the steady state of science investments. There are indications (Van Raan, 2000) that the growth factor with a doubling time of 15 years (c.f., Price, 1963 and Ziman, 1984) still applies. In order to scrutinize developments in science and in research fields, a tool providing an overview is essential. Price already noted the impossibility of one person to keep up with all developments in a field (Price, 1963).

It could be discussed which form such a tool should have. Following the argument provided by Ziman (1978) to visualize theories, this may best be a map. The knowledge output of a field may well be seen as a current theory (or set of theories).

It is natural to refer to such a representation as a map. It is important to emphasize that this reference is itself metaphorical. Scientific knowledge is a peculiar epi-phenomenon of human existence, and can only be uniquely itself. There seems no absolute necessity that it should be structurally isomorphous with anything so topically specialized as, say, a graph of vertices (in map language, 'places') connected by edges (e.g., 'roads') on a manifold ('sheet of paper') of a few (two, or perhaps three)

dimensions. It could conceivably – and perhaps at times ought – to take wilder, more diffuse forms.

But the metaphor is extraordinarily powerful and suggestive. There are good reasons to believe that human beings are adapted neurologically and psychologically to comprehend information presented in map form.

(Ziman 1978, p. 78)

And to explain this metaphor some more:

(...) What we also recognize is that a sketch map can convey significant and reliable information, without being metrically accurate. What such a map represents of course is the topology of the relationships between recognizable geographical features – for example, the sequence of stations and their interconnections on the London Underground. In many fields of science, what we call qualitative knowledge has these characteristics – for example, the ethologist's account of the courtship behaviour of birds or baboons. Is such knowledge 'unscientific' because it is not quantitative – because the subway map does not, so to speak, show the actual positions of the stations by latitude and longitude. The question is, rather, whether the sketch or diagram correctly represents the significant relationship between identifiable entities within that field of knowledge – often a ver moot point that cannot be resolved by mechanical counting or 'measuring'.

(Ziman, 1978. p. 84)

During the past three decennia science maps have been created to monitor research field structures. However, the utility has been questioned at the same time. An often heard comment to science maps is: 'interesting, but what can we do with it?' Moreover, the validity of the generated structure was often doubted: 'does this map really represent the structure of the field?'

Although the scepticism towards maps of science will probably always exist, we have made an attempt to improve the utility by making the maps interactive. The technological developments to access the Internet, provide an excellent platform to accomplish that. The graphical interfaces developed to browse through the worldwide web enable us to create clickable maps. Through this interactivity, the validation of the generated structure (the map) becomes much better and easier. Moreover, the interactivity improves the utility of the map as users have more choice to extract information from the maps.

In view of this utility, we focus in this book on the applicability of science maps as a science policy and research management support tool. It concerns the procedure to construct the field structure (the map) as well as the information 'product'. Regarding

the procedure, we propose an interface to enable the field expert to provide goal-directed input to the preliminary results of the analyses. With respect to the information product (the map and additives), we provide the user with an interface both to extract information in view of the raised issue, and to evaluate the validity of the generated structure (2D map). As mentioned before, this interface does not primarily improve the methodology to construct a map, but rather improves its utility. To illustrate the utility, the interface can be compared to the computerized route planner for travelers. Ten years ago, a traveler needed a certain amount of geographical maps in order to find his way in a country. A traveler by car needed less detailed and therefore fewer maps than a traveler by foot. Still, each time he took a look at the map, he had to list new instructions to plan the route to his goal. All the information he needed would already be on the maps, but each time he would have to determine his present location and to adjust his perspective in order to be able to extract the relevant information. Nowadays, a computerized route planner enables a traveler to extract the same information each time he is consulted. However, in this case the relevant information can be provided instantly without all the 'surrounding' information. Like the paper maps, the route planner incorporates all the information but focuses on the relevant instructions, at any chosen level of detail.

In the case of science maps, the available information could be printed on paper and through a clever reference system all the information could be disclosed. However, the user would easily become overwhelmed by the amount of 'potential' information. By presenting the map of a science field, and allowing the user to extract only the information he is interested in, he is less likely to become overwhelmed. Thus, he will be able to determine easily the proper perspective and to disclose relevant information at any level of detail.

In a more methodological sense, we have explored in great detail the possibilities of using titles and abstracts to extract keywords to create the maps. The application of a linguistic analysis appeared to add an essential component to the co-word analysis. Hence, the selection of relevant keywords to structure a research field became possible without the input of (often absent in bibliographic databases) indexed terms.

1.1 Introduction to bibliometrics

Bibliometrics is another word for quantitative analysis of bibliographic data. Bibliographic data discloses the main elements of a publication. For information retrieval in libraries, it is a most important data source. The elements are used to retrieve information about publication data from large bibliographic databases. Nowadays, bibliometrics has at least four areas of application.

Performance analysis

In this area, scientific research units are evaluated on the basis of performance within a particular science field. These units can be on all levels of aggregation: continents, countries, regions, universities, faculties, departments or even individuals. In most cases performance is measured and compared to other units. Performance has three main aspects: activity, productivity and impact. Generally, activity is measured by the number of publications within a certain time span, but some studies measure activity by the number of published pages. By linking the activity of a research unit (for instance, a country) to the number of inhabitants (or active scientists), or the Gross National Product, an indication of productivity is obtained. By linking the scientific output of a research unit to the number of citations received, an indication of impact, influence, or at least of visibility is obtained.

Mapping science

A second application area of bibliometrics, concerns the monitoring of scientific activity and science evolution. This area of bibliometrics unravels a structure of science and investigates its development. The research output (in this case, publications) is subject to clustering and scaling analyses in order to determine the structure and to monitor its changes. Regarding the policy relevance of this particular area, it is assumed that this approach indicates what the important areas in a science field are, how they develop(ed) and what we may expect in the future. This area is known as 'mapping of science' or 'cartography of science'.

This application is particularly important for science policy in view of the ever blurring of disciplinary boundaries of science, and growth of scientific output (Braam, Moed and Van Raan, 1989).

Information retrieval

A third area in which quantitative studies of bibliographic data are applied, is the field of Information Retrieval. Searching for publications about a topic *A*, someone may be interested in publications about a related topic *B*. The relatedness of topic *A* and *B* can be determined by bibliometrics (e. g., word co-occurrences). The idea is that patterns in frequency distributions in bibliographic databases can be used to detect important characteristics, which can be useful to retrieve the proper information from these databases (Egghe and Rousseau, 1990). Recently, the application of, in particular, citation data, has become less popular. In Ingwersen (1996) a plea for reinforcement has been published. Furthermore, Garfield (1998) supports this application.

Library management

Finally, in libraries bibliometric data is used to manage the (journal) collection. This part of library operations research may use, for instance, the impact of a journal (a

measure based on the number of citations received per article) to maintain and update a library collection (e.g., Van Hooydonk et al., 1994). An extensive overview of the techniques and applications is presented in Egghe and Rousseau (1990).

Although bibliometrics has a long history, the most frequently used application is rather young. It concerns the use of bibliometric data to evaluate the scientific performance in terms of published papers and their impact. A scientific publication discloses the methods, results, and perspectives of research. A database containing all scientific publications is therefore virtually a source of all scientific knowledge. Evaluative bibliometricians base their research on these assumptions. 'Evaluative bibliometrics', a term coined by Narin (1976), concerns the quantitative analysis of bibliographic data of scientific publications with the objective to find characteristics of research performance. There are, of course, some important issues to be taken into consideration in order to operationalize bibliographic data to evaluative bibliometric studies.

The achievements of science are reported in scientific publications. It is a basic principle of science that research results are made public (Ziman, 1984). Scientific discourse is vital for progress (among other functions, c.f. Roosendaal and Geurts, 1999). Most of it is published in discussions in journals (Moed, 1989).

Although a large part of the communication does not take place in the form of scientific journals, (...) it is assumed that eventually, all important research findings are reported in the serial literature. (Moed 1989, p. 4)

This observation is of great importance. An evaluation based on bibliographic data over a 'longer' period of time, requires a certain stability. That is, a comparison of output indicators from year to year, requires a certain consistency of sources. The use of serials 'guarantees' such a consistency. The use of books (as unique publications) does not. Furthermore, the availability of electronic data is of vital importance in view of the reliability and utility of the study. Evaluation of the activity of a research entity (person, institute, university, country, etc.), demands a publication database of that particular entity, and of at least one comparable entity. The collection of objective data requires a database that is objectively composed and 'publicly' available to guarantee the reproducibility of the results. The number of 'reference points' (i.e., to which a research entity's performance is compared) correlates with the reliability of the results. In other words, the more entities included in a study, the more reliable a study becomes. Ideally, a research performance study makes use of the worldwide publication collection in a certain field in order to assess the performance of a particular research unit. Moreover, evaluative bibliometric studies often aim at presenting the worldwide characteristics of a certain field in terms of scientific activity. For these reasons, we cannot do without huge worldwide bibliographic databases of scientific publications. In most cases such databases disclose data from publications in serials. Some examples of important ones are:

- The ISI Citation Indexes (SCI, SSCI, A&HCI, etc.): a worldwide, though somewhat Anglo-Saxon biased multidisciplinary database containing standard bibliographic data including all addresses of authors mentioned in the publication, abstracts, and all the cited references. These properties make the ISI databases unique. Wouters (1999) provides an extensive overview of the history of this famous database. The Science Citation Index, the Social Science Citation Index, and the Arts & Humanities Citation Index cover journal articles only. The ISI specialty Indexes (Biotechnology, Neuroscience, Materials Science, Biochemistry & Biophysics, Chemistry and Computer Science & Mathematics) contain other serials material as well (conference proceedings etc.);
- MEDLINE: a standard worldwide biomedical bibliographic database (including abstracts) produced by the National Library of Medicine (NLM) with added keywords and classification. It contains only the first author's address and no references;
- INSPEC (including Physics Briefs): a worldwide database in the fields of Physics, Electrical & Electronic Engineering, Computer Engineering, and Information Technology. It contains standard bibliographic data as well as the authors' abstracts, an added classification, and keywords. Since 1995 the Physics Briefs database is included as well. It contains only the first author's address and no references;
- COMPENDEX: an INSPEC-like database in the field of Engineering. It contains only the first author's address and no references;
- Chemical Abstracts: an extensive worldwide abstracts database in chemistry, biochemistry and chemical engineering, including all relevant bibliographic data. Unique is its coverage of both scientific and patent publication data.
- PASCAL: a multidisciplinary database covering publications in several languages. More than 90% of the documents are journal articles, The rest are conference proceedings, theses and monographs. Provided references, all relevant bibliographic fields are disclosed.

1.2 Introduction to science maps

A science map is two or three dimensional representation of a science field, a 'landscape of science', where the items in the map refer to themes and topics in the mapped field, like cities on a geographical map. In these maps the items are positioned in relation to each other, in such a way that those topics that are cognitively related to each other, are positioned in each other's vicinity, and those not or hardly related, are distant from each other.

The most well-known maps of science are those based on bibliographical data, the bibliometric maps of science. As scientific literature is assumed to represent scientific activity (Ziman, 1984; Merton, 1942), or at least in the form of scientific 'production', a map based on scientific publication data within a science field A can be considered to represent the structure of A . It will depend on the information used to construct the map, what kind of structure is generated, and how 'good', i.e., to what extent the structure is recognized by the field expert.

The maps are constructed by the co-occurrence information principle, i.e., the more two elements occur together in one and the same document, the more they will be identified as being closely related. The science mapping principle dictates that the more related two elements are, the closer to each other they will be positioned in a map.

Many different bibliographic elements (fields) from a scientific publications database may be used to generate a structure. Each element reveals a specific structure, unique in a sense, but always related to the structures based on other elements. Generally bibliographic databases disclose per document a range of bibliographic fields (elements). The important ones are:

- authors of the publication;
- title of the publication;
- source in which the document is published, e.g., the journal, proceedings or book;
- year of publication;
- address(es) of the (first) author(s);
- abstract of the publication.

In specialized bibliographic databases, other information may be included as well:

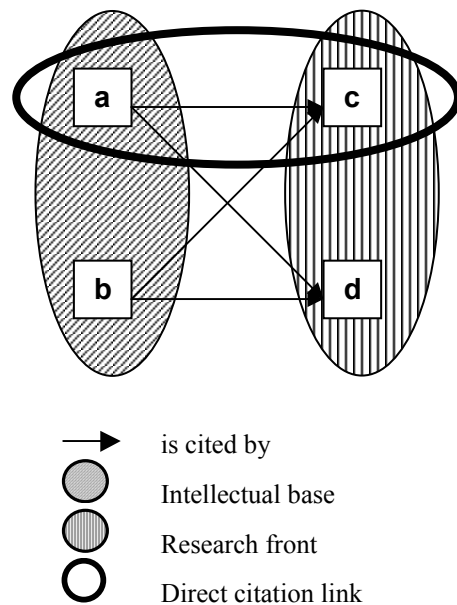
- cited references;
- publisher information of the source;
- keywords (provided by the author or journal editor);
- classification codes (added by the database producer);
- indexed terms (added by the database producer).

As discussed above, it depends on the data elements used to construct the map, what kind of structure is generated. A map based on co-occurrence of authors is more likely to unravel the 'social structure' of a science field, than a map based on co-occurrence of classification codes.

One of the most frequently used information elements in science mapping, in particular in the seventies and eighties, is the cited reference. A most intriguing aspect of the 'publication to publication relation' by citation, is its variety. Apart from the *reason* why a particular publication is cited by the other, the formal relation has at least six different ways of linking publications. First, there are three elements in the formal citation of a specific journal article to another that may be used to define a relation.

- the cited publication as such;
- the cited journal;
- the cited author.

Furthermore, a relation between publications may be defined either by their direct citation relation (*c* cites *a*), or by the fact that *a* and *b* are both 'co-cited' by other publications (*c* as well as *d* cite both *a* and *b*). In view of the latter relation they are considered to belong to the same part of a field's intellectual *base* (Persson, 1994). The relation between *c* and *d* may also be determined by the fact that they *cite to* the same publication(s). In that case they are 'bibliographically coupled' and these publications are considered to belong to the same part of a field's research *front*. In such terms, the *base* relates to the past and the *front* relates to the present.



1.3 Introduction to science maps as policy-supportive tool

Since the seventies, science maps have been developed to be used as policy supportive tool. They have been based mostly on co-citation and co-word data. The co-citation techniques were developed in the seventies (Small, 1973; Small and Griffith, 1974; Griffith et al., 1974; Garfield, Malin and Small, 1978). In the eighties, a series of projects were set up to explore the possibilities and limitations of co-citation analysis as policy supportive tool (Mommers et al, 1985; Franklin & Johnston, 1988). In the same period, co-word techniques were developed for policy purposes. Particularly, at the Ecole National Supérieure des Mines, together with other French researchers and researchers from the Netherlands and England, Michel Callon made an important effort to establish this tool, called *Leximappe* (Callon et al., 1983; Callon, Law and Rip, 1986; and Law et al., 1988). Callon and his colleagues mistrust the citing behavior of scientific authors. They argued that a scientist may have many reasons to cite an other publication. Apart from 'non-scientific' reasons to cite (see Van Raan, 1998), scientists may cite, on the one hand, earlier work for different reasons within the argumentation of the *citing* publication. On the other hand, different parts of the argumentation in the *cited* publication may be the reason to be cited.

At the end of the eighties, co-citation and co-word mapping of science suffered a great deal of criticism. Data and method of co-citation analysis were criticized (Edge, 1979; Hicks, 1987; Oberski, 1988). Moreover, the results (the generated maps) were rejected and the utility was heavily questioned (Healey, Rothman and Hoch, 1986). It must have been this debate that has blocked the development of at least co-citation modeling during the nineties. It seems that studies at the Leiden Centre for Science and Technology Studies (CWTS) of Braam (1991), Tijssen (1992), and Peters & Van Raan (1993) have been the last serious attempts in methodological development for a long period of time. Case studies (with no methodological developments) have still been published after this period of time. At CWTS, the emphasis shifted to co-word analysis. One of the reasons was the possibility to create maps based on other databases than ISI's. For instance to map an 'applied' field in which most research is published in proceedings, co-citation analysis is not appropriate, as proceedings papers contain very few references. A more fundamental, 'scientific' reason for the shift is the fact that co-citation analysis precludes a combined study of field dynamics and actors' activity (see Chapter 6). The idea is that a trend analysis of actors' activities can only be combined with a study of the field dynamics, if a certain rigidity is applied to the identified structure (delineation of subdomains by words or citations). For instance, if we are analyzing field dynamics from period t to $t+1$, the subdomain delineation may be determined by the $t+1$ data and this delineation is to be applied to t . In this example, we would be able to compare the evolution of and interaction between during t and $t+1$, as well as to investigate the activity trends of actors in a meaningful way. By using citations, we may encounter severe problems as the

citations used to structure $t+1$, may not have been published yet in t . The citations are 'replaced' by others per se, because scientific progress is reported by publication. A word (being a building block of any publication) does not have to be replaced per se. In view of the scientific communication, the 'invention' of new words is not preferable. As a result, an average publication is likely to have a 'shorter life' than an average word or phrase.

Since the mid nineties, science mapping experiences some sort of revival. Most likely, this revival is due to the increasing interest in information technology. The applicability of new analytical software (e.g., neural networks, Grivel, Mutschke and Polanco, 1995) and the availability of hypertext software (Lin, 1997; Chen et al., 1998), provided new impulses for science mapping, in particular based on co-word data.

Roughly, two types of science maps can be distinguished. One represents the network of items on which the map is based. The other type represents the structure of the field on a higher level of aggregation (a thematic map, cf. Law et al., 1988). Technically, in the latter type a clustering analysis is performed on the data, which is directly input for the map of the former type. The identified clusters¹ are mapped in relation to each other, thus providing a thematic or general overview map. The distinction between the two types is by no means trivial. If we consider science maps as a tool for research policy, each type can have its own function in the communication process from scientometrician to (policy-related) user. Maps of science can be considered a tool to translate scientific activities to science/research policy. In order to assure the validity and utility of this tool, the (mapped) scientific researchers should validate the derived structure. As mentioned before, science maps can be located somewhere in-between the communication line from science to policy and management. Consequently, the network map is closer to the science end, and the thematic map closer to the policy end (see Figure 1-1).

¹ Callon refers to them as themes. We refer to them as subdomains.

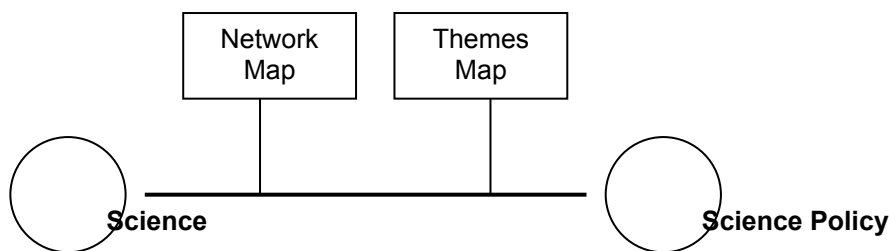


Figure 1-1 Schematic location of network maps and thematic maps

If we take the example of co-word maps, scientists recognize topics (terms, words) in the network map mainly in terms of specific research themes and their relations. Policy makers, however, prefer to see more 'utility' in the map, mainly in terms of 'overview', i.e., clusters of topics (subdomains). Analysis of these subdomains allow users to filter out general actor and field characteristics.

The digitalization of maps – i.e., clickable maps on a computer screen, rather than on paper – provides opportunities to merge both kinds into one 'product'. The interactivity of such maps allows the user in a broad sense (i.e., 'from politician to scientist') to retrieve his/her information of interest without being 'annoyed' with other information.

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