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SCIENTOMETRICS: STATE-OF-THE-ART

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In this presentation we argue that the core research activities of scientometrics fall in four interrelated areas: science and technology indicators, information systems on science and technology, the interaction between science and technology, and cognitive as well as socio-organisational structures in science and technology.

We emphasize that an essential condition for the healthy development of the field is a careful balance between application and basic work, in which the applied side is the driving force. In other words: scientometrics is primarily a field of applied science. This means that the interaction with 'users' is at least as important as the interaction with colleague-scientists. We state that this situation is very stimulating, it strengthens methodology and it activates basic work. We consider the idea of scientometrics lacking theoretical content or being otherwise in a 'crisis-like' situation as groundless.

Scientometrics is in a typical developmental stage in which the creativity of its individual researchers and the 'climate' and facilities of their institutional environments determine the progress in the field and, particularly, its relation with other disciplines. These aspects also contribute substantially to the reputation of scientometrics as a research field respected by the broader scientific community. And this latter point is important, both to let quantitative studies of science and technology take more advantage of an academic environment, as well as to keep it innovative and thus attractive in terms of applications at the longer term.

Overview of the scientometric research enterprise

Scientometric research is devoted to quantitative studies of science and technology. It aims at the advancement of knowledge on the development of science and technology, also in relation to societal and to policy questions. A special, but certainly not exclusive emphasis is placed on the role of quantitative, in particular bibliometric (i.e., based on data from scientific and technological literature) methods.

Generally, scientometric research is both problem-oriented as well as basic in nature. It is also interdisciplinary, using methods from the natural as well as the social

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and behavioural sciences. We mention for instance statistics and other mathematical methods, sociological network models, psychological survey and interview methods, computer science and related fields.

There are interesting links with philosophy of science (e.g., the Kuhnian paradigma model) and with (computer-) linguistics (e.g., in co-word mapping approaches). Furthermore, important aspects of scientometric research can be seen as information science, in the sense that parts of scientometrics involves sophisticated data handling and data-base building activities.

I think the core interests of scientometric research fall in four interrelated areas:

(1) development of methods and techniques for the design, construction, and application of quantitative indicators on important aspects of science and technology;
(2) development of information systems on science and technology;
(3) study of the interaction between science and technology;
(4) study of cognitive and socio-organizational structures of scientific fields and developmental processes, in relation to societal factors.

The first area is strongly related to one of the most important 'roots' of the field. The driving force is the empirical wealth of bibliometric data. In the last decades we see the development of methodologies and techniques to measure important aspects of scientific and technological activities such as performance, impact, international collaboration, R&D specialization (*Braun* et al.;[1] *Van Raan*[2]). Research performance measurement is based on advanced bibliometric, in particular citation analysis. It is made possible by many empirical studies on publication and citation characteristics, notions of scientific quality, differences in communication practices in the different disciplines, comparison with qualitative judgements by peers, and so on. The above activities all focus to the central objects of research: the investigation of knowledge transfer and dissemination, as well as the study of scientific progress and change and their relation with society in its many aspects.

The second area, information systems on science and technology is, together with the first, strongly related to, what is called in the recent years, 'informetrics' (*Egghe*[3]) and also to library science. Here we find an important bridge to the acquisition, handling and use of data in general. The position of the journal *Scientometrics* – in terms of journal citation relations – very clearly shows this connection, as demonstrated in Fig. 1 (a and b).

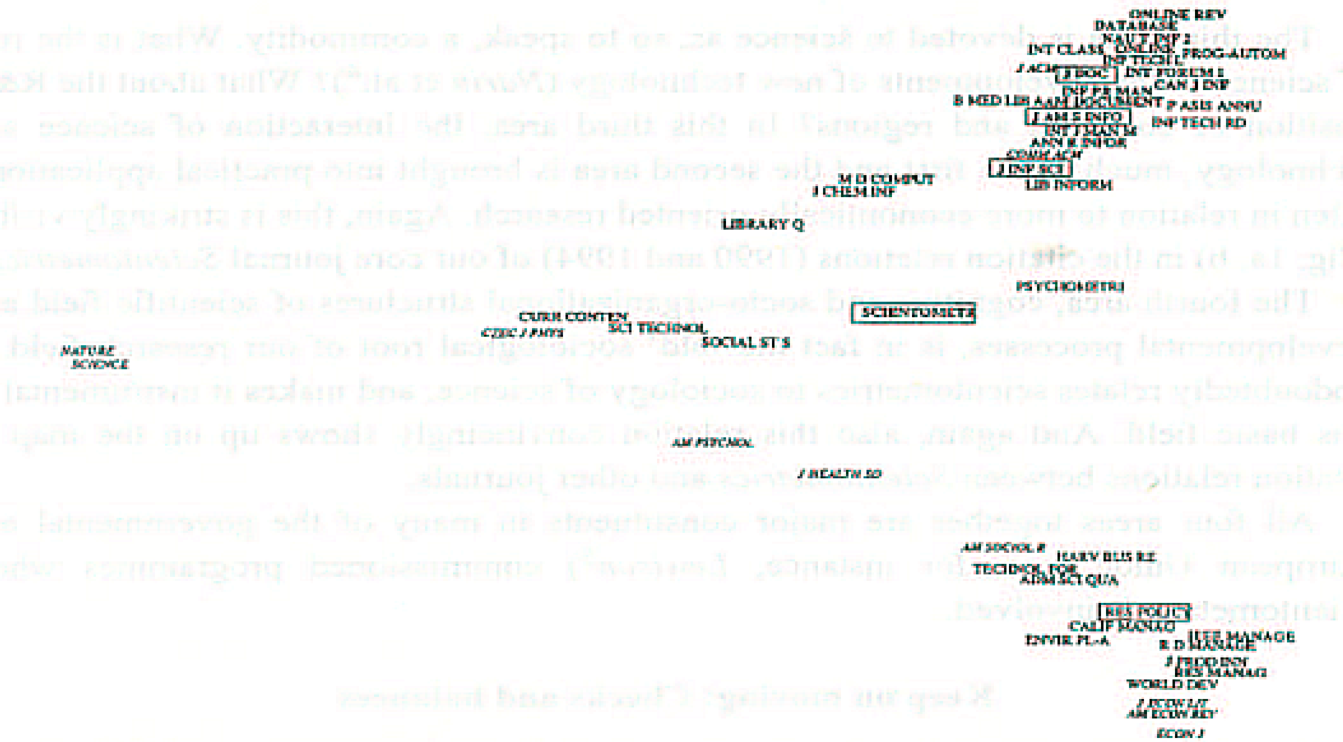

Fig. 1a. Journal citation map of *Quantitative Studies of Science & Technology*, based on the 1990 journal-journal citation frequency data produced by the Institute for Scientific Information (ISI)

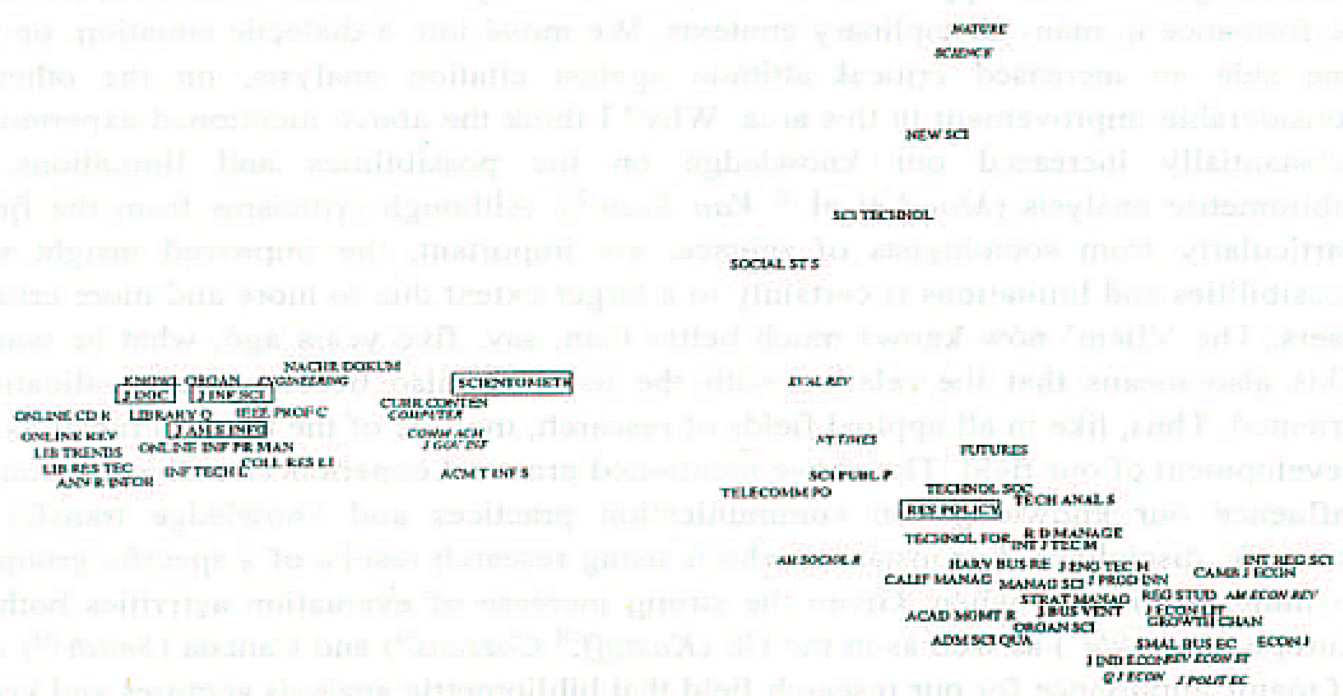

Fig. 1b. Journal citation map of *Quantitative Studies of Science & Technology*, based on the 1994 journal-journal citation frequency data produced by the Institute for Scientific Information (ISI)

The third area is devoted to science as, so to speak, a commodity. What is the role of science in the developments of new technology (*Narin* et al.[4])? What about the R&D position of countries and regions? In this third area, the interaction of science and technology, much of the first and the second area is brought into practical applications, often in relation to more economically oriented research. Again, this is strikingly visible (Fig. 1a, b) in the citation relations (1990 and 1994) of our core journal *Scientometrics*.

The fourth area, cognitive and socio-organizational structures of scientific field and developmental processes, is in fact the 'old' sociological root of our research field. It undoubtedly relates scientometrics to sociology of science, and makes it instrumental to this basic field. And again, also this relation convincingly shows up on the map of citation relations between *Scientometrics* and other journals.

All four areas together are major constituents in many of the governmental and European Union (see, for instance, *Lewison*[5]) commissioned programmes where scientometrics is involved.

Keep on moving: Checks and balances

One of the most essential to-be-or-not-to-be aspects of scientometrics is the balance between application and basic research. In the last few years an extensive experience has been gained in the application of bibliometric analysis in the assessment of research performance in many disciplinary contexts. We move into a dialectic situation: on the one side an increased critical attitude against citation analysis, on the other a considerable improvement in this area. Why? I think the above mentioned experiences substantially increased our knowledge on the possibilities and limitations of bibliometric analysis (*Moed* et al.;[6] *Van Raan*[2]). Although criticisms from the field, particularly from sociologists of science, are important, the improved insight into possibilities and limitations is certainly to a larger extent due to more and more critical users. The 'client' now knows much better than, say, five years ago, what he wants. This also means that the relation with the user has also become more validation-oriented. Thus, like in all applied fields of research, the role of the user is crucial to the development of our field. The above mentioned practical experiences will also strongly influence our knowledge on communication practices and knowledge transfer in scientific disciplines. For instance, who is using research results of a specific group or institute, where and when. Given the strong increase of evaluation activities both in Europe (*Gabolde*[7]) as well as in the US (*Kostoff*;[8] *Cozzens*[9]) and Canada (*Smith*[10]) it is of major importance for our research field that bibliometric analysis acquires and keeps a vital role in evaluation. It is in this environment of growing interests in evaluation practices that a part of the science and technology studies research community and related consultants reinforced their critical attitudes against bibliometric methods by stressing that bibliometric indicators are just social constructs.

Are we, scientometricians, troubled by poverty of theoretical content as some pessimists in our community preach (*Glänzel* and *Schoepflin*[11])? I don't think so. Do not expect a classical mechanics of scientometrics. It doesn't exist. At the most there are 'reasonably strong' models providing us with a reasonably coherent set of theoretical notions which allow us to reasonably interprete observed phenomena. But models are just as-if-things. An nice example of such a 'reasonably strong' model is the idea of science as a complex, self-organizing system. Theoretical notions belonging to this model are based on analogies with physical, chemical and biological complex systems. It offers us the possibility to understand more about the many skew, 'power-law' distributions that characterize so many scientometric phenomena. Work on Lotka-distributions, but even more on Zipf-distributions is still interesting, not because of its umpteenth prove that this or that shows again the Zipf-distribution, but to understand this distribution and especially small deviations from the usual power exponent, as fingerprints of specific complex systems. The study of self-organizing properties provides us interesting models of scientific development, without the claim of being 'The Theory'.

Other theoretical issues concern, for instance, citation practices. We mention the work on 'cognitive resemblance' between citing and cited articles. But still 'reference behaviour' remains as a subject which has to be explored more thoroughly. Fortunately, there are new and exciting possibilities in relation to the rapidly evolving phenomenon of electronic publishing (*Roosendaal*[12]).

In fact most theoretical issues are concentrated around one earlier mentioned central question: what is scientific progress, and, more specifically, how is the network of scientists and its 'external features' such as publication and citation practices related to the concept of progress. And how does scientific progress exert influences on, and is influenced by society?

In the above, I emphasized the duality between applied and basic research. This means that a major part of research management in our field must be devoted to keep a balance between application and basic work. Governments, European Community, universities and research organizations commission research and services for practical activities such as measuring scientific strengths and weaknesses. Research councils fund work on basic research topics such as the dissemination of knowledge in and between fields of science. This balance between application and basic work is also reflected in the research output of the scientometric community. Research results of our scientometric community can be found in typically application-oriented reports to the

European Commission. And rather exotic basic-research work in published in *Nature*. We notice that it is not the field as such that manifests itself. It is always the active scientist who puts a smaller or larger milestone in an area which he or she finds relevant. He or she, the active scientist, in fact defines what the field looks like, and how it relates to other fields of science. Scientometrics is not in a crisis, but in a fascinating stage of development. As science and technology directly relate to the entire domain of human knowledge, there is a manifold of possible relations between scientometrics and other disciplines to explore.

Next to citation-analysis based approaches, relational techniques or 'mapping' represent a second main methodological development based on bibliometric data. Here too we have the stimulating duality of application and basic research. Techniques related to co-citation and co-word analysis are used to map scientific fields (using publication data) and technological fields (using patent data), as well as their development over time (*Tijssen* and *Van Raan*[13]). Cluster analysis, multidimensional scaling, and related mathematical methods are applied and extended in order to develop a cartography of science and technology. Recently, also neural network based techniques are used to shape structures of scientific fields. Such 'abstract' landscapes of science, with the position of the major actors on the map, are specific representations of scientific activities. They do have practical ('strategic overviews') as well as more cognitive values (e.g., what type of scientific activities are primarily represented on the map). Such maps are the object of discussions, particularly on a more or less philosophical, 'ontological' level: what do we really see on these maps, what do they represent? The development of bibliometric cartography, although basic principles such as co-citation and co-word relations are already known for a long time, is far from a mature state. It is again primarily the user who decides about the value of a cartographical representation. This interaction with users has become an inalienable part of our research work. It incorporates, as argued before, the process of validation. Therefore, it is also one of the major sources of progress in our field. The near future of these mapping techniques, however, will undoubtedly not lie in scientometrics but in a much broader scope of generic technologies called 'data-mining' and 'knowledge discovery'.

Will this interaction with users make the scientometrician a user-dependent, or even 'un-critical' scientist? Not at all. Two things are important here. First, the spectrum of users should be broad enough to create a relative independence with respect to specific users. For example, not only users in the private, business sector, but also in the public-domain, the more societal-relevance oriented users. Second, as stated before, one has to keep the balance between application and basic research. Here, leading researchers carry a management responsibility to balance basic and practical work. This interaction between application and basic work is necessary, for instance, in the definition and operationalization of concepts such as relatedness of scientific (or technological) subfields, interdisciplinarity, internationality, 'ageing', 'growth', or rather: progress of knowledge.

Scientometrics: An application-driven research field

Given the many possibilities for application, it is not a surprise that a considerable part of scientometric research is in fact devoted to the development and 'maintainance' of information systems on science and technology. Therefore, we mentioned this activity as the second main part of scientometric research. The know-how acquired in the first part, the indicators work in all its aspects, together with the basic data, must be systematically structured in what we could call a 'bibliometric information system'. So this system does not only contain typical citation index data. It must also contain data from other sources as well: keywords, classification codes, abstracts, etcetera. But above all it must incorporate 'solutions' for the many technical and methodological problems related to the design and construction of all types of bibliometric indicators. These solutions are encoded in the system in the form of software algorithms (for a discussion of these 'added values' see *Van Raan*[2]). This makes it possible to deal with the so-called 'standardisation' problems of bibliometric indicators (see for instance: *Glänzel*;[4] *Braun* et al.;[1] *Moed*;[15] *Katz*[16]) as the encoded algorithms are a clearly visible part of the applied indicator procedures.

Based on experiences, i.e., the results of successive applications, the bibliometric data system 'grows' continuously by adding important practical knowledge, again in an encoded way. For instance, variants of author names and addresses; information about institutional, regional or national infrastructure; and additional data from institutional research reports such as the many types of 'non-SCI publications'. Also based on experiences are the methodological improvements such as better standards for international comparison of impact. And last but certainly not least, any advanced bibliometric data-system must be organised in such a way that the rapid developments in electronic publishing and in relevant Internet facilities – such as the high-energy physics SPIRES database of the Stanford Linear Accelerator Centre (SLAC) – can be included as soon as these developments prove to play a non-negligible role in bibliometric studies. For our group in Leiden it is a major task to meet the bibliometric challenges of this expanding data universe (*Roosendaal*[12]).

Needless to say that this part of the scientometric research programme necessitates high-quality work on system design and software development in order to handle the enormous amount of data (GBytes) and to apply algorithms for the calculation of a wide range of indicators. Here scientometricians are information scientists, some of us are even respectable software engineers.

This, call it 'instrumental' progress, will also improve our basic work in quantitative studies of science considerably. Compare it with astronomy and its development based on increasingly better instruments. It is clear that a bibliometric data-system – in Leiden we often call it The Machine – is becoming better and better by addition of further 'modules' of new, well-organized data, new algorithms, and other new, encoded information. Important examples are the addition of 'high quality' addresses and of patent data, more particularly patent citation data.

We already mentioned that these approaches (translated in algorithmic routines) brings scientometrics into a new domain of information science: sophisticated 'data mining' and 'knowledge discovery'. It is fascinating to identify the main 'hidden patterns' in the enormous amount of data as all these publications and patents are connected by common references, words, classification codes ('co-occurrence' of references, words and codes). The earlier mentioned co-citation and co-word techniques are examples of approaches to unravel this gigantic network of interrelated pieces of scientific knowledge. Although conceptually the above mentioned techniques are quite old, it is just a begin of fascinating possibilities to image cognitive processes. Don't blame a painter that he is not original because he is using an old fashioned paint brush.

We defined as a third area of scientometric research the interaction between science and technology. Investigations include studies on author-inventor relations (i.e., scientists who are active both in writing research publications as well as in creating technological breakthroughs), citation relations between patents and publications, and mapping representations of the 'interface' of science and technology. Recently, we also observe the increasing importance of the combination of non-bibliometric approaches (data on the social and organizational infrastructure of R&D fields) and bibliometric approaches to map the different aspects of networks in scientific communities with strong technological interests.

The fourth area of scientometric research, the study of cognitive and socio-organisational structures, draws heavily on both main instrumental pillars of scientometrics: citation-analysis and mapping. The aim is to find the best possible representations on different aggregation levels. Although certainly one single or a few data-source will not cover the disciplines involved completely, major structures and developmental trends (by making a time series of maps) have been made visible. Other projects are devoted to the lower aggregation levels, such as disciplines or, in particular, emerging fields (*Debackere* and *Clarysse*[17]). Especially on the disciplinary and field level it is possible to further explore the earlier mentioned idea of complex and 'self-organizing structures' in scientific and technological development. But, as said before, we should not expect miracles of this model. After all, about everything happening on this planet is the result of 'self-organisation'. We need more thorough empirical work to aggravate our model-based framework. This work is typically basic, and a good example of research in which more theoretical and empirical research goes hand in hand.

Important results and further prospects

Bibliometric research performance analysis is now advanced in several places to a level that can be characterized as methodologically and technically sophisticated in terms of variety of indicators, applied to different aggregation levels, and automation.

After pioneering work on the basic principles and first large-scale application of bibliometric analysis on the level of research groups, we now see more and more applications often in fruitful combination with peer review assessments (*Moxham* and *Anderson*;[18] *Van Raan*[2]). We also mention important work on the application of bibliometric analysis in the social sciences, the humanities, and in the applied sciences (see, for instance, *Nederhof* and *Noyons*[19]). Given the almost epidemic increase of evaluation procedures all over the world, it is important to strive for bibliometric work of the highest possible quality, in order to have an invariant, objective reference frame.

Important discipline-specific studies reveal communication and collaboration characteristics on the national, regional and international level (*Zitt* et al.[20]). Bibliometric assessment of research performance proves to be a valuable method for the identification and evaluation of strengths and weaknesses in scientific achievements, together with a clear, empirically supported set of conditions determining the applicability of indicators. These conditions concern the nature of the specific discipline or field of science, aggregation level, communication practices. We already emphasized that criticisms within our field and from neighbouring fields such as sociology of science are not able to contribute more than the improvement of bibliometric indicators stimulated by users. This means a kind of 'cognitive switch' in scientometrics. The user is often more important than the colleague-scientist. This is perhaps the most striking proof that quantitative studies of science and technology has become primarily a field of applied research.

The construction of science and technology information systems and their empirical foundation are highlighted in technical reports as well as in publications in which specific parts and properties of the system are described. Very important and heavily underestimated instrumental facilities are the creation of high-quality databases of unified and 'hierarchized' addresses of scientific institutions worldwide and an extensive automation of bibliometric analysis together with a further development of user-interfaces. Advanced bibliometric performance analysis has now become a highly computerized procedure. Only this makes it possible to develop better and more user-specific 'options' of bibliometric information products.

The creation of national and international observatories and the incorporation of bibliometric indicators can be considered as a milestone. We see a rapid addition of scientometric-but-not-bibliometric data, such as data on human resources, infrastructural facilities, and funding. Several important publications in international conferences and scientific journals mark the state-of-the art in the study of the interaction between science and technology. Examples are research on the development of socio-economically important R&D fields (*Grupp* et al.[21]). Recent work on patent citations (*Narin* et al.[4]) revealed remarkable features of the role of US universities with respect to technological progress. These findings are quite contradictory to, for instance, the ideas of governmental advisory committees (particularly here in the Netherlands) about the research function of universities.

An important development is the analysis of actor-networks in socio-economically important fields of science and technology. Here also bibliometric and non-bibliometric techniques are combined increasingly. Such developments prevent that scientometrics and quantitative studies of science and technology in general degenerate to a rather isolated field of research.

The study of cognitive and socio-organizational processes in the development of scientific and technological fields is largely driven by efforts in the advancement of mapping methods. The discovery of the fractal nature of co-citation clusters reinforced an important programme line devoted to the idea of the 'self-organized' cognitive structure ('ecosystem') of science. The meaning of fractal dimensions and of power-law cluster-size distributions are central theoretical issues. An essential piece of work will be to explain power-law cluster-size distributions (a spatial property) in terms of ageing and growth of knowledge (a temporal property). We emphasize that the concept 'self-organizing system' can mean two related but still discernable things. First, the idea of science and technology as a complex, self-organizing system in the formal sense. And second, the use of self-organizing 'mechanisms' to make a structure of science and technology. For instance by using algorithmic rules for clustering 'knowledge carriers' – such as publications and patents – on the basis of similarities. I call this the algorithmic idea of self-organizing structuring.

After pioneering work important new approaches to clustering of data and imaging of the cluster-(dis)similarities are now being explored. Major methodological and technical problems are optimal mapping at the different aggregation levels and their interconnections, and the transformation of maps as a function of time. Both theoretical and empirical work is aiming at solving these problems. For instance, the problem of revealing dynamical properties from a time series of maps.

In the next few years scientometric research will proceed along the main lines of the above sketched programme. Recent large-scale application of bibliometric indicators lead to important questions that have to be solved in order to make further progress. For example, one of the most challenging problems is the 'delineation' of scientific and technological fields, in particular inter- and multi-disciplinary fields. What precisely is energy research, environmental research, information science, or cognitive science? How are these fields related to their different 'mother disciplines'? As such interdisciplinary fields are of increasing societal and economic importance, it is necessary to have as good as possible methods to assess the state of the art of these fields (past, present, and near-future). Substantial contributions to the solution of this problem can be expected from a further development of mapping methods, in particular those based on what we called earlier the algorithmic idea of self-organizing principles. Here evidently this programmatic line merges with the study of the cognitive structure and development of scientific fields.

Another important research issue is the influence of types of scientific communication other than publication in international journals (e.g., 'non-indexed' journals, books, proceedings, reports, and, not in the last place, the electronic media). Such a study is necessary for a better understanding of research performance in the different fields of science, particularly in application-oriented fields.

In the coming years we foresee important progress in the extension and improvement of the earlier mentioned large bibliometric information systems. Crucial will be our capabilities to effectively merge major databases. Here collaboration with science publishers is crucial, in terms of financing as well as of the indispensable exchange of know-how. The work on the extension of databases of scientific addresses is a very important part of the information system. Such a database allows us to study the relation between production, distribution and 'consumption' of scientific information. In fact, it is 'all there', but it must be organized and combined in a sophisticated way.

Recent improvements of bibliometric research performance assessment methods will allow us to identify and analyse the role of collaboration networks, the position of centres of excellence within or outside such networks, the influence of increasing external funding on scientific progress and on distribution modalities of scientific information. Undoubtedly, the application of bibliometric methods may induce intended or unintended 'feed-back' effects. Thus we will pursue studies aiming at 'induced' changes of publication practices and of research scope.

An essential part of the research – at least for us in Leiden – will be a considerable improvement of co-word analysis. A new method, based on the application of automated natural language analysis will enable us to create a 'next generation' mapping instruments. The application of Kohonen neural networks is part of this challenging research project. Needless to say that especially this part of our programme is very appropriate to create strong research themes with data theory, experimental psychology, cognitive science, information science and psycholinguistics.

Another important research issue will be the 'tracing' of breakthrough-events in the interface of science and technology in order to improve our understanding of the genesis of innovations. Perhaps it is possible to find characteristic patterns, especially in the way different earlier breakthroughs are 'locked-in' together before a socially and economically radical innovation can take place.

The above sketch of current and near future developments in quantitative studies of science and technology also makes clear that our research work, the field of scientometrics, has a societal impact. Needless to say that evaluation of scientific and technological development is an important political issue, given the large amount of money involved and the crucial influence of science and technology on society. Performance assessment methods are becoming more and more accepted and are increasingly more applied, on a national scale and internationally. Also the media and the public are interested to know the state of the art in science and technology. Results of assessments studies often find their way to newspapers, weeklies, radio, and presentations for groups of scientists, policymakers, interested laymen. Scientometric researchers are frequently asked for such 'enlightenment' activities. The societal relevance of scientometric research is also clearly visible in the large amount of applied research, service work and consultancy for universities, research organizations, government, European Commission, and the business sector.

The bibliometric information system is an important development for information technology in general. We already mentioned applications of the algorithmic self-organizing approach. This approach is not only of importance to find a way in the ever-expanding universe of data. It can also be used to explore and to exploit our existing knowledge (the 'human knowledge archive'). Indeed, this archive is so large (growth rate about a million publications and patents per year!) that new techniques are necessary to see 'what knowledge we already have', the cohesion and connections of all this knowledge and, very importantly, to observe and analyse the relation between new knowledge at the archival knowledge.

Concluding remarks

For the health of scientometric research we emphasized the balance between applied research (often in relation to services and consultancy) and basic research. In my role as an institute's director, it is a major research management challenge to keep these aspects, applications and basic work, empirical and theoretical approaches, in balance. Next to this 'conceptual balancing' it is of vital importance to strengthen the relations of scientometrics with a broad spectrum of disciplines. The most essential point here is that scientists from those 'other' disciplines get interested in scientometric work. That makes a scientometrics research programme attractive, colourful, and of high quality.

We have to improve the relation with the 'customers', particularly in evaluation procedures. Recently, we have become confronted very severely with extreme reactions from the side of researchers who are involved in these evaluation procedures. Especially when such evaluations are evidently related to budget decisions, we need more attention for aspects as accuracy of data collection, possible 'options' for indicators and their meaning for current situations. Bibliometric analysis must more than ever be accompanied by very careful advisory work based on extensive experience in scientometric research and applications. In the coming electronic publishing developments we probably will see a merging of new modalities of citation behaviour with new ways to certificate quality of papers.

I already mentioned that science and technology are directly related to the whole domain of human knowledge. This offers many possibilities to explore the linkages between scientometrics and other academic disciplines. It indicates the role scientometrics can play in an academic environment. The extent to which we'll be able to succeed in making these linkages fruitful in both a scientific as well as an applied sense, will largely determine the role scientometrics can play in the next future in the arena of established disciplines.

In most cases, do not expect progress from 'theoretical breakthroughs', new 'visionary ideas' or other things that may sound conceptually attractive but remain practically vague. The way we in Leiden contribute to the development of this field is simply the following. We have taken mostly small and sometimes a few bigger steps, trying to enhance our capabilities and to gain experience by feedback from colleagues but also, and very importantly, from the users.

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