HANDBOOK OF QUANTITATIVE STUDIES OF SCIENCE AND TECHNOLOGY

Edited by

A. F. J. VAN RAAN

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PREFACE

Although numerous publications address general and specific topics in quantitative studies of science and technology, practically no book or other compilation of writings approaches these topics in an integrated manner.

The principal purpose of this handbook is to present this wide range of topics in sufficient depth to give readers a reasonably systematic understanding of the domain of contemporary quantitative studies of science and technology, a domain which incorporates theory, methods and techniques, and applications.

In addressing this domain, the handbook aims at different groups of readers: those conducting research in the field of science and technology, including (graduate) students, and those who are to use results of the work presented in this book.

Although the handbook is thorough in its coverage of topics, it is not and cannot be a complete guide to the field, in all its facets and details. The handbook is rather an integrated set of sketches aiming to capture the most representative aspects of a field which is undergoing significant change.

Many thanks are due to the contributors of this handbook, without whose energy and commitment this volume would not be possible.

I am also indebted to a number of colleagues and guests at the Leiden Science Studies Unit for their criticisms and comments on earlier versions of the contributions and of the book, including its content and organisation.

Thanks go to all those who supported the technical preparation of this book under typically hectic conditions. In particular, my thanks go to Olga van Driel-Stuurop, Rebecca van Rossum-Hamer, Suze van der Luijt-Jansen, and Ludy Piël. Their cooperation reduced the tensions which unavoidably arise when coordinating the work of many contributors and meeting deadlines.

Writing or editing a book is a heavy burden on family life. I want to express my gratitude for the patience of my family, in particular to Clemens and Lukas, who provided technical support for some of my editing activities, and to Paula and little Paul.

Just as this book was going to press, we received the tragic news of the death of one of our distinguished authors Nicholas C. Mullins, on July 6th, 1988. Editor and authors would like to express their deepest sympathy to the relatives and colleagues of Nick Mullins. He will always be remembered as one of the pioneering scientists in the field of science studies and his untimely death will be a great loss to our research community.

A.F.J. Van Raan, Editor.

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Handbook of Quantitative Studies of Science and Technology
A.F.J. van Raan (editor)

INTRODUCTION TO THE HANDBOOK

A.F.J. Van Raan

In studies of science and technology, researchers increasingly are using quantitative methods and techniques. Indeed, this new field, 'quantitative studies of science and technology', is flourishing as result of both a demand from science policy and research management, and the push from those science studies using increasingly advanced statistical and computerized data-handling techniques. Quantitative studies of science and technology therefore represent the research field of utilization of mathematical, statistical, and data-analytical methods and techniques for gathering, handling, interpreting, and predicting a variety of features of the science and technology enterprise, such as performance, development, dynamics. Challenging and potentially powerful methodologies have opened new ways to monitor these scientific and technological features. The field of quantitative studies of science and technology therefore has both strongly developed applied research as well as basic research characteristics.

On the applied side, the demand from science policy for 'objective' data and specific manipulations of data ('science and technology indicators') is a continuous driving force for the development of quantitative studies of science and technology. For a first and appealing review at the end of the seventies we refer to 'Toward a Metric of Science: The Advent of Science Indicators', Elkana et al. (1978). On the basic side, science is a complicated system of knowledge production and knowledge exchange, and the use of empirical methods in which sophisticated data-collection and data-handling techniques play a substantial role, is undoubtedly a prerequisite for the advancement of our understanding.

Inevitably, a handbook is just a snapshot of ongoing developments. But especially in a rapidly developing field like quantitative studies of science and technology, it is important to draw up an inventory, with the character of a review having a special place for new, promising developments as well. The field of quantitative studies of science and technology can be divided in the following, partly overlapping main subfields. First, methods and techniques to develop indicators for the measurement of research performance, applicable for science policy and in research management. Second, methods and techniques to develop indicators for technological performance and for the scientific base of recent technology, applicable for technology policy and in R&D management. Third, methods and techniques to

study cognitive processes of the development of scientific fields and the interaction between science and technology.
In this Handbook, we will follow a more topic-oriented division of the various contributions. The architecture of the book is as follows:
Part I deals with science in a social context; Part II explores the many features of evaluation of research performance and mapping of science; Part III focuses on science and technology, and, in particular, the interaction between the two; and, finally, Part IV addresses some advanced data-analytical methods and techniques.

The book opens with a critical review by Michael Moravcsik. In his chapter, Moravcsik discusses fundamental aspects in the use of science indicators: problems on classification systems used in input indicators; problems in assessing science and, in particular, the use of bibliometric indicators in the developing countries; and problems with respect to assessment methods for areas of Big Science. This latter case is very interesting, since these fields of science are close to the limits of perceptibility, as Moravcsik argues.
Paula Stephan and Sharon Levin address the measurement of scientific output in relation to age. They argue that the aging of the American scientific community has generated renewed interest in the popular hypothesis that science is a young person's game. The empirical evidence bearing on this question, however, is limited and largely inconclusive. They extensively discuss inadequacies of models and methodologies used so far and, most importantly, the problems generated by the lack of a comprehensive longitudinal database with relevant information. The pièce de résistance of their work therefore is the linkage of scientific outpunt measures with the unique US Survey of Doctorate Recipients. Age-productivity profiles for scientists in four research fields are constructed. Special attention is paid to a case study of solid state physics using multivariate techniques.

Nicholas Mullins, William Snizek, and K. Oehler analyse the structural elements which comprise a standard scientific paper: title, authors, affiliation, abstract, text, tables, graphs, charts, photographs, references. They focus on the history, normative tradition, and sociological analysis of a selection of those elements.
Wesley Shrum and Nicholas Mullins focus on the social network concept in the study of science and technology, the analysis of the 'scientific community'. They describe three main classes of quantitative network studies: those which focus on intra-organizational relations; those which focus on inter-organizational relations (e.g., scientific 'specialties'); and bibliometric networks which are linkages of 'products' rather than of people. Shrum and Mullins review these appoaches to illustrate possibilities of network analysis but also to show serious deficiences at all levels of analysis.

Evaluation of research performance and 'mapping of science' are very policy-relevant topics. In their chapter, Andras Schubert, W. Glaenzel, and Tibor Braun emphasize the need of proper reference standards in applying citation-based indicators for evaluative purposes. They present the construction of relative scientometric indicators and demonstrate the applicability of these indicators by comparison of scientific output and impact of twenty countries in four scientific fields. The authors stress the importance of statistical reliability and techniques for useful graphical representation.
Henk Moed and Anthony Van Raan present a review of their 'micro-scale' research performance measurements by bibliometric indicators (the Leiden Science Indicators Project) together with the results of a follow-up study devoted to, in particular, the application of these indicators in a university context. Important methodological, technical, and applicational problems are extensively discussed. Moed and Van Raan emphasize a very central aspect of the use of bibliometric indicators in the assessment of research groups: these indicators are not to be used by non-peers since background information is necessary to interprete the quantitative findings. In fact, their 'micro-scale monitor' can be seen as an interactive tool for peer-review evaluation procedures. Finally, the authors discuss the possibilities for a 'scaling-up' of their method: the application of the developed monitor system to all universities in a country ('Netherlandizing'). This would address an important science policy relevant issue: the assessment of strengths and weaknesses in two 'dimensions': for all fields per university, and for a whole country per field.

Anton Nederhof focuses in his chapter on the validity and reliability of evaluations of scientific performance. A review is given of past applications of bibliometric indicators and peer review. Constraints in the use of bibliometric indicators and peer review with regard to validity and reliability are discussed. Results of a number of relevant current studies are presented. One of these studies is a very interesting comparison of research performance by 'cumlaude' and 'non-cumlaude' Ph.D. students. This study provide further evidence with regard to the validity and reliability of bibliometric research performance indicators. The application of bibliometric indicators in the humanities and social sciences is also covered.

Olle Persson discusses the measurement of scientific output by online techniques. Basic principles and problems of online bibliometrics- as far as output measurement concerns - are outlined. A number of practical examples are given and the results are compared with data generated by other methods. Online bibliometrics is a very topical subject, as witnessed by the recent dispute between Leydesdorff (1988) and Martin, Irvine and co-workers (Anderson et al., 1988). Like Persson's contribution, these papers also concern only output

analysis. Online citation-analysis completes 'online bibliometrics', but it causes important additional problems, especially in the case such techniques are used in the context of evaluation procedures. We refer to recent work of Moed (1988) for a thorough discussion of possibilities and limitations of online citation-analysis.

Arie Rip addresses the lack of systematic, independent data characterizing current activities in 'science map' in a form that can be used by policy makers. He argues that bibliometric 'models' or 'maps' of the literature output of specific scientific fields form a particularly promising possibility to overcome the lacune. As a general definition, Rip takes a map of science to be the visualization of the topology of relationships between elements or aspects of science. Technical and conceptual issues in constructing und using maps are discussed, and the relation to policy goals and utilization is emphasized. A comparison with the development of environmental mapping and impact analysis allows some further critical reflection on the status and policy role of science maps.

Luke Georghiou, W. Giusti, Hugh Cameron and Michael Gibbons describe in their contribution to the Handbook an experimental approach for assessing links between researchers in a collaborative programme. The so called 'co-nomination analysis' was carried out for an interdisciplinary field: man-machine interface research. In co-nomination analysis researchers are asked to nominate those researchers whose work is most simular or relevant to their own. With these data, networks can be constructed by assuming links between co-nominated researchers. The constructed networks were then subjected to expert analysis. Georghiou and his co-workers conclude that co-nomination analysis is particularly useful in areas where bibliometric approaches are inappropriate.

William Turner, G. Chartron, F. Laville and B. Michelet report on the application of co-word analysis, one of the two major bibliometric mapping techniques. They discuss the use of co-word analysis to develop aids for scientific and technological decision-making. The authors designed co-word analysis techniques to monitor the flow of scientific and technical information entering into large databases. This monitor can be used for a systematic analysis of publications in order to produce research field 'profiles'. Turner and his co-workers present results of their work on patent applications in the field of industrial ceramics. The work was aimed at defining the technical specifications of these profiles for use in fixing scientific and technological priorities.

The other major bibliometric mapping technique, co-citation analysis, is extensively discussed in two chapters, one by Jeffrey Franklin and Ron Johnston, and the other by Peter Weingart, Matthias Winterhager

and Roswitha Sehringer. The Franklin and Johnston contribution seeks to advance the process of improving co-citation analysis as a tool for science and technology policy and R&D management. They thoroughly review conceptual and methodological aspects of 'bibliometric modeling' (the alternative name for co-citation analysis). The authors raise and clarify major problems concerning validation, methodology, and utilization for policy purposes. They extensively illustrate 'real-world' policy applications and interpretations of co-citation maps, using recent national policy studies in Great Britain, the United States, Spain, Sweden, and Australia as examples. They argue that difficulties and limitations encountered in these practical applications have led to important innovations in the techniques. Many of the observations are drawn from experiences in an ongoing program in Australia for the exploration of bibliometric models in which the authors are involved. A special problem of co-citation analysis, however, is the commercialization of the technique, which 'obscures' these methodological and technical improvements, since these improvements are partly classified. Peter Weingart, Matthias Winterhager, and Roswitha Sehringer present the application of co-citation analysis to assess strengths and weaknesses of West German science. Another approach to analyze the comparative standing of German science is the use of time series of publication and citation indicators. Also, possibilities to use both approaches in sequence as well as limitations of such a coupling are discussed.

A quite different contribution is Jona' Oberski's criticism of co-citation analysis. He examines the statistical stability of co-citation clusters by means of a model based on a computer simulation. Furthermore, the results of a co-citation analysis commissioned by the Netherlands Advisory Council for Science Policy (RAWB) were judged by Dutch physicists. To his opinion, it seems unjustified to expect the results of co-citation analysis to be of use in the formulation of research policy. Although the RAWB co-citation model must be regarded as a 'first generation' map, the problem of statistical stability raised by Oberski is undoubtedly a very fundamental one.

In the meantime, the work on co-citation analysis is advancing rapidly. The two major problems in mapping of science still are on the one hand of a the cognitive (interpretation, meaning) nature, and of a methodological/technical nature on the other. Both are strongly related: substantial improvement of methods and techniques might improve the cognitive value of the maps. A striking example is the development of scientific fields as a function of time. At this moment, mapping techniques do not allow for a reliable 'linkage' of maps from successive periods of time. In other words, the static pictures cannot be combined into an acceptable 'movie'. Even the single, static pictures (maps) still have severe methodological problems: stability of

the calculated clusters with respects to (small) variations of threshold values; significance versus 'noise'; and, not the least, representativiness of the fields concerned. Very recently, Braam et al. (1988) succeeded in a substantial improvement of the mapping capabilities of co-citation analysis by a combination of data from different data bases. Furthermore, this combined co-citation and word analysis appears to be a powerful tool to test the significance of the co-citation cluster composition and stability.

A rapidly growing area of research interest is the link between science and technology: their mutual interaction, the 'interface' between science and technology, and, in particular, the 'scientific base' of recent technological developments. Francis Narin and Dominic Olivastro discuss the use of the US patent system, in particular citations to and from these patents for the construction of technology indicators. They show that there are valid reasons for believing that highly cited patents are patents of more than average technological impact, and also that patent citations indicate linkages between companies, between technological areas, and between technology and science. The authors emphasize the prominent position of Japan in the US patent system. The application of patent analysis to corporate technological performance is discussed, including the use of indicators of activity, linkage, and impact in application to competitor assessment, merger acquisition targeting, and investment strategy decisions.

Keith Pavitt reviews in his chapter the possibilities and the problem of using patent statistics in analysis and policy making related to technological activities. Advances in information technology have increased the actual and potential uses of patent statistics as a proxy measure of inventive and innovative activities. Pavitt discusses the possibilities of patent analysis in describing and explaining international patterns of technological activity and their effects on economic performance, volume, sectoral pattern, geographical location, and dynamics of technological activity in specific firms and their effects on competitive performance, as well as links between science and technology.

Kees Le Pair argues that bibliometric techniques can lead to erroneous results when used for the evaluation of technology-oriented fields of research. By reviewing an earlier study on the development of the electron microscope, he describes a 'citation gap' and shows that many thousands of citations to technological research ('applicable science') have inevitably been missed in the Science Citation Index. Paolo Saviotti discusses in his contribution to the Handbook various methods used in the measurement of changes in technological output represented products. A technological product is represented by several characteristics, which can be described by specific variables.

As products evolve, their characteristics change, but at different rates. The measurement of technological change then consists of the measurement of the distance between the point representing a particular artifact and some other point representing for example the first technological artifact of a given type. Other methods are based on a combination of technological characteristics and of economic variables. In general, all methods require the manipulation of considerable masses of data. According to Saviotti, the necessity of constructing data bases gives the opportunity to monitor and assess changes in technology.

Hariolf Grupp and Olav Hohmeyer present a quantitative model for the assessment of technological standards for research-intensive product groups and international competitiveness. With this 'technometric' model, the authors discuss technological disparities and national technological standards in the field of lasers, industrial robots, sensors, photovoltaic modules, immobilized biocatalysts, and genetically engineered drugs. Time series up to 1985 for the relative export-import indicator 'Revealed Comparative Advantage' for several western countries are discussed and related to the quantitative findings for the corresponding technological product specifications. Furthermore, trade positions are related to technological standards. The authors arrive at the conclusion that the factor 'technology', and thus 'applied R&D-output', seems to be a very important one when interpreting international competitiveness. Other factors as trade barriers, management ability, and exchange rates probably cannot compensate for technological disparities. For the six technological fields indicated above relations of disaggregated trade classes and technology classifications are analyzed. Serious shortcomings are signalized, and hence requirements for future data bases are discussed.

Quantitative studies of science and technology implies the use and development of advanced data-analytical methods and techniques. In this book, the braod range and variety of these methods and techniques are illustrated by a contribution on a specific topic (the role of journals in the dissemination of scientific knowledge) and by a contribution providing a general overview of multivariate analysis. Elliot Noma reviews in this chapter the method of 'influence weights' for determining the scientific importance of journals. In addition, the author compares influence weights with other influence measures and shows that citation frequency is most determined by journal size (i.e. the number of references given by all articles appearing in the journal) and by journal prestige (as measured by the number of citations received per reference given). Robert Tijssen and Jan De Leeuw present an overview of multivariate data-analysis methods in bibliometric studies. Their contribution focuses on basic possibilities of this analytic toolkit. In addition, the authors introduce a con-

ceptual framework, generating principal types of bibliometric data to which general subclasses of multivariate analysis methods are linked.

The work described in the above discussed chapters of this Handbook is a clear 'measure' of the continued vitality of research in the field of quantitative studies of science and technology and its possible future directions.

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PART I
SCIENCE IN A SOCIAL CONTEXT