publications in a particular subfield *j*, compared with that country's share in citations attracted by publications in the whole field. Again, a value higher (lower) than unity would reflect a higher (lower) than average impact in the given subfield, relative to the world's average.

## Mapping Scientific Publications

Publication output and received citations can be used to assess the research performance of various actors, ranging from individual researchers to departments, universities and research institutes (Irvine and Martin 1985; Martin and Irvine 1983; Rappa *et al.* 1992), scientific communities (Debackere and Rappa 1995; Rappa and Debackere 1992) or even entire countries (Narin 1976) or regions. Since the beginning of the 1990s, a considerable amount of experience has been gained in applying bibliometric analysis in the assessment of research performance (Luwel, various publications on academic performance in Flanders during the period 1995–1999; van Raan 1997). The assessment of research activity involves the computation of a variety of indices that reflect the production, the productivity or the impact of, for example, research groups.

The second stream of research relevant to science policy is concerned with the 'mapping' of scientific (sub)fields. Maps of science can be created with different techniques (Noyons *et al.* 1994, 1998, 1999), among which we find: the co-citation technique (Small 1973), the co-word technique (Callon *et al.* 1986; Law *et al.* 1988; Tijssen 1992), and the combination of both co-citation and co-word techniques (Braam 1991; Braam *et al.* 1989; van Raan and Peters 1989). The aim of mapping science is mainly concerned with understanding both the structure and the evolution of scientific (sub)fields or, as Braam (1991) mentions, displaying both the structural and dynamic aspects of scientific research (Luwel *et al.* 1999; Noyons *et al.* 1998).

Based on the analysis of information from the scientific literature, quantitative techniques are used to display both structural and dynamic aspects of scientific research. Its main purpose often is to display the foci of interest and attention that prevail in a particular scientific area (field or subfield) over a certain period of time (Braam 1991). Maps of science are constructed to display relational aspects in scientific development. Contrary to indicators in the form of frequency lists, ranks or tables, maps can easily provide information on links between scientific entities (Tijssen 1992). Maps, in this sense, are particularly helpful for visualizing the pattern of such a large and/or complex structure inherent in the data.

In his work 'Mapping of Science: Foci of Intellectual Interest in Scientific Literature', Braam (1991) identifies four steps in the bibliometric mapping of science:

(a) the selection of (a set of) relevant scientific documents covering an area of scientific research and the subsequent collection of bibliographic data, derived from these scientific texts;
(b) the construction of a separate data set in which the data are structured in a way appropriate for analysis;
(c) statistical analysis of the bibliometric data; and
(d) some guiding theoretical framework for the interpretation of the results.

The mapping of science is performed by means of relational, two-dimensional indicators that are based on the analysis of the number of times different information items, such as author names, keywords, classification counts or citations, occur together (co-occurrence) (Hinze 1997). By investigating connections through the 'co-occurrence' of references, words and/or classification codes, it becomes possible to unravel the immense network of interrelated pieces of knowledge, and to uncover major 'hidden patterns' in the vast amount of information carried by the scientific literature (van

Raan 1997). The result of such an exercise is often represented in a two-dimensional way, a 'map', in which information items (and the publications containing these items) are structured according to their links, as uncovered in the 'co-occurrence' analysis (Luwel *et al.* 1999). As such, mapping techniques make a systematic use of the information carried by scientific articles possible (Hinze 1997).

In these 'maps of science', the network of cognitive structures present in the scientific activities as reflected in the scientific literature is represented. Mapping is thus based on relational indicators. The co-occurrence of different information items, such as keywords, classification codes or citations is studied, since it is assumed that they reflect linkages between the papers concerned and, as a consequence, also between the underlying scientific activities (Hinze 1997).

As already mentioned, different techniques, making use of different information items included in scientific articles, are used in order to map scientific fields, as well as their development over time.

## Techniques for the Mapping of Science

Within the domain of the mapping of science, four principal types of bibliometric maps can be distinguished: (1) journal-to-journal citation maps; (2) co-classification maps; (3) co-citation maps; and (4) co-word maps. Mapping analyses using co-citation data or co-word data are by far the most popular (Tijssen 1992).

### Mapping by Means of Data on Journals

In this approach, maps of science are derived from existing inter-journal networks. By examining the links between journals as created by citations given to and received from other journals, it is believed that the macro-level structure of scientific activities can be captured. The assumption underlying this approach is that inter-journal citation frequencies reflect the magnitude of subject relation between journals (Tijssen 1992).

### Co-classification Maps

The structure of scientific fields may be studied by representing the relations between subfields as described by classification codes. As a rule, different classification codes are assigned to an individual publication. As such, the co-occurrence of classification codes (or subject-classification terms) can be studied. The number of times different classification codes occur together is taken as a measure of similarity. By means of multivariate statistical methods, this similarity can be represented in a 'map of science', in which the structure of the analysed scientific areas becomes visible. Studies based on co-occurrence analysis of classification codes include van Raan and Peters (1989).

The main advantage of this approach is the relative 'straightforwardness' of the method. Since all classification codes have well-defined meanings, the interpretation of the resulting map should not pose many problems. However, this relative 'straightforwardness' at the same time illustrates the main drawback of the method. Since this kind of analysis is based on an existing classification system, it can never reflect the development of new scientific (sub)fields in an adequate way, simply because classification systems are not updated on a continuing basis (Hinze 1997).

### Co-citation Maps

The mapping of the structure of scientific research can also be done on the basis of citations given by authors in their publications. This is done in co-citation analysis, initiated by Small at the ISI in Philadelphia (Small 1973), and nowadays one of the major quantitative techniques used to map both the structure and the dynamics of scientific (sub)fields. In co-citation analysis, information on how often pairs of articles are cited together in other papers is used to construct maps of scientific research (Hinze 1997). The resulting frequency of co-citation is used to measure the degree of association between two documents. The clustering of documents in co-citation analysis is thus based on existing co-citation relations and, as such, this approach is considered to be an alternative to existing classifications of scientific research activities (Braam 1991).

### *Co-word Maps*

In the field of 'mapping of science', co-word analysis has been developed as a rival technique to co-citation analysis by Michel Callon and his colleagues at the 'Centre de Sociology de l'Innovation' of the École des Mines de Paris, in co-operation with British and Dutch scientists (Callon *et al.* 1983, 1986). Whereas co-citation analysis builds on co-occurrences of pairs of cited documents in publications, co-word analysis focuses on the co-occurrences of pairs of content words related to these publications. These words can consist of manually or automatically established terms, words appearing in the title, in abstracts or from the full text (Braam 1991).

Assuming that words designate specific loci of interest, the number of publications associated with a given word then provides an indication of the number of people involved and time invested in research activities focusing on that particular 'locus of interest'. The degree of overlap between distinct loci of interest can then be measured by the amount of times words occur together in a set of publications. If a set of words appears to co-occur relatively frequently, this can be interpreted as constituting a broader 'problem area' or 'research theme'. Interrelations between distinct problem areas or research themes are then indicated by co-occurrences of words from these different areas (Braam *et al.* 1989).

In order to map the structure of science, co-word analysis can be based on *indexing terms* – 'controlled terms' – which are externally supplied by journal editors or professional indexers at documentation services, or on *keywords* – 'uncontrolled terms' – terms supplied by scientists themselves (Tijssen 1992). The use of 'controlled terms' in a mapping exercise resembles the above-mentioned co-classification analysis, since either some pre-specified terms or some pre-specified classification codes are assigned to the publication. As a result, as in co-classification analysis, when performing a mapping exercise by using 'controlled terms', most recent developments will most likely not be reflected (Hinze 1997).

Moreover, when using 'controlled terms' or classification codes, the result of the mapping exercise may be flawed by what is called an 'indexer effect' (Healey *et al.* 1986). Since both 'controlled terms' and classification codes are assigned to publications by professional indexers, their view about a particular scientific paper may influence the results of the analysis in cases where the assigned terms or classification may not correspond with the authors view. Therefore, co-word analysis based on 'uncontrolled terms', keywords provided by the authors themselves, rather than terms given by the database producer, should be used in preference (Hinze 1997).

The resulting network of co-occurrences between different words, collected from a set of publications, can then provide a detailed insight into the structure of the publication contents. By comparing publications with respect to the occurrence of similar word pairs, co-word maps provide a direct quantitative way of linking the conceptual contents of publications. As such, through the relationships between various research themes as reflected in the occurrence of word pairs, research activities within a particular scientific domain can be depicted (Tijssen 1992). A computer program, LEXIMAPPE, was developed for obtaining graphical representations of co-word maps (Callon *et al.* 1983).

Compared with co-citation maps, co-word maps are found to be more inclusive and more up-to-date, in that the emerging specialities are included relatively more quickly in co-word maps. The main drawback of co-word analysis is that words, or at least their meanings, are not always unambiguous and are frequently context dependent (Hinze 1997; van Raan 1993).

As for the 'mapping of science' in general, Tijssen (1992) notes that such maps are, by definition, only artificial 'snapshots' of abstract structures within the science system, which, in addition, are in a constant state of ongoing development.

## Conclusion

In today's increasingly global and knowledge-based economy, competitiveness and growth depend on the ability of an economy to meet fast-changing market needs quickly and efficiently through the application of new science and technology. The capacity to assimilate and to apply new knowledge in order to improve long-term growth, relies on scientific *inventiveness*. But it is also fundamentally affected by the conditions favouring *innovativeness*. While innovation is ever more important and pervasive, it is recognized that innovation is systemic rather than linear. That is, the process of innovation is multidimensional, involving many different players, firms, researchers, university research centres and policy-makers. Innovation requires highly interconnected systems to be in place, ensuring the transfer of know-how between the different agents mentioned. These transfers are not simply from science to technology, but the agents are typically simultaneously source and destination of know-how transfers. Within this systemic view of innovation, the systems of science and technology are complementary. This requires the development and the application of appropriate measurement instruments and indicator bases allowing both systems to be mapped. In this paper, we have provided a detailed overview on how the system of science can be mapped. We are aware of the fact that the quantitative indicators should be complemented with the fine-grained and shaded opinions and qualitative evaluations of experts in the field. However, this qualification can only benefit from the quantification just outlined. As a consequence, we can expect the need for and the interest in quantifications of the system of science to arise further in the near future. The extensive overview of the basis for quantification, as outlined in this paper, will therefore become an essential element in the 'toolkit' of the science manager and policy-maker alike.

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