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The use of bibliometric indicators to explore industry–academia collaboration trends over time in the field of membrane use for water treatment

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Abstract

Industry–academia collaboration has become a subject of great interest to academics, industry leaders and policymakers, as it is now acknowledged that such relationships are valuable for innovation. The aim of the study reported here is to explore collaboration trends over time in the field of membrane use for water treatment by carrying out bibliometric analysis of scientific publications related to the field. It is part of a broader project looking at factors that influence industry–academia collaborative research in the water sector. Thousand six hundred and seventy eight papers from eight journals from the years 1967 to 2001 were analysed for co-authorship patterns. Thousand three hundred and seventy papers from the last decade were examined for a snapshot view of inter-institutional, cross-disciplinary, industry–academic and international collaboration trends. Results show that the field is highly collaborative with the majority (87%) of papers involving two or more authors. In terms of industry–academic collaboration, there was an increase in the number of papers from 1994 onwards, and a very high proportion (91%) were cross-disciplinary.

Keywords: Bibliometrics; Industry–academic collaboration; Innovation; Membrane science; Water

1. Introduction

In recent years, industry–academia collaboration has become a subject of great interest to academics, industry leaders and policymakers, as it is now recognised that such relationships are very valuable for innovation. New and commercially useful knowledge is the result of interaction and learning processes among various actors in innovation systems, i.e. producers, users, suppliers, public authorities, and scientific institutions (Polt et al., 2001). Also, it is not just new knowledge that contributes to innovation; recombined and rediscovered knowledge also plays a role (Stewart, 1999). The generation and transfer of scientific and technological knowledge are non-linear processes of problem identification and analysis, communication, interaction, and learning by and among the various partners in the innovation process.

Recent studies on industry–science relations have shown that universities as well as public research centres are important as co-operation partners in innovation projects (Polt et al., 2001). Many major technological advances and innovations have resulted from interactions between academics and industrialists (Hameri, 1996). It is well proven that academics contribute to innovation activities mainly by producing new knowledge in specialised fields and offering practical help and assistance (Rappert et al., 1999). Scott et al. (2001) reveal seven key benefits from public research for innovation from previous SPRU (Science and Technology Policy Research) reviews: (i) producing new scientific information; (ii) training skilled graduates; (iii) supporting new scientific networks and stimulating interaction; (iv) expanding the capacity for problem-solving; (v) producing new instrumentation and methodologies/techniques; (vi) creating new firms; and (vii) providing social knowledge. In a study of industry–academic interactions in three fields of advanced technology, Senker et al. (1998) found that the greatest contribution of academia to innovation takes the form of indirect and intangible flows of ideas, knowledge and expert assistance. They, therefore, concluded that the main way to increase academia's contribution to innovation is to increase the number of (informal) communication channels (and thus knowledge flows) between academia and industry.

Although, there are various ways in which academics contribute to innovation, there is widespread lack of

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agreement in many advanced countries on how and to what extent academic research is useful. Calvert and Patel (2002) explain the reasons for this lack of agreement and state that effective policy making, for example on further developing the linkages between academic and industrial research, depends increasingly on timely and accurate information on the nature and extent of research collaboration between universities and industry, and on how it varies across discipline, type of university, sector, firm ownership and time.

Whilst the quality of university–industry interfaces might be a key factor in promoting innovation, the complex and varied nature of such interfaces need to be understood and explored (Rappert et al., 1999). There are various mechanisms via which information and know-how are transferred between universities and industry. These include formal and informal, premeditated and unplanned, direct and indirect channels. Scott et al. (2001) identified four main types of communication channels from the literature: (i) codification (e.g. publications, patents); (ii) cooperation (e.g. joint ventures, personnel exchanges); (iii) contacts (e.g. meetings, studentships, networks); (iv) contracts (e.g. licences, contract research). Regardless of economic sector or industry, the vast majority of industry–university partnerships are of the 'research partnership' type, which mainly involve applied firm-specific research, and where funding from industry is received in exchange for 'intellectual horsepower' in the form of research services and technology (Koch et al., 2000).

Although, there are various types of collaborations, they are all characterised by an exchange of knowledge among participants. It is, however, very difficult to evaluate and measure the effectiveness of this knowledge exchange and its impact on innovation (Polt et al., 2001). The various forms of industry–academia interactions can result in a variety of outputs including new instrumentation, methodologies, prototypes, patents, spin-offs and may also produce co-authored papers. Due to the variety of activities and outputs, no single measure is fully able to capture the complete range of industry–academia collaborations (Calvert and Patel, 2002).

Various barriers and constraints may occur in industry–academia relationships as a result of differences in the purposes, cultures, procedures, consents, value systems and incentives of universities and companies, making communication and collaboration challenging. There has been increasing attention in recent years on the identification of mechanisms for effective university–industry collaboration (Konecny et al., 1995; Rappert et al., 1999; Scott et al., 2001; Barnes et al., 2002). There is evidence that industry–academia relationships are becoming more efficient, particularly in recent years, as a result of changing structures, perceptions (increased appreciation, awareness, mutual trust) and greater flexibility amongst both parties. Another important factor is the increasing support from governments.

There is evidence that the level of industry–academia research collaboration has been increasing over the last 20–30 years (Katz and Martin, 1997; Calvert and Patel, 2002). Various professional, economic, social and political factors encourage research collaboration. The increased value of (science-based) knowledge and information, the 'scientification' of technology, increased costs of scientific equipment, and insufficient government funding are some of the pressures on universities to shift from a 'public model' to a 'commercial model' (Fassin, 1991, cited in Rahm et al., 2000). Katz and Martin (1997) provided six main factors for the increasing level of research collaboration, these are: (i) escalating costs of conducting fundamental science at research frontier; (ii) substantial fall (in real terms) in cost of travel and of communication, accompanied by growing availability and easy access; (iii) science is a social institution where advances depend crucially on interactions with other scientists; (iv) increasing need for specialisation within certain scientific fields, especially those where the instrumentation required is very complex; (v) growing importance of interdisciplinary fields, as some of the most significant scientific advances come about owing to the integration or 'fusion' of previously separate fields; and (vi) various political factors encouraging greater levels of collaboration among researchers.

Some analysts have produced bibliometric evidence of increasing research collaboration. Jointly authored papers reflect collaborative research and are one indicator of links between industry and universities (Katz and Martin, 1997). Using joint scientific publications as an indicator of university–industry collaborations in the UK over 20 years, Calvert and Patel (2002) found a rapid increase in the volume of such collaborations, since the 1980s, but the biggest increases were before the major government policy measures of the mid-1990s (1993 Government White paper). They believed that the increases might be due to the growing need on the part of firms to collaborate with leading edge academic research in an increasing number of new fields of technological opportunity. There is evidence that many new forms of collaboration and communication between universities and industry came about during the 1970s as a result of the recession, which led to major shifts and changes in university–industry relations as traditional approaches were found insufficient (OECD, 1984). During the 1980s, science came to be seen as an activity that needed to be more closely linked to technology with a view to improving economic competitiveness (Calvert and Patel, 2002). According to Meyer-Krahmer and Schmoch (1998), the exchange of knowledge is an important motive that has led to a considerable growth of university–industry interaction in recent years.

Although, universities and industry have various motivations to collaborate with each other (see AURIL, 1997, for an extensive list of such motivations), nowadays many academics see industrial collaboration as a way of gaining increased financial support for their research

(due to lack of public resources) and in industry there is a growing awareness of opportunities for the commercial uses of knowledge (Calvert and Patel, 2002). Also, due to increasing global competition and rapid technological change, governments are actively encouraging collaboration as a means of improving innovation efficiency and therefore, enhancing wealth creation (Barnes et al., 2002).

There have been several studies in the past, in particular large-scale studies, that have explored or measured research collaboration using bibliometric indicators such as co-authorship (analysis of multiple-author or multiple-address publications; e.g. Tijssen and Korevaar, 1997; Hicks et al., 1996; Qin, 1994) or citations (references/citations in papers indicate use of research by others). Cross-sectoral and cross-disciplinary collaboration can be explored by looking at the institutional and disciplinary affiliations of authors, which may be obtained from their correspondence addresses in scientific publications. Bibliometric indicators also provide information on a country's rate of publishing, the rate at which their researchers collaborate internationally and changes in collaborative patterns over time. Very few studies have looked specifically at industry–academia collaboration patterns. Calvert and Patel (2002) point out that despite increasing interest amongst policy makers and others, there have been few attempts at gathering systematic data on the nature and extent of research collaborations between universities and industry.

Although, there are several advantages of evaluating collaboration through bibliometrics, including the public availability of the information, there are some inadequacies in using this method. This has been pointed out by several authors, for example, Katz and Martin (1997) explained in detail why bibliometric indicators such as co-authorship can never be more than a rather imperfect or partial indicator of research collaboration between individuals. Numerous collaborations do not result in a published paper signed by several institution, thus they cannot be detected by co-authorship based indicators (Martin-Sempere et al., 2002). There are also a number of cases where co-authorship may occur without a substantial degree of research collaboration (Calvert and Patel, 2002). Tijssen (1998) states that co-authored research papers listing both a university and a firm are inadequate in reflecting the nature and intensity of public-private R&D linkages. Bibliometric data cannot tell us about the relationship between collaborators, the factors that influence the initiation and ongoing process of collaborative research, how scientists communicated the information, etc. (Qin et al., 1997). It is, therefore, best to combine bibliometric measures with qualitative data when analysing industry–academia collaborations.

The study reported here is part of a broader ranging project which aims to find ways of improving industry–academia collaborative research in the water sector through the use of a number of qualitative and quantitative research methods. The water industry is a good example of a multidisciplinary environment where a range of subject disciplines and scientific, technological and industrial sectors are involved. In the past, the water industry has been characterised as having an extremely well developed internal network, but a generally inadequate external network (Maclean, 2001). In this study, we are looking at research collaboration patterns in the field of membrane use for water treatment through the use of scientific publications. This field is a speciality in the water industry that is characterised by both strong science and strong application (i.e. it is an applied, not pure, science area).

2. Methodology

The aim of this study is to obtain quantitative information on the extent and nature of research collaboration in membrane science and technology for water using bibliometric techniques. In addition to our broad objective of describing the development of collaboration in a relatively new field of research and application, such information is to be used to test a model that illustrates the evolution of research collaboration patterns in the field of membrane use in water treatment over time. Our proposition is that, during the early stages of a new field of research interest, there will be a low level of collaboration in terms of co-authoring, inter-institutional and interdisciplinary collaboration. Then, as more interest and exploitation opportunities are generated and the field becomes more developed, a significant increase in collaborative endeavour occurs. This increase is then followed by a levelling out in collaborative patterns as interest in the field fades and opportunities to contribute dry up. To test this model, we want to investigate the following simple hypotheses:

- the proportion of collaborative papers (those with two or more authors) increases with time;
- the proportion of industry–academia collaborative papers (those with authors from both academic and industrial institutions) increases with time;
- the proportion of collaborative papers with two or more unique subject disciplinary affiliations increases with time (to show interdisciplinarity trends).

Two databases, Aqualine and Water Resources Abstracts, within the Cambridge Scientific Abstracts Internet Database Service, were used to retrieve papers containing the keywords 'membrane' and 'water' from eight scientific journals that publish articles on the application of membranes to water treatment. We asked a small group of experts to name top journals in the field. The journals used for this study are: Aqua (IWA Publishing), Desalination (Elsevier), Environmental Technology (Selper Ltd), Filtration and Separation (Elsevier), Journal of the American Water Works Association (AWWA Publication), Journal of Membrane Science (Elsevier), Water Research (IWA Publishing/Elsevier), and Water

Science and Technology (IWA Publishing). Although, the database search retrieved 1678 papers from the years 1967 to 2001, we collected the disciplinary data (institutional, subject and country) from papers from the last decade (1991–2001) to gain a snapshot view of the patterns in the later stages of the historical evolution of research collaboration in the field.

Where available, we retrieved the following data from the authors' correspondence addresses: institutional affiliation according to type of institution (academic, non-academic research, industry, or government), disciplinary affiliation (subject field of department or industry sector) and nationality (country). A very large number of subject fields were obtained from the authors' disciplinary affiliations, reflecting the interdisciplinary nature of membrane science and technology. A classification scheme was therefore created for all the subjects to facilitate coding of the authors' disciplinary affiliations. All the data was entered into an SPSS (Statistical Package for the Social Sciences) database and after calculating the number of different authors, institutions and countries in each paper, we were able to explore changes over time in the following measures:

- the proportion of single and co-authored (collaborative) papers;
- the proportion of papers corresponding to three different types of collaboration: (i) intra-departmental, (ii) inter-institutional within a country, and (iii) international;
- the proportion of interdisciplinary papers, i.e. those involving two or more unique subject disciplinary affiliations; and
- the proportion of academic–industry (non-academic) collaborative papers.

The results are presented in the following section (Section 3). We would also note that there are some limitations to the bibliometric measures used in this study. These include:

- not all the authors associated with a particular paper may have actually worked together, especially in papers where there is a large number of authors.
- there may be some inaccuracy in the classification of the subject affiliation of some authors as some may not correspond with the author's actual specialisation.

Therefore, the results will only give us an approximate picture of the extent and interdisciplinarity of research collaboration patterns in the studied field.

We also analysed the technological output of the field of membrane use in water treatment over time by collecting information on patents related to this field. Most technology transfer from universities comes in the form of patents. We carried out a search of patents containing the word 'membrane' in the title and 'water' in the title or abstract on the online worldwide database of the European Patents website (ESPACENET.com). A total of 1966 patents were retrieved from the years 1967 to 2001. The results of this search are presented at the end of the results section.

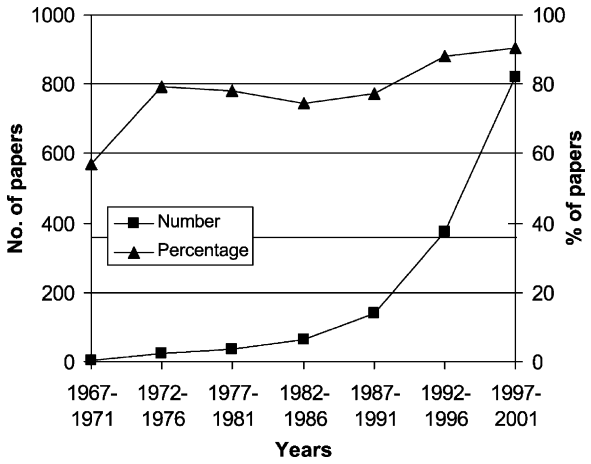

Fig. 1. Trends in the number and percentage of collaborative (co-authored) papers.

3. Results

During the database search we retrieved all the authors' names for all papers (1678) published from 1967–2001 so we were able to calculate the number of authors in each paper and, therefore, the number of single and co-authored papers for the last 35 years. Of the 1678 papers, only 218 papers (13%) were single-authored and the rest (87%) were co-authored papers (i.e. involved two or more authors). Fig. 1 shows the number and percentage of co-authored papers from 1967 to 2001 (5-year ranges).

In Fig. 1, we can see a large increase in the number of collaborative papers over the last 35 years and that the biggest increase occurred over the last 15 years. The proportion of collaborative papers also increased over the 35 years from 57.1% in 1967–1971 to 90.4% in the last 5 years (1997–2001). Fig. 2 shows trends in the percentage of

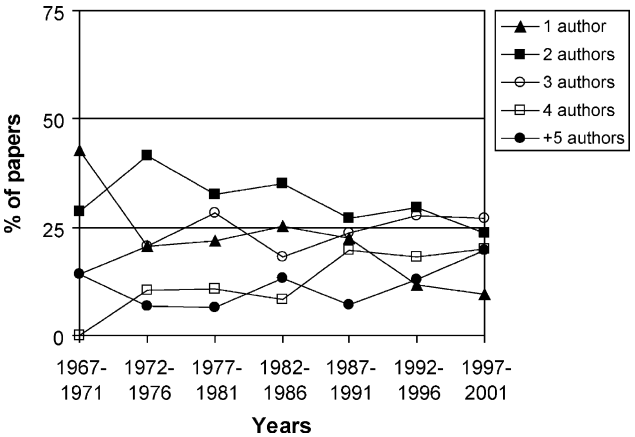

Fig. 2. Trends in the percentage of papers by number of authors.

Table 1
Mean number of authors per paper

Year	Mean no. of authors/paper
1967–1971	3.00
1972–1976	2.78
1977–1981	2.94
1982–1986	3.11
1987–1991	3.18
1992–1996	3.12
1997–2001	3.57

papers by number of authors. No clear trends can be seen here because of the unevenness of the data, but the majority of papers involved two authors throughout the 35 year period. An interesting feature we can see in Fig. 2 is a decrease in the proportions of single and two-authored papers, while the proportions of four and five or more authored papers increased, overtaking that of single-authored papers during the last 10 years.

The mean number of authors per paper was calculated and the results are shown in Table 1. The mean number of authors increased from a minimum of 2.78 in 1972–1976 to a maximum of 3.57 in the last 5 years.

We now turn our attention to a detailed (disciplinary) analysis of the papers from the last decade (1991–2001). Of all the co-authored papers published during that period, half (50.5%) involved collaboration between two or more different institutions and only 14.5% involved international collaboration (between two or more countries). Fig. 3 shows the trends in the percentage of collaborative papers corresponding to three different types of collaboration: (i) intra-institutional (where all authors in the paper come from the same institution), (ii) inter-institutional collaboration within a country, and (iii) international collaboration.

No clear trends can be seen in Fig. 3 in particular for intra-institutional and inter-institutional collaboration which both follow very erratic patterns. Intra-institutional

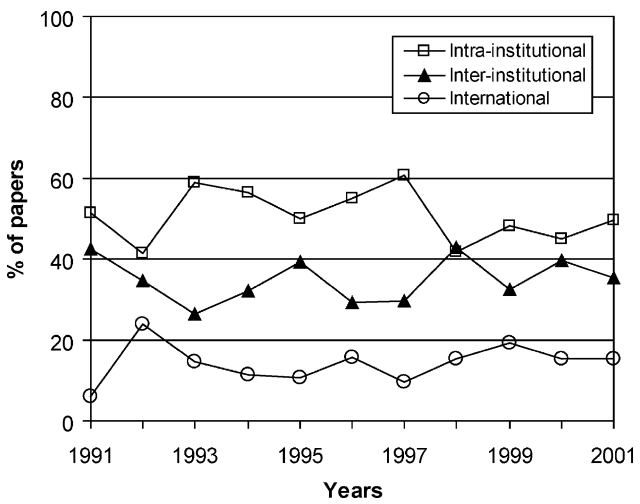

Fig. 3. Trends in the percentage of papers by three types of collaboration.

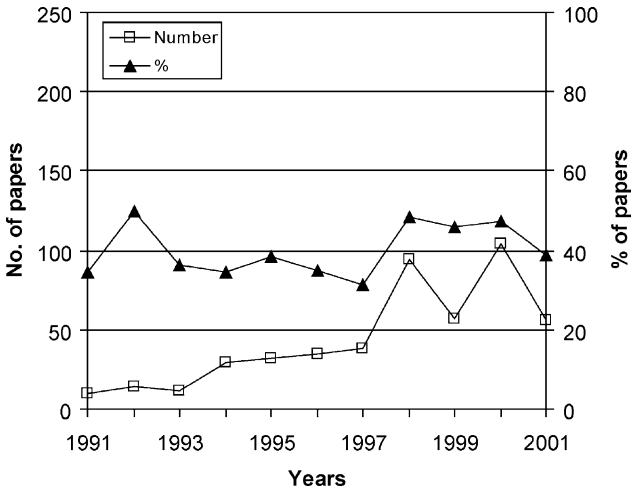

Fig. 4. Trends in the number and percentage of interdisciplinary collaboration papers.

collaboration remained the main form of collaboration throughout the decade. This type of collaboration, however, was lower during the last four years than previously, when the proportion of international collaboration papers was slightly higher (ignoring the % in 1992 which is due to missing data for many papers in that year).

Of all the co-authored papers, 41.5% involved two or more unique author disciplinary affiliations (interdisciplinarity). Fig. 4 shows the changes in the number and proportion of interdisciplinary collaborative papers. A gradual trend towards interdisciplinarity can be seen by observing the increase in the number of interdisciplinary papers over the last decade. Also the proportion of papers that are interdisciplinary was higher during the last 4 years than previously (again ignoring the 1992 data point).

Of all the co-authored papers, 20.7% involved collaboration between academics and industrialists (non-academics). As shown in Fig. 5, there was an uneven increase in both the number and proportion of industry–academic collaborative papers from 1994 onwards (the high percentages for the first few years are due to the low

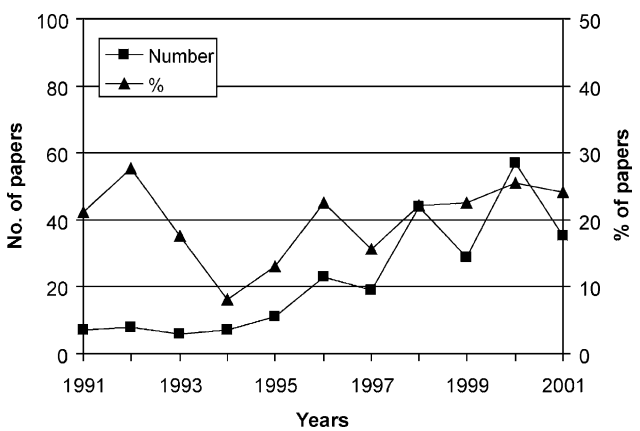

Fig. 5. Trends in the number and % of industry–academic collaborative papers.

Table 2
Mean number of authors per industry–academic collaborative paper

Year	Mean no.of authors/ industry–academic paper
1991	4.00
1992	3.75
1993	4.17
1994	4.00
1995	3.82
1996	4.00
1997	4.37
1998	4.52
1999	4.17
2000	4.70
2001	4.43

Table 3
Proportion (percentage) of industry–academic collaborative papers that are national, international, single-discipline and interdisciplinary

Year	National	International	Single-discipline	Interdisciplinary
1991	100.0	0.0	0.0	100.0
1992	62.5	37.5	0.0	100.0
1993	100.0	0.0	0.0	100.0
1994	71.4	28.6	16.7	83.3
1995	81.8	18.2	9.1	90.9
1996	69.6	30.4	18.2	81.8
1997	89.5	10.5	5.3	94.7
1998	75.0	25.0	7.1	92.9
1999	65.5	34.5	0.0	100.0
2000	73.7	26.3	10.7	89.3
2001	65.7	34.3	14.3	85.7

number of papers). There was also an erratic increase in the mean number of authors per industry–academic collaborative paper, which ranged from a minimum of 3.75 authors in 1992 to a maximum of 4.70 authors in 2000 (Table 2).

Fig. 6 shows the trends in the percentages of industry–academic collaborative papers by number of authors. Interestingly, the proportion of papers involving five or more authors remained higher than the proportions of papers involving 2, 3 or 4 authors during the last 5 years (1997–2001).

Table 3 shows the percentage of industry–academic collaborative papers that are national and international, and of those that involve a single subject discipline and two or more subject disciplines (interdisciplinary) as reflected in the disciplinary affiliations of authors. There are no clear trends in Table 3, but a very high proportion of the industry–academic papers were interdisciplinary (91.1% of all industry–academic papers are interdisciplinary). Just over a quarter (26%) of all the industry–academic papers involved international collaboration.

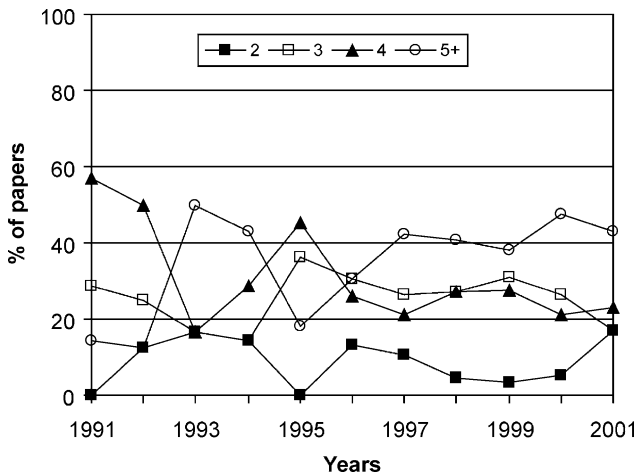

Fig. 6. Trends in the percentage of industry–academic papers by number of authors.

We also analysed the differences in collaborative patterns between different countries. Historical development, cultural and social attitudes, political decisions and objectives, institutional settings and economic specialisation and structures result in country-specific patterns of industry–science relations (Polt et al., 2001). In 1991, 17 different countries published a paper in the field of membrane applications to water treatment and in 2001 45 different countries published a paper. Table 4 shows the number of papers that involved authors from four dominant countries: UK, USA, Japan and France, over the last decade. The UK has the lowest number of papers published in the field compared to the three other countries. The proportion of 'UK', 'USA', 'Japan', and 'France' papers that involved international collaboration (for each year) are shown in Table 5.

France has the highest proportion (40.7%) of international collaborative papers and Japan has the lowest proportion (17%). For the UK, the proportion of international collaboration appeared to have significantly increased over the last decade, from 0% in the early 1990s to 55.6% in 2001. Table 6 shows the proportion of industry–academic collaborative papers for each of the four countries. The UK has the lowest proportion (13%) of industry–academic collaborative papers and France has the highest proportion (36.3%).

Table 4
Number of papers with authors from UK, USA, Japan and France

Year	UK	USA	Japan	France
1991	3	1	9	7
1992	3	13	7	3
1993	4	5	2	8
1994	7	27	32	7
1995	14	27	7	6
1996	11	9	17	10
1997	11	15	11	11
1998	17	36	24	32
1999	10	26	11	16
2000	15	36	32	25
2001	9	27	13	10
Total	104	222	165	135

Table 5
Collaboration with other countries (percentage of papers/year)

Year	UK	USA	Japan	France
1991	0.0	0.0	11.1	14.3
1992	0.0	23.1	0.0	100.0
1993	0.0	0.0	50.0	37.5
1994	14.3	18.5	18.8	42.9
1995	28.6	3.7	0.0	50.0
1996	27.3	22.2	11.8	50.0
1997	18.2	20.0	9.1	27.3
1998	35.3	25.0	16.7	34.4
1999	20.0	19.2	18.2	56.3
2000	26.7	25.0	25.0	36.0
2001	55.6	33.3	23.1	50.0
Total	26.0	20.7	17.0	40.7

Fig. 7 shows the patent output for the field over the last 35 years. The number of patents started to increase significantly from the mid 1970s, but the biggest increase occurred between 1995 and 2000. The trend is quite similar to the trend in the number of publications in the fields (Fig. 1).

4. Discussion and conclusions

The first point to note about the data set we have analysed is that the field of membrane science applications to water treatment is a highly collaborative area of research. In relation to the hypotheses, which were laid out above, the study findings showed that:

- there was an increase in the proportion of collaborative papers (those involving two or more authors) over the last 35 years;
- there was an increase in the proportion of industry–academic collaborative papers from 1994–2001 (the patterns prior to 1994 were erratic due to insufficient data);
- there was no increase in the proportion of collaborative papers with two or more unique subject disciplinary affiliations over the last decade, but the percentage did remain higher during the last 4 years than previously.

Table 6
Academic–non-academic collaboration (percentage of papers per year)

Year	UK	USA	Japan	France
1991	0.0	0.0	33.3	28.6
1992	0.0	46.2	0.0	66.7
1993	0.0	20.0	50.0	12.5
1994	0.0	3.7	12.5	42.9
1995	21.4	3.7	14.3	33.3
1996	0.0	22.2	29.4	40.0
1997	18.2	6.7	18.2	18.2
1998	5.9	22.2	29.2	37.5
1999	10.0	15.4	27.3	43.8
2000	13.3	30.6	43.8	36.0
2001	44.4	29.6	23.1	50.0
Total	12.5	19.4	26.1	36.3

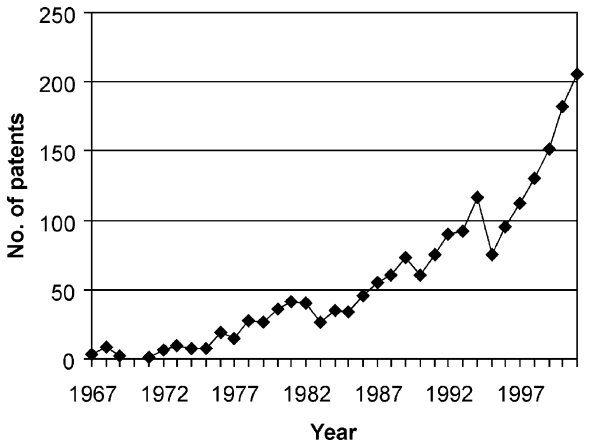

Fig. 7. Number of patents from 1967 to 2001.

In general terms, the results demonstrate the growth in the field of membrane use for water treatment over time by the increase in the number of papers. The rate of growth was slowest during the early stages of the field (1967 to mid 1980s; see Fig. 1) and fastest during the last decade as the field becomes more developed. The disciplinary trends over the last decade, however, only partly support the model we proposed and there is clearly a case for looking at trends over an extended time period. An unanticipated and interesting feature of the data analysis is the decrease in the number of single-authored papers and the increase in the number of four or more authored papers over the last 35 years. Also the proportion of industry–academic collaborative papers involving 5 or more authors was greater than those involving 2, 3 or 4 authors during the last 5 years. Specifically, the increase in the number of papers authored by large (>4 authors) groups might suggest that larger collaborative groups become gradually more common (or just more successful?) in mature fields of research.

It appears that the higher proportion of interdisciplinary papers during the last 4 years (1998–2001) is related to the lower intra-institutional collaboration, and therefore, higher inter-institutional collaboration (in particular international) observed at the same period. The increase in the proportion of papers involving industry–academia collaboration happened before that period, in 1994. It occurred at about the same time as the major government policy measures of the mid-1990s (1993 Government White paper). This will, however, need to be confirmed by analysing the early papers. Another factor related to the higher interdisciplinarity is the increase in the number of papers involving four or more authors, in particular the high proportion of industry–academic papers involving five or more authors observed during recent years (1997–2001). The increase in industry–academia collaboration, which started in 1994, appears to have contributed to the rapid increase in the number of patents from 1995 onwards.

We can conclude that although some interesting aspects have been obtained from this study, the 11-year snapshot view does not provide us with enough data to be able to assess whether the model illustrating the chronological evolution of research collaboration in the field of membrane use in water treatment is supported, because the timescale of available data is relatively short. Also, as indicated by the rapid increase in the number of papers in recent years, the field does not appear to have reached maturity yet. It would, however, be useful to analyse the disciplinary patterns of the earlier publications, from the earliest year (1967) to 1991 to obtain a clearer and more complete view of the development of both industry–academia and interdisciplinary collaboration in this field. The outputs from this study have provided us with an approximate but nevertheless interesting overview of the collaboration patterns of individuals involved in the use of membranes for water treatment over the last decade.

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References

AURIL, 1997. Research partnerships between industry and universities—a guide to better practice. AURIL (Association for University Research and Industry Links)/ICARG. CBI (Confederation of British Industry) Publications.

Barnes, T., Pashby, I., Gibbons, A., 2002. Effective university–industry interaction: a multi-case evaluation of collaborative R&D projects. European Management Journal 20(3), 272–285.

Calvert, J., Patel, P., 2002. University–industry research collaborations in the UK. Report on Phase 1 of a project funded by EPSRC/ESRC Contract No. P015615. SPRU, Brighton.

Fassin, Y., 1991. Academic ethos versus business ethics. International Journal of Technology Management 6(5/6), 533–546.

Hameri, A.-P., 1996. Technology transfer between basic research and industry. Technovation 16(2), 51–57.

Hicks, D.M., Isard, P.A., Martin, B.R., 1996. A morphology of Japanese and European corporate research networks. Research Policy 25, 359–378.

Katz, J.S., Martin, B.R., 1997. What is research collaboration. Research Policy 26, 1–18.

Koch, N., Auspitz, C., King, B., 2000. Using the web to enable industry–university collaboration: an action research study of a course partnership. Informing Science 3(3), 157–166.

Konecny, E., Quinn, C.P., Sachs, K., Thompson, D.T., 1995. Universities and Industrial Research. The Royal Society of Chemistry, Cambridge.

Maclean, A., 2001. Network on the control and prevention of odour emissions. Review of Year One October 2000–October 2001. Cranfield University, [http://www.cranfield.ac.uk/sims/odournetwork/background/ann_rep_1.pdf] (accessed 22/05/04).

Martin-Sempere, M.J., Rey-Rocha, J., Garzon-Garcia, B., 2002. The effect of team consolidation on research collaboration and performance of scientists. Case study of Spanish university researchers in Geology. Scientometrics 55(3), 377–394.

Meyer-Krahmer, F., Schmoch, U., 1998. Science-based technologies. University–industry interactions in four fields. Research Policy 27, 835–851.

OECD, 1984. Industry and university—new forms of co-operation and communication. OECD (Organisation for Economic Co-operation and Development), Paris.

Polt, W., Rammer, C., Schartinger, D., Gassler, H., Schibany, A., 2001. Benchmarking industry–science relations in Europe—the role of framework conditions. EU Project (DG Enterprise). Brussels, [WWW document: ftp://ftp.cordis.lu/pub/improving/docs/ser_conf_bench_polt.pdf] (accessed 22/05/04).

Qin, J., 1994. An investigation of research collaboration in the sciences through the philosophical transactions 1901–1991. Scientometrics 29(2), 219–238.

Qin, J., Lancaster, F.W., Allen, B., 1997. Types and levels of Collaboration in interdisciplinary research in the sciences. Journal of the American Society for Information Science 48(10), 893–916.

Rahm, D., Kirkland, J., Bozeman, B., 2000. University–industry R&D collaboration in the United States, the United Kingdom, and Japan. vol. 1. Library of Public Policy and Public Administration, Dordrecht.

Rappert, B., Webster, A., Charles, D., 1999. Making sense of diversity and reluctance: academic–industrial relations and intellectual property. Research Policy 28, 873–890.

Scott, A., Steyn, G., Geuna, A., Brusoni, S., Steinmueller, E., 2001. The economic returns to basic research and the benefits of University–Industry relationships. Report for the Office of Science and Technology, by SPRU (Science and Technology Policy Research). University of Sussex, [WWW document: http://www.sussex.ac.uk/spru/publications/econreturnsost.pdf] (accessed 22/05/04).

Senker, J., Faulkner, W., Velho, L., 1998. Science and technology knowledge flows between industrial and academic research: a comparative study. In: Etzkowitz, H., Webster, A., Healey, P. (Eds.), Captilizing knowledge: New Intersections of Industry and Academia, Albany, New York, pp. 111–132.

Stewart, G., 1999. The partnership between science and industry: co-operation or conflict of interest. The British Library, London.

Tijssen, R.J.W., 1998. Quantitative assessment of large heterogeneous R&D networks: the case of process engineering in the Netherlands. Research Policy 26, 791–809.

Tijssen, R.J.W., Korevaar, J.C., 1997. Unravelling the cognitive and interorganisational structure of public/private R&D networks: a case study of catalysis research in the Netherlands. Research Policy 25, 1277–1293.

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