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Unravelling the cognitive and interorganisational structure of public/private R&D networks: A case study of catalysis research in the Netherlands

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Abstract

This paper presents findings of a study that discloses key features of the Dutch R&D network in the area of catalysis, a sub-domain of industrial-relevant chemistry. The input comprises empirical data on collaborative research publications, informal network ties, and formal R&D linkages. The study aimed at identifying all public and private sector research organisations involved in the network, characterising their R&D output in terms of international scientific papers and patents, and describing and analysing relational and positional dimensions of their interorganisational network. The results provide an overview of Dutch activity within the worldwide cognitive landscape of catalysis R&D – from both a scientific and technological perspective. The interorganisational relationships reveal a strong and integrated network comprising many universities, public research labs, and private enterprises. The results of a mail survey held among academic and industrial researchers who are active within the network not only corroborate these empirical findings, but also elicited relevant criticisms concerning the efficiency and effectiveness of the network, and provided useful suggestions for its improvement. The paper concludes by looking at the benefits of this methodology, which links external quantitative information and qualitative expert opinions, as an analytical tool for government S&T policy and R&D management purposes.

1. Convergence of academic research and corporate R&D

Starting in the early 1980s, a revolution has taken hold of publicly financed research in many industrialised countries, based on the notion that scientific and technological knowledge and know-how have become a critical factor in modern knowledge-driven societies. Applied science and science-based technology are now recognised to be of vital importance in the major knowledge-based economies (OECD, 1992). The traditional divide between basic and applied research, between academic and industrial research – and to some extent between science and technology is becoming obsolete (Narin and Noma, 1985); it is superseded by a distinction between research into new areas at the research frontier and research targeted towards improving and developing industrial products and processes (Brooks, 1994). According to Gibbons et al. (1994), "scientific and technological knowledge is coming to be produced in new ways... The familiar discipline-based, inter-

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nally driven, individually dominated structures that currently dominate the universities and the public sector laboratories are yielding to practically oriented, transdisciplinary, network-dominated, flexible structures that are characteristic of the mode of organisation of science and technology in the most advanced sectors''. The S&T knowledge infrastructure is now characterised by a stronger reliance on academic–industry relationships with an emphasis on applied academic research and basic technological research – in addition to academia's task of training and supplying personnel as well as basic scientific knowledge.

A new type of academic knowledge production has emerged that specifically contributes to meeting industrial needs (Mansfield, 1995). The main objective of this convergence between public research institutes and the business sector is to help to develop or improve products and processes of economic value (Faulkner, 1994); these innovations are now regarded to be one of the major driving forces in domestic and global economic competitiveness. Many universities and other public research labs have now entered both short-term and long-term research partnerships with industry – a shift that might well prove detrimental to some sectors of curiosity-driven academic research (Feller, 1990; Dasgupta and David, 1994). New types of S&T policy measures and R&D management practices are evolving in the wake of this re-orientation of the public S&T system. A concomitant growth has occurred of R&D support activities at relevant interfaces between science, technology and R&D-based production (e.g. university/industry networks, transfer agencies). Most industrialised countries and regions have implemented S&T programmes based on concerted actions that aim at initiating and fostering collective knowledge building and problem solving. Many of these programmes involve formal institutional networks connecting R&D activities at universities, public research organisations and innovating science-based firms.

S&T policy analysis has followed suit – the traditional linear models of ''demand pull'' and ''technology push'' have now been replaced by evolutionary models that describe and analyse these developments in terms of interacting and co-evolving networks of institutions and techno-economic infrastructures (Nelson and Winter, 1982; Dosi et al., 1988; Leydesdorff and van den Besselaar, 1994). These networks provide a relatively efficient way to link universities or public research institutes to industrial needs. Evaluation studies of national network activities based on these models have given ample empirical evidence that formal and informal R&D links between the public and private research sector do indeed foster knowledge diffusion and contribute to innovative activities (e.g. Callon et al., 1992; Faulkner and Senker, 1994). Many of those R&D networks transcend national borders – on their own accord or as a result of S&T policy measures. The EU programmes and Eureka for example have been particularly instrumental in helping create and foster public/private R&D networking within the European Union (e.g. Dahl and Lahlou, 1991; Larédo, 1995; Malacarne, 1995).

2. Public/private R&D linkages in the Netherlands

Dutch S&T policy nowadays is characterised by terms such as ''utilitarian science'' and ''prioritisation''. One of its corner-stones is the aim to optimise the utilisation of scientific and technological knowledge within areas of economic importance throughout the entire Dutch S&T system. Establishing new institutes and R&D networks to support, enhance and extend the interaction between the Dutch universities, public research institutes and corporate labs has therefore become an important item on the agenda of S&T policy makers.

A survey study by Bureau Bartels (1994) indicates that about 80% of Dutch industrial R&D is carried out by the firms themselves. The remaining 20% is done through collaboration and subcontracting. About 50% of the external R&D involves public sector research institutes (universities: 35%, other labs: 15%). The larger Dutch corporations, with their own labs, are most prone to appropriate knowledge through these public/private R&D links, mainly to supplement their own in-house R&D. Small and medium-sized enterprises (SMEs) in the Netherlands tend to be more reluctant and use other sources of information such as clients and suppliers (Brouwer and Kleinknecht, 1994). The findings are confirmed by figures on R&D expenditure from the latest Dutch S&T Indicators Report which show that Dutch public research on the whole makes only a relatively small contribution to R&D in the Dutch private sector (Tijssen et al., 1996a). The enterprises contributed about 16% of the funds going into the entire public R&D sector in 1993, which is relatively high compared with other advanced OECD countries. However, this source of funding has dropped from 24% in 1985. On the other hand, there are signs that R&D ties between academia and science-based industry in the Netherlands seem to be strengthening. Industry funded only 2% of academic research in 1993 – which is very low compared with most other OECD nations – but this particular contribution to public R&D has almost doubled in comparison since 1990. Scientometric data from the same indicators report also show comparatively low numbers of public/private co-authored research articles in international scientific and technical journals in many disciplines (including chemical technology) in comparison to the UK, Germany, Denmark and Belgium. Further analysis indicates a dominant position of the largest Dutch multinational firms in the linkage between public research and industrial R&D in the Netherlands (Tijssen et al., 1996b).

Public/private R&D networks are not a new phenomenon in Dutch S&T policy. From the 1980s onward, a series of support programmes was launched by the Dutch government to help mobilise, organise and manage collaborative R&D activities involving Dutch universities and Dutch firms within formal networks. They were meant to achieve three types of objectives:

- stimulating and directing transfer of scientific and technological knowledge between the public and private sector;
- co-ordinating and concentrating collaborative R&D efforts aimed at creating and sharing strategic competences among firms;
- conducting R&D geared specifically towards demonstration projects and industrial innovation.

These dedicated networks have become an important and fairly successful organisational vehicle within the Dutch S&T system. However, the present state of Dutch S&T (as indicated above) and a further need for enhancing the level of public/private interaction has given rise to policy studies which determine key features of these networks and to assess their efficiency and effectiveness. It is within this S&T policy context that this study on catalysis R&D should be placed.

3. Study of the Dutch catalysis R&D network

This empirical study set out to describe R&D collaboration and networking in catalysis, a very important sub-field of the Dutch chemical industry with a fairly long industrial R&D history. [1] The area of chemical products is one of the research-intensive industries which are characterised by innovations that are directly linked to technological advances based on results of fundamental scientific and engineering research (Pavitt, 1984; Rosenberg and Nelson, 1994). R&D activities and technological progress within the area of catalysis are considered to be of great importance for key sectors in the Dutch economy, in particular its large (petro)chemical industry [2] and the food industry. R&D linkages between the public sector institutes and enterprises, which are focused on applied research with identifiable and commercial applications, have traditionally been an important vehicle for creating strategic competences in this area.

[1] The term catalysis refers to the phenomenon in which a relatively small amount of substance (a "catalyst") alters the velocity of a chemical reaction. Catalysts augment the rate of the reaction without being consumed, i.e. the substance can be recovered essentially unaltered in form and amount at the end of the reaction. About 90% of the reactions in industrial chemical processes involve catalysts.
Catalysis R&D is an interdisciplinary subject area located at the interface of chemistry, chemical engineering, and biotechnology. Three sub-domains can be discerned: heterogenous catalysis (different physical states), homogeneous catalysis (chemical catalysts and reactants have the same physical state – solid, liquid or vapour), and bio-catalysis (enzymes). This particular study will focus on heterogenous catalysis, the largest of these three sub-domains.

[2] Dutch chemical firms employ about 90,000 people and have an annual turnover of about 30 billion US dollars. Dutch industry is an important supplier of heterogeneous catalysts (e.g. Akzo, Engelhard, Norit), with a 20% share of the 3 billion dollar annual turnover worldwide.

It is for the above reasons that this particular area was selected as a test case for developing and applying an instrument to provide relevant empirical information on public/private R&D networks. In this pilot study we have adopted an institutional approach by emphasising the linkages between the public research organisations and companies through joint research papers, R&D contracts, formal or informal contacts, and joint participation in institutional arrangements. The prime objectives can be summarised in terms of three methodological issues:

1. to develop a robust methodology for collecting and integrating quantitative data and qualitative information in order to describe and analyse key features of R&D networks in applied scientific areas like catalysis;
2. to assess the validity and usefulness of that methodology by confronting the findings with the views of subject experts. This issue deals specifically with the question to what extent external (bibliographic) information can describe catalysis R&D activities satisfactorily, in particular as regards the structure of institutional relationships underlying the R&D network;
3. to provide S&T policy-relevant information about the catalysis network and its participants: Who are the key R&D organisations? What type of network linkages connect the organisations? Is the network "strong" (i.e. the number of active linkages)? Is the network "complete" (i.e. do all main organisations participate)? Is it a coherent interlinked network? How do the network activities supported by government-financed programmes fit into the relational structure?

4. Methodology

4.1. Introduction

The two-tier analytical procedure used in this study started with collecting scientific and technological information on Dutch catalysis R&D research papers and patents, and the subsequent quantitative (scientometric) analysis of their content. This was followed up by a survey of subject experts that was aimed at generating information which could be used to correct and enrich the scientometric data. The main methodological steps in this procedure (definition of catalysis research, data collection, and data analysis) hinge on the choice of various information sources, and the way the bibliographic information retrieved was handled. This section will specifically elaborate on the selection of relevant bibliographic data sources, and the lexical and statistical analysis of that information.

4.2. Information sources

The first main source comprises printed matter available in the public domain. This provided us with a first overview of on the R&D activities and co-activities of institutes in the area of catalysis. It concerns three types of documented information:

1. Bibliographic information on the international scientific literature. The following databases were used to retrieve relevant research publications in international scientific and technical journals and proceedings series: *Chemical Abstracts* (chemistry), and *Compendex* (engineering). *Compendex* publications dealing with catalysis research were selected according to two selection filters: (i) titles of publications containing the term "catalysis" or variations and extensions thereof (e.g. "catalytic process"); (ii) indexer-given keywords explicitly referring to the term catalysis and/or its variations. The delimitation within *Chemical Abstracts* was based entirely on its subject classification system. In this case all publications were selected that were assigned to the section "Catalysis, Reaction Kinetics, and Inorganic Reaction Mechanisms" (i.e. code 67). The institutionally co-authored publications in the selection were used as a proxy measure of collaborative R&D as well as an indicator of R&D network linkage. [3]
2. Bibliographic information on the international patent literature. Relevant patents were retrieved from the database of the European Patent Office

[3] The address information on the affiliation of the co-publishing authors was retrieved from the Science Citation Index, a database compiled by the Institute for Scientific Information (ISI).

(EPO) according to a pre-selected set of International Patent Classification (IPC) codes (Korevaar and van Raan, 1992).

3. Reports issued by two Dutch government organisations involved in financing catalysis public/private R&D activity: IOP Catalysis [4] and the Netherlands Technology Foundation (STW). [5] These documents contained the full list of public R&D organisations and companies participating in each R&D project concerning catalysis.

The second main information source concerns a nationwide survey held among the catalysis R&D community in the Netherlands. The survey consisted of a mail questionnaire and interviews conducted both before and afterwards. The mail questionnaire was distributed among universities, public research institutes and private companies active in co-authoring catalysis research publications and/or participating in those two government-supported R&D networks. This source of input was used not only to fill in missing bibliographic details, but also to elicit information on relevant features of the networks that were not covered by the bibliographic sources. The main objectives of the survey were:

- to validate the findings of the scientometric analysis of the research and patent literature;
- to uncover formal network links which were not listed in the other bibliographic sources;
- to identify organisations that had recently entered the network (and their network partners and linkages);
- to identify the underlying network of informal interorganisational links;
- to classify each R&D link according to four dimensions:
  1. the main activity: R&D resulting in a joint public research publication; R&D with other types of output; organisational/managerial activities;
  2. its prime objective: for example, seeking or giving advice, supervision or co-ordination of R&D activities/projects;
  3. the direction of the transfer of knowledge and/or goods: two-way or one-way;
  4. the administrative status of that contact (i.e. formal or informal, where formal contacts are based on signed agreements).

4.3. Scientometric mapping

Quantitative data resulting from the lexical analysis of the bibliographic information can be used to produce images ("scientometric maps") of the cognitive structure underlying a corpus of research literature (Tijssen and van Raan, 1994). In this study we applied "co-word analysis" to the data array of co-occurrence links between selected words in those texts. Co-word analysis is one of the more traditional scientometric techniques to unravel and display the cognitive relationships hidden within co-occurrence data (Callon et al., 1983). This approach is based on the assumption that the co-occurrence frequency of each pair of words provides a proxy of the strength of their cognitive relationship, where cognitively related words will co-occur more frequently in texts than those without such a relationship.

The input for the co-word analysis comprised of the most frequently occurring titlewords or indexer-given keywords in the selected catalysis research literature (i.e. in *Compendex* and EPO patents). Co-word maps were obtained by combining multidimen-

[4] Innovation oriented research programmes (IOP) are among the largest government initiatives in terms of funding. IOPs are funded by the Ministry of Economic Affairs and aim at initiating and fostering academic–industry relationships by sponsoring academic research for pre-competitive applications. Each IOP consists of a number of projects, each with a separate steering committee including at least one representative of Dutch industry. Catalysis research in the Netherlands receives additional governmental support through IOP Catalysis, which was launched in 1989 with a budget of about 6 million US dollars and involved about 30 researchers (PhD students mainly). The programme dealt mainly with heterogenous catalysis. The second part of the programme started in 1994 with twice that budget and covers all sub-domains of catalysis (see footnote 1).

[5] STW's main mission is to support research projects within the engineering sciences, with the explicit aim of funding academic research for pre-competitive industrial relevance. STW projects are focused on applied research and industrial applications. Each research project is accompanied by a board consisting of representatives of Dutch firms with an interest in (potential) use of the research output, and linking the academic research organisation(s) involved to several companies. The 1993/94 budget of STW for catalysis research amounted to about 2 million US dollars.

sional scaling and cluster analysis techniques. [6] Separate maps were made for the co-word data retrieved from scientific publications in *Compendex* (the "science map"), [7] and for co-word data based on the selected patent literature (the "technology map"). The data-analytical procedure generates "clusters" of words, that is mutually exclusive sets of strongly interlinked words for which the within-cluster linkages are stronger than those with words outside the cluster. These clusters represent the most prominent R&D themes in the literature. The distances between and within the clusters of words are indicative of the relative strength of cognitive linkage between them: clusters and words with relatively high levels of co-occurrence are located close to one another. These two-dimensional geometric maps portray the underlying relational structure of the co-occurrence links between words and clusters. As such, this spatial configuration represents relevant features of the main cognitive structure of worldwide catalysis R&D – as manifest in the public domain.

Two types of labels were added to each cluster in this cognitive landscape. First, the list of Dutch R & D organisation(s) with catalysis publications/patents that included one or more of those words. [8] Second, the list of words occurring less frequently in the selected publications/patents, but which nevertheless have relatively high levels of co-occurrence with one or more of those high-frequency words on the map. [9]

5. Results

5.1. Worldwide cognitive structure of catalysis R&D

The scientometric study pertains to publication activity in the period 1991–1993. The literature searches generated well over 10,000 scientific publications worldwide. The Dutch share amounts to 570 publications (i.e. those with at least one affiliate address referring to a Dutch organisation). As for the patenting activity, the worldwide output in 1991–1993 amounted to 2465 EPO patents of which 115 patents were taken out by Dutch organisations.

Fig. 1 juxtaposes the 1993 science map (Fig. 1(a)) and the 1993 technology map (Fig. 1(b)). Similar maps were made for 1991 and 1992, which show more or less the same configuration of words and clusters. The complex network of co-word relationships within the 1993 research literature was broken down into six main clusters. The core cluster (cluster 1) on the science map comprises the term "catalyst", and is surrounded by clusters representing more specific R&D themes (e.g. on polymers, car exhausts, and electrochemicial applications). The (network of) themes investigated by the international scientific community thus appear to be closely organised around the core subject matter in this area: the catalyst itself. The lists of Dutch organisations in the boxes linked to each cluster point out that most of the publication activity is accounted for by 10 organisations. The private sector is represented by three large multinational companies (Shell, DSM and Philips). The most active representatives of the public sector are the three Dutch technical universities (Eindhoven, Twente and Delft) and four of the general universities (Amsterdam, Utrecht, Groningen and Leiden).

[6] The cosine index was used to compute the relative strengths of each co-occurrence link for each of the most frequently occurring words. The data matrix of resulting pairwise values was fed into the SPSS multidimensional scaling programme (ALSCAL) to generate the spatial coordinates for each word. SPSS cluster analysis (complete linkage clustering) was used to further group these words in clusters.

[7] The co-word structure on the worldwide science map was based entirely on *Compendex* publications. *Compendex* was preferred over *Chemical Abstracts* for its broader subject scope, and for its off-line availability which significantly reduced the cost of constructing the necessary (large) co-word data matrix (a CD-ROM version of *Chemical Abstracts* was not available at the time). However, on-line information from *Chemical Abstracts* was used for retrieving additional data on Dutch publication activity.

[8] Including Dutch subsidiaries and branches of foreign firms (e.g. Exxon, DOW and Engelhard).

[9] The Dutch publications selected in *Chemical Abstracts* are added to clusters according to their titlewords and keywords. All selected publications are indexed by the keyword "catalysis". So, if they do not contain any of the other selected words they are, by default, linked to the main cluster (i.e. including "catalysis").

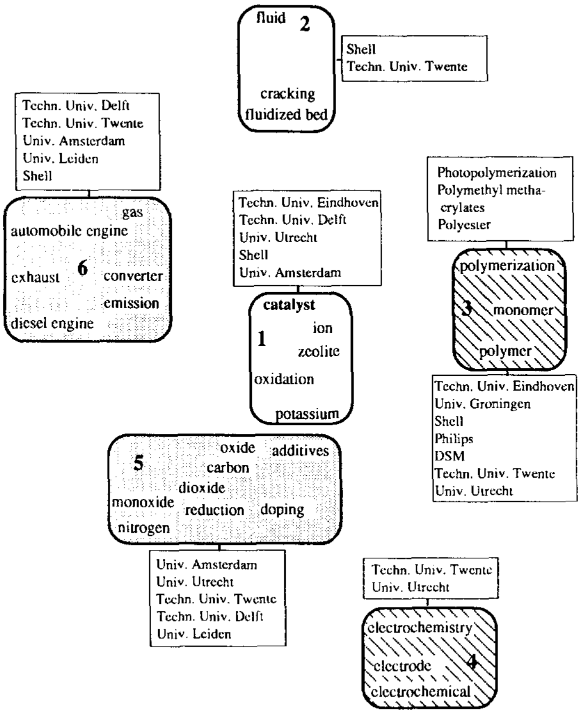

Fig. 1. (a) Science map of worldwide catalysis research, 1993. Based on international research papers. Boxes list the top 5 most actively publishing Dutch organisations (above the threshold of one publication) in decreasing numbers of papers. The additional box linked to cluster 3 lists additional words that co-occur frequently with words in that cluster.

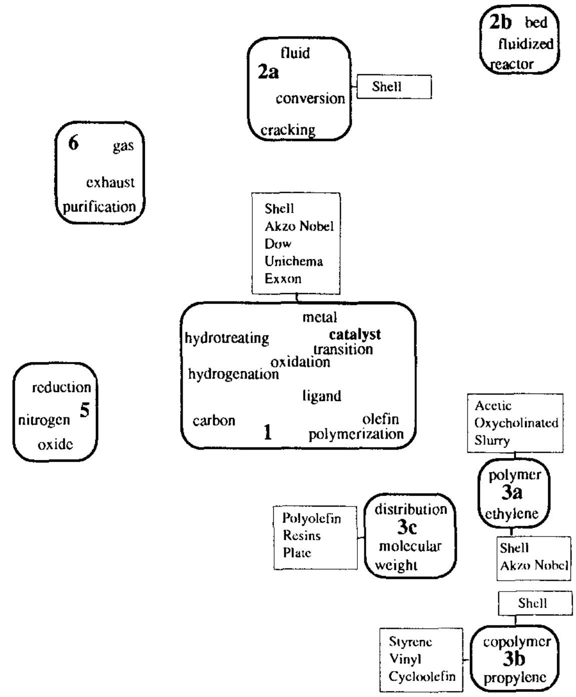

Fig. 1. (b) Technology map of worldwide catalysis R&D, 1993. Based on EPO patents. Boxes list the Dutch firms with patents. The additional boxes linked to clusters 3a and 3b list additional words that co-occur frequently with words in that cluster.

The grey-shaded clusters indicate relatively high levels of Dutch publication output compared with the worldwide output. The diagonally striped clusters on the map indicate under-activity on the part of Dutch researchers. Even though Dutch research is under-represented in the cluster dealing with catalysis-related polymer research (cluster 3), we do see quite a few organisations involved in publishing with a relatively large share of companies: Technical University Eindhoven (4 publications), University of Groningen (3), Shell (3), University of Utrecht (2), Philips (2), and DSM (2). This cluster is, by way of example, also labelled with its most related keywords, i.e. those with co-occurrence frequencies just below the threshold value for inclusion on the map. This research theme is further characterised by the keywords "photopolymerisation", "polymethyl methacrylates" and "polyester".

The technology map, based on the patent literature, exhibits a similar kind of cognitive structure. [10] This outcome illustrates the close cognitive interrelationship between the scientific and technological domain (the most noticeable difference at the cluster level concerns the absence of patenting activity referring explicitly to electrochemistry). Shell's patenting activity across the entire spectrum of catalysis R&D, in combination with its widespread publication activity, is illustrative for the key position that this multinational company holds in both knowledge domains.

Returning to the previous example on the sub-domain of catalysis-related polymer R&D, the map shows that the closely linked words derived from

[10] We refrained from highlighting the clusters according to relative Dutch patenting activity because of the small numbers of patents involved which yield statistically unreliable results.

patents are split into three sub-clusters (3a–3c). Related words with less strong ties, such as "polyolefin", "styrene", "vinyl" and "acetic", further disclose the content of these clusters. Adding the names of the Dutch firms which apply for patents in these sub-domain reveals the presence of Shell and Akzo Nobel. Although the numbers of patents involved are small, it is interesting to note that, in contrast to Shell, Akzo Nobel is not represented in the 1993 science map – nor in the 1991 and 1992 maps. This outcome raises questions concerning differences between the R&D strategies and publication strategies that both firms pursue. The following section will in fact reveal that Akzo Nobel and Shell are both quite active in R&D networking, but that Akzo Nobel is much less visible in terms of scientific publication output or patenting.

Further comparison of both maps indicates that the overall correspondence between Dutch scientific publication activity and patenting activity only holds true for the clusters 1, 2 and 3. The relatively large Dutch research effort in clusters 5 and 6 has not (yet?) resulted in EPO patenting activity of Dutch firms in the corresponding technological clusters – that is, as far as captured by the words that were used to characterise these R&D themes. Note that certain types of catalysts are difficult to patent. They are considered "proprietary catalysts" by Dutch industry and their development is kept secret. Nevertheless, such a striking discrepancy should warrant close attention of management involved in running public/private R&D programmes.

5.2. Dutch R&D organisations active in catalysis R&D

Table 1 presents a list of all Dutch organisations (at main organisational level) that were active in the area in 1991–1993 and a classification of their R&D activity. This overview distinguishes between three interrelated aspects of R&D activity, each captured by the associated indicators presented between brackets:

- scientific research (publishing a research paper included in *Compendex* or *Chemical Abstracts* databases);
- technological development (applying for a EPO patent);
- R&D network activity (participation in formal R&D projects of the STW and/or IOP programmes).

The organisations are classified according to their main institutional sector: (i) universities, (ii) other non-university public institutes, and (iii) companies and private research labs.

The list comprises 29 firms and private labs, 10 universities, and 5 public research labs and other (semi-)public organisations. The table shows the "classical" distinction between the industrial sector, with its emphasis on patenting activity, and public sector organisations focusing on scientific publication output. Both sectors are alike in their high degree of network participation. The selection includes the five major producers of catalysts (Shell, Akzo Nobel, DSM, Engelhard and Norit), but also all five major Dutch multinational industrial corporations (i.e. Shell, Akzo Nobel, DSM, Unilever and Philips). This clearly indicates the strategic importance of catalysis as a relevant sub-sector for the Dutch chemical industry as a whole. Overall, these findings seem to point out that at least four large multinational firms (i.e. Shell, Akzo Nobel, DSM and DOW) should be considered core actors within Dutch catalysis R&D. These firms show significant R&D activity on all counts: they are not only very active in corporate R&D in terms of publishing a substantial part of their scientific research and technological advances in the open scientific and technical literature, but they are also extensively engaged in networking with public research institutes.

This finding corroborates results from other studies of public/private R&D co-operation, which indicate that these large firms are not only engaged in basic catalysis research to meet longer term in-house R&D objectives, but must also invest in basic research to create the capability to recognise, absorb and exploit external scientific knowledge (e.g. Hicks, 1995). To this end, industrial researchers release information through publications in the open literature to signal the existence of tacit knowledge and other resources, thus building credibility needed to find partners in knowledge exchange and to improve their links with researchers in the public sector.

Table 1 also shows that the large majority of Dutch publicly funded research organisations were engaged in network activities as well as in scientific

Table 1
Dutch R & D organisations by type and level of R & D activity and output, and by institutional sector (universities, U; non-university public organizations, P; firms, F), 1991–1993

	Scientific publications	European patents	R & D projects	
			IOP	STW
Formal R & D networks and publications and patents				
Shell (F)	69	75	9	6
Philips (F)	20	1		1
Akzo Nobel (F)	13	9	10	2
DSM (F)	9	1	10	10
DOW (F)	8	3	3	2
KEMA (F)	7	1		1
Unilever (F)	3	1	2	2
Exxon (F)	2	5	4	2
Formal R & D networks and publications				
Technical University of Eindhoven (U)	118		5	7
University of Utrecht (U)	93		11	1
Technical University of Delft (U)	89		7	3
Technical University of Twente (U)	78		1	6
University of Amsterdam (U)	67		3	1
University of Leiden (U)	40		2	2
University of Groningen (U)	27		7	
University of Nijmegen (U)	8		3	
Free University of Amsterdam (U)	6			
Agricultural University of Wageningen (U)	4		2	
TNO – Netherlands Organisation for Applied Scientific Research (P)	2		1	3
Formal R & D networks and patents				
Engelhard (F)		3	4	
Publications and patents				
Gastec (F)	2	2		
DSM Andeno (F)	1	2		
Formal R & D networks				
Solvay Duphar (F)			4	1
Quest (F)			3	1
Gist Brocades (F)			4	
Norit (F)			3	
Hoogovens (F)				2
Comprimo (F)			1	
Dyson Refractories (F)				1
Fluor Daniël (F)				1
ECN – Netherlands Energy Research Foundation (P)				1
TIM (F)				1
Publications				
FOM – Foundation Fundamental Research on Matter (P)	11			
SEP (P)	2			
VROM (P)	1			
Patents				
General Electric (F)		3		
Unichema (F)		2		
Aqualon (F)		1		
Eskla (F)		1		
National Starch (F)		1		
Neste Oy (F)		1		
Stork (F)		1		
Toyo Engineering (F)		1		
UOP (F)		1		

publishing. At least seven out of all 13 Dutch universities are very active in catalysis R&D in terms of publication output. The lack of patenting by the universities is partially due to their general reluctance to take out patents in view of the relatively high costs and risks involved, but also follows from agreements with industrial partners concerning intellectual property rights and commercial exploitation. The four "outliers" in the public sector are ECN and FOM (both large applied research institutions), SEP (a public utility organisation), and VROM (the Dutch ministry dealing with environmental policy). None of them were directly engaged in industrial-relevant catalysis R&D.

About two-thirds of the firms are active in the public/private R&D projects within the STW or IOP programmes. The large firms are strongly presented. About a quarter of the firms in Table 1 are involved in network activity, but show no sign of scientific activity in terms of (co-)publishing international research papers, nor are they active in patenting. This includes some large innovative firms with R&D interests mainly in other industrial sectors (e.g. the steelworks company Hoogovens) and some smaller firms manufacturing catalysts (e.g. Norit). An explanation for these low R&D profiles could be the time-lag between carrying out successful R&D and disseminating results in the open literature. On the other hand, it may also indicate a "free rider" attitude, or the absence of any immediate short-term interests in this area. Another quarter of the firms seem only to generate patents. Again, both large R&D-intensive firms, such as Stork, and smaller enterprises are represented. This collection of firms might be of interest as future potential participants within the R&D network. In fact, Gastec, one of the two firms which not only took out patents but also (co-)published some scientific papers, did become a participant in an IOP project in 1994.

5.3. Unravelling the Dutch catalysis R&D network

The network structure of institutional relationships between Dutch organisations was analysed from two perspectives: (i) co-authored scientific publications and shared patents, and (ii) joint participation in the two formal public/private R&D networks. Each type of information is represented by a set of connective lines and superimposed on the same diagram depicting the configuration of R&D organisations (see Fig. 2(a) and (b)). The relative locations of the various organisations in these diagrams was determined by all their interorganisational ties (either co-publications, formal network links, or informal links). [11] The combined interorganisational network encompasses 92% of the organisations listed in Table 1. [12] Fig. 2(a) displays the core of the network based on co-publications and shared patents in the period 1991–1993. It concerns only the interorganisational links representing two or more joint research publications (displaying all links would generate a highly interconnected network that would be too complex to represent in print). This part of the network comprises one co-patent link and 18 co-publication linkages. The mixture of the various kinds of organisations on this map is in itself indicative of the strong interrelationships between public and private sector. Clearly, industrial researchers in the four core companies (Shell, DOW, Akzo Nobel and DSM) are noticeably involved in co-authoring scientific publications. Shell is one of the central network nodes in this respect. These high levels of co-publication activity by firms occur predominantly in relation to the Dutch universities and other public labs such as FOM. There are only a few interfirm R&D linkages, which is not surprising in view of the fierce competition between some of the companies. Obviously, scientific publications present only the tip of the iceberg in this area. It may well be the case that some institutions (e.g. SMEs) produce hardly any publicly available scientific papers considering the time and effort involved in writing such a publication, and/or in view the strategic and commercial interests that might be at stake. Moreover, results that are published may be disseminated by each of the partners in separate scientific publications instead of co-authored papers.

Complementary data on R&D network linkages

[11] The relative location of the organisations on the map is based on the multidimensional scaling (MDS) analysis of the data matrix containing the number of network links and co-publications shared by the pairs of organizations.

[12] The remaining 8% of the Dutch organisations without any R&D links of this kind were discarded from further analysis.

are provided in Fig. 2(b). This map is based on formal joint participation in the R&D projects (STW or IOP) according to the 1991–1993 data. This network diagram portrays the various network links between firms (as participants within the same STW or IOP projects) and the links between the firms and public research organisations. The links represent three or more co-participations in those projects, irrespective of the kind of participation (which may vary from active involvement in carrying out R&D

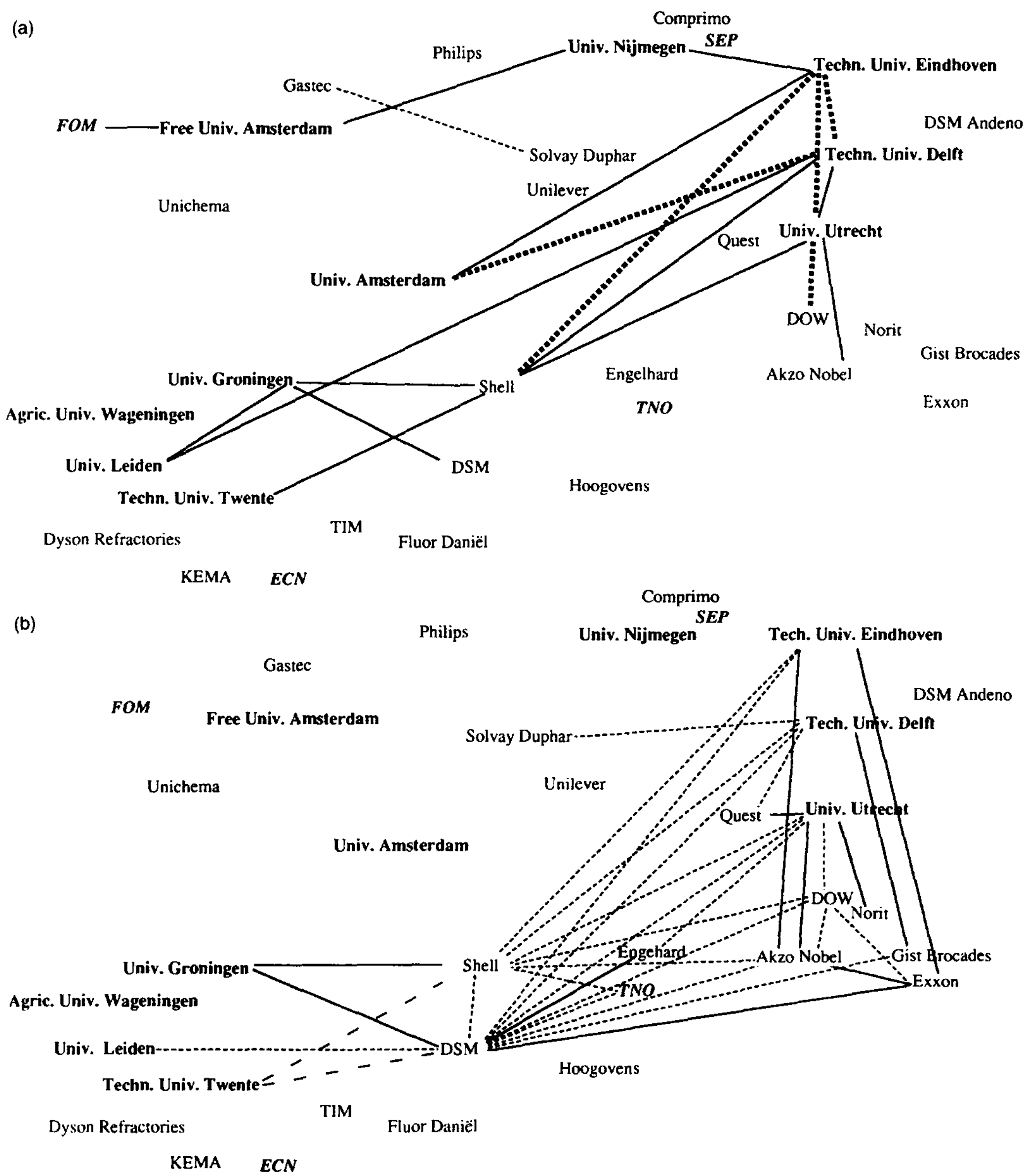

Fig. 2. (a) Dutch R&D organisations in the field of catalysis. Main relational structure of co-publication and copatenting activities, 1991–1993. Universities—**bold**; other public R&D organisations—***bold italics***; firms—plain print. Connective lines: --- 1 co-patent; —— ≥ 2 co-publications < 6; ■ ■ ■ ≥ 6 co-publications.(b) Dutch organisations in the field of catalysis. Main relational structure of formal R&D network links, 1991–1993. Universities—**bold**; other public R&D organisations—***bold italics***; firms—plain print. Connective lines: --- ≥ 2 joint STW and IOP projects; – – – ≥ 2 joint projects (STW only); ———— ≥ 2 joint projects (IOP only).

to the passive role of absorbing information as a member of a project steering committee).

The IOP and STW network show a considerable degree of overlap – not only do they involve the same set of major actors in the field, they also share a significant fraction of the R&D linkages between those firms and public sector organisations. Moreover, these two formal networks tend to cover most of the interorganisational research links as indicated by co-publications. This outcome can in part be explained by the fact that many of these linkages represent long-standing R&D relationships that are embodied in both formal network participation and co-publication activity. Note that Shell and DSM share a great number of R&D links with the research organisations in the public sector, whereas Akzo Nobel is mostly linked to other firms – which is largely due to joint membership of IOP and STW steering committees.

Results from the mail survey (see Section 5.5) reveal that not all ties among the R&D organisations are formalised (i.e. arrangements based on written contracts). In some cases there are just informal contacts. This additional "hidden" network of informal R&D ties is quite different from the previous two structures. Most of these links concern public research organisations. The University of Amsterdam appears to be one of the major actors in the informal network. Only five firms indicate that they are also engaged in informal R&D relationships (Shell, Exxon, Kema, Engelhard and Comprimo). In those cases where strong informal links exist but are not accompanied by formal interorganisational links, it is not unlikely that some ties will eventually lead to joint participation in formal government-financed R&D networks such as STW and IOP.

5.4. *Characterising the catalysis R&D network*

The above information concerning the catalysis R&D network can be summarised in terms of the following key characteristics:

- Institutional range – the network is *heterogeneous*, that is, all types of R&D organisations are present (universities, public research labs, private research labs). The range of firms comprises both large multinational companies and SMEs. The results of the survey also indicate that the network is *complete*, in terms of all relevant catalysis R&D organisations being represented.
- Network density and structure – the network can be described as *interconnected*. It constitutes a relatively tightly knit structure of interorganisational relationships without any noticeable subsets or cliques. The core of this network consists of four large multinational firms and a group of about eight universities. Firms like Shell and DSM are core nodes in the R&D network with many links to universities and other public R&D institutes. There are only a few explicit interfirm R&D linkages.
- R&D objectives – the network is of a *hybrid* type which comprises not only public/private R&D network activities geared toward basic technological research and corporate R&D needs, but also an academic network linking university researchers.
- Organisational strength – the network is *strong* in the sense that it is firmly embedded within the Dutch S&T system. The entire network encompasses, and is reinforced by, two formal R&D networks (STW and IOP). These public/private networks accompanied by auxiliary formal networks connecting catalysis researchers at the universities serve as the academic backbone in terms of knowledge exchange and diffusion within the public research system. [13]

5.5. *Survey among Dutch R&D organisations*

As regards the mail survey, 60 questionnaires were distributed among relevant representatives of organisations on the maps (senior researchers and R&D managers mostly). The questions dealt with their R&D-related contacts involving other Dutch organisations. The sample included seven universities, 13 companies, and two publicly financed research labs. The response rate was 75% and more or less the same for each of these three sectors. Half of

[13] Pertains to a section of SON, the Foundation of Chemical Research, and the Research School for Catalysis (NIOK). These two academic networks are discussed in detail in Korevaar et al. (1994).

the interorganisational R&D contacts were classified as formal, another 25% were informal. The status of the remaining 25% was not sufficiently clear or unknown. About 70% of the formal contacts were concerned with exchange of scientific knowledge and technical know-how. The other 30% dealt with R&D activities such as the chemical specification of catalysts, development and joint use of instruments and machinery, joint contract research, and the use of software. On the whole, most formal and informal contacts pertained to activities related to joint funding of R&D projects and research commissioned by industry (45%), and the exchange of knowledge and goods (34%).

The results of the survey were also used to assess the coverage of the 1991–1993 data concerning formal network relationships as indicated in the IOP and STW programme reports. Using the input from the catalysis research community as a benchmark, 74% of those formal R&D contacts were identified through these documents (other contacts involved, for example, EU-financed R&D programmes). A total of 38 R&D contacts were added by the survey respondents. This addition unearthed two Dutch organisations which are to some extent also active in catalysis R&D: Novem (the Netherlands Agency for Energy and the Environment), a semi-public R&D transfer agency, and the Dutch branch of the US firm Dupont.

The catalysis researchers were also asked to check the set of scientific co-publications that were identified in the literature searches and to add missing publications. The results of this validation showed that our procedure succeeded in identifying 93% of their joint publications in 1991–1993.

The questionnaire included a question regarding views on the functionality of public/private collaboration in R&D projects of the STW and IOP programmes. In general, the findings indicate that the participants on the one hand tend to value the interaction between the public and private sector, but on the other hand criticise the effectiveness and efficiency of these projects due to administrative complexity, lack of timeliness, organisational constraints, and ambiguities about (legal) terms and conditions.

Two general problems were voiced relating to fundamental differences between the R&D objectives in the public sector and in the private sector.

- Universities express the need for additional basic research, whereas firms argue that academic research is often too theoretical to be of immediate use.
- Researchers in the public sector stated that firms should define their R&D objectives more clearly, whereas the private sector researchers complained about the fact that public research organisations sometimes fail to specify their abilities to meet those objectives.

In addition, the following critical comments were given with regard to propriety issues and bureaucracy related to network activities:

- Managerial and organisational network activities take up too much time.
- Bureaucratic delays regarding formal application procedures for government funding are partly responsible for universities being unable to keep up with the pace and needs of corporate R&D.
- The effectiveness and efficiency of university–industry collaboration is hampered by protective measures of firms regarding their own strategic R&D knowledge.
- Intellectual property rights of the partners are sometimes not sufficiently dealt with in the R&D funding contracts.

The following main suggestions were offered for improving the way in which R&D in those networks could be organised and conducted:

- Separate lines of government funding should be integrated into one central funding agency (the Dutch Ministry of Economic Affairs for example uses three R&D programmes for distributing funds to industry).
- A separate funding programme should be launched for R&D dedicated to industrial innovation involving exclusive contracts between only one firm and one or more public research organisations ("focused partnerships").
- Dutch industry should be granted a larger say in developing, implementing and executing R&D programmes.

In sum, these findings suggest that there still seems to be ample room for improvement within Dutch catalysis R&D network arrangements. Particularly with respect to the amount of red tape involved in projects financed by Dutch government agencies, the match of industrial R&D needs and public sector research capacity, and legal ambiguities concerning propriety issues.

6. Discussion

This case study was primarily meant to develop and validate an instrument for collecting and integrating both quantitative and qualitative data on national R&D network activity. The study was not designed to be a fully fledged study of the Dutch catalysis network covering all actors in detail and all relevant aspects of their interorganisational relationships. Several methodological points should therefore be noted. First, the analytical level was restricted to the main organisational level. Hence, data concerning lower levels of aggregation (e.g. university departments and separate company research laboratories), or pertaining to individuals or separate R&D outputs (research papers and patents) were not taken into consideration. This limitation rules out a number of interesting additional ways of disclosing further information on cognitive links between scientific and technological activity and the R&D organisations active in those domains. For example, by examining the references made in patents to research papers, identification of individuals who publish scientific papers and file for patents (e.g. Noyons et al., 1994), or by analysing the citation or co-citation links between papers or researchers (e.g. Penan, 1996).

Moreover, the results of the analysis provide no indication of the size and scope of those organisations in terms of R&D portfolios, budget or personnel. In this particular case, it is important to know that some of the Dutch chemical companies employ a substantial R&D workforce – the Shell R&D labs in the Netherlands alone employ about the same number of industrial researchers as all chemistry faculties of the Dutch universities combined.

Each source of information we used in this study is subject to certain limitations that deserve some elaboration in order to appreciate the usefulness and validity of these results. First of all, it is well known that publicly available published matter suffers from some fundamental drawbacks when used to represent the cognitive structure of an industrial-relevant field like catalysis R&D. The most important constraints of publications as an information source are:

- they represent yesterday's state-of-the-art, due to time-lags involved in printing and disseminating publications;
- they tend to emphasise the formalised R&D contacts and network linkages;
- not all research results are published in the open scientific literature, particularly in areas where R&D findings can be of great strategic or commercial value;
- technological developments and artefacts are often protected by secrecy or other means of appropriation instead of by patents.

There are obviously also some drawbacks attached to eliciting information from R&D staff active within such a competitive industrial area. Not only may one expect a certain degree of subjectivity due to experts' limited or biased views, but in this particular case there is also the risk of (partially) unreliable responses in order to protect company interests. A case in point is the response to the mail survey by one of the larger Dutch companies. Several R&D staff members received a separate questionnaire, but it was decided by R&D management to return only one completed questionnaire representing the "company view".

Furthermore, one should take into consideration that a fair number of the identified R&D network links were not initiated or promoted by S&T policy actions, but were already present as a result of formal long-standing relationships between Dutch industry and the public R&D sector (e.g. some catalysis professors at Dutch universities are also employed part-time by Dutch firms). Clearly, these personal ties were – and are – particularly important in forging links that resulted in formalised interaction between the public and private domain that, in turn, enabled universities to engage in and maintain collaborative R&D projects with industry.

Finally, some of the respondents in the survey pointed out that formal joint R&D projects and co-publications are indeed key elements in characterising public/private interaction and relationships, but their importance should also be put into proper perspective. There are several other important indicators of interaction and knowledge transfer between the public and private sector. Informal transfer and exchange of tacit know-how, skills, methods and techniques was considered equally important, along with exchanging and recruiting university-educated researchers and engineers.

The above response from the catalysis research community illustrates one of the main benefits of the two-tier methodology: the ability of the objective scientometric data to evoke useful information on internal characteristics of the network from the R&D community itself. The resulting mix, incorporating quantitative and qualitative information, provides a fairly reliable, valid and policy-relevant picture of the main cognitive and institutional characteristics of the catalysis network. Note that the success of this study, in terms of the methodology's efficiency and its yield of information, should be seen in the light of the very state of this particular network: a relatively stable and tight-knit structure of both personal and formal interorganisational linkages, supported by several national programmes (which have been in place for some years) aimed at supporting and promoting public/private co-operation. The general usefulness of the methodology, however, is not determined by the institutional state of an area or the prominence of existing socio-cognitive networks, but depends almost entirely on the appropriateness and quality of the input data and the willingness of the R&D community to participate in such a study.

7. Concluding remarks

Objective and empirical information on both the cognitive and interorganisational structure of R&D networks, linked to accounts of the network participants themselves, provides an intelligence base that can be put to use by several types of interested parties and for different reasons. First of all, for S&T policy issues, to map out key features of a private/public network. Such an overview may provide insight into the degree of convergence/divergence between the public and private sector research activities and agendas, and the stabilisation/durability of the network. Information on formal and informal network arrangements and activities may, for example, show that universities have taken up their role as suppliers of scientific and technological knowledge for private enterprises. Conversely, it may indicate that industry has succeeded in stimulating or asking for relevant research activities at those universities. Background information of this kind is particularly useful for policy making, because the success of (future) government-sponsored public/private R&D programmes may critically dependent on whether or not a core of effective R&D linkages already exists. In fact, decision makers at the Dutch Ministry of Education, Culture and Science and at the Ministry of Economic Affairs have recently used findings of this particular study as one of the inputs for verifying that a sufficiently well-developed R&D base exists to consider the foundation of a new national technological institute that can act as the bridging institute between catalysis R&D in the public and private sectors. [14] Hence, these findings do not constitute a mere empirical description of a network, but also have strategic implications as a way of learning about, and acting upon, R&D networking activity. As such, the data could also be fed into government S&T policy studies that specifically evaluate productivity and effectiveness of R&D linkages and partnerships.

Information on R&D networks can also provide strategic intelligence for R&D management purposes. Particularly for enterprises that are active in those technological areas where in-house R&D is increasingly affected by knowledge and know-how created elsewhere, and in which academic research contributes significantly in the development of industrial innovations. Corporate industrial labs will not only have to keep abreast of rapid scientific and technological developments – which are becoming increasingly dependent on trans- and interdisciplinary science, but also need to access opportunities induced by the latest results of scientific research and related science-based technologies, and try to avoid duplication of R&D. These externalities place a greater demand on industry's absorptive capacity of both academic research and corporate R&D, and force companies to identify and to link up with other (potentially) relevant R&D organisations. Hence, R &D management may have a number of reasons for wanting to know "who is doing what, and with

[14] Personal communication by a spokesman of the Ministry of Education, Culture and Science.

whom" – both within and outside their own network. Scientific publication activity, patenting and network relationships provide input data that may help enterprises to assess their own position vis-à-vis competitors, and identify who are well positioned in promising new R&D areas. This kind of information can be of great use for those engaged in R&D network activities where strategic positioning and partnering is called for to mobilise forces and to exchange knowledge and assets (Penan, 1996). Note that R&D networks are not only sources of industrial innovation and competitive advantage to actors within the network, but also to outsiders who monitor the network and its R&D products in order to, for instance, track down candidates who might be able to supply complementary knowledge and competence.

In conclusion, it seems that the analytical methodology presented in this paper provides an external aid for unravelling and characterising both the cognitive and organisational structure of a public/private R&D network. Moreover, the results can be used as an empirical reference base for discussing and conveying relevant features of such a network. Although this case study was restricted to just one period of time, thus producing only one set of data and static presentations of network features, this kind of information can obviously also be used as a baseline for describing and monitoring the evolution of an R&D network.

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References

Brooks, H., 1994, The relationship between science and technology, Research Policy 23, 477–486.

Brouwer, E. and A. Kleinknecht, 1994, Innovation in the Dutch manufacturing and service sector (1992), BTE Report Series no. 27, Ministry of Economic Affairs, The Hague (in Dutch).

Bureau Bartels, 1994, R&D networks of Dutch companies (Bureau Bartels, Utrecht/Assen) (in Dutch).

Callon, M., J.-P. Courtial, W.A. Turner and S. Bauin, 1983, From translations to problematic networks: An introduction to co-word analysis, Social Science Information 22, 191–235.

Callon, M., P. Larédo and V. Rabeharisoa, 1992, The management and evaluation of technological programs and the dynamics of techno-economic networks: The case of AFME, Research Policy 21, 215–236.

Dahl, M. and S. Lahlou, 1991, Measurement of network effects from the EC Science/Stimulation programmes, Scientometrics 21, 325–342.

Dasgupta, P. and P. David, 1994, Toward a new economics of science, Research Policy 23, 487–521.

Dosi, G., C. Freeman, R. Nelson, G. Silverberg and L. Soete (eds.), 1988, Technical change and economic theory (Pinter, London).

Faulkner, W., 1994, Conceptualising knowledge used in innovation: A second look at the science–technology distinction and industrial innovation, Science, Technology and Human Values 19, 425–458.

Faulkner, W. and J. Senker, 1994, Making sense of diversity: Public–private sector research linkage in three technologies, Research Policy 23, 673–695.

Feller, I., 1990, Universities as engines of R&D-based economic growth: They think they can, Research Policy 19, 335–348.

Gibbons, M., C. Limoges, H. Nowotny, S. Schwartzman, P. Scott and M. Trow, 1994, The new production of knowledge: The dynamics of science and research in contemporary societies (Sage, London).

Hicks, D., 1995, Tacit competences and corporate management of the public/private character of knowledge, Industrial and Corporate Change 4, 401–424.

Korevaar, J.C. and A.F.J. van Raan, 1992, Science base of technology: Bibliometric mapping as a tool for national science and technology policy – Part 1: Recent developments in catalysis and environmental chemistry, Report CWTS-9208 (CWTS, Leiden).

Korevaar, J.C., R.J.W. Tijssen and A.F.J. van Raan, 1994, Actors at the interface of science and technology: Collaboration and networks in Dutch catalysis research, Report CWTS-9403 (CWTS, Leiden) (in Dutch).

Larédo, P., 1995, Structural effects of EC ST&D programmes, Scientometrics 34, 473–487.

Leydesdorff, L. and P. van den Besselaar, 1994, Evolutionary economics and chaos theory: New directions in technology studies (Pinter, London).

Malacarne, M., 1995, Large-scale installations as focal points for innovation networks, International Journal of Technology Management 10, 557–566.

Mansfield, E., 1995, Academic sources underlying industrial innovations: Sources, characteristics and financing, Review of Economics and Statistics 77, 55–65.

Narin, F. and E. Noma, 1985, Is technology becoming science?, Scientometrics 7, 369–381.

Nelson, R. and S. Winter, 1982, An evolutionary theory of economic change (Harvard Press, Cambridge, MA).

Noyons, E.C.M., A.F.J. van Raan, H. Grupp and U. Schmoch, 1994, Exploring the science and technology interface: Inventor–author relations in laser medicine research, Research Policy 23, 443–457.

OECD, 1992, Technology and economy: The key relationships (OECD, Paris).

Pavitt, K., 1984, Sectoral patterns of technical change: Towards a taxonomy and a theory, Research Policy 13, 343–373.

Penan, H., 1996, R&D strategy in a techno-economic network: Alzheimer's disease therapeutic strategies, Research Policy 25, 337–358.

Rosenberg, N. and R.R. Nelson, 1994, American universities and technical advance in industry, Research Policy 23, 323–348.

Tijssen, R.J.W. and A.F.J. van Raan, 1994, Mapping changes in science and technology: Biblometric co-occurrence analysis of the R&D literature, Evaluation Review 18, 98–115.

Tijssen, R.J.W., Th.N. Van Leeuwen, B. Verspagen and M. Slabbers, 1996a, Netherlands observatory of science and technology: Science and technology indicators 1996 (CWTS/MERIT, Leiden/Maastricht) (in Dutch).

Tijssen, R.J.W., Th.N. Van Leeuwen and J.C. Korevaar, 1996b, Scientific publication activity of industry in the Netherlands, Research Evaluation (forthcoming).