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# Quantitative assessment of large heterogeneous R&D networks: the case of process engineering in the Netherlands [1]

Robert J.W. Tijssen *

*Centre for Science and Technology Studies (CWTS), University of Leiden, P.O. Box 9555, 2300 RB Leiden, Netherlands*

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**Abstract**

Large R&D networks are characterised by complexity. They are usually extremely heterogeneous in terms of their variety of interconnected institutions from both the public sector and private sector, and the various activities outcomes and effects which make up this web of relationships. Clearly, numerous analytical problems have to be faced when examining such a network's key characteristics and trying to establish its effectiveness. This article presents key results of an empirical case study aimed at analysing such an R&D network. The study deals with a nation-wide innovation-oriented network in the Netherlands in the field of process engineering, covering both Ph.D. training, R&D, and design activities. Relevant information about the network was derived from a combination of data extracted from an annual R&D report and opinions of network participants gathered through a subsequent mail survey. Various quantitative indicators were used to describe and compare institutional features of this cross-institutional network and determine the effectiveness of its bilateral links. On the whole, the results reveal a diversified, vigorous and fairly successful network. The network seems less effective in terms of technological development and innovation activities in comparison to knowledge creation and transfer.

*Keywords:* Innovation-oriented R&D network; Academic–industry relations; R&D collaboration; Knowledge creation and transfer; S&T indicators

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## 1. Introduction

### 1.1. R&D networks and the science base of technological development

Production and transfer of scientific and technological knowledge in modern S&T systems usually emerges as a result of an interactive and collective process within a web of personal and institutional connections that evolve over time. Sustained and focused interest of researchers, engineers and technicians engaged on related scientific and technological activities on related R&D topics tends to organize itself in a 'techno-scientific community': a social and cognitive system based on interrelated connections and dependencies. Such a set of social actors and their interconnections can be institutionally defined and analysed in terms of a 'network'. [2] Rappa and Debackere (1992) define these networks in sci-

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* Corresponding author. Tel.: +31-71-5273960; fax: +31-71-5273911; e-mail: tijssen@cwts.leidenuniv.nl.

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ence-intensive technology areas as a ‘group of scientists and engineers, who are working on an interrelated set of technological problems and who may be organizationally and geographically dispersed but who nevertheless communicate with each other’. These diversified R&D networks incorporate a variety of R&D performing institutions ranging from competing multinational firms to public research institutes and universities. Such an institutionally heterogeneous (or ‘hybrid’) network is obviously composed of a wide range of bilateral and multilateral linkages and a variety of R&D activities and topics. [3] For example, technical network links occur when two companies pool their resources and assets on the development of industrial prototypes, or share the use of complex and costly test equipment. Science-driven knowledge-related ties may involve academic scientists cooperating in a research project or exchanging information about each other’s scientific knowledge pool. Public–private R&D linkages within the network may incorporate industrial contract research being carried out by public research institutes. Clearly, inputs, throughputs and outputs of such a network can be quite diverse, varying from human resources (qualified engineers and Ph.D. graduates), codified scientific knowledge and related tacit skills, to various forms of tangible technological results like patents, technical designs, equipment, substances, and prototypes. Some of the R&D results are fed into related ‘downstream’ actors or techno-economic networks where they are modified into economically valuable innovations (new or improved products, processes or services) for production and ultimately introduced into the market (e.g., Freeman, 1991; Callon et al., 1992). Such heterogeneous networks tend to play a crucial role in facilitating cross-sectoral communication and interaction in science-intensive technology areas and related industries (e.g., Mansfield, 1995). In fact, R&D collaboration and networking between the public science infrastructure and corporate R&D is increasingly viewed as one of the key features of the knowledge infrastructure in the industrialized world (e.g., Gibbons et al., 1994). The relevance of cross-sectoral R&D cooperation and knowledge diffusion processes—and subsequent economic spill-over effects —has spurred implementation of several institutional mechanisms for transfer and exchange of new knowledge and technologies. Promoting and fostering collaboration between the public research sector and industrial R&D, and enhancing industry’s access to the public science base, are now often key factors of regional, national or supra-national programs on technological development and industrial innovation.

### 1.2. S&T policy on R&D networks in the Netherlands

Many formal and informal public–private networks have now been in operation for several years in the Netherlands. In line with international developments, S&T policy in the Netherlands has emphasized the necessity of strengthening public–private R&D links with the specific aim of initiating and fostering collective knowledge building and problem solving to help develop or improve products and processes of economic value (see for example the joint White Paper by the Ministry of Economic Affairs et al., 1995). A range of governmental policy measures and programs were enforced to encourage

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[2] The network concept has emerged as both a fruitful theoretical model and practical method within sociological studies of science and technology (e.g., Shrum and Mullins, 1988) as well as within economic theory (e.g., Håkansson, 1989; Powell, 1990). The network approach is based on the theoretical assumption that social phenomena can be described and explained by a combination of two key factors: (a) the features and attributes of organizations and (b) the way in which organizations are connected to each other. Social networks is an attractive concept from an analytical perspective because it focusses on the relationships between actors and emphasizes the role of interorganisational relationships within knowledge interaction and diffusion processes.

[3] Generally speaking, such an R&D network can be defined as an evolving mutual dependency system based on resource relationships in which their systemic character is the outcome of interactions, processes, procedures and institutionalization. Activities within such a network involve the creation, combination, exchange, transformation, absorption and exploitation of resources within a wide range of formal and informal relationships. These network resources comprise of various kinds of capabilities, competencies and assets, which can be divided into ‘tangibles’ (e.g., codified knowledge, substances, and technical facilities such as software and equipment), and ‘intangible’ resources (skills, know-how, experience, and personal contacts).

private sector R&D and optimize the use of R&D resources in the Dutch S&T system, including institutional arrangements supporting and facilitating R&D networks.[4]

The policy interest is now gradually shifting from an emphasis on creating new R&D connections and networks, to one of identifying the benefits, problems and (re-)directing those networks that already exist. To this end, R&D networking was included as a separate element in a series of government commissioned policy studies that were undertaken to map the main institutional, relational and cognitive characteristics of 16 science-based fields of technology (Schaffers et al., 1996). Each of those fields are of particular interest to the general viability of Dutch S&T system and of crucial importance to Dutch industry. Further empirical studies have been carried out to provide a more in-depth description of the institutional interface between the public and private sector, with an emphasis on national public–private R&D networks within those fields (e.g., Tijssen and Korevaar, 1997). This article presents the results of such an follow-up study on the R&D network in the field of process engineering.[5] The chief objective of this case study was to develop a set of indicators to describe the main institutional characteristics of this network and to assist in determining its effectiveness, while taking into account its diversity in terms of the different types of R&D linkages involved (intra-sectoral vs. cross-sectoral) and incorporating views of the public and private sector on the network's performance.

### *1.3. Process engineering R&D in the Netherlands*

Patent-based studies at the international level indicate process engineering is amongst those technological areas with the highest and most wide-ranging technological spill-over potential to other technological sectors—while exhibiting an average level of science intensity at the global level (e.g., Grupp, 1996). Bibliometric analyses of the Dutch research output indicate that the science intensity of Dutch industry is relatively high in this area: corporate researchers and engineers account for about 20% of all Dutch papers in international scientific and technical journals, which is far above the average share of industry in Dutch publication output across all research disciplines in the natural sciences, life sciences and engineering (Tijssen et al., 1996). Process engineering is regarded a key R&D field for several industrial sectors in the Netherlands, in particular the (petro)chemical industry, the food industry, and the environmental waste sector. Dutch process engineering R&D is characterized by a very heterogeneous group of institutions which includes large diversified multinational corporations, small and medium-sized firms, private R&D labs, and several large public research institutes and universities. The large industrial corporations that are active in the Dutch chemicals industry are: Shell, DSM, Esso/Exxon, Akzo Nobel, Dow Chemical, and General Electric Plastics. Important companies in biotechnology and food industry sector are Unilever, Organon, Gist-Brocades, and Nutricia. The equipment manufacturing industry is represented by Stork and AKF. Comprimo and KEMA are two of the largest Dutch engineering firms involved in this field. Research in the public domain is carried out by the majority of the Dutch universities (including all technical universities), as well as the following applied research institutes: (1) The Netherlands Organisation for Applied Scientific Research (TNO), which is particularly active in a wide range of areas related to food, waste treatment, and energy; (2) Netherlands Energy Research Foundation (ECN), which is involved in R&D on ceramic membranes, chemicals conversion processes, and

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[4] The S&T policy initiatives include: tax reduction and government subsidies for extramural R&D; establishing transfer agencies and R&D programs such as STW and IOP (see, e.g., Tijssen and Korevaar, 1997), technological guidance services, and innovation consultancies; subsidies for selected R&D cooperation projects; cooperative R&D institutions (e.g., the recently founded Technological Leading Institutes based on close interactions between the public research infrastructure and the private sector); and educational and training facilities and programs (e.g., academic research schools).

[5] The common shorthand version of research and development is used throughout this article. Note that in this particular study, 'R&D' is used as a broad concept which includes a range of related scientific and technical activities including technical designs. This study also includes education and training as an institutional element of the network, although these activities are explicitly excluded from the internationally accepted definition of R&D according to OECD's Frascati Manual.

high temperature separation of gases; (3) Delft Hydraulics Lab (WL) with activities in the field of hydrodynamics; (4) the agricultural research department of the Ministry of Agriculture (DLO) which is mainly involved in research on bioprocesses and food.

This case study will focus on networking amongst the larger R&D-performing institutions with a special focus on cross-sectoral links involving the universities. The analytical approach was specifically designed to produce a quantitative aggregate-level description of the network's key institutional characteristics and to develop indicators of its functionality. Note that the cognitive dimension of the network was not examined in the case study, although this aspect is clearly an important one considering the transdisciplinarity of the network given the wide range of scientific and technological areas and domains of industrial application involved.

The research questions touch on various issues which can be grouped under the following general headings:

- Network structure and contents.

  Are all important Dutch institutions involved? What do the relational features of the network look like? What are main R&D activities and objectives of bilateral links within this network?
- Network performance.

  Is it considered a relevant and successful network by its participants? What are the network's strong and weak elements? To what extent are the objectives of its various R&D links achieved?
- The network as an institutional interface.

  Are there significant differences between cross-sectoral public–private R&D links and intra-sectoral links? Does the network succeed in linking R&D interests of both sectors?

## 2. Research methodology

### 2.1. Bibliographic mapping of the R&D network

A reliable and valid empirical analysis obviously needs appropriate information sources, preferably those containing publicly available objective data. Codified texts disseminated through publication channels in the open R&D literature constitute a prime candidate for supplying such data. Large-scale systemic studies of research networks often draw on institutionally co-authored research papers for identifying collaborative links between those R&D organizations listed as the affiliate addresses of the authors (e.g., Tijssen and Korevaar, 1997). However, the subject experts that were consulted in the preparation of this study objected to this approach, arguing forcefully that these papers deal mainly with basic research and are therefore inadequate to reflect (cross-sectoral) R&D linkages in this field which is predominantly characterized by applied research and technical development activities.[6] Their objection was indeed corroborated by a substantial share of respondents who participated in the survey.[7] Other types of written material on R&D outputs give rise to other practical difficulties, primarily because many of these texts (e.g., patents, contributions to conference proceedings, internal technical reports) are not available on a large scale, or in a systemic and easy accessible form. More importantly, these documents often lack sufficient explicit references to the all important institutional partners involved in the R&D. A third category, administrative or policy reports issued by the R&D institution(s), funding agencies or S&T policy bodies involved, provides a useful alternative source of factual information. In this particular case, we were able to draw on the annual report of the Dutch academic research school for

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[6] Co-authored papers do not necessarily indicate joint R&D activities (e.g., Katz and Martin, 1997). A co-authored research paper listing an address referring to a public sector institution and one referring to a firm may for instance result from academic researcher that were employed by industry as they finish their Ph.D. degree who list both their previous and current addresses when publishing their research, or it may result from a single author holding a joint appointment.

[7] Only a third of respondents in the public sector agreed on the statement that 'co-authored research papers listing both a public research institute or university and a firm reflect the nature and intensity of public–private R&D linkages'. Another 30% was undecided on this issue. Almost 45% of the respondents in the private sector considered these research papers to be valid indicators, while 17% neither agreed nor disagreed.

process engineering (the ‘Onderzoek School Proces-Technologie’—OSPT), providing an overview of its on-going and new R&D projects. The list of project participants and sponsors of each project allowed us to extract baseline information on institutional features of the Dutch R&D network in this field.[8] Co-occurrences of two main institutions within the same project were defined and counted as one institutional R&D link, thus enabling statistical analysis of linkage patterns (e.g., Tijssen and van Raan, 1994).[9] The linkage data were converted into a graphical image depicting the main features of the relational structure beneath these OSPT projects (see Fig. 1 in Section 3.1).

### 2.2. Mail survey

The data extracted from the OSPT R&D projects served as a entry point for the second stage of the study: a nation-wide mail survey held among members of the process engineering R&D community in the Netherlands.[10] The first section of the questionnaire dealt with the accuracy and validity of R&D network structure as represented in the diagram depicting OSPT’s institutional network. The second section comprised of questions dealing with factual information on a limited number of (on-going or completed) bilateral R&D links pertaining to the period 1995–1996. Each respondent was free to chose one or more (in)formal links—preferably one within the same institutional sector and one cross-sectoral linkage. The questions address each link’s main organizational and cognitive features, such as the type of R&D activity, knowledge flows, and objectives. The third section of the questionnaire consisted of attitude scales designed to elicit views and opinions regarding general features of the entire domestic R&D network.

A sample of 93 individuals was drawn from the OSPT file on senior scientists or R&D managers who are engaged in and/or responsible for process engineering R&D in Dutch institutions. The sample was stratified in order to obtain equal shares from the public and private sector, while incorporating all major R&D performing actors within OSPT projects. The entire sample covers six universities, three applied research organizations, and 17 companies (11 large multinationals or affiliates of foreign multinationals, and six medium-sized domestic firms). A written reminder and a final telephone reminder in case of non-response, achieved an overall response rate of 47%, with a fairly equal contribution of both sectors (public sector: 42%; private sector 52%). The realized sample comprises of 44 respondents, originating from 19 organizations: five universities, three applied research institutes, and 11 firms (including three of the medium-sized firms).

In view of the size and sectoral distribution of this sample one may expect that aggregate data will produce a fairly reliable overview of the network’s basic features and a valuable first impression of its effectiveness both the vantage point of the firms as well as the public research sector. Note that these actor accounts obviously have their limitations: not only are they subjective, one can also never be sure that the interviewer and interviewee share the same meaning about concepts used in the questionnaire. Moreover, one must also be aware that the evaluative questions may have evoked some biased responses (e.g., to influence decision making or protect stakeholder interests).[11]

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[8] This annual report showed some lacunas in its coverage of OSPT projects and their institutional participants. The missing data on projects involving external interest/funding from the private sector was gathered by OSPT through a survey held amongst the university units involved.

[9] Data analysis is done at the aggregate level of main institutions. The selection of Dutch firms includes affiliates of foreign enterprises.

[10] The questionnaire was used as relatively cheap and fast in collecting quantifiable information on a number of network participants which is large enough to allow for statistical analysis of the survey data. The structured questionnaire consisted mostly of multiple choice questions followed by insets for adding additional information in a free format. The questionnaire was designed and prepared by CWTS. It was refined and tested in collaboration with OSPT staff during the pilot stage of this study.

[11] The respondents participated on a voluntary basis. Anonymity of each respondent’s identity, and confidentiality and their answers, was guaranteed at the start of the project.

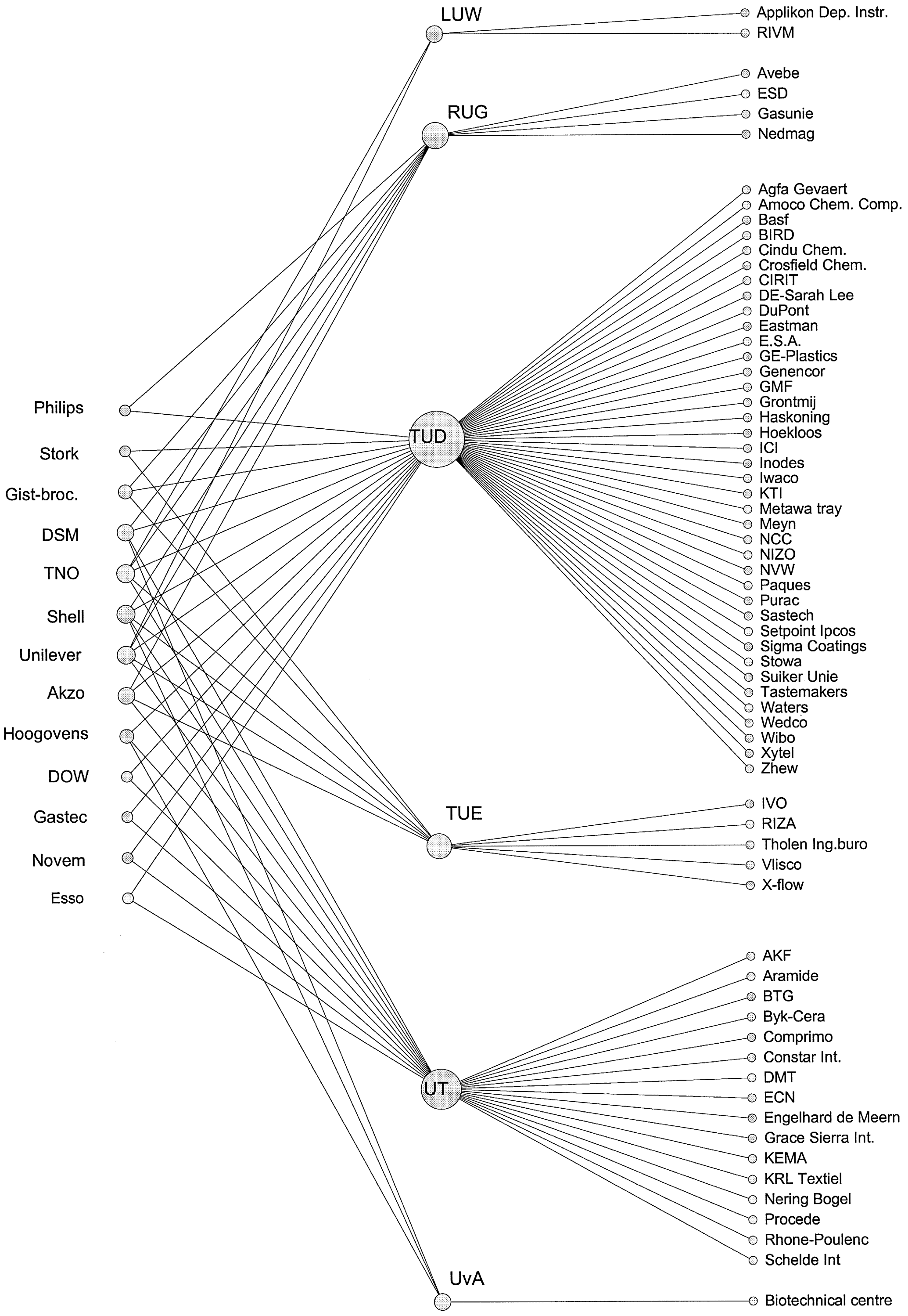

Fig. 1. OSPT network links from the perspective of the universities.* Source: OSPT research report 1994, supplemented by OSPT data collected from universities.

## 3. Main findings and discussion

### *3.1. The academic–industry core of the R&D network*

Linkages between public research institutions and enterprises have traditionally been an important vehicle for creating strategic competencies in process engineering in the Netherlands. There are several long-standing interorganisational relationships between industry and the public sector, where professors at Dutch universities are also part-time employed by Dutch firms. These personal ties are particularly instrumental in forging and maintaining institutional couplings that enable universities to engage in joint projects with companies dealing with research and technological development and focused on commercial applications and innovations across a wide range of process industries (e.g., chemicals and food processing, energy supply systems, and environmental waste treatment). These fruitful public–private linkages form the institutional basis of the present-day national academic research school in the field of process engineering (denoted from now on by its acronym OSPT). [12]

OSPT incorporates some 50 staff members (researchers and technical staff) and about 150 graduate students. The three technical universities (University of Delft-TUD, University of Eindhoven-TUE, University of Twente-UT) constitute its academic backbone, each one adding their own broad areas of expertise: process integration (TUD), chemicals reactors (UT), and separation technologies (TUE). OPST also includes research units at two general universities (University of Groningen-RUG, and University of Amsterdam-UvA), and at the Agricultural University of Wageningen (LUW). Their collective R&D portfolio and design activities cover a spectrum of industrial relevant applications ranging from oil, nafta, and natural gas to bioprocesses. OSPT researchers assist Dutch industry in articulating and translating their needs into R&D projects carried out in the public domain, and contributes knowledge and expertise to industry's own R&D and design activities. OSPT's chief objective is to educate and train specialist scientists and engineers (Ph.D. students and design engineers). Each OSPT R&D project consists of at least one researcher (mostly Ph.D. graduates, but also, some post-doc's), or a trainee design engineer. Many of those OSPT projects involve one or more external institutions (public institutions or firms) acting as an R&D partner and/or sponsor. [13] Overall supervision is provided by OSPT's tenured academic staff. As such, OSPT can be regarded as a dispersed centre that formalizes and institutionalizes both intra-sectoral and cross-sectoral R&D links, acting as an important organizational vehicle in the governance of the interface between the public research sector and industry. [14] This research school can therefore be regarded as the core component of a hybrid domestic network connecting universities, companies and applied research institutions.

Given the fact that this research school acts as an established national focal point for academic R&D in process engineering, it is quite reasonable to assume that the OSPT's projects which are (partially) funded by external sources provide an adequate overview of the key R&D-performing actors in the field. Table 1 contains key statistics of all 136

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[12] A 'research school' is a government-funded cooperative association of organizational units within and between universities where high-quality research and Ph.D. training are combined. Research schools are the result of a government science policy initiative which was implemented in the early 90s. There are now 97 of these schools in the Netherlands (VSNU, 1996).

[13] Includes all funding sources other than the block grant to universities by the Dutch government (i.e., research councils, contract research, etc.).

[14] OSPT is governed by a management team of eight, comprising of senior scientific staff of each of the six main contributing universities (mainly, research professors). This team is advised by a research committee and a training committee. The OSPT Board of Directors consists of external high-level scientific representatives from the same universities. The Industrial Broad is composed of representatives from external organisations and comprises about a dozen large Dutch firms and a few Dutch applied research institutes. This board advises on the design and implementation of OSPT's training and research programme. OSPT's administrative unit is located at the Technical University of Twente, at the home organisation of its current Scientific Director.

Table 1
Institutional linkage profile of OSPT R&D projects, 1994

Distribution of project partners and sponsors across institutional categories (% of links)

| | Netherlands | Foreign |
|---|---|---|
| Other universities | 3.0 | 13.9 |
| Public research institutes | 8.6 | 27.8 |
| Firms and private R&D laboratories | 52.3 | 22.2 |
| Government funding agencies and research councils | 36.0 | 36.1 |
| Total number of partners/sponsors | 197 | 36 |

Pairs of R&D performing Dutch institutions listed as partners/sponsors (number of projects)

| | Universities | Public research institutes | Firms |
|---|---|---|---|
| Universities | 6 | | |
| Public research institutes | 17 | 1 | |
| Firms (incl. private R&D laboratories) | 103 | 4 | 23 |

projects listing one or more external funding sources and/or R&D partners (i.e., other than the university involved). First, we see that the large majority of these external linkages mainly involve Dutch institutions ($n = 197$), and that most of these formal links concern public funding sources, or firms (as a sponsor and/or collaborator). The comparatively small number of linkages involving foreign institutions ($n = 36$) are more equally distributed across R&D partners and funding sources, the EC being the chief source of foreign funding. The second section of this table deals with the network linkages between the Dutch institutions. The results highlight the important role of firms as sponsors/partners in relation to the universities: 103 of the projects involve a link between one university and at least one firm. Many of these projects are in fact one-to-one academic/industry linkages. However, 23 projects include more than one Dutch firm (one project even lists 11 firms as co-sponsors).

These linkage data point out that this network is predominantly Dutch and characterised by public–private R&D links, many of which are one-to-one project links between a university and a firm as partner or sponsor. The OSPT network diagram, visualized in Fig. 1, focuses on these two key elements: it shows the links between the six core universities and their separate R&D partners, where each university is displayed as separate key node within the network. R&D partners with two or more project links to the different universities are located on the left side, while the institutions with only one link are grouped to the right. The majority of the institutions on the left are large industrial corporations, including several R&D-intensive or technology-driven Dutch multinationals, most of which covering a wide variety of process engineering-relevant industrial sectors and technological fields.[15] This group also includes public research organisations such TNO, and NOVEM which is a (semi) public transfer agency dealing with R&D projects on issues related to energy and/or the environment. The organizations on the right represent a large and diverse collection of organizations including large public research institutes (e.g., ECN, RIVM and RIZA), industrial corporations (e.g., Avebe and DuPont), private R&D labs (NIZO), and many SMEs including several engineering firms such as Haskoning and Grontmij.[16] These OSPT data helped gauge the approximate number of main institutions in the entire Dutch R&D network, and identify its key networkers. Based on these data one can discern a network core comprising of the three technical universities (TUD, TUE, and UT), one general university (RUG),

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[15] Concerns un-consolidated firms only (i.e., subsidiaries are listed separately).

[16] The UT also shows a link to the firm Procédé. This is UT's industrial liaison office in the field of process engineering, which acts as a technology brokerage company between academic research and interested industrialists.

Table 2
Views on the coverage, strength and relevance of the R&D network (% of answers; number of respondents within parentheses)

| Statement | Public institutions | Firms |
|---|---|---|
| Fig. 1 lists all important Dutch R&D organizations | ($n = 14$) | ($n = 21$) |
| Fully agree | 29 (4) | 62 (13) |
| Partially agree | 57 (8) | 19 (4) |
| Neutral | 14 (2) | 0 (0) |
| Disagree (fully/partially) | 0 (0) | 19 (4) |
| The network of R&D activities is strongly interconnected | ($n = 16$) | ($n = 23$) |
| Fully agree | 19 (3) | 9 (2) |
| Partially agree | 37 (6) | 26 (6) |
| Neutral | 13 (2) | 30 (7) |
| Disagree (fully/partially) | 31 (5) | 35 (8) |
| Participation in the network is important for my organization's current R&D activities | ($n = 16$) | ($n = 22$) |
| Fully agree | 81 (13) | 54 (12) |
| Partially agree | 13 (2) | 41 (9) |
| Neutral | 0 (0) | 0 (0) |
| Disagree (fully/partially) | 6 (1) | 5 (1) |

a large applied research organization (TNO), and some of Holland's largest industrial firms (e.g., DSM, Shell, Unilever, Akzo, and Hoogovens).[17]

## 3.2. Survey results

### 3.2.1. Views on the network's basic characteristics

Are the institutions listed in Fig. 1 an accurate representation of all relevant process engineering R&D actors in the Netherlands? And if so, can the entire network of interrelationships between those institutions be described as 'dense' (i.e., interconnected and integrated)? Moreover, is this network important for the R&D activities which are carried out within those institutions? These questions were included in the mail survey that was distributed amongst representatives of institutions in both the public and corporate sector. Table 2 presents the respondent's views on the related characteristics of the R&D network:[18] institutional coverage, internal cognitive strength, and practical relevance. The results indicate that the list of organizations engaged in OSPT projects as depicted on Fig. 1 appears to provide a fair representation of all Dutch institutional actors. The majority of the respondents in the corporate sector (62%) confirm that this overview lists all important Dutch R&D-performing institutions. The respondents at the universities and other public research institutions seem to take a broader view: only 29% fully agree. In their view, several firms (such as Fluor Daniel, and Solvay) and a few non-profit research institutes and national laboratories are missing (e.g., DLO–ATO).

Another key structural feature of the network concerns its interconnectedness of R&D activities: only 19% of the respondents in the public research

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[17] Note that these links capture only those formalised network links related to university-based training and R&D activities related to OSPT. Obviously, other formal links (contracts, licenses) and informal (personal) ties will exist between the institutions outside the OSPT setting. Moreover, given the wide range in process engineering activities in the Netherlands, OSPT will most likely not cover all sub-fields, nor all Dutch institutions—particularly SMEs and their small niche areas.

[18] Although the concept 'network' was used explicitly in the questionnaire to describe the organizational structure of institutional interrelationships, no definition was given of this concept. Only one respondent objected to this network representation approach, stating that the interorganisational structure should primarily be regarded in terms of bilateral relationships rather than an interconnected structure. One may therefore safely assume that the majority of the respondents accepted the network representation, and perceive the structure of interconnections as such.

sector fully agree that the network is strongly interconnected. A further 37% can only go along with this statement to some degree. The private sector is less positive, as indicated by shares of only 9% and 26% respectively. Bearing in mind that the respondents were asked to react to a statement which was formulated in rather strong positive terms, these findings bear out that both sectors do not perceive the network to be dense, but judge its organizational strength as average at best.

The R&D relevance of the network is quite evident, especially for the public sector. More than 80% of the respondents in the universities and other public research institutes agree that 'the network is important for my organization's current R&D activities'. This is to be expected considering the status of OSPT as the government endorsed focal point in public domain for academic education and research activities. More interesting is the view of the firms, of which more 54% agree fully, while an additional 41% indicate that the network is at least partially relevant to them. Dutch companies (including many large multinationals) thus clearly appreciate the network as a local source of scientific knowledge and technical expertise. In brief, these first findings bear out the importance of OSPT, and its associated R&D network, within the Dutch knowledge infrastructure and innovation system.

### *3.2.2. Person-embodied knowledge transfer between the public and private sector*

Collaboration and knowledge flows are the basic fabric of R&D networks. However, much of the essential knowledge and skills reside within in tacit form within experienced individual researchers or engineers—as a result of a personal learning process and as part of the set of tools and capabilities acquired unconsciously alongside that process. Among the most important of these non-codifiable skills are the acquisition and effective utilisation of knowledge. This person-embodied expertise is generally difficult to transfer through written information or statements, and can often only be passed on effectively by face-to-face contacts, or by physical transfer of people who are carriers of the knowledge. Human capital is a crucial factor in an cross-sectoral R&D network where training and recruitment of R&D personnel is an important linkage and diffusion mechanism between academia and industry: graduates entering corporate R&D come equipped with experience of tackling complex scientific and technical problems and are often also plugged into (inter)national research networks. In fact, several studies have highlighted that skilled graduates as one of industry's major benefits gained from the public research and education sector (e.g., Hoch, 1990; Pavitt, 1991; Senker, 1995).

To what extent are these academic graduates actually appreciated by the firms in this network? And how do their views compare to those of the public research sector? All respondents were asked to indicate the significance of different kinds of person-embodied knowledge transfer between the public and private sector for R&D activities as seen from the perspective of their own organization. The results in Table 3 show a rather large degree of consensus between firms and public institutions on this topic. In the both cases, about 90% of the respondents indi-

Table 3
Views on the relevance of the R&D personnel as transfer channel between the public and private sector (% of respondents per category; number of respondents within parentheses)

| Importance: | Public institutions | | | Firms | | |
|---|---|---|---|---|---|---|
| | Very | Moderately | None | Very | Moderately | None |
| Academic education and training | | | | | | |
| Trainee design engineers | 62 (8) | 31 (4) | 8 (1) | 41 (9) | 50 (11) | 9 (2) |
| Research trainees, Ph.D. students | 64 (9) | 35 (5) | 0 (0) | 32 (7) | 50 (11) | 18 (4) |
| Other[a] | | | | | | |
| R&D trainees | 27 (4) | 67 (10) | 7 (1) | 29 (7) | 50 (12) | 21 (5) |
| Seconded researchers and engineers | 27 (3) | 36 (4) | 36 (4) | 13 (2) | 53 (8) | 33 (5) |

[a] Including those from non-academic higher education institutions, non-academic public research laboratories, and other firms.

Table 4
Linkage characteristics of R&D relationships (% of respondents per category; number of linkages within parentheses)

| Linkage type (P—public sector; F—firms) | P–P | P–F | F–P | F–F |
|---|---|---|---|---|
| Intensity: average number of annual interactions | | | | |
| less than 6 | 48% (20) | 40% (17) | 44% (23) | 38% (6) |
| 6 to 25 | 52% (21) | 36% (15) | 48% (25) | 31% (5) |
| more than 25 | 0% (0) | 24% (9) | 9% (4) | 31% (4) |
| Stability: duration of link | | | | |
| less than 2 years | 32% (13) | 15% (6) | 19% (10) | 19% (3) |
| 2 to 5 years | 44% (18) | 51% (21) | 37% (19) | 38% (6) |
| more than 5 years | 24% (10) | 34% (14) | 44% (23) | 38% (6) |

cate that academic trainees (either graduate researchers or design engineers) constitute a ‘very important’ or at least ‘moderately important’ transfer channel. However, the data show that public sector seems more convinced of their importance, which is not surprising considering the key role of OSPT as a training facilitator within this network. Note that such differences in opinion may also indicate a somewhat different set of criteria used by the private sector to assess their relevance, or may even hint toward unfulfilled expectations and perhaps a certain degree of dissatisfaction on the part of industry. Interestingly, the firms are equally appreciative of other (non-academic) trainees as another important complementary source of new knowledge. It seems that knowledge and skills brought into R&D-intensive enterprises by academics are but one of the important person-embodied transfer channels. Researchers and engineers that are seconded from other organizations are perceived as less important in terms of knowledge transfer benefits.

### *3.2.3. Bilateral R&D linkages within and between the public and private sector*

As noted above, the respondents were asked to supply information on selected bilateral links of their own choice. Each respondent was requested to provide details on an R&D link (either formal or informal) involving at least one R&D partner in the same main institutional sector (either in the public sector-P, or a firm-F), and one including a partner from the other sector. They were also requested to provide data on five main characteristics of each link: (1) duration and contact intensity; (2) main activities, (3) activities that increased in the last 2–3 years, (4) main objectives, and (5) objectives were achieved to a satisfactorily degree. The findings are presented at the aggregate level of the two main institutional sectors (i.e., the public sector and private sector) or are aggregated to the following four categories of bilateral linkages:

1. linkages involving two public sector institutions (P–P);
2. public–private linkages, as viewed by public sector institutions (P–F);
3. public–private linkages, as viewed by firms (F–P);
4. linkages involving two firms (F–F).

Note that the respondents were free to chose from their own bilateral links. As a consequence, categories 2a and 2b do not represent the same set of links. These two sub-categories will be analysed separately to assess similarities and differences in the perceptions of public–private R&D links in general.

The duration of a bilateral relationship and the number of interactions between both parties are two key linkage parameters providing insight into the organizational strengths and weaknesses of the linkages. The findings in Table 4 show a large variation.[19] More than 40% of the links involve an average of less than six contacts on an annual basis (either in writing or verbally). About a quarter of the bilateral P–F links (i.e., data provided by the public sector) and nearly a third of the inter-firm links can be considered intense, with average of no less than 25 or more contacts per year. With regard to the age

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[19] Cross-tabulation of intensity and duration for each of the four categories reveals a fairly uniform distribution.

of the links, about a third of the links within the public sector a relatively novel, existing less than two years. The share of these network entries varies from 15 to 30% of linkages, indicating substantial network dynamics both within and across the institutional sectors. Note that about 40% of the linkages are older than five years and were therefore established prior to the foundation of OSPT in 1992. Here we see clear evidence of a mature network founded on stable long-term connections between key actors in both sectors (many of which dating back more than one decade). Such relationships are often based on personal interactions between industrial researchers and public-sector scientists, which are essential in building up the mutual trust and respect which is needed to forge effective and mutually-rewarding institutionalized linkages between public-sector research and industry.

Table 5

a: Main activities within bilateral R&D links (% of responses per type of linkage; number of responses within parentheses)

| Type of linkage (P—public sector; F—firms) | P–P | P–F | F–P | F–F |
|---|---|---|---|---|
| R&D and training | 31% (45) | 35% (56) | 51% (77) | 43% (12) |
| Applied research, design, and technological development | 14% (20) | 23% (36) | 28% (41) | 36% (10) |
| Basic and strategic research | 10% (14) | 8% (12) | 16 (24) | 7% (2) |
| Education, training, seminars | 8% (11) | 5% (8) | 6% (9) | 0% (0) |
| Transfer and exchange | 48% (69) | 52% (82) | 36% (53) | 39% (11) |
| Transfer of knowledge, ideas, opinions | 19% (27) | 21% (34) | 18% (26) | 14% (4) |
| Exchange of R&D results, technical specifications | 16% (23) | 19% (31) | 9% (13) | 21% (6) |
| Dissemination of R&D results | 7% (10) | 6% (9) | 2% (3) | 0% (0) |
| Recruitment of R&D personnel | 5% (7) | 3% (5) | 4% (6) | 4% (1) |
| Exchange of R&D personnel | 1% (2) | 2% (3) | 3% (5) | 0% (0) |
| Other activities | 20% (29) | 13% (21) | 13% (19) | 18% (5) |
| Committees, steering groups | 11% (16) | 3% (5) | 8% (12) | 0% (0) |
| Use of equipment, software, and other facilities | 7% (10) | 7% (11) | 2% (3) | 0% (0) |
| Other | 2% (3) | 3% (5) | 3% (4) | 18% (5) |
| Average number of main activities per linkage | 4.0 | 4.1 | 2.7 | 1.8 |

b: Main activities within bilateral R&D links with increased activity (% responses per type of linkage; number of responses within parentheses)

| Type of linkage (P—public sector; F—firms) | P–P | P–F | F–P | F–F |
|---|---|---|---|---|
| Overall | 41% (59) | 48% (77) | 36% (53) | 46% (13) |
| R&D and training | 56% (25) | 54% (30) | 39% (29) | 67% (8) |
| Applied research, design, and technological development | 55% (11) | 64% (23) | 46% (19) | 70% (7) |
| Basic and strategic research | 71% (10) | 50% (6) | 29% (7) | 50% (1) |
| Education, training, seminars | 36% (4) | 13% (1) | 33% (3) | |
| Transfer and exchange | 36% (25) | 49% (40) | 34% (18) | 27% (3) |
| Transfer of knowledge, ideas, opinions | 41% (11) | 53% (18) | 46% (12) | 0% (0) |
| Exchange of R&D results, technical specifications | 43% (10) | 55% (17) | 15% (2) | 33% (2) |
| Dissemination of R&D results | 10% (1) | 33% (3) | 0% (0) | |
| Recruitment of R&D personnel | 29% (2) | 40% (2) | 33% (2) | 100% (1) |
| Exchange of R&D personnel | 50% (1) | 0% (0) | 40% (2) | |
| Other | 31% (9) | 33% (7) | 32% (6) | 40% (2) |
| Committees, steering groups | 38% (6) | 20% (1) | 25% (3) | |
| Use of equipment, software, and other facilities | 10% (1) | 45% (5) | 67% (2) | |
| Other | 67% (2) | 20% (1) | 25% (1) | 40% (2) |

Table 5a provides an overview of the four linkage categories in terms of their activity profiles. Overall, these profiles appear to be rather similar in terms of their 40:40:20 distribution across the three aggregate categories of activities: R&D and training, Transfer and exchange, Other activities.[20] However, some noticeably differences show up in the sub-categories. For example, in R&D and training, where inter-firm technology-driven links (F–F) show a relatively strong propensity for activities in the category Applied research, design, and technological development with a share of 36%, whereas the science-driven linkages (P–P) reach a level of only 14%. Not surprisingly, the latter type of inter-sectoral linkages are also characterized by a stronger emphasis on Basic and strategic research (10%), and on Education, training and seminars (8%). In line with expectation, the cross-sectoral transfer-driven links (P–F and F–P) show an intermediate position in terms of these activities.

The main category Transfer and exchange shows fairly similar profiles for each of the four types of linkages. A noteworthy difference concerns Dissemination of R&D results, which is listed in 7% of the science-driven links, but is non-existent in industry-driven links. This is in line with the propensity of one-directional knowledge flows from the public sector to firms, and related corporate strategies to protect their intellectual property.

The category Other activities shows the importance of formal interaction through committees and steering groups at the science side of the network, whereas inter-firm linkages are marked by a significant activity grouped under the heading Other, which comprises of a variety of activities such as licensing, marketing support, and joint development of equipment. The figures on the sub-category Use of equipment, software, and other facilities suggest that these assets are more likely to be shared by the public sector institutions than by firms. Although this kind of network activity is mentioned less often than those referring to codified knowledge and tacit person-embodied skills, the joint use and transfer of advanced instrumentation and methodologies may represent considerable added value for opening up new opportunities to industrial R&D and speeding up the pace of technological development.

In summary, the comparison these aggregate activity profiles provides some clear evidence of the diversity among the various types of network links and highlights relevant features of the heterogeneity within the network.

The respondents were also asked to indicate recent changes in the network, i.e., which types of activities had increased (either in volume and/or intensity) over the last few years. The results are presented in Table 5b. On average, slightly more than 40% of the activities increased. The highest levels of increase are found in the main category R&D and training, where Basic and strategic research activities in intra-sectoral public linkages tops the list with 71% of the cases showing an increase. On the whole, all major activities within each of the main categories have increased significantly, with little difference between the four linkage categories.[21] Moreover, there is only one systematic difference at the level of the sub-categories. The noteworthy exception is the zero growth of inter-firm activities related to Transfer of knowledge, ideas, opinions, which is remarkable because this happens to be one of the main activities of these links (see Table 5a). Moreover, the data in Table 6b indicate that this kind of transfer within inter-firm links is perceived as fairly successful. One likely explanation for the reluctance to follow the general trend are corporate disclosure strategies aimed at safeguarding further developments with a bearing on their own core competencies. Although the underlying numbers are rather small, this finding underlines the existence

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[20] Significant positive Spearman rank correlations are found between the following activity profiles: P–P and P–F ($r = 0.80$); P–P and F–P ($r = 0.80$); P–F and F–P ($r = 0.63$); F–P and F–F ($r = 0.65$). Note that the sample of bilateral R&D linkages in this study are almost entirely concerned with the largest R&D-intensive actors in the network. Incorporating smaller-sized institutions, especially the SMEs, may noticeably affect this activity profile, most likely by attributing a larger share to activities related to the category Transfer and exchange.

[21] No significant Spearman rank correlations were found between the activity profiles.

of fundamental differences in the rationale, strategies and objectives between the inter-firm links within this network as compared to those involving the public sector.

The increased activity in these network links can be taken as clear a sign of this network's vigour and effectiveness. But to what extent is this success related to main objectives of the network links? More in particular, which R&D objectives show the highest success rates, and which the lowest? And are the cross-sectoral links achieving their transfer objectives? Table 6a presents a categorization of those objectives, accompanied by data on their distribution across the four linkage categories. We see that these objectives in each of the four linkage categories span the entire R&D process—from obtaining scientific knowledge research to contributing to innovations. Couplings between two public sector institutions show a clear preference for objectives in the aggregate category Knowledge creation and transfer, with a prominent place for Obtaining scientific knowledge and technical expertise which accounts for 26% of the answers. In contrast, inter-firm linkages are dominated by aims related to Technological development and innovations, in particular with regard to Contributing to process innovations representing 27% of the responses by the corporate respondents. As expected, the cross-institutional ties are more balanced in terms of their objectives. One finds an almost equal share of objectives referring to Knowledge creation and transfer and those related to Technological development and innovations—regardless of the

Table 6

a: Main objectives of bilateral R&D links (in % of responses per type of linkage; number of responses within parentheses)

| Type of linkage (P—public sector; F—firms) | P–P | P–F | F–P | F–F |
|---|---|---|---|---|
| Knowledge creation and transfer | 61% (65) | 51% (59) | 51% (72) | 28% (9) |
| Obtain scientific knowledge/technical expertise | 26% (28) | 15% (17) | 33% (47) | 21% (7) |
| Transfer scientific knowledge/technical expertise | 17% (18) | 25% (29) | 6% (8) | 6% (2) |
| Training and education of R&D personnel | 18% (19) | 11% (13) | 12% (17) | 0% (0) |
| Technological development and innovations | 39% (42) | 47% (55) | 46% (64) | 67% (22) |
| Contributing to process innovations | 23% (25) | 25% (29) | 28% (39) | 27% (9) |
| Contributing to technological development | 11% (12) | 9% (11) | 11% (15) | 15% (5) |
| Contributing to product innovations | 3% (3) | 10% (12) | 5% (7) | 12% (4) |
| Other technical and engineering support | 2% (2) | 3% (3) | 2% (3) | 12% (4) |
| Other objectives | 1% (1) | 2% (2) | 4% (5) | 6% (2) |
| Average number of main objectives per linkage | 3.0 | 3.0 | 2.6 | 2.1 |

b: Achieved objectives of bilateral R&D links (% responses per type of objective; number of responses within parentheses)

| Type of linkage (P—public sector; F—firms) | P–P | P–F | F–P | F–F |
|---|---|---|---|---|
| Overall | 59% (64) | 60% (70) | 67% (95) | 82% (27) |
| Knowledge creation and transfer | 68% (44) | 75% (44) | 78% (56) | 67% (6) |
| Obtain scientific knowledge/technical expertise | 64% (18) | 82% (14) | 79% (37) | 71% (5) |
| Transfer scientific knowledge/technical expertise | 72% (13) | 66% (19) | 100% (8) | 50% (1) |
| Training and education of R&D personnel | 68% (13) | 85% (11) | 65% (11) | |
| Technological development and innovations | 45% (19) | 45% (25) | 55% (35) | 86% (19) |
| Contributing to process innovations | 48% (12) | 41% (12) | 44% (17) | 100% (9) |
| Contributing to technological development | 42% (5) | 64% (7) | 67% (10) | 60% (3) |
| Contributing to product innovations | 33% (1) | 25% (3) | 71% (5) | 100% (4) |
| Other technical and engineering support | 50% (1) | 100% (3) | 100% (3) | 75% (3) |
| Other objectives | 100% (1) | 50% (1) | 80% (4) | 100% (2) |

perspective taken (i.e., as perceived by the public sector or by the private sector). However, institutional differences are quite significantly with regard to sub-category Knowledge creation and transfer: the public sector emphasizes Transfer of knowledge and expertise as an important objective (25% share), whereas the firms stress the importance of obtaining it (33% share). Here we see clear evidence of the asymmetric nature of these public–private linkage in terms of knowledge flows, where firms stress the importance of absorbing and appropriating the knowledge and skills supplied by the public research sector.

The objectives related to Technological development and innovations shows that objectives of public–private links are more concerned with assisting in innovation activity (especially, process innovations) than with contributing to technological development, problem solving and related technical support. It appears that the public sector is not only used by the corporate sector as a source of new scientific knowledge and technical expertise, but that their input extends all the way to working on industrial innovations. Note that the inter-firm links tend to be more focused in terms of their set of objectives; the respondents from the private sector list an average of 2.1 different objectives compared to an average of almost 3 objectives in the other types of linkages.

Uncertainty about the relevance and usefulness of results are an intrinsic property of the R&D process in general. The related common divide between, on the one hand, the goals of R&D projects and, on the other hand, their actual outcomes is clearly illustrated in Table 6b, which describes the share of objectives that were achieved. The overall figures indicate significant differences in the overall success rate, which vary from 59% of the objectives in the case of public–public links to as much as 82% for inter-firm linkages. The latter score can probably be partly attributed to the more focused and application-oriented nature of these alliances, as indicated by the smaller average number of objectives stated by the respondents (see Table 6a). The objectives related to Knowledge creation and transfer show slightly higher scores for the cross-sectoral links, which is understandable considering their emphasis on the objectives related to transfer. The major differences in success rate concern Technological development and innovations.[22] Particularly in the case of Contributions to process innovations and Contributions to product innovations, where inter-firm links show 100% success rates as compared to about 45% scores for the other linkages categories. Those comparatively low levels suggest that many R&D projects involving the public sector do not seem to live up to expectations, which is a significant finding considering the fact that contributing to innovations appears to be one of the key objectives of these network links. It raises important questions about (misconceptions regarding) the feasibility of innovation-related objectives, and—at a higher level—the possibility of functional inadequacies within these links, or in the network as a whole, that ought to be addressed. This particular mismatch between goals and achievements might explain some of the less positive views of the respondents from the corporate sector regarding the network's overall relevance (see Table 2). This in turn suggests that (partial) failure of these activities related to technological development and innovation might indeed signify dysfunctional relationships or undesirable developments within the network. Note that this finding is probably highly specific for this particular R&D network, with its rather strong orientation on industrial process innovations. It does not tie in with results from other studies on public–private R&D linkages which point out that science-intensive corporations are often more interested in idea transfer than actual knowledge transfer from the public sector, or use those links primarily to access expertise or advanced instrumentation (e.g., Roessner, 1993; Faulkner and Senker, 1994).

Further statistical analyses of the survey data failed to produce any highly significant relationships which may point toward general features of the network linkages that prove to be obstacles in reach-

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[22] The remarkable difference between the views of the public sector and the private sector regarding the success rate of contributions to product innovations (25% vs. 71%) might simply result from insignificant statistical variance due to the small numbers involved.

Table 7
Views on suggested general improvements of the network (% of responses per category; number of responses within parentheses)

| Degree of necessity[a]: | Public institutions | | | | Firms | | | |
|---|---|---|---|---|---|---|---|---|
| | (*n*) | + + | + | 0 | (*n*) | + + | + | 0 |
| *Scientific and technological* | | | | | | | | |
| Taking advantage of new scientific and technical developments | (12) | 67% | 25% | 8% | (22) | 50% | 41% | 9% |
| Creating new knowledge and skills | (11) | 55% | 22% | 18% | (21) | 38% | 57% | 5% |
| Utilization of knowledge, skills and R&D products | (10) | 50% | 30% | 20% | (20) | 45% | 50% | 5% |
| Linking activities to international R&D programs | (12) | 42% | 50% | 8% | (21) | 57% | 43% | 0% |
| Dissemination of knowledge, skills and R&D products | (10) | 40% | 50% | 10% | (22) | 50% | 36% | 14% |
| Matching activities and interests of the public and private sector | (11) | 27% | 64% | 9% | (19) | 37% | 47% | 16% |
| *Institutional and administrative* | | | | | | | | |
| Funding and subsidies by national government and agencies | (12) | 42% | 50% | 8% | (19) | 32% | 42% | 26% |
| Including additional Dutch R&D institutions | (11) | 9% | 36% | 55% | (14) | 7% | 28% | 64% |
| National regulations and administrative procedures | (10) | 0% | 20% | 80% | (13) | 0% | 23% | 77% |

[a] Symbols: + + necessary improvement, + desirable improvement, 0 unnecessary improvement.

ing these goals.[23] It seems that determinants for not achieving objectives are much more likely to be link specific or project specific.[24] The survey did however provide some general information regarding sources of (potential) dissatisfaction. The respondents were presented with nine types of improvement and invited to rate their importance for enhancing the network's overall performance on a three-point scale (1 = necessary, 2 = desirable, 3 = unnecessary). Table 7 provides the results which are broken down into the views of the respondents in the public research sector and those belonging to the corporate sector. The findings indicate that there is ample scope for improvement. On the whole, the large majority of both groups feel that all areas of improvement deserve at least some attention. The respondents clearly indicate that changes are necessary in all but two of these nine categories. Those two exceptions are: (1) the enlargement of the network by including additional R&D institutions, which ties in the majority view that most of the important Dutch actors already participate (see Table 1), and (2) changes in regulatory and administrative arrangements, which probably reflects the negative attitude of the Dutch R&D community regarding the bureaucratic red tape involved (see also Tijssen and Korevaar, 1997). The noticeably differences between the views of both sectors reflect their main interests in the network: the researchers in public sector expect considerable improvement from Creating new knowledge and skills, whereas the corporate researchers favour Linking activities with international R&D programs and Dissemination of knowledge, skills and R&D products. Finally, it is interesting to note that Matching activities and interests of the public and private sector is not considered a top priority for improving the network, yet another sign that this network seems to be performing relatively well in bridging R&D in both sectors.

## 4. Discussion and general conclusions

This case study was primarily devoted to developing indicators for describing and assessing institu-

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[23] The Pearson correlation analysis included the following six network variables for each of the four linkage types: frequency of interaction; age of linkage; number of activities; share of increased activities; number of objectives; share of objectives achieved. The two highest positive correlations are: interaction frequency versus the share of achieved objectives within the group of F–F links ($r = 0.41$), and the number of increased activities versus the share of achieved objectives in the case of P–P links ($r = 0.40$). Note that each correlation accounts for only 16% of the statistical variance of both variables.

[24] This level of analysis was outside the remit of this particular case study. Such an in-depth assessment should take into account several cognitive or interorganisational factors related to these objectives, such as social and organisational costs involved in establishing and maintaining R&D links, the pre-existing objectives and levels of network activity, and whether or not parties involved (regulatory and financing bodies, network partners, analysts) perceive these objectives as highly relevant within the context of network arrangements.

tional features of a national R&D network which aims at linking public research and private sector R&D in the area of process engineering. Such studies may face numerous methodological and analytical problems due to lack of systemic data and the large number of (in)formal links and the variety of interconnected actors active within such a network. Fortunately, this particular study has benefited significantly from information on an established R&D-performing network institution—the academic research school OSPT—which occupies a core position at the public–private interface of Dutch R&D related to process engineering.[25] However, using OSPT as the only institutional point of entry to such a large network is likely to introduce a bias in favour of the academic actors in the network and their R&D partners. Parts of the web of relations will be missing, especially the strategic alliances between firms, and links based on contract R&D projects involving firms and applied research institutes. Identification of all important institutional actors in large and continually evolving networks requires several independent information sources. Surveys seem an obvious choice for gathering complementary data. The subsequent mail survey used in this study was designed to cast a wider net and has indeed provided detailed network data from several firms and non-university public research institutes. On the whole, one may therefore assume that the combination of both information sources offers an adequate overview of network's main features, while the indicators have provided a comparative analysis in the variety of R&D links among network participants and some insight into the network's effectiveness.

The results of this study indicate that the OSPT network seems to be quite effective in linking the various R&D actors in the Netherlands. Moreover, the data show that many bilateral R&D projects are achieving their objectives. Here, one should take note that these findings are based on (subjective) opinions of those who participated in the survey. Although corroboration of these findings by objective measures was beyond the scope of this study, the related issues of reliability and validity clearly deserve some attention. This reliance on subjective information can be (partially) resolved by incorporating more information on the network's characteristics and its general performance. Fortunately, the systemic level data resulting from this indicator-based approach offers an empirical basis to so. Quantitative results can be used as empirical input to elicit further information from withdrawn participants in the network or from non-participants in the survey. Such a follow-up could for instance take place via separate interviews or by adopting a formal iterative process geared toward consensual decision making (e.g., a Delphi survey). Adding such a second stage, may also present an opportunity to move away from a reliance on historical data and towards a more dynamic and forward-looking perspective. In conclusion, the quantitative empirical approach adopted in this case study seems quite suited as a first exploratory stage of an external assessment procedure, in which indicators and quantitative data can help to unfold and describe the network. Results can be fed into informed debate and be used to (re)direct incentives to stimulate networking, or focus further evaluation by expert panels, site visits, and the like.

This study has emphasized the institutional structure and workings of a 'heterogeneous R&D network'—as a dynamic knowledge creation and transfer system—instead of focusing on collaboration and knowledge flows between 'science' and 'technology' as two separate domains of activities and governance. By using such a conceptual framework it becomes more easy to analyse and compare the various linkages and their elements (education and training, R&D, innovations and industrial application), and to appreciate the importance of the network as a dynamic self-organizing system which shapes and contributes to a cumulative body of scientific and technological knowledge. To quote Callon (1994): "...we need to abandon the notion of information and use the network in its place. In

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[25] In the event that such a convenient institutional entry point is absent, one might consider using expert opinions and/or documents (project descriptions of collaborative R&D programmes, members of users groups, joint research articles) to identify some of the (likely) core actors in such a network. A survey amongst those actors may help identify their relevant R&D partners (for example by a co-nomination technique). Successive surveys may extend this range of actors by identifying the 'partners of the partners' until a sufficient degree of convergence is achieved.

effect, the main result of scientific activity is not to produce information but to reconfigure heterogeneous networks.... These interactions modify and transform the entities concerned and make new ones appear in the form of statements, instruments, skills, beliefs and substances. Thus, it is appropriate to talk about the process of the production of scientific knowledge as reconfiguration.'' From this viewpoint, network analysis should therefore not only be regarded as a method for generating numerical information on structural and relational characteristics, but also as means to produce relevant process indicators.

The policy relevance of results derived from network studies obviously depends on the role of those R&D networks within S&T systems—especially in those cases where these networks are strongly related to a technological core competencies and belong to institutional structures that underpin national research and innovation system (cf. Callon et al., 1991; Webster, 1994; Faulkner, 1995). In the case of the Netherlands, it is clear that flexible and application-oriented R&D networks have become a key institutional element in the Dutch knowledge infrastructure. Several new networks and related network-based organizations have been launched in recent years to institutionalize and promote linkages between universities, public sector research institutes, and R&D-intensive corporations (see [4]). However, government programmes may prove counterproductive if a proper social and institutional environment is lacking: top-down initiatives and incentives may for instance force new network alliances on a techno-scientific communities which are in conflict with, or undermine, productive informal contacts which already exist, thereby weakening public–private links between rather than strengthening them. Determining the state of development in the private and public R&D base in such targeted areas—a precondition for establishing an effective formal national network —and monitoring these emerging or changing networks in such areas is therefore clearly a matter of S&T policy concern in the Netherlands.

Case studies involving quantitative network analyses can provide useful general information on both the static and dynamic features of a network in terms of its links and processes, and are therefore valuable in ascertaining a network's effectiveness and benefits.[26] Findings of such analyses enable a comprehensive and in-depth analysis of network strengths and weaknesses within their national institutional setting, and provides a means to assess the network's scientific and technological performance, internationalisation, and economic impact. Moreover, numerical indicators can be a highly economical way of presenting empirical information on network features—both within and between networks—and their developments over time. These data may provide a quantitative underpinning of results indicating which vital links in networks need strengthening, possibilities for creating and transferring scientific and technological knowledge and skills, or breaking down traditional dependencies and institutional barriers. Not only can this contribute to R&D management as a leverage point to help reconfigure the network, but it may also provide relevant input to government S&T policy debate and decision-making on the impact of policy measures as part of the government's role as facilitator and funding source of such knowledge production and diffusion mechanisms.

Case studies of a large cross-sectoral R&D networks inevitably provide an incomplete picture of their varied nature and dynamics. Results of this study are therefore also difficult to generalise beyond the institutional context, the subject area and analytical perspective in which the study was conducted: characteristics of a process engineering R&D network in the Netherlands are obviously to some extent nation-specific, sectoral-specific and field-specific—in terms of its institutional and legal frameworks, organizational arrangements and interconnections, and its patterns of scientific and technological specialization. Nonetheless, we believe that this particular study can offer an illustrative example of an indicator-based methodology for systematic empirical analyses of these particular networks which are becoming increasing important transfer mechanisms in the S&T systems of advanced knowledge-based economies.

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[26] Measures of the network's effectiveness worth considering are: number of research projects (partially) based on external funding; size of total external funding; duration of R&D projects; number of different sponsors from industry; number of projects co-sponsored by different organisations.

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