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Does technology affect network structure? A quantitative analysis of collaborative research projects in two specific EU programmes

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Abstract

The promotion of collaborative R&D through Framework Programmes is a top priority of European RTD policy. However, despite the considerable sums involved, surprisingly little is known about the structure of the resulting research networks. Arguing that the underlying technological regime critically affects the structure of collaborative R&D, this article examines the structure and topology of collaborative research networks in the telecommunications and the agro-industrial industry in two specific programmes of the 4th EU Framework Programme. We find systematic differences which we attribute to differences in the underlying knowledge base, the research trajectories pursued in EU-funded R&D and the organisation of knowledge production in the two industries. As expected on the basis of prior research, we show that collaborative research projects involve a larger number of partners and require greater funding in the telecommunications industry, and that actors from science are positioned more prominently in the agro-industrial collaborative R&D network. Contrary to expectations, we find fewer and less intense interactions between science and industry in the agro-industrial industry. We provide a tentative explanation for this result and discuss policy implications.

JEL Classification: O33, O38, C69

Keywords: framework programmes, research collaborations, technological regime, sectoral innovation system, social network analysis, science-industry interactions

1. Introduction

Since the early 1980s, the promotion of collaborative R&D has become one of the top priorities of modern science and technology policy in industrialised countries (see Caloghirou *et al.* 2002). At present, these policies are justified on essentially two grounds: *First*, as the costs of creating new technology have risen exponentially in many areas, individual organisations can no longer innovate on their own. Collaborative research allows achieving critical mass, exploiting economies of scale and sharing risks. *Second*, and perhaps more importantly, innovation is conceptualised as a complex, interactive learning process, in which a wide set of actors from industry, science and government collaborate to generate new knowledge or novel combinations of existing knowledge (see e.g. Fagerberg 2005; Etzkowitz and Leydesdorff 2000). In order to accelerate the creation of economically useful knowledge, linkages between these actors need to be optimised.

At the European level, the first policies to promote collaborative research were implemented in the early 1980s in response to widespread concerns about the competitiveness of European industry. Since 1984, the funding of collaborative research has been bundled into successive, multi-annual Framework Programmes (FPs) on Research and Technological Development (RTD). The objective of the FPs is to strengthen the competitiveness of European science and industry and improve economic cohesion through co-funding multinational and multi-actor projects of limited duration that mobilise private and public funds at the national level. Priorities have changed over time from enhancing European abilities to *produce* new technologies (FP1-FP4), to enhancing the ability to *use* them effectively (FP5), to developing scientific and technical excellence in a European Research Area (FP6), but the promotion of collaborative R&D has remained the cornerstone of European RTD policy.

Although total funding of the FPs is only about 6% of what is spent each year by national governments on RTD policies, the sums involved are far from negligible (the budget of the FPs has increased from EUR (ECU) 3.8 billion in FP1 to almost 18 billion in FP6). Given their strategic importance and the amount of money devoted to them, it is surprising how little is known about the structure and composition of the research networks that have emerged in the FPs.

Recent work has started to fill this gap. Breschi and Cusmano (2004), Barber *et al.* (2006), and Roediger-Schluga and Barber (2006) present evidence on global topological and structural features of various R&D collaboration networks induced by EU funding through FP5.

These papers show that at a global scale, networks are scale-free and of small world type, i.e. they are characterised by a heavily skewed degree distribution following a power-law and by a short average path length with high local clustering.

At a less aggregated scale, however, sub-networks exhibit considerable variation, as FPs cover a wide range of R&D activities in a broad set of technological areas. Research on inter-organisational networks and strategic alliances of biotech firms working on human therapeutics and diagnostics (e.g. Owen-Smith et al. 2002; Powell 1998; Powell et al. 1996), and on strategic alliances in the semiconductor industry (e.g. Stuart 2000; Stuart and Podolny 1999; Stuart 1998) has shown that the nature of the knowledge base, the institutional set-up of knowledge creation and firms' position in the network critically affect how many external links firms establish and maintain, with whom they collaborate and where they are positioned in future periods. These findings suggest that external variables, in particular technology, may introduce considerable heterogeneity into observed network structures. Verspagen and Duysters (2004) provide tentative evidence by observing different topological features of strategic technology alliance networks in the chemicals and food industry, and the electrical industry.

In this paper, we take a step towards systematically addressing this issue. Specifically, we want to pose the question in a general theoretical framework and explore how different technological regimes impact the structure of collaborative R&D networks that have emerged in the EU FPs. We contend that the nature of the knowledge base, the research trajectories and the institutional organisation of knowledge production determine the set of actors involved in the innovation process (see Marsili and Verspagen 2002), how they interact and the nature of their joint activities.

We proceed by investigating the structure and composition of collaborative research networks in two specific programmes of FP4 (1994-1998), ACTS (Advanced Communications Technology and Services) and FAIR (Fisheries, Agriculture and Agro-Industrial Research). ACTS and FAIR are comparable in terms of funding, yet target entirely different industries, namely the telecommunications and the agro-industrial industry. These are based on vastly different technologies and are therefore good examples to test our argument.

We believe an answer to our question is relevant far beyond the scientific discourse. Understanding the structure of joint research in Europe is critical for understanding the institutional structure of the European Research Area. Knowing whether technology systematically affects patterns of collaborative research is a crucial input for policymakers in the design of appropriate policies.

The paper is structured as follows. In Section 2, we present the theoretical underpinning and four research hypotheses that guide the empirical analysis. In Section 3, we examine descriptive features of the dataset and test the first two hypotheses. In Section 4, we analyses structural properties of the collaborative research networks in ACTS and FAIR and address hypotheses three and four. In Section 5, we summarise the main findings, discuss policy implications and conclude with some directions for future research.

2. Theoretical background and research hypotheses

Research partnerships are a socially beneficial organisational form that may improve the competitiveness of the actors involved and increase economic welfare. The public funding of collaborative R&D is justified by arguments drawn from the theoretical literature on transaction costs, strategic management and industrial organisation (see Caloghirou et al. 2003; Combs and Link 2003): R&D collaboration creates specific assets that facilitates R&D transactions, especially the transfer of tacit knowledge, which in turn improves collective learning.[1] It may create competitive advantage by raising profitability through the exploitation of economies of scale and scope in R&D, the ability to speed up the development of higher quality goods, and the ability to reduce risk through the pooling of resources. R&D alliances may also reduce the risk inherent in expanding into new markets by working as options which can be exercised as information about technology and markets improves over time. Through the internalisation of knowledge spillovers, collaborative R&D may raise collective R&D investment. Finally, even though there may be collusion in product pricing, the IO literature generally predicts that consumers may benefit from research partnerships through increased competition (innovation races) and higher product quality, as well as lower consumer prices due to lower production costs.

Although a considerable part of the literature on R&D partnerships focuses on inter-firm relationships, innovation networks also comprise actors from science and government. Casual empiricism as well as theoretical considerations suggest that observable patterns of interaction may be systematically affected by technology. In the literature on the economics of innova-

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[1] Note that this argument conflicts with the common rationale for the public funding of R&D, namely the imperfect appropriability of knowledge which causes private actors to invest less than would be socially optimal (see Martin 2003). Rather than being imperfectly appropriable, the main problem is seen in the tacit nature of scientific and technological knowledge, which impedes socially beneficial knowledge transfer. In other words, there is too much rather than too little appropriability (see e.g. Mowery 1994).

tion and technological change, it is well documented that innovation processes differ across technologies and industries (see Malerba 2005).

The main theoretical concept to account for these differences is the technological regime (Nelson and Winter 1982), referring to the learning and knowledge environment in which firms operate. Nelson and Winter distinguish two basic types, a 'science-based' and a 'cumulative' regime. These give rise to 'enterpreneurial' (Schumpeter Mark I) or 'routinised' (Schumpeter Mark II) patterns of innovation and industrial competition (Winter 1984). In the former regime, the knowledge base is broad and universal, and originates in science, outside the industry. In the latter regime, the knowledge base is narrow and targeted, and is built cumulatively through learning processes in the firm.

Dosi (1982) elaborates on these basic types and suggests that a technological regime can be characterised with respect to three fundamental dimensions: (i) the properties of the learning processes associated with the firm's problem solving activities; (ii) the system of sources of knowledge, internal and external to the firm, relevant for such problem solving activities; and (iii) the nature of the scientific and technical knowledge base upon which the firm draws in solving problems.

Malerba and Orsenigo (1997; 1993) further operationalise the concept with regard to the dimensions suggested by Dosi and empirically identify 'Schumpeter Mark I' and 'Schumpeter Mark II' patterns of innovation in distinct groups of technologies (Breschi et al. 2000; Malerba and Orsenigo 1996). However, the distinction into only two alternative regimes is rather crude in view of the diversity of innovation patterns in different industries.

A richer taxonomy is due to Pavitt (1984), who classifies industries by sources of innovation and appropriability mechanisms and identifies four sectoral patterns of innovative activity. While not referring directly to the definition of technological regimes, the Pavitt taxonomy has proved enormously successful in classifying determinants and directions of technological trajectories in different industries (Malerba 2005).

The major shortcoming of the Pavitt taxonomy with regard to the literature on technological regimes is that it does not consider the nature of an industry's knowledge base. This gap is filled by Marsili (2001), who refines the Pavitt taxonomy by using a combination of data sources (patents, R&D statistics, scientific inputs, innovation surveys). She identifies five distinct technological regimes (Marsili 2001, p. 95): a science-based regime, a fundamental process regime, a complex (knowledge) system regime, a product engineering regime and a continuous process regime. This is done by clustering industries using seven factors that describe the nature of the knowledge base, the level of technological opportunity, the level of technological entry barriers (instead of appropriability mechanisms), the degree of diversity in exploiting technological opportunities, the external sources of knowledge and the dominant technological trajectories (product and/or process innovations) (Marsili 2001, pp. 89-211).

According to Marsili's taxonomy, the telecommunications industry is governed by the physical science-based regime and the agro-industrial industry by the continuous process regime. What does this tell us about the nature of innovative activity in the two industries?

The telecommunications industry encompasses suppliers of equipment and end-user appliances as well as ‘new’ and incumbent operators of networks and service providers (Edquist 2003). It forms the backbone of the information society and consists of predominantly large firms (European Communities 2002, pp. 228, 416). Liberalisation and privatisation have changed the structure of the sector in Europe considerably, as has the emergence of standards such as TCP/IP or GSM and the convergence between data and voice transmission (Dalum and Villumsen 2003).

Technological opportunity is high in the telecommunications industry, which is reflected by high R&D spending and a high rate of mainly product innovations (Marsili 2001, pp. 110, 119, 206-7). These, however, are frequently systemic and therefore require heavy investment and co-ordinated activities by a large number of parties. Applied science and engineering knowledge constitutes the relevant knowledge base, which is fairly narrow (Marsili 2001, pp. 160, 167, 185, 191). Firms' distinctive competences are in computer science and electrical engineering, with background competence in material science. Additionally, innovation also requires competence in mathematics, mechanical engineering and physics (Marsili 2001, p. 188).

Firms in the telecommunications industry generate much knowledge in-house. However, the industry also relies on strong ties with academic research in electronics and computer science (Marsili 2001, pp. 94, 188, 192). For example, Schartinger et al. (2002) find a number of joint projects between manufacturers of electrical and electronics equipment and academia. The most frequently listed external sources of knowledge in innovation surveys are joint ventures with other firms and interactions with users (Marsili 2001, p. 182).

Measured by R&D expenditure, new technological knowledge in the telecommunications industry is mostly created by equipment manufacturers like Cisco, Ericsson, Nokia or Siemens. This indicator, however, underestimates the role of network operators and service providers in setting standards and shaping the functionality of equipment (Edquist 2003). Standard setting activities were particularly important during the period considered in this paper, as FP4 was running at a time when R&D for the development of and agreement on the standards for 3G mobile phone communication (UMTS) was carried out (Luukonen 2002, p. 449).

The agro-industrial sector is among the largest industrial activities in the EU, accounting for 10.3% of manufacturing value added in 2000. On the supply side, it is highly fragmented in several member states (BEL, ESP, FRA, ITA, AUT, POR). In others (DEN, NLD, FIN, SWE, GBR), large enterprises dominate the industry. Three of the five largest consumer food companies (by revenues) are headquartered in Europe (Nestlé, Unilever and Groupe Danone). Following the BSE and foot and mouth disease crises, and the debate on genetically modified (GM) food in the 1990s, tightened governmental regulation, stricter food security control and heightened consumer awareness have become key determinants in innovation processes (European Communities 2002, p. 81). Not least because of concerns about food safety, governments maintain considerably research capacity in this area in most European countries.

Innovation in the industry is characterised by the continuous process regime. According to innovation surveys, R&D intensity tends to be rather low (Marsili 2001, p. 110). The main mode of innovation are process innovations, although R&D also yields a substantial number of new products each year (Marsili 2001, pp. 206-7). Despite its purported 'low-tech' character, with suppliers of production machinery being the main source of innovation, the advent of new general purpose technologies, in particular biotechnology, has boosted technological opportunity and introduced a new technological regime along side the traditional, chemicals-related technological regime in food production (von Tuntzelmann and Acha 2005). This is reflected in a high importance of basic and applied science for innovation in this industry (Marsili 2001, p. 185). Schartinger et al. (2002) find joint research projects between food producers and universities in engineering, chemistry, medicine, pharmaceuticals, biology and agriculture.

This points to a diverse knowledge base in the agro industry, a finding that is confirmed by Marsili (2001, pp. 160, 188). Innovating firms need a distinctive competence in biology and background competences in chemistry, computer science, materials science and mechanical engineering. Moreover, innovation requires competence in chemical engineering, electrical engineering, mathematics, medical science and physics (Marsili 2001, p. 188). Innovation surveys list suppliers, affiliated firms and public institutions (which include academic research) as the most important external sources of knowledge for industrial innovation (Marsili 2001, p. 182).

What does this imply for the properties of collaborative research projects and resulting collaboration networks? Technological opportunity is high in the telecommunications industry which has gone through a period of fairly turbulent technological change over the last decade. Many of the new technologies are systemic, capital-intensive and affect infrastructure. In the agro-industrial industry, technological opportunity is much lower and new solutions mainly comprise modular improvements of processes and product variations. The advent of genetic engineering has certainly created massive opportunities for radically new products and processes. However, incentives to fully exploit these opportunities have been muted by consumer concerns in Europe. Moreover, these concerns as well as the food crises in the 1990s have stimulated a sizeable amount of public funding of research on food safety.

From these observations, we expect R&D in the telecommunications industry to require greater capital investment relative to the agro-industrial industry[2]. Greater capital investment increases project risk, which can be spread by involving a greater number of partners. Moreover, successful standard setting requires the participation of all or at least most of the relevant actors. However, a greater number of partners come at a cost, as they raise co-ordination needs. In R&D governed by the continuous process regime and in projects concerned with food-safety, there is little need to incur these costs. We therefore posit the following two interrelated hypotheses:

Hypothesis 1: *The average collaborative R&D project in the telecommunications industry involves a greater number of partners than in the agro-industrial industry.*

Hypothesis 2: *The average collaborative R&D project in the telecommunications industry requires* (a) *greater total funding and* (b) *greater funding per participant than in the agro-industrial industry.*

Note that the latter hypothesis combines two effects. Assuming a minimum amount of funding per partner and keeping this constant, a greater number of partners automatically leads to

2 Note also the differences in the size distribution of firms in the two industries. A considerably greater number of large firms in the telecommunications industry points to a larger minimum efficient scale, which in turn depends heavily on technology.

higher funding per project. In addition to this, we expect to observe greater funding per partner, necessitated by the higher capital intensity of R&D in the telecommunications industry.

Regarding network structure, the key variables are research trajectories, the properties of the knowledge base and sources of learning. Prior research has shown basic and applied research to be considerably more important for innovation in the agro-industrial than in the telecommunications industry. Such research is typically conducted by universities and public research organisations in Europe, especially in the field of biotechnology (for evidence from the life sciences, see Owen-Smith et al. 2002). Moreover, research on food safety is mainly conducted by (government sponsored) actors from science. Also, the lower capital intensity of research in the agro-industrial industry may facilitate participation of actors from science that have no internal cash-flow to support a portfolio of related research activities (see Luukonen 2002). We therefore contend that

Hypothesis 3: *Actors from science play a more central role in the network of collaborative R&D projects in the agro-industrial than in the telecommunications industry.*

How does this affect interactions between science and industry? Prior research shows that science is an important external source of knowledge in both industries. However, average firm size is smaller and the knowledge base more dispersed in the agro-industrial industry, suggesting fewer capacities for internal knowledge generation. At the same time, research capacity is high among European universities and research centres and important for innovation in the agro-industrial industry. We thus expect that

Hypothesis 4: *Science-industry interactions are more frequent and stronger in the agro-industrial than the telecommunications industry.*

In the remainder of this article, we test these four hypotheses.

3. Descriptive features of the dataset

The aim of ACTS (Advanced Communications Technology and Services) was to develop advanced communication systems and services in Europe, to accelerate their deployment and to strengthen collaboration between users of advanced communications applications (European Council 1994a). FAIR (Fisheries, Agriculture and Agro-Industrial Research) was established to increase the competitiveness, efficiency and sustainability of the agricultural, fishery and related industry sectors by the development of new technologies, to improve product and food quality, and to promote rural development (European Council 1994b).

Both Programmes were designed to encourage the participation of actors from industry, government and science[3], with special emphasis on the involvement of small and medium-sized enterprises. Importantly for our purposes, the programme documents reveal no differences in programme design that would indicate preferential treatment of any particular group of actors. ACTS had a budget of ECU 671 million, while total funding in FAIR amounted to ECU 739.5 million, in each case about 5% of the total budget of FP4 (CORDIS 2006b, 2006a).

The networks induced by ACTS and FAIR are the result of self-organised partnering by participants within the structures imposed by EU funding rules. They are exploration networks (see Rothaermel and Deeds 2004) whose prime objective is to generate and diffuse knowledge, rather than marketable products and services. In these regards, they differ from networks constructed from other data sources on R&D collaboration, such as alliance data, patents, scientific publications or surveys, and may offer complementary evidence. Not only do they cover repeated collaborations between a fairly stable set of actors, but also short-term collaborations in single R&D projects. Moreover, our data may include a wider set of actors, especially from government, that contribute to innovation processes in sectoral or territorial innovation systems.

Data on the research networks in the two programmes is drawn from the most recent version of the sysres EUPRO database, maintained by ARC systems research. This database has been constructed from the CORDIS projects database (CORDIS search 2006) and presently includes all projects funded in FP1 to FP5 (for details, see Roediger-Schluga and Barber 2006).

In total, 223 projects were funded in ACTS over the period from Sep 1995 to Aug 2000 and 869 projects were funded in FAIR from Oct 1995 to Mar 2003.[4] Although multi-partner projects by definition, 195 project records in FAIR list only one participating organisation. This can only be explained by the Commission's disclosure policy, as no systematic pattern (e.g. by contract type) could be detected. Since this paper focuses on *collaborative* research networks, the 195 records were excluded from the dataset.

Organisations participating in ACTS and FAIR projects vary considerably in terms of size and economic focus. In order to create comparable organisational entities that reflect a coher-

3 See Article 130j of the Treaty of the European Union.

4 Time lags caused by administrative requirements (public tender, evaluation, contract negotiation) are substantial. In all FPs, total research activity peaks after their official end date and carries on for several years (Roediger-Schluga and Barber 2006).

ent bundle of resources and competencies, heterogeneous organisations such as universities, large research centres or conglomerate firms are broken down into subentities such as faculties, institutes, divisions or subsidiaries. Based on the available contact information of participants, subentities have been identified for a significant number of entries (for details, see Roediger-Schluga and Barber 2006).

Table 1 displays some descriptive features of the two data sets. It shows that after standardisation, a total of 1,110 organisations participated in 223 projects in ACTS, and 2,400 organisations took part in 674 projects in FAIR. Comparing the mean number of projects per organisation yields a slightly higher average of 2.4 projects per organisation in FAIR versus 2.2 projects per organisation in ACTS. A Kruskal-Wallis test[5] shows this difference to be statistically insignificant.

Table 1: Data set – Descriptive statistics

	ACTS	**FAIR**
# projects	223	674 (869)*
# organisations	1110	2400 (2514)*
mean # projects per organisation (Std.Dev)	2.2 (3.3)	2.0 (2.8)
mean # organisations per project (Std.Dev)	10.8 (5.1)**	7.1 (4.7)**
mean funding/participant (Std.Dev) (€ 1,000)	307 (156)**	145 (105**
mean funding/project (Std.Dev) (€ 1,000)	3590 (2083)**	784 (441)**

Note: * unrestricted number of projects/organisations in parentheses. ** Pairwise differences asymptotically significant at the 0.001-level (Kruskal-Wallis). Mean funding per participant and project computed from information on 142 projects in ACTS and 667 projects in FAIR.

Source: sysres EUPRO

While the two programmes are similar in terms of participation intensity, the average project has 10.8 partners in ACTS and 7.0 partners in FAIR. This difference is statistically significant, supporting Hypothesis 1. Similarly, average funding per project *and* partner is much higher in ACTS than in FAIR, as expected by Hypothesis 2.

One might object that this difference is due to the different composition of ACTS and FAIR, with the former consisting only of shared-cost contracts and co-ordinated research actions. However, a comparison of the average funding of shared-cost contracts in ACTS and FAIR yields a similar ratio of 3:1, which further corroborates Hypothesis 1.

5 The Kruskal-Wallis test is a non-parametric analysis of variance by ranks for multiple non-normally distributed samples.

Table 2 shows the organisational background of the actors participating in collaborative research projects in ACTS and FAIR. More than 60% of the organisations attracted by ACTS are firms, about 20% universities and 10% research organisations. In FAIR, the shares of these main organisation types are all in the order of 30%, although firms are also the largest category. In both programmes, other actors account for less than 10%. The share of governmental organisations is three times higher in FAIR than in ACTS.

Table 2: Distribution of organisation types

Organisation type	**ACTS**		**FAIR**	
	no.	**%**	**no.**	**%**
Consulting	24	2.2	18	0.7
Education	218	19.6	716	29.8
Government	14	1.3	96	4.0
Industry	687	61.8	778	32.4
Non Commercial+Other	43	3.9	101	4.2
Research	125	11.3	692	28.8
Total	1110	100.0	2400	100.0

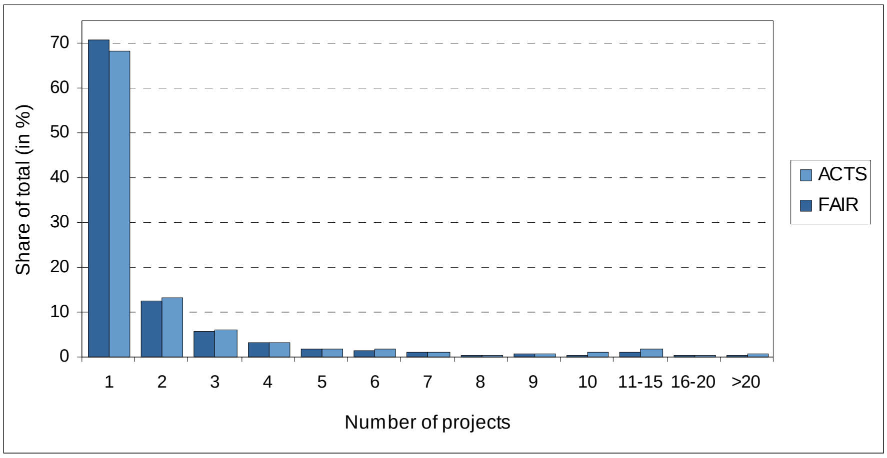
Note: Education comprises universities and other higher education organisations. "Non Commercial+Other" includes non-profit organisations, industry associations, lobby groups, and organisations that cannot be classified. Differences between ACTS and FAIR are asymptotically significant at the 0.001-level.

Source: sysres EUPRO

So far, only average numbers have been presented. However, not all actors are equally active in the EU FPs (see Roediger-Schluga and Barber 2006), which is also true of ACTS and FAIR, as shown in Figure 1. In both programmes, the large majority or actors participate in only one or two collaborative research projects. However, at the other extreme of the distribution, there are some very active organisations, participating in up to 51 projects in ACTS and 42 projects in FAIR.

This result suggests that some actors are positioned more prominently than others. These, however, cannot be identified by simple descriptive statistics. To characterise structural properties, it is necessary to use methods that exploit the relational information on the networks. This is done in the next section.

Figure 1: Participation frequency in collaborative R&D projects



4. Structural properties of the collaborative research networks

The networks formed by the collaborative research projects and the participating organisations form an affiliation network, which can be represented by a bipartite graph. Bipartite graphs consist of two subsets of nodes with edges existing only between the two sets. To simplify the analysis of bipartite graphs, it is common practice to construct collaboration networks, i.e. a unipartite or one-mode projection that preserves only one type of node and connects all nodes that share a common neighbour in the bipartite graph (see, e.g. Christensen and Albert 2006). Since we lack detailed information on intra-project linkage structures, we follow this practice.

We construct organisation graphs in which organisations are connected by joint memberships in collaborative research projects, thus assuming each project to be a fully connected subgraph of organisations, or a clique. This is an idealised graph type that, although not fully representative, is a reasonable approximation to the actual intra-project structure of all but very large projects. Since the vast majority of projects in our data set have fewer than 15 participants, our construction rule is considerably more accurate than assuming the other idealised type of a star structure, in which each participant is only connected to the project coordinator as central vertex.

Table 3 displays a few descriptive statistics on the resulting networks in ACTS and FAIR. The 2,400 nodes in the FAIR network are more than twice the number of nodes in the ACTS network, yet FAIR contains only about 1.6 times as many edges. Thus, ACTS is considerably denser, with the density being defined as the ratio of the number of edges to the number of possible edges.

Table 3: Structural properties of the networks[6]

	ACTS	FAIR
# organisations	1110	2400
# edges	12,764	19,941
Number of components	3	37
Size of the largest component	1099	2222
as a percentage of all nodes (organisations)	99.0	92.6
Size of the second largest component	8	14
Density (of largest component)	0.021	0.007
Diameter	5	8
Mean degree (Std.Dev.)	23.0 (27.5)	16.6 (21.5)
Maximum degree	326	246

Graph density has been observed to decrease with network size (e.g. Roediger-Schluga and Barber 2006). This is not unexpected in a growing network. Each new node could connect to all existing *n* nodes. In order to maintain the same density, the number of edges per node would have to be proportional to the total number of nodes, so the number of edges required for the new node would be ever increasing[7]. However, since establishing and maintaining links is costly, there is a budget constraint: for any organisation, there is a point at which the network becomes too large to link to a sufficiently large number of organisations. Because of this budget constraint, density declines in larger networks.

However, the exact functional relationship is an open problem in graph theory (see Barber et al. 2006 for a possible benchmark random graph model that, however, relies on rather strong assumptions). Thus, there is at present no comprehensive statistical argument on how the density depends on network size. This caveat notwithstanding, we do interpret that fact that the ACTS network is three times as dense as the FAIR network as an indication of closer integration between collaborating organisations in ACTS.

Following Walker et al. (1997), a denser network can be interpreted as an indication of greater social capital (Coleman 1990), which implies access to a greater pool of information (see Gulati 1998) and hence a greater potential for knowledge spillovers. Naturally, the extent to which knowledge actually flows depends a) on the production of knowledge that is useful not

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6 All measures computed with PAJEK, a freeware programme for the descriptive analysis and visualisation of large networks (Batagelj and Mrvar 2003).

7 In an undirected graph, the number of edges k is $O[n(n-1)/2] = O[n^2/2]$, where n is the number of nodes. Thus, if we double the number of nodes, the number of edges has to increase by a factor of four for the density to remain constant.

only to project participants and b) participants' absorptive capacity, i.e., their ability to make sense of and leverage new knowledge (Cohen and Levinthal 1990). Moreover, local network structure may be critical as closely interlinked organisations may have little to learn from each other, whereas ties bridging densely connected subgroups may transport considerably more novel information (see Burt 2001).

More fundamentally, however, nodes need to be linked for knowledge, in particular tacit knowledge to flow. Thus, there need to be paths through which nodes are reachable in a network. In a connected network, all pairs of nodes are reachable. If this is not the case, the network can be partitioned into at least two connected subsets (subgraphs), which are referred to as components. Table 3 shows both networks to consist of one giant component that comprises virtually all participants in the respective programmes and a few small components consisting of at most two projects.

However, with a length of five, the diameter (the longest shortest path in a network) of the ACTS network is considerably smaller than the diameter of the FAIR network. This underscores the closer integration of organisations in the ACTS network and hence a greater potential for knowledge spillovers.

Table 3 also lists the mean degree of the two networks. The degree d of a node is the number of its direct neighbours and can be interpreted as an indicator of how actively an organisation collaborates with other organisations in a network. The mean degree is the arithmetic mean of all node specific-degrees d_i. It is slightly higher in ACTS than in FAIR, indicating that the average organisation in ACTS collaborates with a slightly greater number of organisations. This was to be expected from the greater average project size in ACTS. [8]

However, the considerable standard deviations indicate that the average degree has limited informational value. This is a common property of many real-world networks, which frequently exhibit highly skewed degree distributions (see, e.g. Christensen and Albert 2006). Figure 2 shows that the ACTS and FAIR networks also exhibit this property. It plots the cumulative degree distributions on logarithmic axes, with the degree on the x-axis and the cumulative probability on the y-axis, i.e. the probability that the degree is d or greater.

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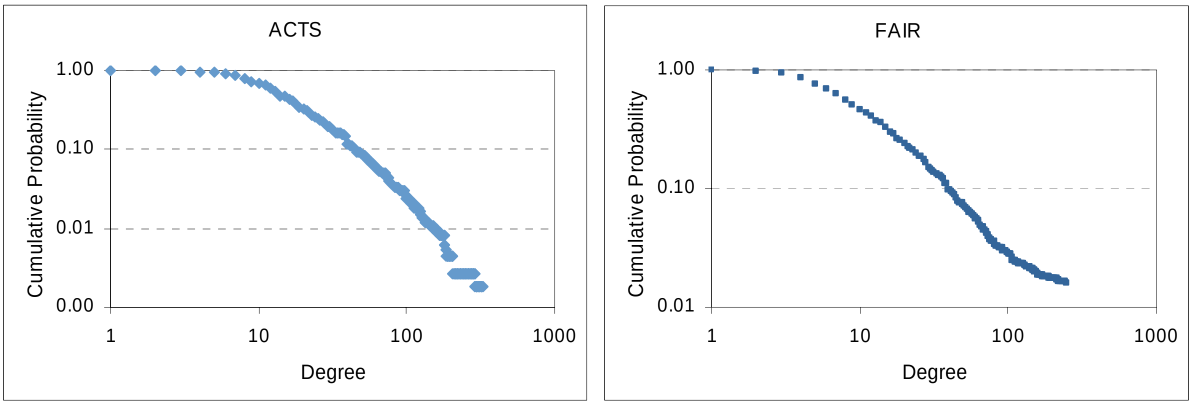
[8] Note that the rules of statistical inference do not apply in this case, as the average degree has not been computed from a sample but the entire population of nodes and connections in both networks.

The figure shows that that the majority of organisations have a low degree (the median degree is 14 in ACTS and 9 in FAIR). However, a few organisations have degrees that are more than an order of magnitude higher. Thus, some organisations have considerably more prominent positions in the respective networks.

There are several measures of centrality to quantify this node property (see Wasserman and Faust 1994), two of which will be examined in this paper. The first is based on the idea that nodes which are connected to many neighbours have power in many social settings. They are highly visible and should be recognised by others as major channels of relational information. This notion is quantified by the actor degree centrality $C_D(n_i)$, which is defined as the ratio of degree d_i and the maximum degree d_{max} in a network of the same size.

Figure 2: Cumulative degree distribution



The second measure of centralisation is based on the betweenness of actors. Interactions may take place not only between directly adjacent actors, but also via organisations that lie on the path between two organisations. Such a position may be of high strategic importance, as the organisation may act as gate keeper, controlling access to or information flows between two nonadjacent actors. Moreover, actors with a high betweenness centrality may be invited more frequently to participate in other research consortia. The actor betweenness centrality $C_B(n_i)$ is defined in a connected graph as the fraction of geodesic (shortest) paths between any pair of vertices on which n_i lies.

Table 4: Top 10 central actors in ACTS and FAIR[9]

rank	Org	Orgtype	C_D	C_B	# Projects	# P.C.	rank	Org	Orgtype	C_D	C_B	# Projects	# P.C.
1	Telecom Italia Lab Spa	ROR	0.294 (1)	0.109 (1)	51 (1)	7 (3)	1	WUR/Agrotechnology and Food Science Group	ROR	0.103 (1)	0.084 (1)	42 (1)	16 (1)
2	France Telecom R&D	IND	0.261 (2)	0.092 (2)	45 (2)	4 (5)	2	Danish Institute of Agricultural Sciences	ROR	0.101 (2)	0.043 (4)	29 (4)	1 (102)
3	PT/Centro de Estudos de Telecomunicacoes (CET)	IND	0.186 (3)	0.051 (4)	21 (5)	1 (47)	2	WAU/Department of Agrotechnol-ogy and Food Sciences	EDU	0.089 (4)	0.044 (2)	24 (8)	3 (24)
4	Siemens AG	IND	0.165 (6)	0.053 (3)	21 (5)	2 (18)	4	IFREMER/Direction des Ressources Vivantes (DRV)	ROR	0.080 (5)	0.039 (5)	32 (2)	5 (7)
5	Deutsche Telekom AG	IND	0.186 (3)	0.044 (7)	23 (4)	–	5	SLU/Faculty of Agriculture, Land-scape Planning and Horticulture	EDU	0.091 (3)	0.036 (8)	26 (5)	5 (7)
6	NTUA	EDU	0.168 (5)	0.043 (8)	27 (3)	1 (47)	6	BBSRC/Institute of Food Research	ROR	0.072 (7)	0.038 (6)	30 (3)	6 (3)
7	North West Labs Ltd	ROR	0.151 (9)	0.049 (5)	9 (39)	–	6	UPM/E.T.S. Ingenieros Agronomos	EDU	0.072 (6)	0.038 (7)	19 (11)	–
8	Intracom SA	IND	0.163 (7)	0.042 (9)	19 (10)	2 (18)	8	CSIC/Ciencias Y Tecnologia De Alimentos	ROR	0.059 (13)	0.044 (3)	26 (5)	2 (42)
9	PTT/Research	ROR	0.163 (7)	0.040 (10)	20 (7)	–	9	INRA/Centre de Recherche de Versailles-Grignon	ROR	0.059 (13)	0.034 (9)	21 (7)	2 (3)
10	Tele Danmark A/S	IND	0.121 (13)	0.048 (6)	12 (19)	1 (47)	9	INRA/Centre de Recherche d'Avignon	ROR	0.063 (11)	0.027 (11)	25 (10)	6 (42)
							9	AUTH/Faculty of Geotechnical Science	EDU	0.066 (9)	0.026 (13)	18 (15)	–

Notes: P.C. … project co-ordinator; ranks in parentheses; Orgtype … organisation type (EDU … universities and other higher education, IND … industry, ROR … research centres); Acronyms: AUTH … Aristoteles University of Thessaloniki, BBSRC … Biotechnology and Biological Sciences Research Council, CSIC … Consejo Superior de Investigaciones Cientificas, IFREMER … Institut Française de Recherche pour l'Exploitation de la Mer, INRA … Institut National de la Recherche Agronomique, NTUA … National Technical University of Athens, PT … Portugal Telecom SA, PTT … Koninklijke PTT Nederland NV, SLU … Swedish University of Agricultural Sciences, UPM … Universidad Politecnica de Madrid, WAU … Wageningen Agricultural University, WUR … Wageningen UR

9 Actor degree (C_D) and betweenness (C_B) centrality are computed with PAJEK (Batagelj and Mrvar 2003).

To identify the most central organisations in our networks, we compute centrality weights for each node. We then compute an aggregate score of nodes by taking the unweighted sum of their individual rankings according to each centrality index. The intuition for this methodology is that central vertices should rank prominently along both dimensions quantified by the centrality indices we use. Table 4 shows the resulting ten most central organisations in the ACTS and FAIR network.

As is well known from the literature (see Wasserman and Faust 1994), $C_D(n_i)$ and $C_B(n_i)$ are strongly correlated. The Pearson correlation coefficient shows a linear association between the two centrality indices of 0.86 in the ACTS and 0.82 in the FAIR network. However, the ranks given by the two indices do not necessarily coincide. While the most active participants are also most central in both networks, there is some discrepancy further down the list between actors with a high number of direct ties and actors occupying the strategically most important positions in the networks.

Furthermore, there is also a strong linear association between actors' activity level and their centralities $C_D(n_i)$ and $C_B(n_i)$, with values of 0.89-0.92 in ACTS and FAIR. In contrast, the number of projects each organisation co-ordinates and its centrality are less strongly associated. The difference is more pronounced in ACTS, where the correlation is 0.42 for both indexes; in FAIR they are 0.62 and 0.69, respectively. This is due to the fact that the most active project co-ordinators and the most active participants do not always coincide, as evidenced by a linear association between the two measures of 0.54 in ACTS and 0.71 in FAIR.

These results point to a different topology of the two networks. Especially in the ACTS network, there are a sizeable number of peripheral actors that co-ordinate projects. Since the network is closely integrated, a possible explanation is that these actors make the additional effort involved in co-ordinating projects to gain access to the network and thus EU funding.

Looking at aggregate figures, 12.4% of organisations funded in ACTS and 20.0% of organisations funded in FAIR co-ordinate at least one project. Thus, the set of project co-ordinators is more concentrated in ACTS than in FAIR. Table 5, which consists of two subtables, displays further information on project co-ordinators in the two networks.

The first column in each subtable shows that the large majority of projects in ACTS are co-ordinated by firms. In FAIR, the distribution is more balanced, with research organisations and universities each co-ordinating about a third of the projects. A χ^2-test shows the differences to be non-random. The second columns in the subtables show the average number of projects co-ordinated by universities, firm and research centres in ACTS and in FAIR. Only firms differ significantly in the two networks. The third columns in the subtables display the ratio of projects co-ordinated to project participations. These are remarkably high for all organisation types. Firms in FAIR stand out; they co-ordinate 9 out of 10 projects in which they participate.

Table 5: Information on project co-ordinators in ACTS and FAIR

Orgtype	ACTS			FAIR		
	P.C.	**# P.C.**	**# P.C./# participation**	**P.C.**	**# P.C.**	**# P.C./# participations**
	% of total*	**Mean (Std.Dev.)**	**Mean (Std.Dev.) (%)**	**% of total***	**Mean (Std.Dev.)**	**Mean (Std.Dev.) (%)**
EDU	11.6	1.25 (0.58)	66.0 (36.1)	34.9	1.35 (0.74)	53.8 (32.7)
IND	70.3	1.70** (1.38)	58.8** (36.3)	24.6	1.06** (0.33)	93.7** (19.2)
ROR	10.9	1.47 (1.55)	61.9 (37.5)	35.3	1.67 (1.66)	52.3 (33.1)

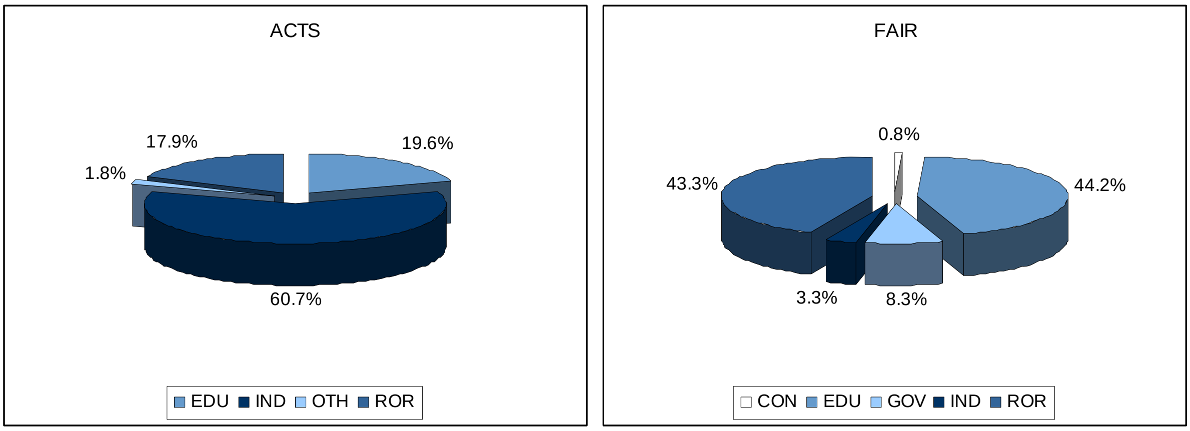
Notes: P.C. … project co-ordinator; Orgtype … organisation type (EDU … universities and other higher education, IND … industry, ROR … research centres); * Differences between ACTS and FAIR asymptotically significant at the 0.001-level (X^2-test); ** Pairwise differences asymptotically significant at the 0.05-level or less (Kruskal-Wallis test).

The high shares in the third columns are mainly driven by organisations that only participate in one project, which they also co-ordinate, since the co-ordination intensities displayed in columns two are low. Thus, co-ordination indeed appears to be an entry ticket for many less active organisations to become part of the networks.

Table 5 largely reflects the distribution of organisation types in the ACTS and FAIR network reported in Table 2. ACTS is dominated by firms, while the FAIR network is predominantly composed of actors from science. Table 4 suggests that this difference is even more pronounced in terms of the centrality ranking. Among the ten most central actors, there are predominantly firms in ACTS, while there are only research centres and universities in FAIR. Indeed, the most central firm in FAIR, Nestec Ltd (Nestlé Research Centre), is ranked only 21^{st} by C_D and 43^{rd} by C_B.

To explore this issue more systematically, we examine the top 5% of the centrality ranking distributions in ACTS and FAIR. Figure 3 displays the breakdown by organisation type. The difference is striking: in ACTS, about 60% of the actors in the top 5 % of the distribution are firms; in FAIR, only 3% are firms, while almost 90% are a university or a research centre, and 8% are governmental organisations. This result strongly supports Hypothesis 3. The high centrality of some governmental organisations in FAIR confirms the importance of research on food safety in this area.

Figure 3: Centrality ranking distribution: Top 5 percentile, breakdown by organisation type



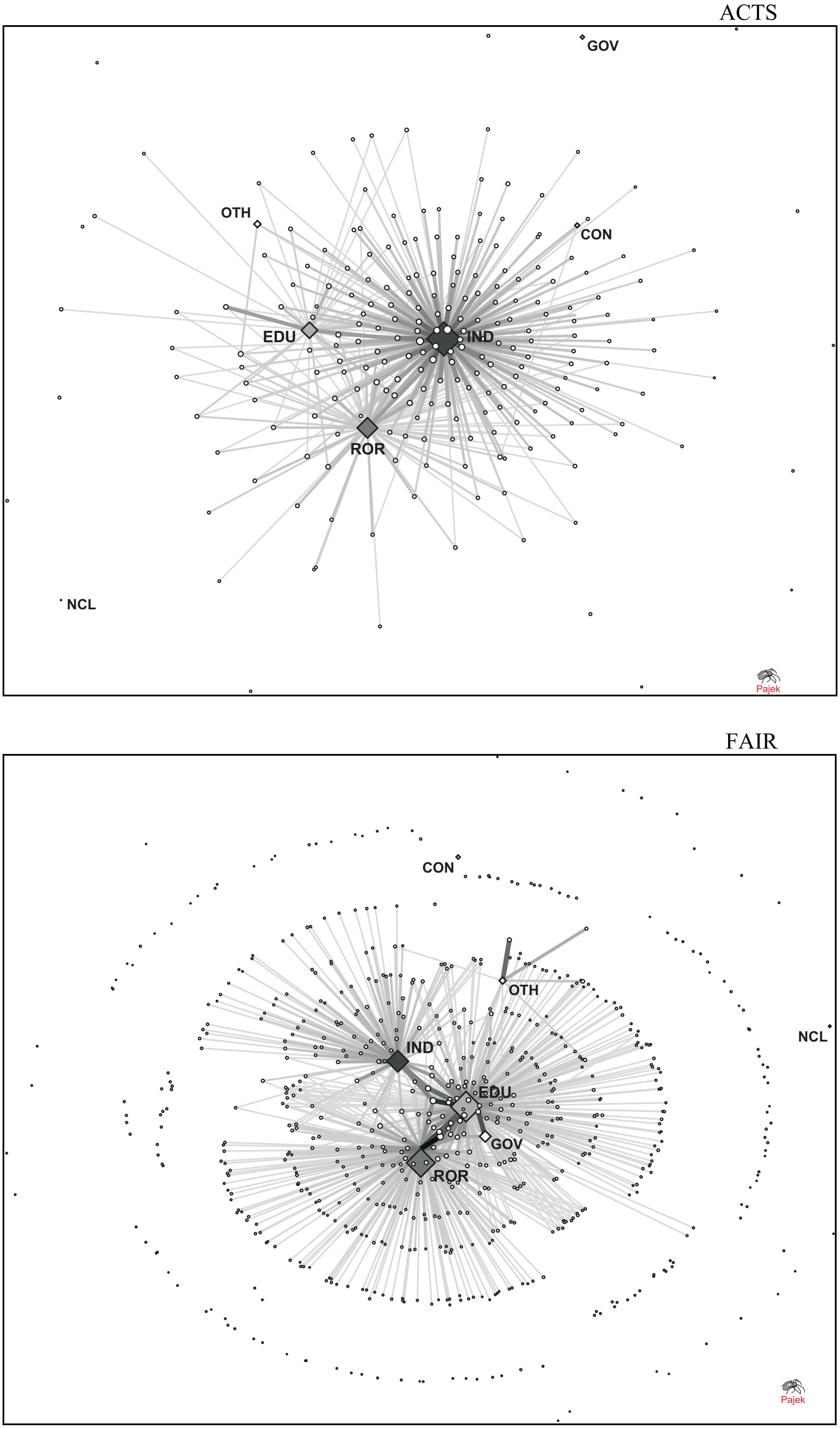
With regard to the structure of science-industry interactions in the two networks, Figure 3 creates a puzzle. If central actors in FAIR are mainly from science while firms are the largest group of actors participating in FAIR, scientific and industrial research may be poorly integrated. This would refute Hypothesis 4.

A simple, yet powerful way to explore this issue is to visualise the networks. Graph visualisation is a powerful tool for exploratory data analysis that is particularly well suited for networks of small and medium size (see the excellent book by Krempel 2005).

To test Hypothesis 4, we draw the bi-partite graphs of projects and participants labelled by organisation type with Pajek (Batagelj and Mrvar 2003), using a combination of the Fruchterman-Reingold (1991) and the Kamada-Kawai (1989) graph drawing algorithms. Both are variants of minimum-energy or 'spring embedded' algorithms, which produce robust representations of network relationships in two-dimensional Euclidean space (for details on the methodology, see de Nooy et al. 2005; Owen-Smith et al. 2002).

Figure 4 displays the resulting network maps. Node sizes are proportionate to the incidence of the respective actor type and project. Edge widths are proportionate to edge weights, i.e. the number of organisations of the same type participating in any particular project. Edges are coloured with the darkest colours representing the highest edge weights. To enhance the readability of the maps, all edges with weights one and two are deleted, without changing the position of the nodes.

Figure 4: Projects and organisation types in ACTS and FAIR



The map of the ACTS network shows that it is dominated by industry, which occupies the central position and is linked to all but one project. In 78% of all projects, firms are the dominant actor type. Universities and research centres are located in the west and the south-west of the map and are connected to fewer projects. Universities participate in 89% of all projects funded in ACTS and research centres in 73%. Universities are the most frequent actor type in 9% of the projects and research centres in 3%. In all but one project, scientific actors collaborate with at least one firm. All other actor types are peripheral.

In FAIR, the centre of the map is occupied by universities, research centres, firms and governmental organisations. Research centres participate in 89% of all projects, universities in 75%, firms in 53%, and governmental actors in 23%. Scientific actors are closely integrated, collaborating in more than 80% of the projects they participate in. Links between scientific and governmental actors are even stronger, as all but one of the projects involving a governmental actor also include at least one actor from science.

The ratio of projects involving actors from science and industry to the total number of projects is considerably smaller in FAIR than in ACTS, as industry participation is less intense. However, of the 359 projects involving at least one firm in FAIR, 334 also include at least one university or research centre. 248 projects include at least one actor from all three categories.

What these numbers fail to show, however, is the qualitative difference in the linkage structure between industry and science in the two networks. Whereas ACTS is closely integrated, FAIR is split into two clearly discernible areas, the larger one being dominated by science and the smaller one by industry. Expressed in numbers, research centres are the dominant actor type in 33% of the projects, universities in 31% and firms in 17%. Integration between these two groups is relatively weak.

This result is underscored if we examine the frequency and intensity of links between science and industry in the two networks. In ACTS, the two groups are connected by 37% of all edges present; in FAIR the fraction is only 19%. Interaction is also stronger in ACTS than in FAIR; the mean edge weight is 1.17 (0.63) in ACTS and 1.04 (0.22) in FAIR. A Mann-Whitney U-test[10] shows the difference to be significant at the 0.001-level. All of these results thus comprehensively refute Hypothesis 4.

How can we explain this unexpected result? Recall that our argument in deriving Hypothesis 4 was based on the observation of smaller average firm size and a more dispersed knowledge

10 A non-parametric test for assessing the difference in medians between two independent samples.

base in the agro-industrial industry. From this we inferred that firms would have less capacity for in-house knowledge generation and therefore have a greater need for knowledge that is generated externally by scientific research.

Our results do not refute this argument. Most of the projects funded in FAIR that include firms also include scientific actors. However, we did not find the expected higher frequency and intensity of interactions between industry and science. This may be due to small firms' limited absorptive capacity and their limited ability to participate in EU-funded research projects that require considerable up-front investment. Research based on innovation surveys has shown that small firms tend to benefit less from scientific research than larger firms that have a greater capacity to absorb and leverage external knowledge (see, e.g. Geuna et al. 2006).

A second and possibly more important reason may be that the kind of scientific research funded in ACTS and FAIR may not be equally relevant to firms in the two industries. Research in electronics and computer sciences conducted at universities and research centres is frequently quite applied and may therefore have a greater immediate industrial relevance than more fundamental scientific research in biology, chemistry, materials science and food safety. In fact, more applied research may require closer interaction between scientific investigation and application to take advantage of user-producer interactions.

Moreover, more applied scientific knowledge may be easier to absorb and leverage for industry. Although precompetitive by definition, firms not only participate in EU funded research projects to scan the technological environment, boost their technological competencies and improve their longer-term competitive potential. Rather, a fair share of firms complement the precompetitive research activities in the EU projects with internal projects geared towards commercialisation (see Luukonen 2002). This again favours larger firms with greater internal cash-flow over their smaller competitors.

5. Conclusions and directions for future research

In this paper, we have investigated the impact of technology on the structure of collaborative research networks that have emerged in the EU FPs. To this end, we have compared the characteristics and topology of research networks in the telecommunications and the agro-industrial industry induced by two specific programmes of the fourth EU Framework Programme, ACTS and FAIR. From empirically well-established characteristics of the underlying technological regimes, we formulated four hypotheses that we subsequently confronted with empirical evidence.

The results of our analysis show that, as expected, collaborative research projects in the telecommunications industry involve a greater number of participants and require greater funding. Matching our theoretical expectations, we show that actors from science are more central in collaborative research projects in the agro-industrial than in the telecommunications network. Contrary to our expectations, we find fewer and less intense interactions between science and industry in the agro-industrial industry. We suggest three explanations: first, absorptive capacity depends on firm size, which is smaller on average in the agro-industrial industry; second, EU-funded research is less attractive to smaller firms; and third, the scientific knowledge produced in the networks we study may be more relevant in the telecommunications than in the agro-industrial industry.

Our key result of systematic differences in the structure of R&D collaboration networks in two industries that are governed by different underlying knowledge bases, different research trajectories pursued in EU funded R&D and differences in the organisation of knowledge production has important policy implications. Sectoral innovation systems (see Malerba 2005) are characterised by institutional differences, different innovation needs and different R&D trajectories. Differences in the nature of the knowledge base and different institutional arrangements of knowledge production may require differently structured innovation networks to support innovation and competitiveness. While fostering science-industry linkages may be crucial for competitiveness in some industries, different priorities may obtain in others. This calls for flexible policies that do not focus on a specific objective (such as raising R&D expenditures across the board or focusing only on improving science-industry interactions), but are able to adapt to the idiosyncracies of the specific sectors (see Edquist et al. 2004).

The paper raises a number of questions for future research. *First*, future work should explore the precise motivations of actors with different organisational backgrounds for participating in EU-funded research projects, why they adopt different participation strategies, and why and how they chose their project partners. Luukonen (2002) reports very interesting results on Finnish firms. Further work is needed. *Second*, future work should attempt to gain a better understanding of the kind of knowledge that actually flows between actors in innovation networks. At present, we lack direct measures that would allow us to differentiate between different types of links in innovation networks. *Third*, our analysis should be extended to other technological regimes, industries and specific programmes in order to identify regularities or general 'stylised facts'. *Fourth and finally*, the questions addressed in this paper should be investigated with different data sources. This would show the extent to which our finding can be generalised.

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