Unveiling the texture of a European Research Area: emergence of oligarchic networks under EU Framework Programmes

Stefano Breschi*

Centre for Research on Innovation and Internationalization,
Università L.Bocconi, Via Sarfatti 25, 20136 Milan, Italy
E-mail: stefano.breschi@uni-bocconi.it
*Corresponding author

Lucia Cusmano

Department of Economics, Università dell'Insubria,
Via Ravasi 2, 21100, Varese, Italy
E-mail: lcusmano@eco.uninsubria.it

Abstract: The paper provides a contribution to the recent debate about targets and effectiveness of network policies at the EU level, by presenting an analysis of the R&D network that has emerged over Framework Programmes. Social network analysis is employed to describe structural properties and dynamics of the emerging network, which appears to be dense and pervasive, branching around a large 'oligarchic core', whose centrality and connectivity strengthened over programmes. The paper discusses the degree to which this network structure may respond to EU broad policy objectives and its implications for recent programmes aimed at shaping a European Research Area. Attention is placed on the late focus by European institutions on networking centres of excellence. Since future initiatives are to build on the existing fabric, we argue that understanding how networks formed and evolved following previous stimuli is of great relevance for implementing and assessing the impact of the newly defined network approach.

Keywords: R&D network; technology alliances; European Framework Programmes.

Reference to this paper should be made as follows: Breschi, S. and Cusmano, L. (2004) 'Unveiling the texture of a European Research Area: emergence of oligarchic networks under EU Framework Programmes', *Int. J. Technology Management*, Vol. 27, No. 8, pp.747–772.

Biographical notes: Stefano Breschi is an Associate Professor of Applied Economics at Università L.Bocconi and a member of the Board of Directors at Cespri-Bocconi, Milan, Italy. He has published in various international journals. His main research interests concern economics of innovation, industrial economics, industrial dynamics, regional economics, networks and clusters, industrial and technology policy.

Lucia Cusmano is an Assistant Professor at Università dell'Insubria, Varese, Italy, and has been conducting research for several years at Cespri, Università L. Bocconi, Milan. Her main fields of research relate to economics of innovation and technical change, technology policy and cooperative R&D, national and local innovation systems, innovation and development.

1 Introduction

Over the last couple of decades, the promotion of consortia between firms, universities, research centres and public agencies has gained the central stage of science and technology policy in Europe. Cooperative programmes, in the form of shared-cost R&D consortia, have become the most important source of European Union funding and institutional support to innovation, international competitiveness and, by way of knowledge exchange and diffusion, intra-European cohesion.

Extensive support to research networks dates back to the early 1980s, when cooperative initiatives at the continental level represented a response to the decline of the European industry competitiveness vis à vis US and Japanese companies and to the weakness of national champion policies. Accordingly, the first cooperative programmes concerned those fields, such as Information and Communication Technology, where the European innovative gap was perceived to be large and widening. However, with the full institutionalisation of Framework Programmes, EU medium-term planning instrument for RTD, the cooperative approach has gradually been extended to a wide range of industries and institutions. The aim of fostering competitiveness in high tech fields, by pooling the most advanced resources and capabilities, has been sided by the other major European objective: 'cohesion', that is, the integration of national research communities and the linking of marginal actors to the main component of the EU R&D network.

Cooperative policies have certainly been pervasive and effective in aggregating public and private institutions from national research communities. However, concerns have been expressed about their effectiveness in raising up the level of innovative investments, supporting European competitiveness, and providing an efficient mechanism for creating a critical mass of knowledge and competencies whose benefits may extend to laggards. Following recent political debate and the challenges posed by the future enlargement, the implementation of cooperative policies by way of widespread support to a large variety of projects and institutions is to undergo significant changes. The European Commission has called for a change in approach, that responds to the need for reinvigorating the European research infrastructure and reflects the most recent theoretical and empirical debate about R&D networks. Starting from the sixth Framework Programme (2002–2006), policy actions are to be more focussed on identifying crucial 'nodes' and networking 'centres of excellence', that would represent the backbone of a truly European Research Area and act as catalysts for smaller components or backward areas.

The paper intends to provide a contribution to the debate about targets and effectiveness of network policies at the EU level, by presenting a thorough analysis of the large R&D network that has emerged over Framework Programmes. The concerns expressed by the European Commission in its milestone communication 'towards a European Research Area' (2000) and the recent focus on networking centres of excellence appear to reflect dissatisfaction about the limitations of past cooperative policies in structuring a robust and efficient knowledge and research network. However, little empirical research on the overall structure and evolution of European networks has yet been produced.

We argue that identification and characterisation of networks that have emerged from early European programmes represent a fundamental step for the assessment of past achievements and an important benchmark for future policy design. Indeed, a widespread and robust network, branching around a large 'oligarchic core', has already emerged as a more or less intended consequence of early Framework Programmes. Since future initiatives are to build on the existing fabric of science and technology in Europe, understanding how networks formed and evolved following previous stimuli may be of great relevance for implementing and assessing the impact of the newly defined network approach.

In the paper, social network analysis and graph theory are employed to describe structural properties and dynamics of the EU-wide network stemming from the R&D consortia promoted under the 3rd and 4th Framework Programmes. The analysis provides empirically grounded elements for discussing the degree to which this network structure may respond to EU broad policy objectives of competitiveness and cohesion and its implications for recent programmes aimed at shaping a European Research Area.

The paper is organised as follows. Section 2 discusses aims and articulation of EU Framework Programmes, commenting on the recent debate about refocusing the whole European technology policy, for better coordination of Unions' efforts with national strategies and creating a truly European Research Area. Section 3 provides a description of the EU RJV dataset, while Section 4 discusses some methodological issues arising in the attempt to analyse the R&D consortia by means of network analysis. Section 5 provides an analysis of the RJV network and Section 6 provides a summary and concluding remarks in relation with the debate about the creation of a European Research Area.

2 The cooperative approach of Framework Programmes: changing priorities towards a European Research Area

The single European Act and the Maastricht treaty have given full and clear competence to European Institutions in the area of Research and Technological Development (RTD), although the first genuinely collaborative and EU-wide initiatives, such as ESPRIT, dated back to the early 1980s. The setting of Framework Programmes, which gave greater coherence to existing initiatives, was intended to strengthen the scientific and technological basis of European industry and to encourage it to become more competitive at the international level. When the first Framework Programme was launched, in 1984, the 'technology gap', which was perceived to be of the greatest relevance in explaining European declining competitiveness, was the main concern driving policy action. Along the line of the Single Market approach, the focus of European RTD policies was primarily directed towards overcoming the fragmented national structure of European industry and markets, permitting economies of scale that could not be achieved at the national level. Accordingly, preference was indicated for research conducted on a vast scale, projects addressing common interests that could be best tackled through a joint effort, research contributing to the cohesion of the common market, promoting the setting of uniform laws and standards [1].

Framework Programmes have provided a systematic procedure for discussing and agreeing upon priorities, guidelines and budget allocation, and have become the main instrument of the commission for offering selective support to European companies seeking to undertake collaborative R&D with firms or research institutes in other European countries. In fact, RTD policy has been implemented mostly by supporting shared-cost contractual research, i.e. multinational consortia (or Research Joint Ventures) grouping firms, public agencies, research centres and Universities, focussed, in principle, on pre-competitive research projects [1,2]. The pre-competitive requirement is meant to avoid potential conflict with EU competition policy, which forbids collaboration at the stage of developing products for an immediate market, whereas papers 85 and 86 of the Rome Treaty allow collaboration for pre-competitive research [3].

The collaborative approach has been extended to structure new areas of Union intervention, as the budget of Framework Programmes increased and priorities changed. If competitiveness has remained the primary goal of European technology policy [4], a wider set of objectives has been pursued over time, as the communitarian approach to RTD gained new momentum with the Maastrich Treaty. Since the Third Framework Programme (1990–1994), the Union RTD policy has been recognised as important, though complementary to other EU policies, for reducing unemployment, accelerating structural changes, and, at the same time, ensuring greater cohesion. In this perspective, the latest programmes have shifted the emphasis from supply-side factors, central in the design of the first policies, to diffusion-oriented projects and the increase of learning skills and knowledge among Europeans.

After two decades of active policy-making, the fundamental role of European institutions in promoting scientific advance and technological innovation and the centrality of the collaborative approach have been fully acknowledged. However, the degree to which the existing instruments and schemes of intervention can meet the ever diversified objectives and the challenges posed by future enlargement has been heavily questioned.

Indeed, the current debate about the future of European technology programmes is characterised by the concern that Europe might not successfully achieve the transition to a knowledge-based economy. The 2000 communication of the European Commission 'towards a European Research Area' [5] started a broad discussion on the development of research cooperation in Europe, centred around two main concerns, the persistent lower level of innovative investments in Europe compared to the US and Japan, and the fragmentation of research efforts, to which EU investments often add up without much coherence, creating an ineffective '15+1' static configuration. The fragmentation, isolation and compartmentalisation of national research systems and the disparity of regulatory and administrative frameworks further worsen the effect of the low investment in RTD, limiting the European capacity to produce knowledge and the ability to innovate. Hence, a more concerted effort for the development of a real European Research Area has been called by the Commission as an urgent priority in EU agenda.

The collaboration networks promoted by Framework Programmes and the indirect forms of cooperation to which they have given rise represent a considerable achievement, but, in their current form, they do not appear to suffice for correcting the structural weaknesses of European research nor to be a viable instrument for an enlarged Union. According to the commission, for cooperative efforts to produce a long-lasting effect, they should primarily aim at changing the organisation of research in Europe, rather than simply adding up resources and facilities. In this perspective, the focus of European programmes is to change, from direct support to a large variety of projects and organisations, that often overlap national incentive schemes without forming a coherent whole, to a more limited number of priorities and measures that exert a 'coordinating, structuring, and integrating' effect on European research [6]. Investing on infrastructures, strengthening relations between existing organisations and programmes, improving conditions for political consultation, establishing a common system of scientific and technical reference, promoting greater mobility of researchers represent the priorities of the newly designed European technology policy. Interventions in these areas are meant to create favourable conditions for greater public and private RTD investments and for developing a 'critical mass' in major research fields. In other terms, action at the European level is justified and selected in the view of creating a more supportive and coherent European framework for research. In this perspective, the policy intervention is primarily directed at stimulating resources and expertise to converge on strategic research areas, but self-organisation of 'excellence clusters' is expected to follow and is to be supported.

Within priority areas, clearly defined scientific and technological objectives are to be pursued by mobilising a critical mass of activities and resources, and allowing greater flexibility than in previous programmes for the allocation of resources and management of specific research activities. For this purpose, starting form the 6th Framework Programme, a differentiated range of instruments, that reflect a 'variable geometry' approach, has been set in place. Among such instruments, 'networks of excellence' are to play a prominent role for overcoming the fragmentation of the European research system and strengthening the European position in specific research areas.

The premise by the European Commission is that world class centres of excellence already exist in Europe in a wide range of research fields. However, they are often scattered and only loosely connected, and their expertise is not always sufficiently well known across Europe, especially by firms which could usefully join forces with them. The integration of these centres into long-term R&D consortia, financially supported by the European Union and focussed on leading-edge research, would contribute to enhancing the European position in strategic fields, attracting new resources and expertise, and, mostly, restructuring the way research is carried out in Europe, favouring the development of an overall more collaborative attitude by public and private actors [6].

According to the agenda set out by the commission, the first step towards networking the critical mass of resources and expertise that excel in specific research fields is mapping these centres of excellence, in accordance with transparent and competitive mechanisms. The selected institutions are then required to adopt a joint work programme in a field representing a substantial proportion of their activities, in which their expertise complement each other, and develop interactive working methods, including staff exchange and intensive use of electronic networks. Consortia are therefore expected to carry out a 'cluster' of integrated projects in basic or generic research areas, possibly of a long-term and multidisciplinary character.

The creation of these networks is to be supported with European financing, but their activities should not become dependent from this support. In fact, the European funding is meant to complement resources deployed by the participants and should take the form of a fixed grant for integration. Compared to previous programmes, consortia will enjoy greater freedom in managing their projects, and the follow-up by the commission services will move from detailed monitoring of inputs to a more strategic monitoring of outputs [5,6]. In other terms, the European action is meant to be a stimulus for centres of excellence to 'cluster around' common long-term pre-competitive objectives, network on a permanent basis, and self-organise division of task and information flows.

The policy is clearly oriented towards the original EU objective of strengthening European competitiveness. However, specific requirements are imposed on consortia for the policy to serve the cohesion objective as well. These may include dissemination and communication activities, training of researchers, systematic networking efforts aimed at transferring knowledge to external teams. In other words, the dual role of technology policy that has emerged over Framework Programmes is maintained, although the role of European institutions appears to be one of 'guiding' rather than 'leading' the organisation of research networks, that are expected to produce leading-edge knowledge and best practices and spread them to peripheral actors.

Indeed, the effective impact on cohesion of this excellence policy has emerged as an important concern in the debate which followed the commission's proposal. The European committee on legal affairs and the internal market [7] underlined the risk of a concentration of facilities to the detriment of peripheral areas. The CPMR General Secretariat [8] called for a greater emphasis on the integration of peripheral regions into niches of excellence in a number of highly specialised fields, by way of partnerships between top-level researchers working in peripheral areas and the identified centres of excellence.

However, the more controversial issue, among those debated by European institutions and member states, appears to be precisely the identification, or 'mapping', of these centres of excellence. Both the Italian and Finnish Governments, for instance, pointed to the need for selection to be based on open competition and periodical evaluation and renewal, in order to avoid the risk of a pre-determined, static configuration. The e Framework Programmes Economic and Social Committee [9] recommended the number of these consortia to be limited and, at least during a preliminary pilot phase, their funding to be restricted to a well-defined period, to prevent them becoming a permanent institution. The Committee of Regions [10] urged that excellence be based more on knowledge and cooperation rather than on competition between geographical areas. Along the same line, the European science foundation [11] underlined the need to carefully avoid a selection based on a 'juste retour' to meet national sensibilities, hence clearly separating the 'excellence' and 'cohesion' objectives.

More generally, the Commission's proposal has received a warm welcome by the scientific and industrial community as an attempt to set new priorities and stimulate integration for leading-edge research, but several institutions have expressed doubts about its implementation. The idea of 'identifying' centres of excellence according to top-down procedures has raised doubts and criticisms. According to the Academia Europaea [12] dividing a priori the research community into various classes of excellence could be very counter-productive. A more positive approach from the commission would be to support 'virtual centres of excellence' using broadband communications between units identified by national bodies and let self-reinforcing mechanisms in the research community lead to the strengthening of intra-European networks. A similar position is expressed by the BDI [13], which deems special administration for networking centres of excellence to be neither sensible nor necessary, since, as a rule, European researchers have already formed a comprehensive network with existing respective centres of competence. "New networks do not need to be initiated by special measures but form themselves on their own when the right goals are laid down".

Indeed, the Commission's proposal appears to acknowledge the existence of EU-wide networks and the importance of flexible management, but hints at the loose connectedness of existing webs and lack of coordination, setting priorities and instruments for creating a more rational structure and orienting their focus on precise 'laid down goals', so that dispersion of resources and duplication of efforts may be reduced.

However, European programmes themselves have contributed in the past to the creation of highly dense and pervasive networks, whose structure and dynamics are likely to affect the response to the new policy. The 'networks of excellence' approach aims at creating the backbone of a European Research Area, by stimulating emergence and self-organisation of dynamic consortia, but, we argue, a highly dense texture of direct and indirect linkages, is already in place, as a result of previous actions. Although policy design and instruments partly differ, we may expect these collaborative patterns to be replicated to some degree, or, at least to affect future structures and dynamics. In this respect, understanding how networks formed and evolved following previous stimuli can provide useful guidelines for evaluating the impact of the newly defined networks strategies. Excellence consortia are to emerge, or be selected, from an existing 'fabric', which will influence their ability to acquire and spread knowledge to and from other research nodes, within or outside the excellence core.

In the following sections, we draw attention to the network which formed under previous programmes, focussing on its topological features and evolution over time.

3 The EU RJVs dataset

This empirical section examines the network of R&D joint ventures (RJVs) funded by the European Commission in the time period 1992–1996, within the third and the first part of the Fourth Framework Programmes (FWPs) [14]. The dataset provides detailed information on 3,874 research projects and 9,816 organisations [15]. The 3,874 projects are distributed over 30 technological programmes, with a clear preponderance of ICT-related technological areas. The two leading programmes-ESPRIT 3/4 and BRITE-EURAM 2/3-account, respectively, for 23% and 17% of all projects, whereas the share of biotech and biomedical programmes (BIOMED 1/2 and BIOTECH 1/2) is relatively small (less than 5% of all RJVs). Firms account for the majority (around 64%) of all RJV members, while research and education organisations together account for about 21% of all RJV members.

The average number of organisations per RJV project is 7.09 (Table 1). Around 41% of all RJVs had less than five organisations and slightly more than 85% of them had less than ten organisations. As far as the time-scale of projects is concerned, the majority of RJVs has been conducted over the medium term: about 44% of them have lasted between 31 and 36 months, 31% less than two years, and only less than 13% lasted more than three years.

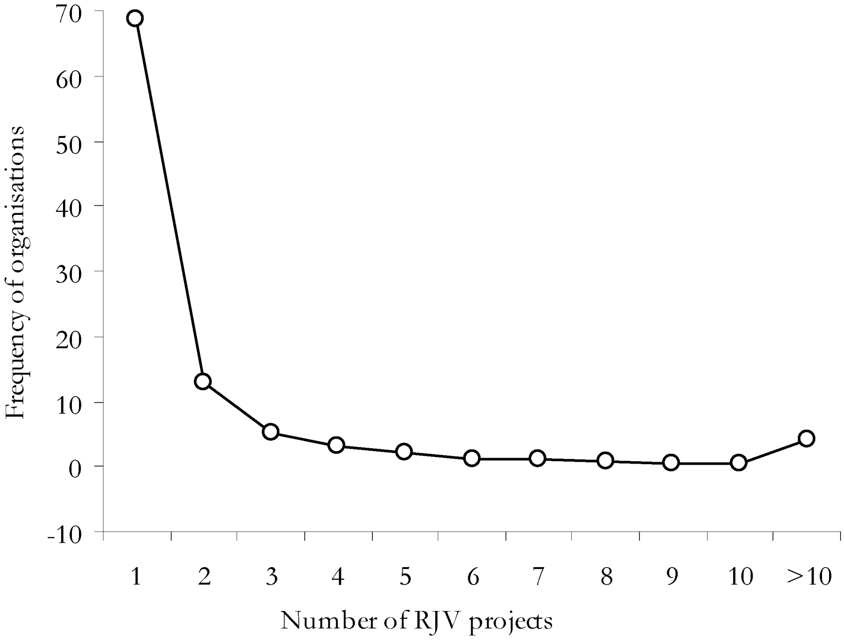
Table 1 The EU RJV dataset: summary statistics

	3rd FWP	*4th FWP*	*Total*
Number of projects	2,131	1,743	3,874
Total number of organisations	6,291	5,335	9,816
Average organisations per project	7.10 (5.12)	7.08 (3.65)	7.09 (4.52)
Average projects per organisation	2.40 (5.17)	2.31 (4.51)	2.79 (7.46)

Standard deviations among parentheses.

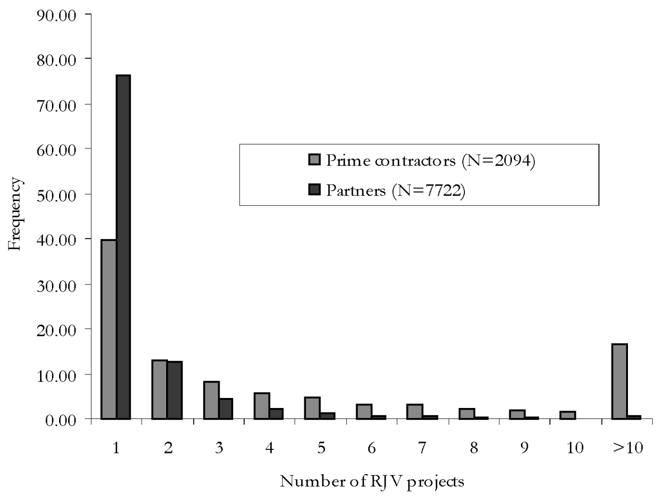
Looking at the frequency of participation into RJVs, the average number of projects per organisation is 2.79 (Table 1). However, the variance across organisations is rather large: a full 91% of all organisations have participated to less than five RJVs, and most of them (68%) have been occasional participants, in the sense that they have joined one RJV only (Figure 1). According to these figures, for the majority of organisations, membership to EU-supported R&D consortia does not represent a frequent event, even though there are a few organisations (mainly large firms and Universities), which participate extensively and continuously to shared cost actions [16].

Figure 1 Frequency of organisations by number of participations into RJV projects



This pattern partly reflects the broad 'political' role of FWPs, whose generic and horizontal objectives lead to a rather frequent and intense participation of European technological leaders, which are present in all of the most important EU R&D consortia. This type of interpretation seems to be further corroborated by the fact that the so-called *Prime contractors* (i.e. the organisations which take the leading role within each R&D consortium, by coordinating the activities of the participants) have participated, on average, to a much higher number of RJVs compared to the *Partners* (Figure 2). Almost 80% of all *Partners* have participated to only one RJV project, while the corresponding percentage drops to 40% in the case of *Prime contractors*. Moreover, about 15% of all *Prime contractors* have participated in more than ten RJV projects.

Figure 2 Frequency of RJV membership: Prime contractors vs. Partners



Prime contractors are the organisations which have played the leading role in the coordination of at least one R&D project. Partners are the organisations, which never assumed that role.

In addition to that, it is also important to remark that, even though 1,495 *Prime contractors* (39%) have played that role only once, 963 (46%) of them have acted as coordinators in three or more RJV projects, and that 1778 (85%) of them have also participated as *Partners* in RJV consortia led by other *Prime contractors* (Table 2). At the same time, it is also rather important to note that, although the vast majority of *Partners* are occasional members of R&D consortia, those *Partners* that participate in more than one RJV project tend to do so by changing the leading Prime contractor with which they collaborate. For example, of the 989 Partners that have participated in two RJV projects, 91% of them have changed Prime contractor (Table 3). Hence, it appears that a significant number of Partner organisations is not simply ancillary to leading institutions, but take advantage of the European projects for connecting with different key actors.

Table 2 Number of partnerships between prime contractors

Number of partnerships with other Prime contractors	*Number of organisations*	*Frequency of organisations*
0	316	15.09
1	359	17.14
2	360	17.19
3	283	13.51
4	164	7.83
5	124	5.92
6–168	488	23.30
Total	2,094	100.00

Number of times each *Prime contractor* has cooperated as *Partner* with other *Prime contractors*.

Table 3 Collaboration with different prime contractors

	Number of RJV participations				
Number of Prime contractors	*2*	*3*	*4*	*5*	*5–48*
1	9.4	2.3	0.0	0.0	0.0
2	90.6	15.9	2.2	1.1	0.0
3		81.8	25.4	4.4	0.0
4			72.4	17.8	2.2
5				76.7	6.2
6					19.5
7					11.1
8					13.1
8–43					47.9
Total	100	100	100	100	100

Number of different *Prime contractors* with which each *Partner* collaborated as function of the number of RJV participations (frequency distribution).

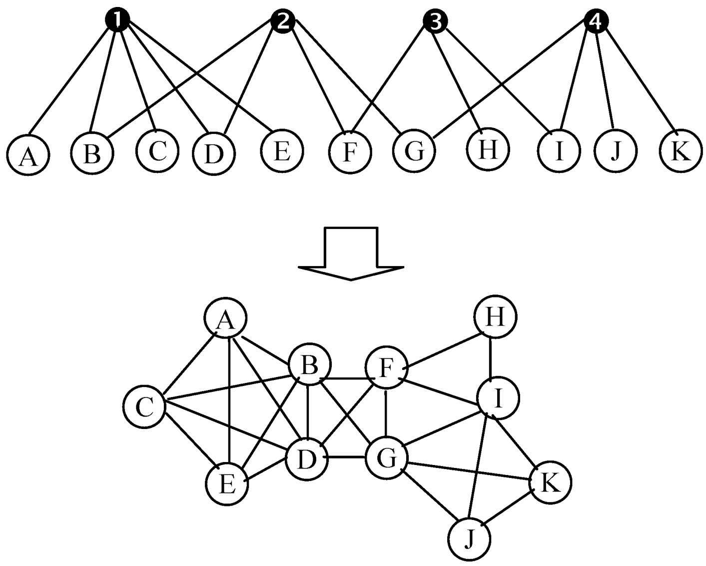
Overall, this evidence seems to suggest that different organisations play a fundamentally different role in the R&D network. On the one hand, organisations that participate only occasionally into R&D consortia contribute little or nothing to the networking activity taking place in the RJV network. On the other hand, most networking activity seems to occur among *Prime contractors*, and among them and the non-occasional *Partners*. These two types of actors represent the backbone of the RJV network, and it is to the analysis of the topological features of this network that the next section is devoted.

4 The RJV network as bipartite graph

The network formed by RJV projects and member organisations can be studied, using the tools of graph theory, as an affiliation network (or bipartite graph). An affiliation network is a network in which actors (i.e. organisations) are joined together by common membership of groups (i.e. RJV projects) of some kind. Affiliation networks can be represented as a graph consisting of two kinds of vertices, one representing the actors and the other the groups (see top part of Figure 3). In order to analyse the patterns of relations among actors, however, affiliation networks are often represented simply as unipartite (or one-mode) graphs of actors joined by undirected edges – two RJV members who participated in the same project, for example, being connected by an edge (see bottom part of Figure 3).

In what follows, we will analyse the unipartite graph of organisations involved into R&D consortia, although this representation may miss some relevant information.

Figure 3 Bipartite graph of RJV projects and organisations



Top: Bipartite graph of organisations (A to K) and projects (1 to 4), with lines linking each organisation to the project in which it participated.

Bottom: The one-mode projection of the same network onto just organisations.

Before proceeding to the analysis of this network, however, we need to discuss in detail a crucial problem arising in the construction of it. Differently from other affiliation networks that have been recently examined (e.g. scientific coauthorship, CEOs of companies), the dataset used here contains some additional information about the role played in each RJV project by different organisations. More specifically, the EU RJV dataset allows to identify for each R&D consortium the organisation acting as Prime contractor (i.e. the coordinator of the activities undertaken within the project). In consideration of the importance of these organisations (see Section 2 above), and given the fact that it is likely that organisations involved into large R&D consortia know the coordinator better than they know each other, an alternative way of representing the unipartite graph is the 'star' network (Figure 4).

Figure 4 Alternative representations of the unipartite graph, (a) Unipartite graph as a completely connected subgraph (no specific role for Prime contractor), (b) Unipartite graph as 'star' network (Prime contractor as co-ordinating agent)

The graphs refer to the unipartite graph of project 2 assuming that organisation B is the prime contractor.

According to this latter hypothesis, *Prime contractors* would then act as intermediaries in the flows of knowledge between partners in the same RJV, and no direct edge would exist between partners.

Both assumptions about the role played by *Prime contractors* are, of course, rather strong and somewhat arbitrary. However, as they seem equally reasonable, in the absence of other reasons to adopt either of the two, we will explore the main topological characteristics of the RJV network with respect to both, by referring to them, where appropriate, as *hp. (a)* and *hp. (b)*, respectively.

5 Analysis of the RJV network

In this section, we examine the main topological features of the unipartite graph of R&D consortia, by deriving a number of indicators, which have been widely applied to the study of a number of other networks [17]. The indicators are reported in Table 4 and results are shown for the cumulative RJV network up to the 3rd FWP (1992–1994) and for the cumulative RJV network up to the 4th FWP (1992–1996).

5.1 Density of network and size of the giant component

As far as the density of the network is concerned (i.e. the ratio between the number of actual links and the maximum theoretical number of possible links), the first result to note is that the value of the indicator differs under the two hypotheses adopted here. This is not surprising given the different way the network is constructed. Overall, the results indicate that the network is quite dense. On an average, each RJV organisation is directly linked to other 21 (*hp. a*) and other four (*hp. b*) organisations. Even more interestingly, the results also show that the density of the network is reducing over time, as more organisations join the network and new links are forged between existing organisations and new participants and also among existing organisations.

A quite important result to note is that the network is highly connected. The largest component found in the network (i.e. the largest connected subgraph of the network) fills a very large proportion of the graph (96.3%), and all the other components are very small. The second largest component, for example, contains only ten organisations (i.e. ≈0.1% of all organisations). This indicates that the vast majority of organisations involved in EU sponsored programmes are, directly or indirectly, connected via collaboration, thus providing a first sign about the effectiveness of such programmes in promoting the integration of the European R&D network. At the same time, one should also observe that the size of the giant component does not increase much from the 3rd to the 4th FWP. In other words, the network seems to be highly connected from the very first moment [18]. This might, of course, reflect the growth of a giant cluster of connected organisations that occurred during the 1st and the 2nd FWP, for which we miss information. However, an alternative hypothesis is that the R&D network we are studying simply reflects a network of relationships that developed over time and well before the coming of EU sponsored programmes.

Table 4 Summary of results of the analysis of the unipartite RJV network

		3rd FWP (1992–1994)	*3rd and 4th FWP (1992–1996)*
Number of nodes (organisations)		6291	9816
Number of edges	hp. a)	65712	103687
	hp. b)	12123	21308
Density (x 100)	hp. a)	0.3321	0.2152
	hp. b)	0.0612	0.0442
Number of components		105	114
Size of largest component		5964	9455
as a percentage of all organisations		94.8	96.3
2nd largest component		13	10
Average degree✧	hp. a)	20.9 (40.6)	21.8 (49.1)
	hp. b)	3.8 (8.9)	4.5 (11.9)
Average distance✧	hp. a)	3.16 (0.44)	3.16 (0.39)
	hp. b)	4.66 (0.72)	4.53 (0.67)
Maximum distance✧	hp. a)	12	8
	hp. b)	14	12
Clustering coefficient✧	hp. a)	0.812 (0.29)	0.816 (0.28)
	hp. b)	0.043 (0.16)	0.048 (0.16)

The indicators marked with the label ✧ have been calculated with reference to the largest component only. Numbers in parentheses are standard errors.

Please note that the connectivity of the network, in terms of size and number of connected components, is clearly not affected by the hypothesis used to construct the graph.

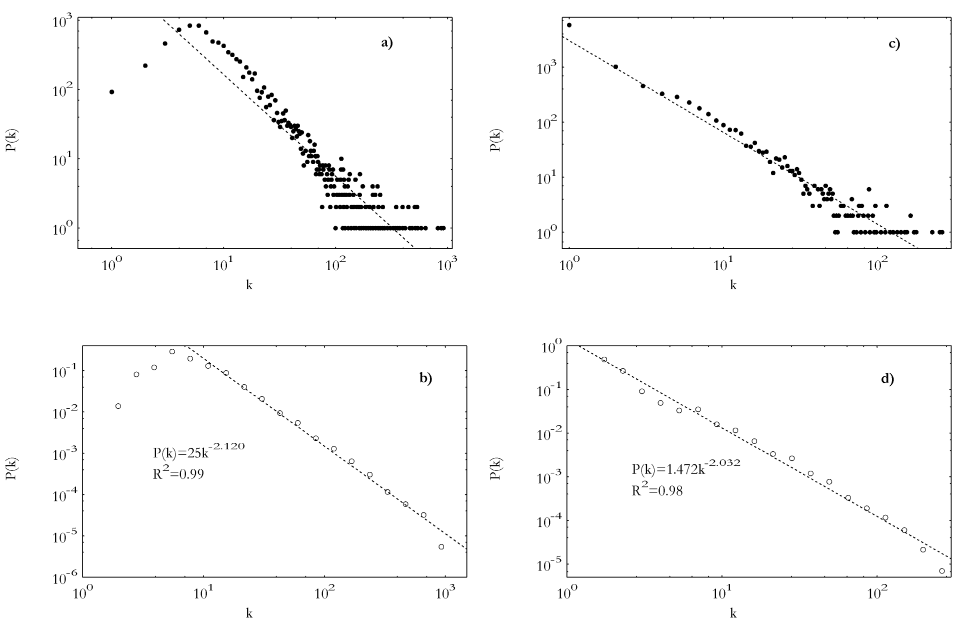
Given the size, and presumably the importance of the giant cluster, in what follows we will restrict the analysis to it.

5.2 Average degree and skewed degree distribution

The average degree (i.e. the number of other nodes to which a node is directly connected) of organisations in the RJV network is around 22 under *hp. (a)* and around 4.5 under *hp. (b)*. The average degree also increases, albeit slightly, from the 3rd to 4th FWP.

A quantity of interest that has been studied recently for various networks is the degree distribution, $P(k)$, giving the probability that a randomly selected node has k links. The distribution of degrees for the giant component of the RJV network is reported in Figure 5, separately for the two hypotheses used here.

Figure 5 Degree distribution for the giant component of the RJV network



Histogram of the degree distribution for the giant component of the RJV network. (a) Raw distribution under *hp. (a)*; (b) Raw distribution under *hp. (b)*; (c) Degree distribution with logarithmic binning under *hp. (a)*; (d) Degree distribution with logarithmic binning under *hp. (b)*. All histograms shown in double-log scales.

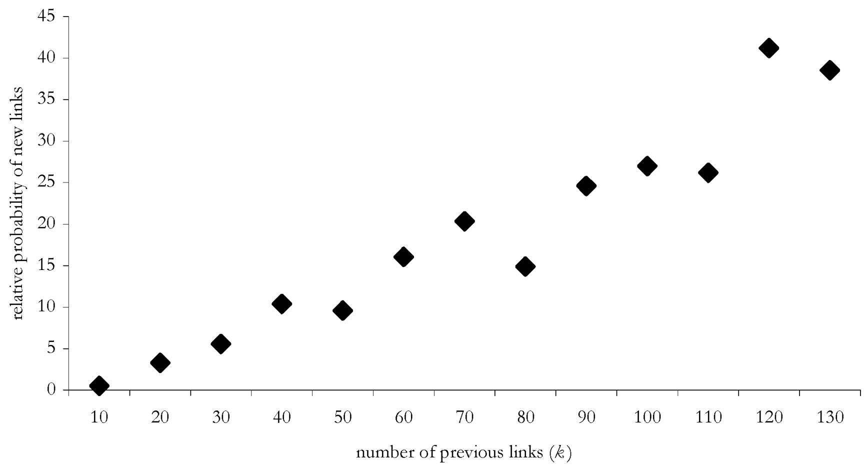
Once again, the distribution of degrees looks slightly different under the two hypotheses used here to construct the network (see top part of Figure 5). The distribution peaks around $k = 6$ under *hp. (a)*, whereas it peaks at $k = 1$ under *hp. (b)*. Moreover, the largest observed degree is higher in the former case (max $k = 933$), than in the latter one (max $k = 262$). Apart from these rather obvious differences, however, the distribution of degrees appears to be highly skewed in both cases. A very large number of organisations have a very small number of direct links with other organisations, but there is fat tail of organisations with a very large number of connections.

Networks showing a skewed degree distribution are quite common, including internet, the WWW, and scientific publications among others [19]. In general, the probability distribution of the number of links that connect a certain node in these networks decays following a power-law $P(k) \sim k^{-\gamma}$ with scaling exponent in the range between two and three [20]. The power law implies that nodes with few links are the most numerous, but the probability of larger numbers of links falls off gradually enough that nodes with several hundred links are to be expected. The power law tail in the case of the RJV network is quite evident from the raw data (see top part of Figure 5). However, because of the large variance in the downward tail of the distribution, a better estimate of the γ parameter is obtained by performing logarithmic binning of the data and normalising data by bin width (see bottom part of Figure 5). Fitting the data in this way indicates that $\gamma = 2.120$ under *hp. (a)* and $\gamma = 2.032$ under *hp. (b)* [20,21].

This result indicates, therefore, that the overall network connectivity is dominated by few highly connected organisations. It is thus interesting to examine the process through which such a distribution is generated. A much used assumption, in this respect, is that nodes link with higher probability to those nodes that already have a larger number of links, a phenomena labelled as preferential attachment [22]. In other words, the probability with which a new node connects to an existing node is not uniform, but there is a higher probability that it will be linked to a vertex that has already a large number of connections. Highly connected nodes become more and more connected, thus generating a power law distribution of degrees.

In order to test this conjecture, we have considered the distribution of degrees of organisations already in the RJV network in the period 1992–1994, corresponding to the 3rd FWP. Then, we have calculated the number of new links established in the period 1995–1996, i.e. during the 4th FWP. In the absence of preferential attachment, the probability that a link added at time t connects to an organisation that has collaborated previously with k others is therefore given by $n_k(t)/N(t)$, where $n_k(t)$ is the number of organisations with degree k immediately before the addition of this link and $N(t)$ is the total number of organisations in the network [17]. To the extent that the proportion of new links added to organisations with degree k exceeds $n_k(t)/N(t)$ and it increases with k, the assumption of preferential attachment should find support. Results for the RJV network seem to support the theory (see Figure 6). Organisations with a larger number of previous links tend to acquire a disproportionately higher number of new links. For example, organisations with a number of previous links $k < 10$ accounted for about 87% of all organisations existing in the 3rd FWP, and obtained only 44% of all new links added in the 4th FWP. On the other hand, organisations with a number of previous links comprised between $k = 50$ and $k = 60$ accounted for only about 0.2% of all organisations existing in the 3rd FWP, and obtained more than 4% of all new links added in the 4th FWP.

Figure 6 Preferential attachment in the RJV network



The relative probability of new links is defined by the ratio between the proportion of new links added to organisations with k previous links, and the proportion of organisations with k previous links on all organisations existing in the network immediately before the addition of the link.

The explanation for the preferential attachment in the case of the RJV network has to be found, at least partly, in the so-called 'Matthew effect' [23]: institutions that are successful in getting funds for their research have a higher probability of producing exploitable research, which improves their probability of joining other projects (and therefore increase their number of links) in the future [23–26].

5.3 Average distance

An often used measure to quantify the efficiency of a network in connecting different organisations and facilitating the flows of information and knowledge is the so-called *average distance*. For any pair of nodes, *i* and *j*, in the network, the ability to communicate with each other depends on the length of the shortest path l_{ij} (i.e. the minimum number of edges), which links them. The average over all pairs of nodes, denoted as $d = \langle l_{ij} \rangle$, is called the average separation (distance) of the network, characterising the network interconnectedness. In other words, the average distance measures the number of steps that have to be taken in order to connect two randomly selected nodes.

An alternative measure that is also used to evaluate the degree of connectedness of a network is its *diameter*, which is defined as the maximum separation of pairs of nodes in the network, namely the greatest distance one will ever to have to go to connect two nodes together.

Once more, it turns out that the values of the average distance and the diameter of the RJV network differ under the two hypotheses used to construct it (Table 4). Apart from this rather obvious result, however, the most interesting finding is that the average separation between pairs of organisations is relatively small. It takes an average of only 3.1 steps (4.7 under *hp. (b*) to reach a randomly chosen organisation from any other. Quite notably, the observed value of the average distance is approximately equal (or even lower for the *hp. (b*) to the value it would assume in a classical random graph – i.e. a network in which nodes are connected to one another uniformly at random with the same number of nodes and same average degree of nodes [27,28] The phenomenon of relatively short paths connecting randomly selected pairs of vertices has been noted in several other networks [29], and has been termed with the label 'small world effect'. In the context of the RJV network, the small world effect implies apparently that the EU supported R&D consortia work as effective means of knowledge diffusion.

5.4 Clustering

A further important characteristic of many real-world networks is that they are *clustered*, meaning that they possess local clusters of nodes in which a higher than average number of nodes are connected to one another. More precisely, a network shows clustering if the probability of a tie between two nodes is much greater if the two actors in question have another mutual acquaintance, or several others. Formally, one can define a clustering coefficient *C* as follows: for any node *i* one picks the k_i other nodes with which the node in question is linked. If these nodes are all connected to one another (i.e. they form a fully connected clique), there will be $k_i(k_i - 1)/2$ links between them, but in reality there will be much fewer. If one denotes with K_i the number of links that connect the selected k_i nodes to each other, the clustering coefficient for node *i* is then $C_i = 2K_i/k_i(k_i - 1)$. The clustering coefficient for the whole network is obtained by averaging C_i over all nodes in the system. The clustering coefficient *C* thus tells how much of a node's collaborators are, on average, willing to collaborate each other.

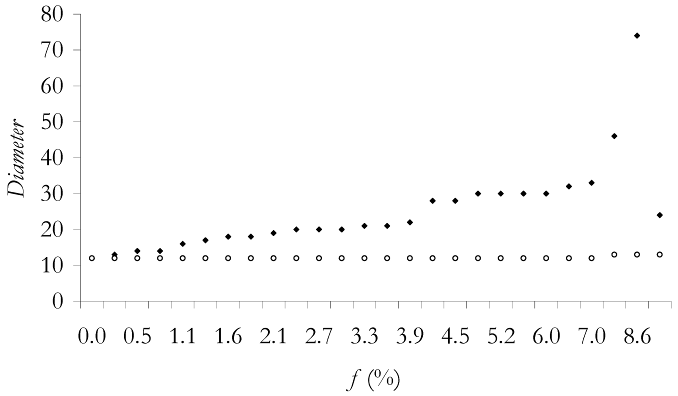
Looking at the values of the clustering coefficient in the RJV network, one observes that *C* takes extremely high values under *hp. (a)*, implying that, on an average, about 82% of the collaborators of a certain organisation also collaborate each other (Table 4). However, this rather extreme value partly reflects the bipartite nature of the graph (see Section 3 above). In the one-mode projection of a bipartite graph, in fact, cliques are automatically formed thus contributing to increase the value of the clustering coefficient. For example, in Figure 4 above, all possible triangles among actors are formed, thus enhancing the value of the clustering coefficient of each node. However, it is also clear that such a clustering only reflects the fact that the four agents have all participated in the same project, and rather than true clustering.

Adopting *hp. (b)* allows us to disentangle true clustering from the trivial effects arising from the specific features of the bipartite graph. The value of *C* drops dramatically to 0.048, being rather stable over time. This implies that, on an average, 5% of the collaborators of a certain organisation also collaborate with each other. A value that is certainly lower than the one found for the unipartite projection of the bipartite graph, but which is still much larger than the value one would observe in classical random graph [30]. This result thus suggests that organisations involved in R&D consortia tend to introduce pairs of their collaborators to each other, engendering new collaborations.

5.5 *Resilience of the RJV network*

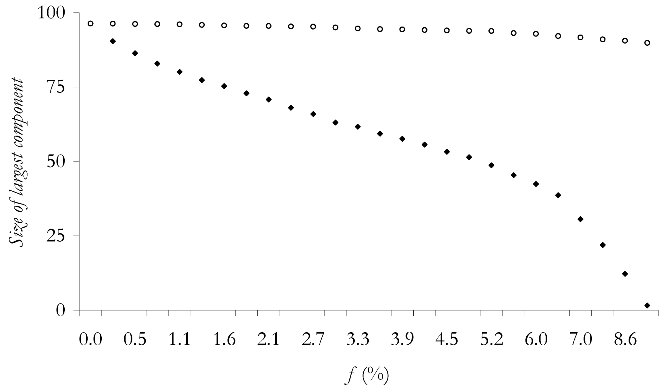
The analysis carried out so far seems to indicate that the overall connectivity of the RJV network is dominated by few important organisations. In order to test how the topological features of the network examined above depend on the activities of few important actors, we have studied the changes in the diameter, average distance and size of the largest component when a small fraction *f* of nodes are removed. More precisely, we have compared how the quantities mentioned above vary, respectively, by removing the most important organisations in terms of number of connections (i.e. degree *k*), and by removing the same fraction of organisations randomly (Figure 7).

Figure 7 Resilience of the RJV network

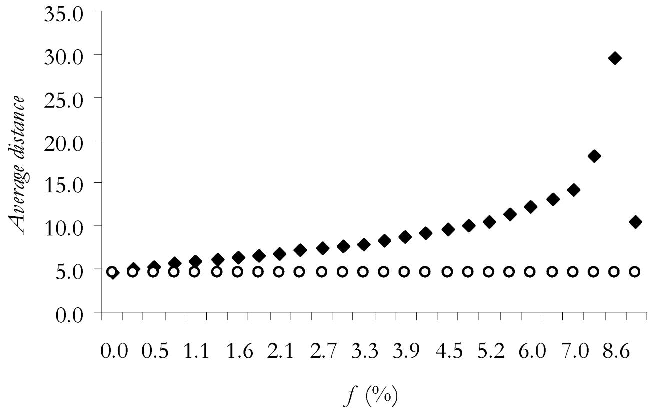


(a)

Figure 7 Resilience of the RJV network (continued)



(b)



(c)

Changes in the diameter, average distance and size of the largest component.

(a) Diameter; (b) Size of largest component as a percentage of the network; (c) Average distance.

In all figures, diamonds show the response when the most connected nodes are removed, circles show the response when a fraction *f* of nodes are removed randomly.

Results show that the network is extremely robust with respect to the random removal of a very high fraction of organisations. Thus, even when as many as 30% of all organisations are removed from the network, the communication between the remaining nodes in the network is virtually unaffected. The largest component still accounts for more than 95% of the remaining organisations, and the diameter and the average vertex–vertex distance remain stable. The reason for this result has to be found in the extremely skewed degree distribution (see above). This implies that the majority of organisations have only few links, and therefore organisations with small connectivity will be selected with much higher probability. The removal of these 'small' nodes does not alter the path structure of the remaining organisations, and thus has no impact on the overall network topology [31].

On the other hand, results also show that the RJV network is highly 'vulnerable' with respect to the removal of the most connected nodes. When such nodes are eliminated, the diameter as well as the average distance among organisations increase rapidly, almost doubling their values when 4% (430) of the most connected organisations are removed. In addition to that, the size of the largest component drops to less than 50% of the remaining organisations when 5% (488) of the most connected actors are removed from the network. Once again, the explanation for this result is related to the inhomogeneity of the connectivity distribution: the connectivity of the network is maintained by a few highly connected organisations whose removal drastically alters the network's topology, and decreases the ability of the remaining organisations to communicate with each other. In this context, the meaning of the term 'removal' must be, of course, interpreted with a grain of salt. The most important message emerging from this analysis is that the overall connectivity of the RJV network is maintained by a few important organisations, whereas the vast majority of the other partners plays no role in this respect.

5.6 Visualising the RJV network

Many of the results reported above could be also grasped by visualising the RJV network. Unfortunately, it turns out almost impossible to draw a meaningful network of nodes and edges of the size considered here. In order to provide a visual illustration of the network, we have therefore shrinked the network by clustering some nodes, using the following procedure.

As noted above, the majority of organisations participated to only one RJV project or to more than one RJV project, but collaborating always with the same *Prime contractor*. In the RJV network, there are 5,762 such organisations. These organisations contribute nothing to the overall connectivity of the network. Moreover, if we take all the organisations that collaborated with one and only one *Prime contractor*, such organisations can be considered as *structurally equivalent*, i.e. actors that have identical ties, so that it is possible to 'collapse' them into a single node.

The remaining 3,693 organisations [32] comprise *Prime contractors* as well as *Partners* that have collaborated *with more than one* Prime contractor [33]. This subgraph comprises (by definition) a single component, i.e. all organisations are directly or indirectly connected, and it can be considered as the *core* of the RJV network. In other terms, if we remove these organisations the RJV network would break up into a very large number of disconnected components, whereas the removal of the other nodes would not affect the connectedness of the remaining nodes.

Table 5 reports the same indicators shown in Table 4 for the subgraph consisting of the 3,693 organisations, which represent the core of the network. It is quite important to note that the density of connections in this subgraph is remarkably higher than for the RJV network as a whole (compare with Table 4). This suggests, not only that the organisations in this subgraph account for the overall connectivity of the RJV network, but that they also entertain a dense web of relationships among each other. This is quite evident also from the value of the average vertex–vertex distance, which is much lower than for the network as a whole, and from the value of the clustering coefficient, which is higher (under the *hp.* (*b*)) than the value for the entire network.

Table 5 The core of RJV network

		3rd and 4th FWP (1992–1996)
Number of nodes (organisations)		3693
Number of edges	hp. a)	60203
	hp. b)	15298
Density (x 100)	hp. a)	0.882
	hp. b)	0.224
Average degree – all core	hp. a)	32.6 (57.5)
	hp. b)	8.28 (15.5)
Average degree – prime contractors	hp. a)	40.2 (74.3)
	hp. b)	12.6 (20.0)
Average degree – partners	hp. a)	23.9 (24.5)
	hp. b)	3.33 (2.8)
Average distance	hp. a)	2.79 (0.37)
	hp. b)	3.66 (0.50)
Maximum distance	hp. a)	8
	hp. b)	10
Clustering coefficient	hp. a)	0.55 (0.27)
	hp. b)	0.13 (0.25)

The core of the RJV network comprises the *Prime contractors* and the non-occasional *Partners* (i.e. Partners that have collaborated with more than one Prime contractor) belonging to the largest component. The subset thus defined includes 3,693 organisations, 1,978 Prime contractors and 1,715 Partners.

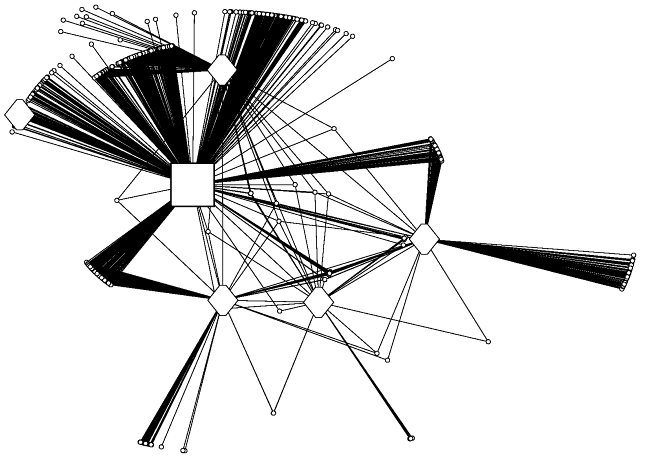
In order to visualise the network, the 3,693 organisations have been further grouped using the number of connections as a clustering principle. More specifically, we partitioned the subgraph of 3,693 organisations by using the notion of *k-core*. A subset of vertices of the graph is called *k*-core or core of order *k*, if every vertex from the subset is connected to at least *k* vertices from the same subset. The notion of *k-core*, therefore, points to areas of the network where interaction among actors is particularly intense [34]. In the network formed by the 3,693 organisations, there are 15 cores. For the sake of network visualisation, we have grouped into a single node all organisations belonging to a *k-core* with $k > 6$. This node contains 674 organisations. Each organisation included in this node has been connected to at least seven of the other 673 organisations.

As for the remaining 3,019 (i.e. 3,693–3,674) organisations belonging to a *k-core* with $k \leq 6$, we have further grouped them according to *p-cliques*. A p-clique consists of a subset of nodes such that each node has a proportion *p* of all its connections inside the clique. In order to group the organisations, we have set $p = 1$ [35].

The overall RJV network, partitioned following the procedure described above, has been visualised in Figure 8. The visual inspection of the network illustrates very well many of the properties noted above.

- In the first place, it is possible to appreciate the short chain of links that connect organisations in the RJV network. Starting from any node in the graph it takes a relatively small number of steps to reach any other node in the network.
- In the second place, the picture also gives account of the highly skewed distribution of degrees. Most organisations involved in the R&D consortia are included in the 'ring' of nodes with only one link to the network. On the other hand, a handful of organisations have a very high number of connections, both with 'occasional' participants, and among each other.
- Thirdly, it is also quite clear why the connectivity of the RJV network is maintained by few highly connected organisations. For example, by removing the 674 organisations in the higher-order *k-cores* (box symbol in Figure 8), it is possible to see how the overall network breaks up into a myriad of smaller components, and how the average distance of the surviving largest component tends to increase.
- Fourthly, the picture also allows us to appreciate that *clustering* tends to be more intense among the most connected organisations. In order to better evaluate this, we have visualised separately the subgraph formed by the 674 organisations included in the higher-order *k-cores* (Figure 9).

Figure 8 Visual illustration of the RJV network

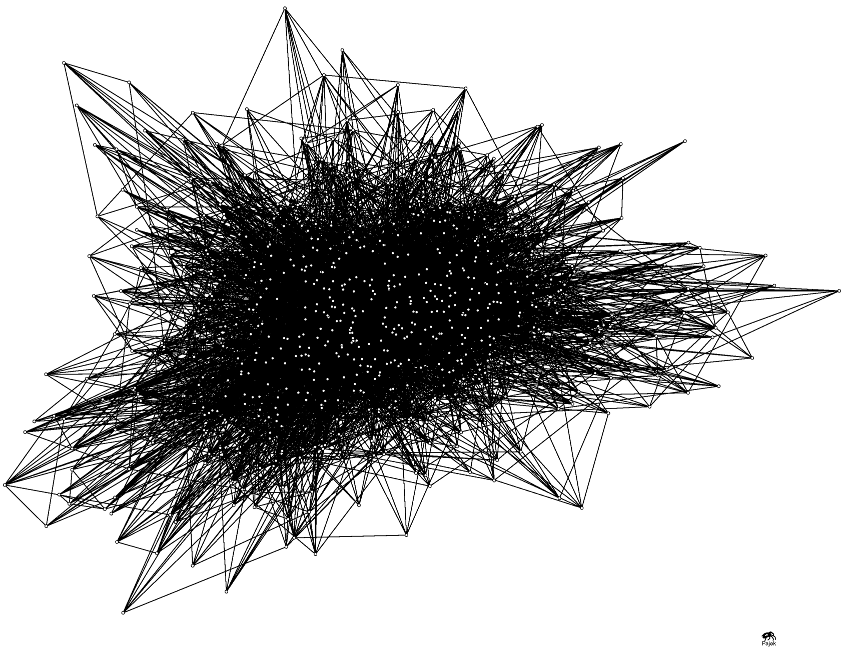


The node marked with the box symbol contains 674 organisations belonging to a *k-core* with $k > 6$.

The nodes marked with the diamond symbol contain 3,019 organisations. Each node is a *p-clique*, i.e. nodes included in it have 100% of their connections within the clique (excluding links pointing externally).

The nodes marked with circles contain 5,762 organisations. Each node contain all the organisations that participated to only one RJV project or to more than one RJV project, but always with the same Prime contractor.

Figure 9 The *k*-core of the RJV network ($k > 6$, $N = 674$)



The figure reports the internal connections among the 674 organisations belonging to the *k-cores* with $k > 6$ (box symbol in Figure 8).

One can observe the highly dense web of connections linking these organisations (density= 30%). Moreover, the clustering coefficient C for this subgraph takes also a very high value (0.17 under *hp. b*, meaning that on an average 17% of the collaborators of a given organisation also collaborated among each other). In other words, this subgraph of highly connected organisations also shows a very high degree of 'transitivity', ie. the collaborators of a certain organisation tend also to collaborate with each other.

6 Implications of oligarchic integration for a European Research Area

In the design of European institutions, a European Research area should gradually emerge from the current fragmented and duplicative national innovation systems and supra-national programmes, once virtual mechanisms of coordination, networking and excellence promotion are set in place. Naturally, for collaborative endeavours to be effective, they must be heavily supported by measures that create 'enabling conditions', such as investments in research infrastructures, more coordinated implementation of national policies, development of a common system of scientific and technical reference, incentives for the training and mobility of researchers, support to risk capital investment.

Much importance is placed on the use of 'variable geometry' instruments, mentioned in the Treaty but seldom exploited, for gearing a critical mass of resources in strategic research fields, achieving world class excellence, and spreading knowledge beyond the leading clusters to peripheral actors. A paramount instrument for achieving these ambitious goals is represented by 'networks of excellence', which would represent the backbone of a competitive European Research area. Top-level resources will be encouraged to cluster and leading institutions to tightly connect for carrying out long-term integrated projects in their fields of expertise, leaving much room for these networks to organise themselves.

The ideal picture that emerges from the current proposals and debate is one in which centres of excellence intensively cooperate into stable consortia that represent primary nodes, directly linked to each other, forming a highly connected core, that serves the objective of enhancing organisation and quality of research and, ultimately, European competitiveness. The cohesion objective would be pursued by connecting peripheral institutions to the nodes of this core, that could therefore act as catalysts and source of spillovers for smaller components or backward areas. In some sense, the European technology policy is to be oriented towards facilitating an 'enlightened' oligarchic integration, so that the best European talents and resources may get proper incentives and converge on issues of common interest, providing benefits to the whole S&T system.

However, the empirical evidence we presented in this paper suggests that oligarchic networks have already emerged as a consequence of previous cooperative programmes. In particular, the network formed by RJVs promoted under the 3rd and 4th FWPs appears to be rather dense and extremely pervasive, while presenting hierarchical topological features. As shown in Section 5, organisations are, on an average, connected by short chains of links, but this high connectivity is strongly dependent on a core of central actors, which take part in a great number of projects, frequently playing the role of *Prime Contractors*. Around this pivotal group of highly frequent participants, that exhibits a high degree of intra-connectedness, we can identify two 'lower' layers. A minor group of rather frequent but low-profile participants, that enter consortia as Partners and take advantage of the programmes for linking with several leading actors, and an extremely large number of Partners for which participation is an exceptional event. In purely topological terms, this 'three-layer' structure should ensure cohesion and efficient transmission of knowledge, since even for the most peripheral agents, the network core, where most interaction and, possibly, most knowledge production and information exchange take place, is only a few edges away. The 'small world' characteristics imply apparently that the European network is apt to diffuse knowledge in an efficient manner.

The core of the network carries the greatest interest for the researcher, as the effective amount and quality of knowledge production and transmission within the overall network clearly depend on the resources deployed by the members of this core, by their expertise and by their degree of integration. In the present analysis, we have emphasised the vulnerability of the emergent European Research area from this pivotal group and focussed on its connectivity. The term 'oligarchic' conveys the idea of a leadership that emerged since the very early stages and strengthened over time, in such a way that removing those actors would imply the current configuration to collapse and the ability of remaining organisations to communicate with each other to dramatically decrease.

Members of the core entered early RJVs as Prime Contractors and gained in connectedness and centrality over time by way of repeated participation and preferential attachment. As we noted, organisations with a larger number of previous links tend to acquire a disproportionately higher number of new links, particularly attracting peripheral actors. However, a high share of cooperative links is directed towards other members of the core, whose density is therefore remarkably higher than for the RJV network as a whole.

This highly dense and connected core comprises industry and technology leaders and a significant number of outstanding public research agencies and academic institutions. In short, it includes many entities which are expected to be natural candidates for the 'networks of excellence' to come, to respond to the call of the commission for the creation of the excellent backbone of a European Research area. To a certain degree, the newly designed policy is then going to replicate existing patterns of interaction, although it is intended to give to these consortia a more focussed orientation on leading-edge research and less of a 'political' role. Indeed, the current analysis emphasised that *connectedness* is not the real problem. The limited effectiveness of previous programmes can hardly be related to lack of interactive opportunities for key actors. Rather, questions arise about the aims and content which have generally characterised consortia involving technology leaders.

The dynamics that characterised the RJV network poses additional question about the impact of policies that aim at introducing novelties in the way research is carried out in Europe. Self-reinforcing mechanisms and structural inertia appear in fact to have played an important role in determining the network configuration. That is, the core of the network formed in the early stages and 'closed' rather quickly around frequent Prime Contractors. Self-organisation of networks could only strengthen this feature and imply risks of lock-in. Late members would be unlikely to acquire hub roles and the network would soon become resistant to significant changes in the structure of relationships, that may, at time, re-orient the network towards more productive research areas. This leads to carefully evaluate the role European, and national, institutions might still play in setting priorities and 'creating' room for new actors within the stratified core.

7 Conclusions

The present paper has provided a preliminary view on the emergent European Research Area, exploring topological features and dynamics of the network which stemmed from RJVs promoted under Framework Programmes. From the empirical analysis, the emergence of a dense and hierarchical network can be inferred. A highly connected core of frequent participants, taking leading roles within consortia, is linked to a large number of peripheral actors, forming a giant component that exhibits the characteristics of a 'small world'. We expect this configuration to have important implications for the policy aimed at 'networking centres of excellence', partly because the same dynamics may replicate, and partly because the existing 'fabric' will exert a significant influence on the creation of new network structures.

Acknowledgements

This paper has received financial support within the EC TSER Programme's KNOW FOR INNOVATION Project (*Innovation-Related Knowledge Flows in European Industry: Extent, Mechanism, Implications*), Contract No. SOE1-CT98-1118, DGXII G4, coodinated by Prof. Y. Caloghirou of the National Technical University of Athens (Greece). An earlier version of this paper was presented at the Athens final workshop of the research group. The authors wish to thank Aldo Geuna, Bart Verspagen and Nicholas Vonortas and all participants at the meeting for useful comments. None of them are, of course, responsible for any possible error. Umberto Fuso provided extremely valuable research assistance.

References and Notes

1 European Commission (1994) *The European Report on Science and Technology Indicators*, DG XIII, Brussels.

2 The composition of consortia is ruled by criteria which normally require the involvement of actors from at least two Member States and preferably located at different stages of the broadly defined 'production chain'. EU covers up to 50% of the costs of the projects, whereas members of the consortium share the burden of the remaining costs. Organisations which have not cost accounting making it possible to reveal total costs, such as Universities or colleges, receive up to 100% of costs [1].

3 Ants, M. and Lee, N. (1997) (Eds.): *The Economics of the European Union. Policy and Analysis*, Oxford University Press, Oxford.

4 Peterson, J. and Sharp, M. (1998) *Technology Policy in the European Union*, Macmillan Press, London.

5 European Commission (2000) *Towards a European Research Area*, Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee, the Committee of the Regions, Brussels.

6 European Commission (2000) *Making a reality of the European Research Area*, Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee, the Committee of the Regions, Brussels.

7 European Committee on Legal Affairs and the Internal Market (2000) *Opinion on the Communication from the Commission Entitled 'Towards a European Research Area'*, Brussels.

8 CPMR (Conference of Peripheral Maritime Regions of Europe) General Secretariat (2000) *Technical Note on the European Commission's Communication entitled 'Towards a European Research Area'*, Rennes.

9 Economic and Social Committee (2000) *Opinion on the Communication from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions-Towards a European Research Area*, Brussels.

10 Committee of the Regions (2000) *Opinion on the Communication from the Commission entitled 'Towards a European Research Area'*, Brussels.

11 European Science Foundation (2000) Response to the Communication of the Commission of the European Communities, *Towards a European Research Area*, Brussels.

12 Academia Europaea (2000) *'Towards a European Research Area': Responses to the Communication from the European Commission*, London.

13 Bundesverband der Deutschen Industrie (2000) *BDI Position Paper on the Communication from the Commission 'Towards a European Research Area'*, Berlin.

14 The dataset has been compiled by the National Technical University of Athens (NTUA), based on the EU CORDIS (Community Research and Development Information Service) database. We wish to thank Yannis Caloghirou for kindly permitting the use of the database.

15 The dataset examined contains information on all EU-sponsored RJVs that include at least one participant from the private sector.

16 More specifically, 39 organisations, of which 13 firms and 17 Universities, have participated into more than 50 and less than 100 RJVs, 10 organisations (two firms, two universities and six research centres) have participated in more than 100 R&D consortia.

17 Newman, M.E.J. (2001) 'Clustering and preferential attachment in growing networks', http://arxiv.org/abs/cond-mat/0104209.

18 For example, at the beginning of the 3rd FWP in 1992, The largest component accounted for about 95% of all organisations already in the network.

19 Albert, R., Jeong, H. and Barabási, A.L. (1999) 'Diameter of the World-Wide-Web', *Nature*, Vol. 401, pp. 130–131.

20 Barabási, A.L. and Albert, R. (1999) 'Emergence of scaling in random networks', *Science*, Vol. 286, pp.509–512.

21 Quite notably, the value of the γ parameter is close to the value found for other networks. For example, Barabasi and Albert [20] found that the probability that k documents point to a certain WWW page follows a power law distribution with $\gamma = 2.1$.

22 Barabási, A.L., Jeong, H., Néda, Z., Ravasz, E., Schubert, A. and Vicsek, T. (2001) 'On the topology of the scientific collaboration networks', *Physics A 311*, pp.590–614.

23 Merton, R.K. (1968) 'The Matthew effect in science', *Science*, Vol. 159, pp.56–63.

24 Merton [23] first introduced the concept in relation to the allocation of credit for scientific work. The terms refer to the Gospel according to St Matthew: "For unto every one that hath shall be give, and shall have abundance: but from him that hath not shall be taken away even that which he hath".

25 Garcia-Fontes and Geuna [26] find evidence of the Matthew effect when examining the BRITE-EURAM I and II Programmes, as 13% of all organisations involved in the programmes got 52% of contracts.

26 Garcia-Fontes, W. and Geuna, A. (1999), 'The dynamics of research networks in Europe', in Gambardella, A. and Malerba, F. (Eds.): *The Organization of Innovation in Europe*, Cambridge University Press, Cambridge.

27 The average vertex–vertex distance in a random graph with same parameters as the RJV network would be equal to [$\log N / \log z = 2.79$], where N is the total number of organisations and z is the average degree of nodes [28]. Under hp. b), the average distance in a random graph with similar parameters would be equal to about six, which is remarkably higher than the observed value.

28 Newman, M.E.J., Strogatz, S.H. and Watts, D.J. (2001) 'Random graphs with arbitrary degree distributions and their applications', http://arxiv.org/abs/cond-mat/0007235.

29 Watts, D.J. and Strogatz, S.H. (1998) 'Collective dynamics of 'small-world' networks', *Nature*, Vol. 393, pp.440–442.

30 In a classical random graph, the clustering coefficient is $C = z/N$, where z is the average degree of nodes and N is the total number of nodes. In a random graph with same parameters as the RJV network the C coefficient would then be equal to 0.0047.

31 Albert, A., Jeong, H. and Barabasi, A. (2000) 'Error and attack tolerance of complex networks', *Nature*, Vol. 406, pp.378–381.

32 We are considering only the giant component of the RJV network, comprising 9,455 organisations.

33 Remember we have defined Prime contractors as those organisations that have played that role at least once, and Partners as those organisations that have never acted as coordinators, but collaborated with more than one Prime contractor.

34 Moreover, one important property of k-cores is that they are nested. For example, all nodes in the two-core are included in the one-core.

35 Please note that a p-clique with $p \leq 1$ is not necessarily connected. Setting $p = 1$ simply means that a given clique will contain nodes which are connected only to other nodes inside the clique.