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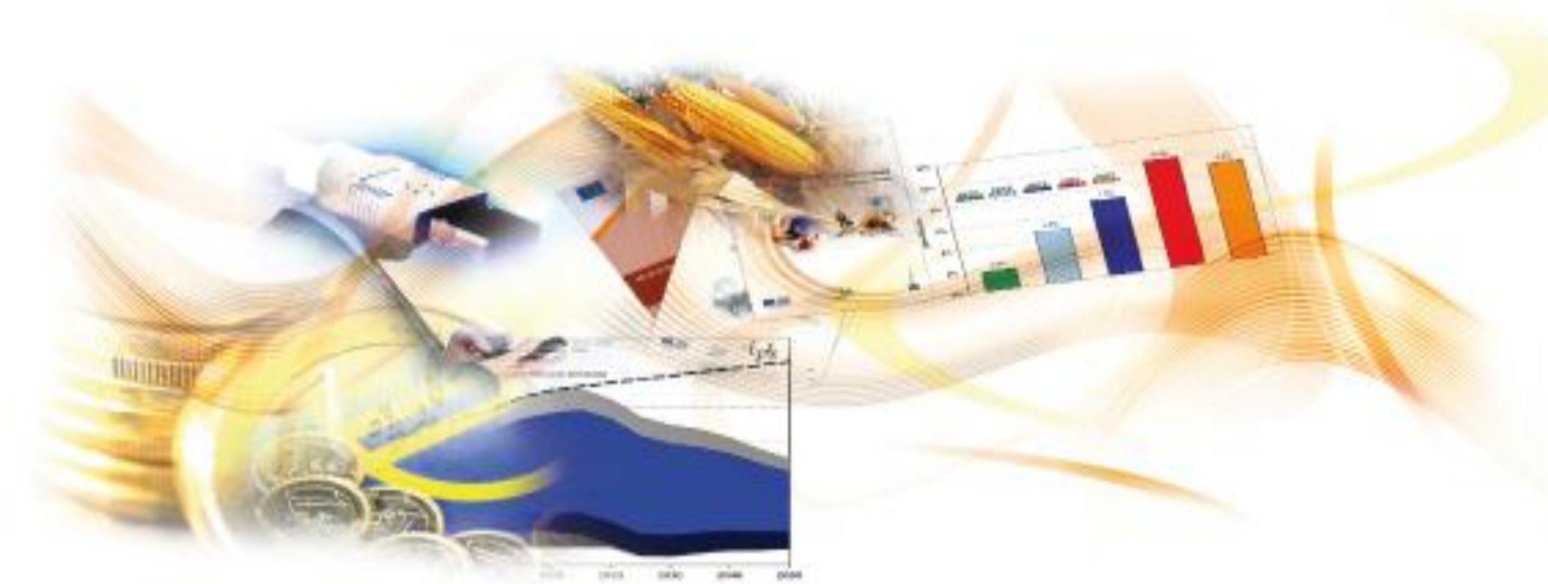

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The global R&D network:
A network analysis of international R&D centres

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Preface

The European ICT Poles of Excellence (EIPE) research project at the Institute for Prospective Technological Studies is investigating the issues of growth, jobs and innovation, which have become main priorities of the European Union's growth strategy programme 'Europe 2020'.

The overall objectives of the EIPE project are to set the general conceptual and methodological conditions for defining, identifying, analysing and monitoring the existence and progress of current and future EIPE, in order to develop a clear capacity to distinguish these among the many European ICT clusters, benchmark them with non-European poles, observe their dynamics and offer a thorough analysis of their characteristics.

The EIPE project started late in 2010 and has, since then, developed a large database of original ICT innovation indicators, enriched with geographical information in order to allow localisation and aggregation at NUTS 3 and NUTS 2 level. The tool helps us to answer such questions as: How is ICT innovation and economic activity distributed and how is it evolving in Europe? What locations are attracting new investments in ICT R&D or manufacturing? What is the position of individual locations in the global network of ICT activity?

To date, the following additional publications have emerged from the research:

- A Framework for assessing Innovation Collaboration Partners and its Application to BRICs. G. De Prato and D. Nepelski, JRC-IPTS Working Paper, (2013).
- Does the Patent Cooperation Treaty work? A Global Analysis of Patent Applications by Non-residents. G. De Prato and D. Nepelski, JRC-IPTS Working Paper, (2013).
- Internal Technology Transfer between China and the Rest of the World. G. De Prato and D. Nepelski, JRC-IPTS Working Paper, (2013).
- International Patenting Strategies in ICT. G. De Prato and D. Nepelski, JRC-IPTS Working Paper, (2013).
- Asia in the Global ICT Innovation Network. Dancing with Tigers, G. De Prato, D. Nepelski and J.-P. Simon (Eds), Chandos Asian Studies Series: Contemporary Issues and Trends, Chandos Publishing, (2013, forthcoming),
- Global technological collaboration network. Network analysis of international co-inventions, G. De Prato and D. Nepelski, Journal of Technology Transfer, 2012,
- Internationalisation of ICT R&D: a comparative analysis of Asia, EU, Japan, US and the RoW, G. De Prato and D. Nepelski, Asian Journal of Technology Innovation, (2012),
- A network analysis of cities hosting ICT R&D, G. De Prato and D. Nepelski, (2013 - forthcoming).

More information can be found under: http://is.jrc.ec.europa.eu/pages/ISG/EIPE.html

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1. Introduction

It is well-recognized that a number of corporations have slowly begun to seek new knowledge sources and opportunities worldwide (Bartlett and Ghoshal 1990, Dunning 1988, Dunning 1994). These "metanational" companies are increasingly building a new kind of competitive advantage by discovering, accessing, mobilising, and leveraging knowledge from a number of locations across the globe (Doz et al. 2001). They do this by locating their R&D centres outside the country where they are headquartered. Once a firm decides to establish an R&D centre in a certain location it creates externalities affecting other firms. Examples of such externalities may include increased competition for skilled labour or R&D spillovers available to other companies. Hence, company decisions regarding the location of R&D activities can be considered as mutually beneficial (or detrimental) and a random distribution of R&D locations is rather unlikely. Consequently, firms' behaviour concerning the location of R&D centres can be expected to fulfil the criteria of a complex network, whose creation is driven by collective actions. Unfortunately, to the best of our knowledge, the available research does not fully capture this perspective. Taking into account the existing gap in treating the internationalization of R&D as a system of inter-linked activities, we apply network analysis to the study of globally dispersed R&D centres as a network. This way, we aim to cast new light on the structure and characteristics of the whole system.

A natural way of constructing an R&D network is by drawing a line between each pair of countries that share an R&D centre, which is located in one country and controlled by a company located in another country. This way we illustrate the direction in which multinational enterprises (MNEs) move to seek R&D assets around the world. We further extend this nexus of links by adding the information on the intensity of R&D performed in each R&D centre and by controlling for the number of activity types. This allows us to track the existence and intensity of R&D relationships between countries. By doing this for all the countries which own and host international R&D centres, we are able to create a unique map of international R&D centres, i.e. the global R&D network.

The analysis is based on a unique dataset that contains information on the location and ownership of over 3,000 R&D centres, belonging to 175 multinational high-tech companies which, in 2011, were located in over 50 countries around the world. In addition, it includes detailed information on the type of R&D activity taking place in these centres and the number of R&D applications and types.

Despite the fact that the topic of R&D internationalization has already attracted a considerable amount of attention, there is still relatively little empirical evidence. Moreover, existing studies are either based on firm-level analysis (Florida 1997, Kuemmerle 1999, Boutellier et al. 2008) or they analyse the internationalization of R&D through the perspective of relationships between individual countries (Patel and Pavitt 1991, Picci 2010, Belderbos et al. 2006). Consequently, to our knowledge, none of the studies takes a holistic view of the entire system or accounts for the inter-dependencies and externalities that arise in this system of interactions. However, understanding these issues is of crucial importance in the context of the very dynamic changes that are taking place in the organisation of global R&D activities. For example, until recently, R&D internationalisation has been limited to a small number of developing countries and economies in transition (UNCTAD 2005). This however is changing (OECD 2009). As the geography of technology-intensive industry continues to change and as Asian countries are becoming essential elements in the global value chain, their importance as knowledge and technology producers is increasing, on the one hand, and their attractiveness as location for higher value-added firm activities such as R&D is growing, on the other hand (Griffith and Miller 2011, Nepelski and De Prato 2012).

In light of these dynamics, the internationalization of R&D creates concerns and questions among national policy makers (Edler and Polt 2008). In developed countries, for example, it is feared that the competition for R&D resources has an impact on domestic R&D expenditures and on the domestic knowledge base. These fears are magnified by the fact that the internationalisation of R&D is primarily taking place in knowledge intensive industries, such as the ICT, chemical or pharmaceutical sectors. These sectors are seen as essential to advanced economies. Thus, policy makers fear that the potential loss of local inventive capacity in high-tech industries to other regions could harm their competitiveness and undermine the state and development of their knowledge-based economies.

Taking into account the gap in our understanding of the dynamics of global R&D organisation, the major contribution of this paper is that it looks at the whole system, rather than at individual relationships and interactions. By applying network analysis, we graphically and analytically study the characteristics of international R&D centre networks and the relationships between countries that import and export R&D services. In addition, we test whether R&D networks exhibit the properties of the core/periphery structure and identify the members of each group. In addition, we introduce network measures in a gravity model in order to cast new light on the drivers of R&D internationalization and the intensity of this process.

Studies of knowledge, R&D and innovation networks already exist. This type of analysis has been applied, for example, to patent data (Chao-Chih 2009, Han and Park 2006, Lai et al. 2011, Stefano and Francesco 2004, De Prato and Nepelski 2012) and bibliometric data (Glänzel and Schubert 2005, Glänzel et al. 1999, Kretschmer 2004). In this context, our work delivers a valuable contribution by extending the analysis of knowledge networks by using a different type of information and focusing on the input side of the innovation process. In addition to mapping the global R&D network, we focus on the analysis of the R&D-related relationship between the countries present in the network and the system of internationalised R&D.

The rest of the paper proceeds as follows: Section 2 describes the process of presenting globally dispersed international R&D centres as a network. Section 3 introduces the data used in the study and Section 4 analyses the characteristics of the R&D network and countries' positions in the network. Section 5 formulates a model of R&D internationalisation and Section 6 presents and discusses the results of empirical estimations. Section 7 concludes and provides some policy implications.

2. International R&D centres as a network

Definition and characteristics of a network structure

A network consists of a graph whose elements include two sets: set of nodes (vertices), that correspond to the selected unit of observation, and a set of lines (relationships), that represent relations between units. A line can be directed – an arc, or undirected – an edge. In a formal way, a network:

$$N = (V,L,W,P) \tag{1}$$

consists of a graph $G = (V,L)$, where V is the set of nodes, A is the set of arcs, if the lines are directed, and E is the set of edges, if the lines are not directed, and $L = E \cup A$ is the set of lines. Additional information on the lines is given by the line value function *W* and on nodes by the value function *P*.

Regarding the structural properties of a network, the density of a network is, among others, a key indicator providing information about the network structure. The density of a network, λ, is the number of edges that is expressed as a proportion of the maximum possible number of connections. It is formally defined as:

$$\lambda = \frac{m}{m_{\max}} \qquad (2)$$

where $m_{\max}$ is the total number of lines in a complete network, i.e. a network where all the nodes are connected to each other.

In order to obtain further information on the structure of a network and the characteristics of the nodes, it is worthwhile to analyse centrality. Centrality is an important concept in studying networks (Freeman 1978). In conceptual terms, centrality measures how central an individual is positioned in a network. The most obvious way of capturing degree centrality of V_i is counting the number of its neighbours, i.e. its degree. The way to compute degree centrality is to count the number of nodes connected to V_i, i.e.:

$$C_i^d = \frac{d}{V-1} \qquad (3)$$

If there is information on the direction of edges, i.e. directed network, the measurement of a node's position can be disaggregated to account for the incoming and outgoing connections to and from the node. Then, the in-degree and out-degree are defined as:

$$k_i^{in} \equiv \sum_{j \neq i} a_{ij} \qquad (4)$$

$$k_i^{out} \equiv \sum_{j \neq i} a_{ji} \qquad (5)$$

where a_{ij} represents the directed link from V_i to V_j and a_{ji} the reverse relationship.

In order to cast more light on the intensity of interactions, the degree measures can be replaced by node strength capturing the sum of weights given to the connections to any V_i. Similarly to the degree measures, it is possible to capture the intensity of incoming and outgoing connections to and from a vertex. Thus, in a formal way in- and out-strength are defined as:

$$s_i^{in} \equiv \sum_{j \neq i} w_{ij} \qquad (6)$$

$$s_i^{out} \equiv \sum_{j \neq i} w_{ji} \qquad (7)$$

where w_{ij} represent the intensity of the directed link from V_i to V_j and w_{ji} the reverse relationship (Squartini et al. 2011).

Nodes' centralities in a network can have large or small variance. On the one hand, a network, where few actors have much higher centrality than other actors is said to be strongly centralised. A typical example is a star network. On the other hand, if unit centrality measures have small variance, the centralisation of a network is low. Thus, in order to assess the level of centralisation of the entire network, we use a network degree centralisation defined as:

$$C^d = \frac{\sum_{i=1}^{V} | C_i^d - C_i^{d*} |}{(V-2)(V-1)}, \qquad (8)$$

where C_i^{d*} is the highest value of centrality measure in the set of units of a network (Freeman 1978). Network centralisation index can take any value between 0, if all units have equal centrality value (cycle graph), and 1, if one unit completely dominates all other units (star graph).

Except for the degree centrality defined in (3), within graph theory and network analysis, there are a number of other measures of the centrality of a vertex within a graph that show the relative importance of a vertex within the graph (Koschützki et al. 2005). We use of two additional most commonly applied measures, i.e. closeness centrality and betweenness centrality.

The closeness centrality of a node *i* is the number of the remaining nodes divided by the sum of all distances between that node and all the remaining ones, i.e.:

$$C_i^c = \frac{V-1}{\sum_{j \neq i}^{V-1} \partial_{ij}}. \quad (9)$$

At the aggregate level, centrality closeness of a network is defined as:

$$C^c = \frac{\sum_{i=1}^{V} | C_i^c - C_i^{c*} |}{(V-2)(V-1)/(2V-3)}, \quad (10)$$

where C_i^{c*} is the highest value of closeness centrality measure in the set of units of a network (Freeman 1978). The index takes values between 0 and 1, whereas the closeness centrality of a star network is 1.

The betweenness centrality of a node is the proportion of all geodesics distances between pairs of other nodes that include this vertex. Formally, the betweenness centrality of V_i can be expressed as:

$$C_i^b = \sum_{j \neq k} \frac{\partial_{jk}^i}{\partial_{jk}}, \quad (11)$$

where ∂_{jk} is the total number of shortest paths joining any two nodes V_k and V_j, and ∂_{jk}^i is the number of those paths that not only connect V_k and V_j, but also pass through V_i. The betweenness centrality of each node is a number between 0 and 1. This property of a network reflects the amount of control that a node exerts over the interactions of other nodes in the network (Yoon et al. 2006). The measure of betweenness centrality rewards nodes that are part of communities, rather than nodes that lie inside a community. Betweenness centrality reflects the shortest path between two others. Therefore, it can be regarded as a measure of gatekeeping and is considered to be a measure of strategic advantage and information control.

Similarly, the network betweenness centralization index measure can be defined as:

$$C^b = \frac{\sum_{i=1}^{V} | C_i^b - C_i^{b*} |}{(V-1)}, \quad (12)$$

where C_i^{b*} is the highest value of betweenness measure among all nodes. This measure compares the variance of betweenness centrality in a network and takes as a reference a star graph (C^b=1). In such a graph, the node in the middle holds the highest betweenness centrality, i.e. a strategic position and the graph is highly unequal or highly centralized.

Further measure of a node's position in the network used in this study relates to the extent of clustering between nodes. This property of a network structure can by captured by the clustering coefficient (Watts and Strogatz 1998), which reflects the percentage of pairs of node *i* nearest neighbours that are themselves partners. In directed networks, the clustering coefficient C_i^{cc} of node *i* is defined as:

$$C_i^{cc} = \frac{e_i}{(k_i(k_i - 1))} \tag{13}$$

where k_i is the degree of V_i and e_i is the number of connected pairs between all neighbours of *i* (Barabasi and Oltvai 2004). The clustering coefficient of a node is always a number between 0 and 1, where for a fully connected network *CC=1*.

International R&D centres as a network

A straightforward way of representing international R&D centres as a network is through drawing a line connecting two countries that share an R&D centre through location and ownership relationship. Moreover, knowing the location of corporate control and the location of a R&D centre, we can build a directed network. In a formal way, we identify our set of nodes, *V*, as the countries, and the set of arcs, *A*, as the bilateral relationships that exist whenever one country hosts an R&D centre owned by a company from a different country. In our analysis, each arrow goes from a country where an R&D centres is located to the country where the controlling company is based. Thus, in a more formal way, we identify our set of nodes, *V*, as the countries and the set of arcs, *A*, as the bilateral relationships that exist whenever one country hosts an R&D centre owned by a company from a different country.

In the following, we focus our attention on bilateral relationships between countries and do not take into account loops, i.e. when a company's R&D centre and headquarter is located in the same country. In this context, based on the number of incoming and outgoing connection to and from a country, we can define the measures of countries' centrality in the following way:

- *In-degree*, as defined in (4), is the total number of connections country *i* maintains with other countries through the ownership of R&D centres located abroad and is measured by the sum of all countries in which firms based in country *i* own at least one R&D centre.

- *Out-degree*, as defined in (5), is the total number of connections country *i* maintains with other countries through hosting R&D centres owned by foreign firms and is measured by the sum of all countries whose firms have at least one R&D centre in country *i*.

Each arc can be weighted by the number of relationships between each pair of countries, i.e. number of R&D sites. Hence, the line value function is $W=w_{ij}$, where *ij* is the link between two countries and w_{ij} is the weight of this link.

Adding a measure of R&D intensity of each R&D centre could permit to control for the intensity of R&D activities per each link, i.e. its strength. However, knowledge intensity of an R&D centre is difficult to measure. Thus, aware of possible limitations, we proxy it by counting the number of R&D types carried out in each R&D centre. By R&D type we mean distinct activities having common traits or characteristics that distinguish them as a group or a class. Thus, for example, hardware and software research activities belong to different R&D types (for a full list of R&D types considered in this study see Table 4). This, together with the above point on the corporate control and location of R&D centres, leads us to the following definitions of R&D activity intensities, or incoming and outgoing strengths of a node:

- *In-strength*, as defined in (6), concerns the intensity of connections country *i* maintains with other countries and is expressed as the sum of R&D types performed in R&D centres located abroad and owned by firms from country *i*.

- *Out-strength*, as defined in (7), regards the intensity connections of country *i* maintains with other countries and is measured by the sum of R&D types performed in foreign-owned R&D centres located in country *i*.

3. Data

The data used in this paper originates from the 2011 edition of an originally assembled company-level dataset dedicated to observe the internationalization of R&D. It includes a list of R&D centres belonging to a number of high-tech companies together with their location and additional information on the type of R&D activity performed in these centres. The data on R&D locations was collected by iSuppli, an industry consultancy.[1] In order to check how representative the sample is, we compared it to the R&D Scoreboard[2] and list of companies filing their patents at the USPTO. The results of this checks revealed that the firms contained in the dataset represent nearly 30% of the 2008 R&D budget of all companies included in the R&D Scoreboard and more than 30% of all patent applications filed to the USPTO in 2009.

Table 1: Distribution of companies and R&D centres by country of origin

Nr	Country	Nr of firms	% of total	Nr of R&D centres owned	% of total
1	United States	60	35,09	1256	38,68
2	Japan	34	19,88	749	23,07
3	France	8	4,68	224	6,90
4	Germany	9	5,26	211	6,50
5	Taiwan	12	7,02	105	3,23
6	China	9	5,26	99	3,05
7	The Netherlands	5	2,92	92	2,83
8	South Korea	6	3,51	82	2,53
9	Canada	2	1,17	80	2,46
10	Italy	3	1,75	68	2,09
11	Switzerland	4	2,34	67	2,06
12	Finland	2	1,17	51	1,57
13	United Kingdom	4	2,34	48	1,48
14	Sweden	2	1,17	46	1,42
15	Bermuda	1	0,58	15	0,46
16	Cayman Islands	2	1,17	15	0,46
17	Hong Kong	2	1,17	14	0,43
18	Turkey	2	1,17	10	0,31
19	Belgium	1	0,58	8	0,25
20	India	1	0,58	4	0,12
21	Singapore	1	0,58	2	0,06
22	Brazil	1	0,58	1	0,03
		171	100	3247	100

Source: Own calculations.

[1] http://www.isuppli.com

[2] http://iri.jrc.ec.europa.eu/research/scoreboard_2010.htm

Table 1 presents an overview of the location of companies together with the number of R&D centres owned. According to the presented distribution, the majority of companies (35%) present in our dataset were located in the US and owned over 38% of all R&D centres located worldwide. With nearly 20% of all firms owning 23% of R&D centres, Japan occupies the second place. Nearly identical situation, i.e. 20% of firms and slightly over 23% of R&D owned centres, can be observed for the European Union, which is here represented by eight countries. The remaining companies are located mainly in such Asian countries as Taiwan, China and South Korea. Interestingly, however, whereas in the case of the US, Japan and the EU countries, the share of firms in the sample was always smaller than the share of their R&D centres, the Asian countries exhibit a reverse relationship. The share of R&D centres owned by Asian firms in the total number of R&D centres is always smaller than the share of Asian firms in the total number of companies. In other words, companies from these countries appear to have a lower, on average, number of R&D centres, as compared to their US, Japanese or European counterparts.

Table 2 displays the distribution of companies by their sector of main activity together with the number of R&D centres belonging to each sector. The first five sectors account for over 50% of the sample in terms of both the number of firms and the number of R&D centres. Nevertheless, the majority of sectors can be described as high-tech industries in which technological competition and, hence, the world-wide quest for knowledge resources are key characteristics dominate the sample. According to Table 3, all these companies own over 3,200 R&D centres in 54 countries. When we exclude loops, i.e. R&D centres located in the same country of the owning company are ignored, there are 1838 international R&D centres. If no parallel links are counted, there are altogether 342 links between the countries.

Table 2: Distribution of companies' activities, by ICB classification

Nr	ICB sector	Nr of firms	% of total	Nr of centres	% of total
1	Computer Hardware	25	14,62	327	10,07
2	Electronic Equipment	19	11,11	336	10,35
3	Telecommunications Equipment	18	10,53	356	10,96
4	Automobiles & Parts	16	9,36	425	13,09
5	Leisure Goods	15	8,77	266	8,19
6	Aerospace & Defence	14	8,19	418	12,87
7	Electrical Components & Equipment	9	5,26	232	7,15
8	Consumer Electronics	8	4,68	59	1,82
9	Diversified Industrials	5	2,92	61	1,88
10	Electronic Office Equipment	5	2,92	70	2,16
11	Semiconductors	5	2,92	73	2,25
12	Computer Services	4	2,34	109	3,36
13	General Industrials	4	2,34	172	5,30
14	Health Care Equipment & Services	4	2,34	57	1,76
15	Household Goods & Home Construction	4	2,34	109	3,36
16	Durable Household Products	3	1,75	23	0,71
17	Pharmaceuticals	3	1,75	66	2,03
18	Technology Hardware & Equipment	3	1,75	10	0,31
19	Software	2	1,17	31	0,95
20	Construction & Materials	1	0,58	8	0,25
21	Industrial Machinery	1	0,58	15	0,46
22	Media	1	0,58	10	0,31
23	Medical Equipment	1	0,58	11	0,34
24	Support Services	1	0,58	3	0,09
		171	100	3247	100

Source: Own calculations.

Regarding the information on the activity of R&D centres, there are two indicators (see Table 4). The first one concerns R&D application and the second one R&D type. Whereas the former one indicates the industry in which R&D takes place, the latter one is related to a particular technology or activity. Taking into account only international R&D centres, the total number of R&D applications and R&D types is 2386 and 2961 respectively.

On average, 1.34 industrial applications performed in R&D centre were reported and 1.69 activity types, when loops are considered, and 1.30 and 1.61, when loops are excluded. These differences in the average numbers of R&D applications and types between the full sample and the no-loop sub-sample indicate that R&D centres located in the same country where a company's headquarter is located perform broader R&D activities than overseas R&D centres. In other words, domestic R&D centres are more R&D intensive than overseas R&D centres.

Table 3: Descriptive statistics

	With loops	**Without loops**
Number of R&D centre linkages	3247	1838
Number of R&D application linkages	4353	2386
Number of R&D activity type linkages	5501	2961
Average number of R&D applications per R&D centre	1.34	1.30
Average number of R&D activity types per R&D centre	1.69	1.61
Countries in the R&D network	54	
Companies in the R&D network	171	
Number of arcs between countries (parallel arcs excluded)	342	

Source: Own calculations

According to Table 4, there are altogether 11 R&D applications and 8 R&D types. Among the international R&D centres, the most common R&D applications include wireless, industrial and automotive, each representing around 14% of the total. Regarding R&D types, hardware, software and components are the most common ones performed in the R&D centres included in the dataset.

Table 4: R&D centres' application and activity types

	R&D application	Frequency	% in total		R&D type	Frequency	% in total
1	Automotive	422	17.69	1	Hardware	1092	36.88
2	Wireless	389	16.30	2	Software	833	28.13
3	Industrial	348	14.59	3	Components	530	17.90
4	Consumer	272	11.40	4	Technology	345	11.65
5	Computer Peripherals	240	10.06	5	Research	92	3.11
6	Wired	176	7.38	6	Others	40	1.35
7	Computer	173	7.25	7	Quality Assurance	16	0.54
8	Military/Aerospace	150	6.29	8	Quality Control	13	0.44
9	Medical	108	4.53		**Total**	**2961**	**100**
10	Power	95	3.98				
11	Others	13	0.54				
	Total	**2386**	**100**				

Note: Data excluding loops. Source: Own calculations

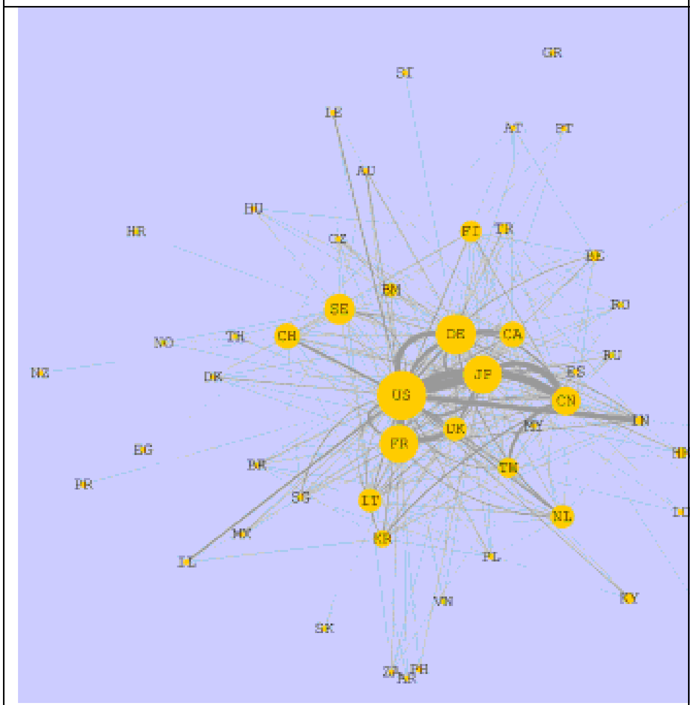
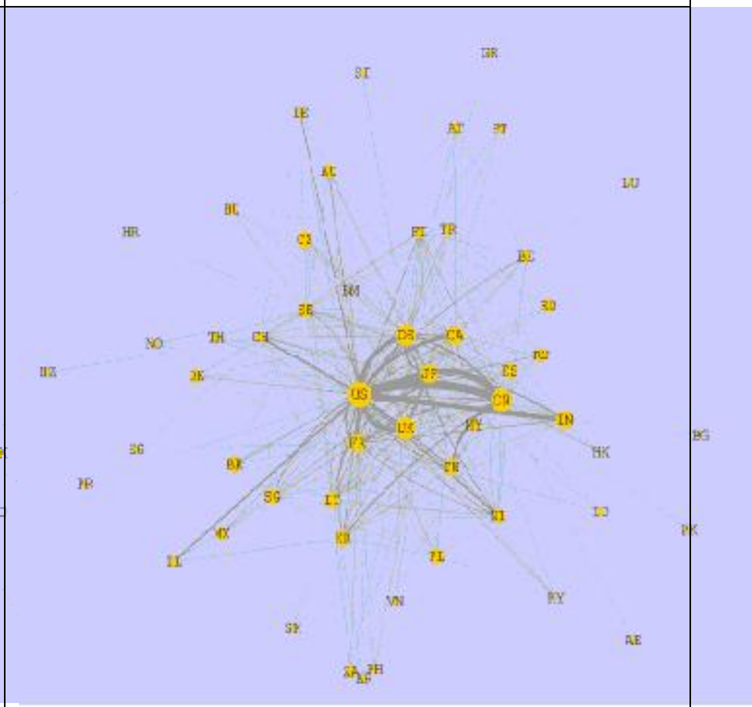
4. Characteristics of the international R&D centres network

Our analysis of the global network of R&D centres starts with its graphical illustration in Figure 1. The arcs represent the existence of a relationship where a company from one country owns an R&D centres in another country. Arcs are weighted by the number of sites owned by country *i* (a) and the number of sites located in country *i* (b). The size of nodes is a function of the number of R&D types a country's firms "receive" through R&D centres located abroad (a) and the number of R&D types a country 'sends' through foreign-owned R&D centres located on its territory (b). This representation aims at capturing the direction and the intensity of R&D activity conducted abroad by multinational firms.

A first look Figure 1a reveals that, on the one hand, there are altogether 22 countries of whose firms own overseas R&D centres. The largest nodes in this network include the US, Japan, France and Germany. On the other hand, there are 54 countries which host international R&D centres (see Figure 1b). The largest location of foreign R&D centres is, again, the US. However, unlike in the R&D ownership network, the second largest location of foreign R&D centres is China, followed by Germany.

These observations allow us to conclude that the ownership of R&D activities is much more concentrated than the location and performance of these activities. In other words, there are more countries contributing to the R&D activities than countries whose companies maintain corporate control over these activities and appropriate their results. Another observation worth mentioning is the relatively big role of China, both in terms of ownership of international R&D centres and as a location of foreign-owned R&D activities. This is a sign of the important position of China as an active actor seeking R&D opportunities abroad, and not only a destination of R&D investment from other countries.

Figure 1: The global network R&D

a) Nodes weighted by the number a country's overseas R&D centres	b) Nodes weighted by the number hosted R&D centres
	

Source: Own calculations.

Connectivity

Table 5 summarises the main measures of the global R&D network. Regarding the general connectivity of the network, the value of the network density parameter is 0.12. This indicates that the network is not regular and far from being complete. This let us conclude that most of the countries included in our sample do not have R&D-related connection with all the remaining countries, but rather select, or are selected as, an R&D partner. In comparison, international trade networks report the value of density between 0.38 (De Benedictis and Tajoli 2011) and 0.6 (Fagiolo et al. 2007). However, as compared to other activities, for example, manufacturing or consumption, there is in general much less R&D performed. As a result, much less R&D activities are preformed across the borders and hence the R&D networks are less dense than international production or trade networks.

Table 5: R&D network indices

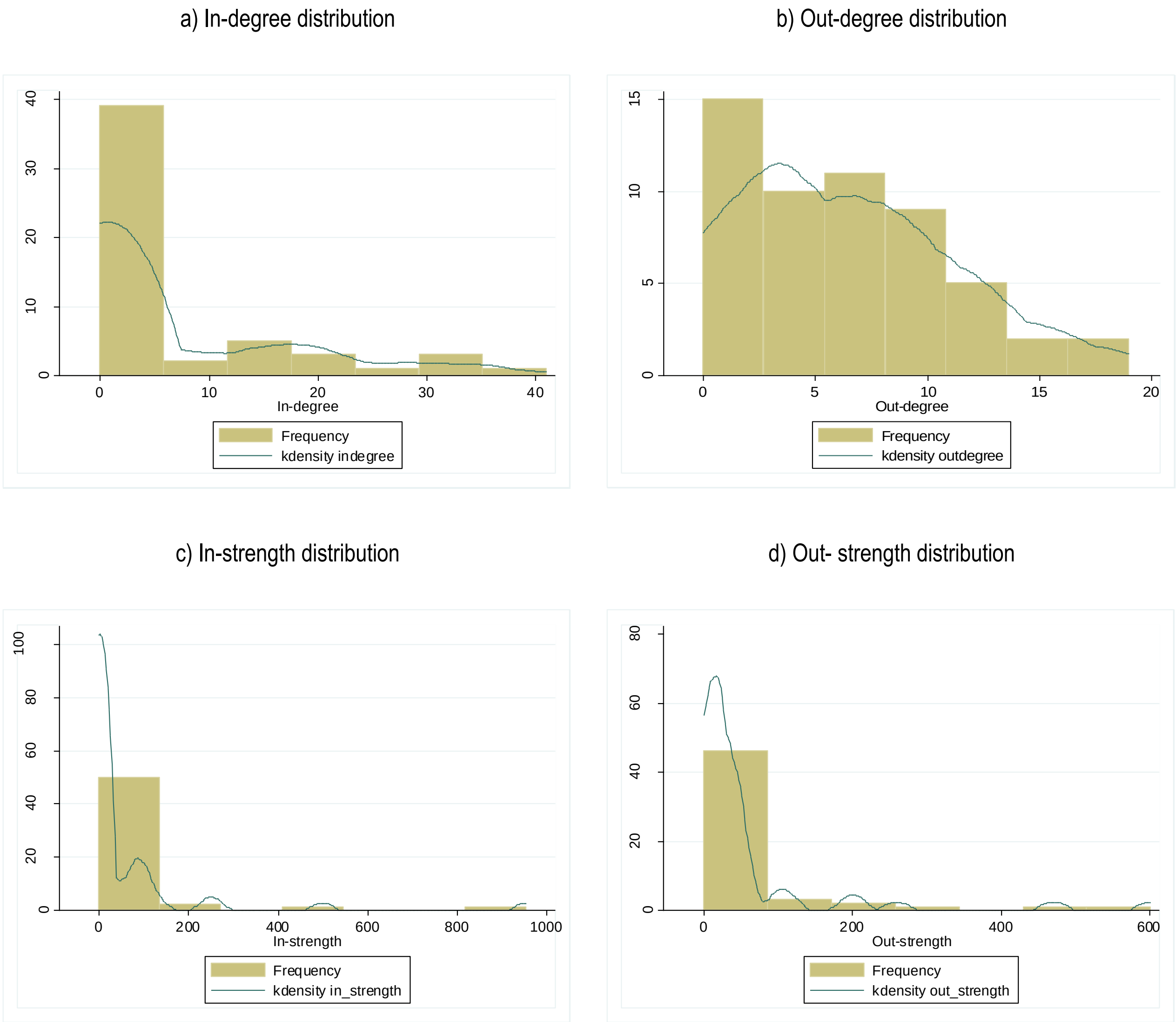
Number of countries	54
Number of arcs	342
Density	0,117
Average in-degree	16,28
Average out-degree	6,7
Average in-strength	141
Average out-strength	58
Closeness centralization	0,107
Betweenness centralization	0,038
Clustering centralization	0,457

Source: Own calculations

Concerning the connectivity level of nodes, the value of the in-degree parameter is 16.28 (Table 5). At the same time, the average out-degree is 6.7 (Table 5). Similarly, the average in- and out-strength are equal to 141 and 58 respectively. One implication of this finding is that there is a systematic difference in the structure of R&D centre location and ownership connections. There is a higher variety in the potential locations of R&D activities that in the number of countries that control them.

Regarding the intensity of interactions between countries, Figure 2 illustrates the frequencies of degree and strength measures together with the probability density function of each measure was estimated using the *kdensity* estimation procedure, i.e. univariate kernel density estimation. According to this visualisation, the distributions of in- and out-strength show that there are very few countries that maintain intensive relationships with other countries. This holds for both: controlling (in-strength) and hosting (out-strength) R&D activities. In other words, negative skewness of the strength distributions indicate that majority of the intensity of R&D links between the countries included in our sample are relatively low.

Figure 2: The empirical distribution of in- and out-degree and in- and out-strength



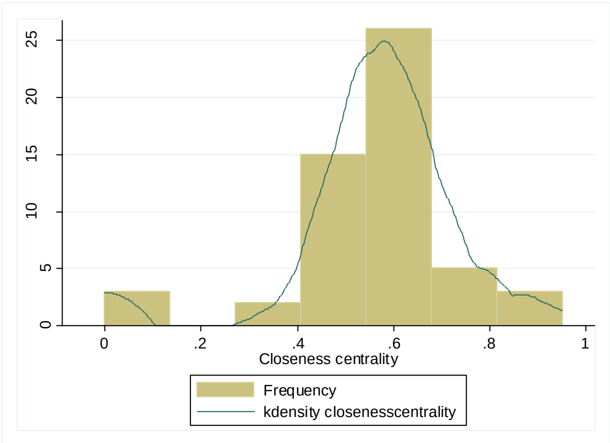
Note: The probability density function of each network measure was estimated using the kdensity estimation procedure, i.e. univariate kernel density estimation. Source: Own calculations.

Further insights on the structural differences between degrees and strengths distributions can be obtained by looking at the correlation of the measures. According to Table 11, the Pearson correlation between in-degree and in-strength is 0.81 and between out-degree and out-strength 0.76, both values significant at the p>0.001 level. This indicates that countries interacting with many partners hold also, on average, more intense relationships with their partners. However, although there is an obvious link between the degree and a link's strength, this relationship is far from being direct and we can observe heterogeneous relationships that exist between countries and the strength of these relationships varies. This is particularly pronounced in the case of out-degree and out-strength, i.e. there are countries that host foreign R&D centres, but the intensity of the activities conducted in them is relatively low. At the same time, when we consider the relationship between in-degree and in-strength, we can also notice that the same is true for countries which locate their R&D centres abroad.

Centrality and clustering

Turning to other measures of the network, we first consider the measure of closeness centrality. According to Figure 3, the negative skewness of the closeness centrality measure indicates that the majority of the countries are rather "far away" from the remaining countries of the network and only few countries are sufficiently well connected to be able to maintain short paths that connect them with the other actors of the technological collaboration network. Interestingly, this pattern can be also observed in co-publication networks (Yan and Ding 2009).

Figure 3: Closeness centrality distribution



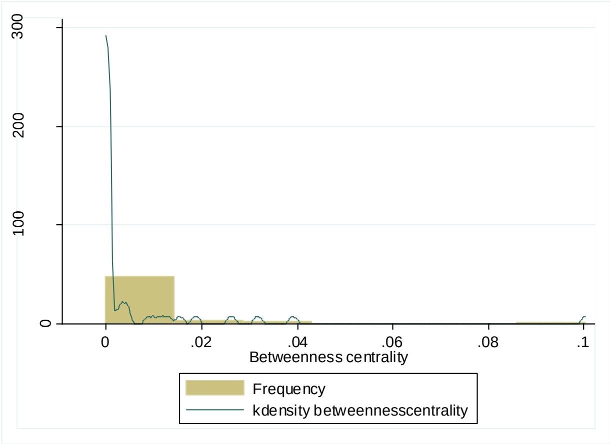
Note: The probability density function was estimated using the kdensity estimation procedure, i.e. univariate kernel density estimation. Source: Own calculations.

Regarding the correlation between the closeness centrality and degree and closeness centrality and strength (see Table 11), we can observe that there is a positive relationship between closeness centrality and both connectivity indices. However, the correlation between in- or out-degree and closeness, i.e. 0.465 and 0.834, is higher than the correlation between in- or out-strength and closeness, i.e. 0.436 and 0.601 (Pearson correlation values significant at the p>0.001 level). In other words, countries having a large number of connections are also likely to be close to the remaining ones, although this does not imply that these relationships are intensive.

Concerning betweenness centrality, Figure 4 shows that the distribution is positively skewed. In other words, there are a few countries that are connected with many other members of the network and numerous countries that are connected only to the core countries. Again, because of these properties, the global R&D network shows strong similarities to the network of international trade, in which there, at least up to recently, no complex network structures have emerged (Fagiolo et al. 2007, Smith and White 1992, De Benedictis and Tajoli 2011). Such distribution of the betweenness centrality measure might be a sigh that the network exhibits a core/periphery structure, in which few countries form the core of the network and the remaining ones are placed at the outskirts of the network.

When analysing the relationship between a node's betweenness centrality and its connectivity measures (see Table 11), we can observe that the in-degree and in-strength indices are correlated with a node's betweenness centrality at the level of 0.796 and 0.931 at the significance level of $p>0.001$. Thus, we can conclude that that countries that maintain many and intensive R&D relationships with other countries are not surprisingly holding the key roles in the network in terms of betweenness.

Figure 4: Betweenness centrality distribution

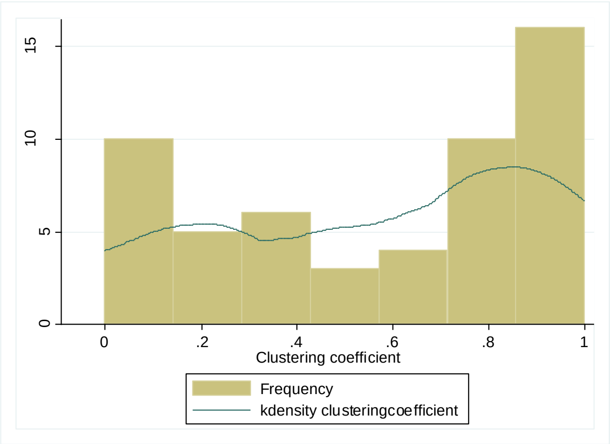


Note: The probability density function was estimated using the kdensity estimation procedure, i.e. univariate kernel density estimation. Source: Own calculations.

Turning to the clustering centrality, it is worth noting that an analysis of this measure can be found, for example, in the studies of international trade and is revealing how much the partners of a node are themselves partners (Fagiolo et al. 2007). From the point of view of geographically dispersed economic activity, like in the case of international trade or international R&D activities, the issue of node clustering is very informative, because networks with strong clustering properties are likely to reflect some strong geographical structure in which short-distance links count more than long-distance ones.

In the context of the R&D network, the value of clustering coefficient is 0.46, which is significantly higher than the value of network density (see Table 5). Thus, in contrast to a random graph where clustering coefficient is expected to be equal to network density, the network of international R&D centres is significantly more clustered than if the links were generated at random. Again, like in the case of international trade, it can be said that countries establish R&D relationships with countries that also trade with each other (Fagiolo et al. 2007). This type of clustering behaviour lets us conclude that 'local' links tend to play an important role. It has to be however noted that local do not necessarily imply geographical proximity and that it can be rather interpreted as a pattern of interaction with the "usual suspects", who may represent either countries belonging to some regional group or just countries at a similar level of development. Furthermore, the negative skew of the clustering coefficient's distribution indicates that most of the countries tend to be members of some local or regional groups and only few countries go beyond these groups (Figure 5).

Figure 5: Clustering coefficient distribution



Note: The probability density function was estimated using the kdensity estimation procedure, i.e. univariate kernel density estimation. Source: Own calculations.

The above point with respect to the "cliquishness" of the network is further confirmed when we look at the relationship between the clustering coefficient and nodes' degree and strength (see Table 11). In general, countries that maintain many (high degree) and intensive R&D relationships (high in-strength) with other countries are less clustered than countries with only few R&D partners. This again resembles the properties of trade networks (Fagiolo et al. 2007, Serrano and Boguñá 2003, Garlaschelli and Loffredo 2005), in which a number of countries is connected only to the so called 'hubs' of the network and do not hold links with other members of the network. Like in the case of the betweenness centrality, this property might hint that the global R&D network has a core/periphery structure.

As a word of caution, it must be mentioned that despite the conceptual differences between network measures discussed above, most of the measures of network centrality seem to be strongly correlated with degree, i.e. the number of a node's connections (Bonacich et al. 1998). This problem has been found to influence the results of some empirical studies (Reagans and McEvily 2003, Gibbons 2004, Shieh and Fouladi 2003). As illustrated by Table 11, among the strongest correlation levels can be observed mainly between the in- and out-strength and the betweenness centrality, where the Pearson correlation value is either close to or above 0.9 at the significance level of p>0.001. To a much lesser extent, it concerns the level of in- and out-degree. Regarding the remaining measures, i.e. closeness centrality and clustering coefficient, the problem of multi-colinearity seems to be of lesser importance. There we can see that the closeness centrality index is correlated the most with the out-degree. In other words, the more foreign-owned R&D centres are located in a country, the closer it is to other countries in the network. The relationship between closeness centrality and the remaining connectivity indices is less pronounced. Nevertheless, being aware of the fact that there is a strong relationship between the degree level and the remaining network measures, the correlation results and the corresponding discussion should be treated with caution.

Countries' positions in the network

Turning to the analysis of countries' positions in the international R&D centres network, one of the most striking finding is that the US appears at the top of each ranking presented in Table 6, confirming its strong position in the network as a source of control over R&D activities and as a location of R&D centres by foreign companies and, above all, as an unquestioned hub of the network. Concerning the in-degree level, along with the US, Japan and European countries such as Germany and France play the key role. Interestingly, also China scores high on the in-degree ranking, casting some light on the increasingly more important role of Chinese companies in seeking R&D opportunities overseas. China's level of in-degree places it ahead such countries as Switzerland, Canada or the Netherlands. However, the last point is slightly moderated when we look at the intensity of offshore R&D centres measured by in-strength. There it is possible to see that Japan and France belong to the countries with the most intensive R&D links, following the US. At the same time, China drops to 12th place after being in 6th place in the in-degree ranking. Although this clearly shows that the number of links between countries in the form of offshore R&D centres has to be validated by the intensity of relationships held, it also indicates the emerging importance of China in the global R&D network not only as a destination for overseas firms, but also as a source of foreign R&D investments.

Regarding the level of out-degree, the number of linkages with other countries, and out-strength, the intensity of these linkages, it was mentioned above that the US holds the leading position. Moreover, here again we can observe the strong position of China and, to a lesser extent, other emerging countries such as India, Czech Republic, Brazil and Poland. The relatively high position of these countries confirms again their increasingly more important role on the landscape of high-tech R&D. At the same time, it reflects the structure of the R&D network that has been formed through companies' decisions with respect to the location of their R&D activities. These decisions have lead to the emergence of a nexus of R&D activities which become much more dispersed across the world than the ownership and control of these activities.

The betweenness centrality index, C_i^b, in Table 6 reflects the position of a country as a core or a hub in the network of international R&D centres. The US holds a clear and strong position as a network hub. Germany, China, and Japan are the subsequent countries in the ranking. Looking at these countries, we can also expect that they play a role of 'regional hubs'. The last column reports the values of eigenvector, which indicates the "coreness" of a country, i.e. how important they are in the network, based on the quality of their connections expressed by having connections with other important nodes. Here again, we can see that the "usual suspects" hold the pole positions. However, it also comes as a surprise that China and India are already part of the core group of the global R&D network.

Table 6: Country positions in the R&D network

Rank	In-degree		Out-degree		In-strength		Out-strength		Closeness		Betweenness		Eigenvector	
	Country	Value	Country	Value	Country	Value	Country	Value	Country	Value	Country	Value	Country	Value
1	USA	41	USA	19	USA	955	USA	602	USA	0,95	USA	0,100	USA	0,306
2	GERMANY	33	CHINA	17	JAPAN	499	CHINA	471	CHINA	0,87	GERMANY	0,039	GERMANY	0,279
3	FRANCE	31	UK	16	FRANCE	260	GERMANY	259	UK	0,83	CHINA	0,032	JAPAN	0,270
4	JAPAN	31	GERMANY	15	GERMANY	241	UK	206	GERMANY	0,80	JAPAN	0,026	FRANCE	0,267
5	SWEDEN	24	JAPAN	13	NETHERLANDS	134	INDIA	194	INDIA	0,74	FRANCE	0,019	CANADA	0,239
6	CHINA	22	CANADA	13	CANADA	114	FRANCE	114	JAPAN	0,74	SWEDEN	0,015	CHINA	0,238
7	SWITZERLAND	19	INDIA	13	SWITZERLAND	104	CANADA	108	CANADA	0,74	UK	0,013	UK	0,231
8	CANADA	19	FRANCE	12	ITALY	99	JAPAN	92	FRANCE	0,71	CANADA	0,011	SWEDEN	0,230
9	NETHERLANDS	17	CZECH R.	11	TAIWAN	89	SINGAPORE	57	CZECH R.	0,68	SWITZERLAND	0,009	ITALY	0,199
10	ITALY	17	ITALY	10	UK	85	ITALY	51	ITALY	0,67	TAIWAN	0,004	NETHERLANDS	0,195
11	UK	17	TAIWAN	10	KOREA	77	AUSTRALIA	51	KOREA	0,67	KOREA	0,004	SWITZERLAND	0,190
12	FINLAND	15	KOREA	10	CHINA	76	ISRAEL	48	TAIWAN	0,67	ITALY	0,004	FINLAND	0,173
13	TAIWAN	14	BRAZIL	10	SWEDEN	76	SWEDEN	46	BRAZIL	0,66	NETHERLANDS	0,002	KOREA	0,171
14	KOREA	11	POLAND	10	FINLAND	57	CZECH R.	44	POLAND	0,66	FINLAND	0,002	TAIWAN	0,166
15	BERMUDA	8	RUSSIA	10	BERMUDA	28	KOREA	42	RUSSIA	0,66	INDIA	0,000	INDIA	0,164

Source: Own calculations

Core and periphery of the R&D network

The observations made in previous section concerning the betweenness and closeness centrality indices delivered some hints indicating that the analysed R&D network might have core/periphery structure. Thus, aiming at obtaining more information about the structure of the network and the position and role of countries in the R&D network, we want to empirically assess to what this network can be described as a core/periphery structure.

The notion of core/periphery is based on the fact that many real world networks can be divided into two distinct sub-groups of actors that can be identified by the type and number of connections. One sub-group is referred to as a core and another as a periphery (Alba and Moore 1978, Laumann and Pappi 1977). The core of network is a dense, well-connected sub-group and, conversely, the periphery consists of nodes loosely connected to each other, but connected to some members of the core. In the terminology of block modelling, the core is seen as a 1-block, and the periphery is seen as a 0-block, where 1 represents the existence of a connection between two nodes and 0 the lack of it. The core/periphery structure has been found in a number of studies on, for example, scientific citations network (Doreian 1985), international trade (Smith and White 1992) or corporate structures (Barsky 1999).

An empirical measure of how well the real structure approximates the ideal one, i.e. where nodes belonging to the core are connected with other nodes from the core and periphery and nodes belonging to the periphery are only connected with some core nodes, can be defined as:

$$\rho = \sum_{i,j} a_{i,j} \delta_{i,j} \qquad (14)$$

$$\delta_{i,j} = \begin{Bmatrix} 1\, if\ c_i = CORE\ or\ c_j = CORE \\ 0\ otherwise \end{Bmatrix} \qquad (15)$$

where $a_{i,j}$ indicates the presence or absence of a connection in the observed data, c_i refers to the group (core or periphery) to which node i is assigned to, and $\delta_{i,j}$ – a pattern matrix – reflects the presence or absence of a connection in the ideal image (Borgatti and Everett

2000). In this framework, ρ, i.e. the measure of core/periphery structure, achieves its maximum when and only when A (the matrix of $a_{i,j}$) and Δ (the matrix of $\delta_{i,j}$) are identical. In other words, ρ reports the results of Pearson correlation and it can be said that a network exhibits a core/periphery structure to the extent that the correlation between the ideal structure and the data is large.

In order to detect the core/periphery structure in our data, we use a genetic algorithm to find a partition such that correlation between the data and the pattern matrix induced by the partition is maximized.[3] The results of the analysis are reported in Table 7. After 50 iterations, we find that the final fitness measure is 0.906 at the significance level p<0.001. Thus, considering that the maximum value of ρ is 1, this indicates that the underlying data exhibits very strong core/periphery structure. This is further confirmed by the reported density measures for individual partitions. Whereas the core-core partition has a density level at 0.886, the same value for the periphery-periphery partition is only slightly higher than zero. In other words, the nodes belonging to the core are very well connected with each other and relatively well connected with peripheral nodes, while on the other hand the latter ones are barely connected with each other.

Table 7: Core/periphery model statistics

Goodness of fit*		
Starting fitness		0,906
Final fitness		0,906
Density matrix		
	Core	**Periphery**
Core	0,886	0,308
Periphery	0,308	0,007

* Fitness measure: Pearson correlation. Number of iterations: 50. Source: Own calculations.

Regarding the composition of each partition, altogether 15 countries belong to the core group, i.e. 28% of the sample, whereas the periphery consists of 39 countries (see Table 8). As expected, the majority of countries in the core are developed countries with a relatively

[3] This algorithm is implemented in UCINET software Borgatti, S. P., Everett, M. G. & Freeman, L. C. 2002. 'Ucinet for Windows: Software for Social Network Analysis.' Harvard, MA: Analytic Technologies..

high level of GDP and a sound R&D landscape. However, the presence of such countries as China, India or Taiwan in the core indicates that these developing countries are slowly taking major and indispensable roles in the global R&D network. At the same time, the periphery consists of mainly developing countries, with such exceptions as Austria, Belgium or Denmark.

In conclusion, based not only on the number of connections, but also on their type, we can conclude that the global R&D network is very strongly polarized and can be divided into two groups of countries. The first one is relatively small and constitutes the core of the network, whereas the second one comprises of a large number of heterogeneous countries that build the periphery of the network. Moreover, what is of particular interest is the presence of some new-comers into the core group, which might be interpreted as a sign of strong dynamics in governing the global R&D network.

Table 8: Block membership by country

Core	**Periphery**
Canada, China, Finland, France, Germany, India, Italy, Japan, South Korea, Netherlands, Sweden, Switzerland, Taiwan, UK, USA	Argentina, Australia, Austria, Belgium, Bermuda, Brazil, Bulgaria, Cayman Islands, Croatia, Czech Republic, Denmark, Egypt, Greece, Hong Kong, Hungary, Indonesia, Ireland, Israel, Luxembourg, Malaysia, Mexico, New Zealand, Norway, Pakistan, Philippines, Poland, Portugal, Puerto Rico, Romania, Russia, Singapore, Slovakia, Slovenia, South Africa, Spain, Thailand, Turkey, United Arab Emirates, Vietnam
Number of countries: 15	**Number of countries: 39**

Source: Own calculations.

5. The determinants of international R&D linkages

In order to find an explanation of the results presented in the previous sections, we should know what determines international R&D activities in terms of the structure of R&D network. Unfortunately, theoretical models dealing with this issue are virtually non-existent and any attempt of dealing with the internationalization of R&D focus on explaining the pattern and intensity of international R&D activities from the perspective of interactions between individual countries, and do not offer insights about the structure of the whole system.[4] Thus, we want to make us of the gravity model of trade, which is the closest empirical concept that is suitable for an empirical analysis of R&D internationalisation. Except for being widely used in the studies of international trade (De Benedictis and Tajoli 2011), the gravity model has already been applied to study this issue (Picci 2010, Thomson 2011). This specification allows us to formulate predictions concerning the structure of a network, i.e. the existence of trade or R&D relationships between countries. The straightforward form of the gravity equation can be expressed by

$$a_{ij} = \frac{GDP_i \cdot GDP_j}{D_{ij}} \tag{16}$$

where two vertices, V_i and V_j, with non-negative GDP included in the value function of a vertex P and the geographic distance D_{ij}, captured by the arc value function W, are expected to develop a positive exchange link (i.e. $a_{ij} = 1$).

The dependent variables in our dataset is the number of R&D centres located in country *j* and owned by a company from country *i* and the sum of R&D types covered by R&D centres located in country *j* and which belong to companies from country *i*. Thus, the dependent variables are count variables. We model the probability that a country *i* establishes a link with country *j*, i.e. a_{ij}, and the intensity of these links, i.e. w_{ij}, as vectors of attributes of both countries (X'_i, X'_j), as:

$$\Pr(a_{ij}) = F(X'_i, X'_j) \text{ and } \Pr(w_{ij}) = F(X'_i, X'_j). \tag{17}$$

The Poisson approach is a common way to specify such a probability function:

$$\Pr(a_{ij}) = \frac{\exp(-\mu_{ij})\mu_{ij}^{\;a_{ij}}}{a_{ij}!},$$
$$\Pr(w_{ij}) = \frac{\exp(-\mu_{ij})\mu_{ij}^{\;w_{ij}}}{w_{ij}!}. \tag{18}$$

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[4] Similar situation is with the issue of international trade, where the most common approach is to look at the trade flows between individual countries, rather than at the whole system of trade.

where $a_{ij} = 0,1,2,...$, $w_{ij} = 0,1,2,...$ and $\mu_{ij} = \exp(X'_i \alpha_i, X'_j \alpha_j)$, where α_i and α_j are vectors of unknown parameters to be estimated. The Poisson estimation requires that μ_{ij} is both the mean and variance. However, as we show in the previous section the dependent variable controlling for the number of R&D centres per link (Figure 2 (b)) and, in particular, the number of R&D types per link (Figure 2 (d)) might not meet these requirements. Thus, an alternative is to select a distribution other than Poisson, which would allow for the variance to be greater than the mean. The negative binomial distribution is often more appropriate in cases of over-dispersion (Cameron and Trivedi 1998). Thus, in order to check the robustness of the results, we run estimations using negative binomial regression.[5]

We proceed with formulating a model in which we expect that a country's position in the global R&D network depends on some of its characteristics. To identify these determinants, we derive a set of factors that are used in studies conceptualising the issue R&D internationalization (Kuemmerle 1999, Boutellier et al. 2008, Narula 2003, Dunning 1988, Dunning 1994). Among the most important drivers of locating R&D centres overseas is the access to the resources that, in most cases, are non-transferable and location-specific (Dunning 1988, Dunning 1994). Examples of such resources include inputs to R&D activity, e.g. scientists and universities, or the knowledge about customers and markets. Another reason to engage into international R&D activities is the access to the market and hence, the potential size of the economy should be also taken as a predictor of link formation among countries.

Indeed, as it emerges from analysis of the empirical studies of the subject, the determinants of the R&D internationalization can be grouped around two main blocks: economic capacity and inventive performance of a country (Picci 2010, Patel and Pavitt 1991, Dachs and Pyka 2010, Guellec and Van Pottelsberghe de la Potterie 2001). These two elements are expected to reflect the asset exploitation and asset seeking behaviour of companies deciding where to establish their international R&D activities (Kuemmerle 1999). Whereas the former one concerns the economic benefit of adapting and customising existing products to the need of consumers and with the aim of selling them on the local, the latter one refers to the attempts of acquiring know-how and technology new to a

5 The additional estimations serve as robustness checks and do not change our results. Results available from the authors upon request.

company. Thus, our function of the of R&D connections between countries takes the following form:

$$y_{ij} = f(Dist_{ij}, Lang_{ij}, GDP_i, GDP_j, Pop_i, Pop_j, Inv_i, Inv_j, CoInv_i, CoInv_j, N_j, \alpha, \varepsilon_{ij}) \quad (19)$$

where y_{ij} represents either the count of R&D centres located in country *j* and owned by a company from country *i* or, in the second specification, the count of R&D types covered by R&D centres located in country *j* and which belong to companies from country *i*. To explain the relationship between the intensity of linkages between countries both, in terms of the number of R&D centres and R&D types, we use a number of variables that are related to a country' characteristics in the following areas: geographical and cultural proximity, economic size, innovative potential, the level of internationalisation of inventive activity and its position in the network.

Concerning the geographical proximity, we use a variable controlling for the distance between countries *i* and *j*, $Dist_{ij}$. In addition, in order to account for other frictions in inventive collaboration resulting from cultural differences, we include a dummy variable $Lang_{ij}$, which indicates whether two countries share a common official language.[6]

Regarding economic size of countries linked through an R&D centre, information on GDP (in current US$ in 2009) of both R&D centre host country *i* and control country *j* is included.[7] These measures are supposed to account for the attractiveness of a foreign market *j* from a perspective of a company with origin in country *i*. A positive sign of a GDP_j coefficient would confirm the asset exploitation strategy, as defined in (Kuemmerle 1999).

Being aware of the fact that also the size of a country might affect the existence and intensity of R&D relationships between countries, we control for the size of population. As in the case of economic size of a country, we include information on the population size of both R&D centre host country *i* and control country *j*. The rationale behind controlling for the size of a control country is that, ceteris paribus, large countries have more firms doing

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[6] The source of the distance and common language variables is CEPII bilateral trade data Head, K., Mayer, T. & Ries, J. 2010. 'The erosion of colonial trade linkages after independence.' *Journal of International Economics,* 81:1, 1-14.. For more information please refer to: http://www.cepii.fr/anglaisgraph/bdd/distances.htm

[7] Data stems from the IMF. For more information please refer to: http://www.imf.org/external/data.htm

R&D and hence are likely to have more links. In turn, including the effect of population size of a host country is motivated by the economic attractiveness of a country increasing in its potential market size.

In addition, expecting that not only distance hiders and economic factors facilitate the establishment of offshore R&D centres, we control for the innovation performance of an R&D hosting and owning country. On the one hand, from the perspective of a host country, *j*, the measure of its inventive performance indicates the inventive capacity which might attract R&D-related investments. On the other hand, from the perspective of an R&D owning country, *i*, it indicates its inventive absorptive capacity. Innovation performance of a country is captured by the total number of patent applications of each country and is computed through fractional counting of inventors in each priority patent application submitted in 2007 to one of 59 patent offices around the world.[8] Our methodology of computing patent statistics for the purpose of this paper follows (De Rassenfosse et al. 2011, Turlea et al. 2011).[9]

Moreover, to control for the results of the R&D internationalisation activity, i.e. how productive or how open a country is to collaboration with foreign innovators, we use as a relative measure of international co-inventions. This measure is defined as the share of a country's inventions with inventors residing in the country and inventors residing outside of the country, in the country's total number of inventions (according to the inventor criterion). Here, we follow (Guellec and Van Pottelsberghe de la Potterie 2001),[10] and define algebraically the measure of co-inventions of country *i* as:

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[8] To the selected patent offices in 2007 were filed 99.7% of the total number of priority patent applications. The complete list of considered Patent Offices includes: EPO, EU27 Member States, USPTO, JPO, Arab Emirates, Australia, Brazil, Canada, Chile, China, Columbia, Croatia, Hong Kong, Iceland, India, Indonesia, Israel, Korea, Malaysia, Mexico, New Zealand, Norway, Pakistan, Philippines, Puerto Rico, Russia, Singapore, South Africa, Switzerland, Taiwan, Thailand, Turkey and Vietnam.

[9] For an extensive description of the methodology and its application to study R&D performance using patent-based indicators please refer to the 2011 De Prato, G., Nepelski, D., Szewczyk, W. & Turlea, G. 2011. 'Performance of ICT R&D.' *JRC Scientific and Technical Report*. Institute for Prospective Technological Studies, Joint Research Centre, European Commission..

[10] For an extensive description of the methodology and its application to study various types of R&D internationalization using patent-based indicators please refer to the 2011 Report on R&D in ICT in the European Union Turlea, G., Nepelski, D., De Prato, G., Simon, J.-P., Sabadash, A., Stancik, J., Szewczyk, W., Desruelle, P. & Bogdanowicz, M. Ibid.'The 2011 report on R&D in ICT in the European Union.' Seville. and to the Report on Internationalisation of ICT R&D Nepelski, D., De Prato, G. & Stancik, J. 2011. 'Internationalisation of ICT R&D.' *JRC Scientific and Technical Report*. Institute for Prospective Technological Studies, Joint Research Centre, European Commission..

$$CoInv_i = \frac{P_i^{II}}{PI_i} \quad (20)$$

where P_{ij}^{II} is the number of patents co-invented be residents of country *i* and country *j* and PI_i total number of patents invented by residents of country *i*. A reference year for the measure of international co-inventions is 2007.

Lastly, a vector of network measures included in the above specification, *N*, includes the measure of in- and out-degree and closeness centrality of country *j*, i.e. a country in which an R&D centre is located. The inclusion of these measures is motivated by the fact that the existence or establishment of bilateral linkages between two countries involving R&D collaboration or trade in R&D services can affect the existence or establishment of such linkages between a different pair of countries. Thus, network measures are expected to capture such externalities, which in practice are frequently treated as unobserved heterogeneity or controlled for with country effect estimators. Like in the case of international trade (De Benedictis and Tajoli 2011), indicators capturing the relative position of a country with respect to the entire system allows to consider interdependence between pair-wise linkages more appropriately.

6. Empirical results

Table 9 reports the results of the regressions where, in the first case, the dependent variable was the number of R&D centres per link (1-3) and, in the second case, the number of R&D types per link (4-6). For each gravity model, we report first estimations with variables controlling for geographic and cultural proximity and economic size of countries. The extended specification includes controls of inventive performance and the levels of internationalisation of inventive activity. Finally, we add the network indices as explanatory variables. The network indices refer to country *j*, a country hosting an international R&D centre.

All the coefficients of the standard gravity model, i.e. distance, common language, the economy size, have the expected signs, though, in some cases are not significant. Also the variable controlling for the size of host country has a positive impact on the likelihood of attracting foreign firms to establish a R&D location. In turn, the reverse effect of the population size of country *i* shows that the corporate control of R&D activity resides in relatively small countries. Furthermore, also the coefficients related to the number of patents and the number of international co-inventions show significant, even if not unanimous, impact on the existence of R&D linkages between countries. From the perspective of country *i*, the positive impact of the innovation performance is related to a country's absorptive capacity and increases the likelihood of establishing an R&D centre in a foreign country. A negative sign observed for country *j* indicates, at the same time, that the knowledge or inventive capacity of an R&D centre hosting country is not the key determinant of a decision to establish such a facility. This conclusion is supported by the relatively strong effect of the market size of country *j*, i.e. its economic attractiveness, measured by both its GDP and population size. Running counter to some previous findings (Kuemmerle 1999), this leads us to the conclusion that mainly market size of a country, rather than its innovation capacity and output is an important factor in the choice of a location for R&D facilities.

Regarding the level of internationalization of co-inventions, it emerges clear from the presented results, that the relevant coefficients show strong and positive impact on foreign R&D investments. A straightforward interpretation is that the readiness of inventors to collaborate with their international colleagues is positively associated with the number of both offshore R&D centres of country *i* and the number of foreign R&D centres in country *j*. Although it can be expected that the causality direction goes from the establishment of an R&D centre to an international co-invention, we can conclude that these result plays a role when considering the pay-off from establishing a foreign research facility. From a company's innovation strategy, it may be a sign of a success from the creation of international R&D sites in the form of inventions developed with domestic inventors, i.e. tapping on the inventive resources in foreign countries.

Turning our attention to the core of our analysis, i.e. the impact of a country's position in the global R&D network on the likelihood of forming a link and its intensity, we observe that it is highly relevant for both the number of R&D sites and R&D types. However, there are considerable differences in the effects of these measures on the dependent variables. For example, whereas the level of in-degree seems to be of no relevance, the coefficients of out-degree variable of country *i* have a negative and significant impact on both dependent variables. Moreover, the closeness centrality coefficient has a very strong positive effect on the number of R&D sites as well as on the number of R&D types existing per link. The negative effect of the out-degree can be interpreted as follows: countries with a higher number of linkages with other countries tend to have less intensive relationships in terms of the number of R&D sites and the number of R&D types performed in their foreign facilities. This rather surprising finding is consistent with, for example, the effect of a country's degree in on its trade linkages, i.e. where there is a decreasing marginal advantage of increasing the in-degree (De Benedictis and Tajoli 2011). In other words, the more relationships a country has, the less intensive these relationships are. It would suggest that R&D exchange operates according to diminishing returns or exclusivity and trade-off regarding these relations. At the same time, however, we can observe that the position of a country in the network expressed by the closeness centrality measure increases the likelihood of being chosen as a location for an offshore R&D centre. Thus, countries that are 'close' to the remaining countries, i.e. those with short geodesic distances to other countries in the network, are strongly favoured over those that are at the "outskirts" of the network. This finding implicitly hints on spillover effects resulting between countries that are an effect of location choices.

The inclusion of network indices has also a considerable impact on the standard gravity variables, which are traditionally considered as important drivers of international collaboration. For example, the positive effect of cultural proximity is considerably weakened. This does not come as a surprise, as the position of a country might be independent from its cultural position, as compared to other countries. The case of the intensive collaboration between, for example, the US and China or some European countries is a clear example of this. Surprisingly, the network indices reduce also the role of GDP and the size of country *j*, i.e. the country hosting R&D activities. In light of the results stemming from a standard gravity model, i.e. regression (1) and (4), this suggest that the economic size of a country selected as a location for R&D activities by multinational companies is less important when we take into account a country's position in the R&D network. This is very well pronounced in the case of the intensity of linkages measured by the number of R&D types.

Summing up, the results presented here show that the inclusion of network indices, controlling for the position of a country in the global R&D network, are well justified. Moreover, in addition to the standard explanatory variables, they deliver additional information explaining the existence and intensity of R&D linkages between countries, which were not considered before in the research on the internationalisation of R&D activities.

Table 9: Estimation results

	Number of R&D centres			Number of R&D types		
	(1)	(2)	(3)	(4)	(5)	(6)
Log distance$_{ij}$	-0,042*	-0,039	-0,064***	-0,024	-0,012	-0,038**
	(0,02)	(0,02)	(0,03)	(0,02)	(0,02)	(0,02)
Common language$_{ij}$	0,464***	0,452***	0,413***	0,468***	0,379***	0,336***
	(0,06)	(0,07)	(0,07)	(0,05)	(0,05)	(0,05)
Log GDP$_i$	1,120***	1,038***	1,034***	1,184***	1,122***	1,121***
	(0,05)	(0,07)	(0,07)	(0,04)	(0,06)	(0,06)
Log GDP$_j$	0,597***	0,253***	-0,144**	0,654***	0,267***	-0,158***
	(0,03)	(0,05)	(0,06)	(0,02)	(0,04)	(0,05)
Log Population$_i$	-0,520***	-0,655***	-0,636***	-0,561***	-0,643***	-0,624***
	(0,045	(0,05)	(0,05)	(0,04)	(0,04)	(0,04)
Log Population$_j$	0,142***	0,228***	0,167***	0,130***	0,228***	0,166***
	(0,02)	(0,02)	(0,03)	(0,02)	(0,02)	(0,02)
Log Patent$_i$		0,252***	0,241***		0,180***	0,169***
		(0,02)	(0,02)		(0,02)	(0,02)
Log Patent$_j$		-0,044**	0,026		-0,060***	0,011
		(0,02)	(0,02)		(0,02)	(0,02)
Log Co-inventions$_i$		0,084*	0,111**		0,076**	0,103***
		(0,05)	(0,05)		(0,04)	(0,04)
Log Co-inventions$_i$		0,385***	0,197***		0,444***	0,250***
		(0,04)	(0,04)		(0,03)	(0,04)
In-degree$_j$			0,001			0,002
			(0,01)			(0,00)
Out-degree$_j$			-0,115***			-0,107***
			(0,04)			(0,03)
Closeness centrality$_j$			9,770***			9,705***
			(1,47)			(1,17)
Constant	-39,786***	-31,623***	-24,889***	-41,988***	-33,763***	-26,343***
	(1,05)	(1,48)	(1,86)	(0,84)	(1,19)	(1,50)
N	342	328	328	342	328	328
LRchi^2	2106,08	2418,21	2559,88	3752,76	4196,80	4433,67
Pseudo R^2	0,488	0,574	0,607	0,545	0,623	0,657

Notes: The dependent variable is (1-3) the number of R&D centres per link and (4-6) the number of R&D types per link. The list of explanatory variables includes: log of distance between two the capitals of each pair of countries; dummy variable controlling for common language; logs of real GDP, population size, inventive performance, measured by the number of patents and the level of international technological collaboration, measured by the number of international co-inventions, of country *i* and *j*. Regression (3) and (6) includes network measures, i.e. in-degree, out-degree and closeness centrality, which control for the network position of country *j*, i.e. a country in which a foreign R&D centre is located. All models report Poisson regression estimates. Standard errors are reported in parentheses. *** Significant at the 1 percent level. ** Significant at the 5 percent level. * Significant at the 10 percent level.

7. Conclusions

The main message of this paper is that the nature of innovation and its organization in the global context is changing and so our way of looking at it should also change. A network perspective offers one way of interpreting and analysing it.

Concerning the characteristics of this network, we can see that the global R&D network is not uniform and is far from being complete. Most countries do not have R&D connections with all the other countries, but rather select, or are selected, as R&D partners. Furthermore, there is a systematic difference in the structure of R&D ownership and location. Whereas the global corporate ownership of R&D activity is very concentrated, its location is globally dispersed. In addition, the R&D network shows signs of "cliquishness", which means that countries establish R&D relationships with countries that are also connected with each other. This type of clustering reveals that there are strong 'local' links, which however do not imply geographical or cultural proximity, but rather a similar level of development. This, together with the fact that most of the countries tend to be members of some local or regional groups and that only a few countries go beyond these groups, explains the strong core-periphery characteristics of the R&D network. In such a network, a number of countries are connected to only a few network 'hubs', which hold very strong positions in the network.

An important finding of this paper is that the number of R&D connections is negatively related to the intensity of these interactions. This shows some similarities to the characteristics of international trade dynamics, where there is a trade-off between the number of links and the volume of flows. It seems that R&D exchange is also subject to decreasing marginal returns of increasing the number of linkages. This is a very relevant point, considering that the likelihood of forming a link in a global R&D network does not depend on the number of connections a country maintains with other countries, but rather on the quality of these connections. In particular, the relative closeness to other countries seems to play the key role.

Our analysis also casts new light on the determinants of the intensity of R&D interactions between countries. The results show that a country's position in the network affects the intensity of its R&D interactions with other countries. Moreover, this position considerably moderates the effect of cultural proximity and economic size of a country, i.e. factors traditionally considered as key determinants of R&D internationalisation.

Summing up, the creation, structure and functioning of the global R&D network challenge the traditional way research and innovation policy making has been done, i.e. it has usually been shaped by a one-sided perspective defined by the notion of competition. If networks become the dominant form of organising economic and innovative, one can expect that network viability and countries' positions in this network will depend on their ability to develop collaboration mechanisms that support co-dependencies between them. The emerging network structure of the R&D system is providing opportunities for countries and managers, and policy makers need to be more alert to these changes than before, so that they can spot opportunities and act on them. Thus, the results of this paper allow us to formulate the following implications with respect to the emergence of the global R&D network and innovation policy:

1. First, the global innovation network is a result of the international division of innovation processes in which countries participate and in which firms have a broader capacity to access and combine knowledge from a variety of sources (Sachwald 2008). Consequently, while designing R&D and innovation policies, policy makers should give them a multinational dimension, acknowledging that whatever happens in one country, affects the other countries and vice versa. That means that although building a strong knowledge base is a necessary condition for participating in the global innovation network, it might not be a sufficient condition to generate the most out of this participation. Rather than designing policies driven by the notion of competition for innovation recourses and the corresponding payoffs, it might be advisable to create a mutually beneficial system of collaboration, taking into account interactions with a large number of players.

2. Second, one of the major reasons behind the emergence of the global R&D network is the increasing complexity of technologies and business processes. This requires both firms and countries to specialize. Thus, innovation policies should include a solid assessment of a country's strengths and mechanisms towards their improvement with a view to finding and maintaining a strategic position in the technological space and, hence, in the network. This point is clearly emphasized by the disproportionally high

number of R&D service sources, as compared to the number of countries procuring these services. A country's attractiveness as a location for R&D activities and hence its bargaining power will strongly depend on its technological uniqueness.

3. Third, innovation policies oriented towards forming and joining a network would include a strategy to identify and select partners with complementary assets. Although such an assessment should be focused on the issue of technological complementarity, it should not neglect the network position of the partners. The reason is that the latter has an implication for the network position of both countries.

4. Lastly, with respect to the previous point, we show that the expansion of the R&D network is driven not by the large and industrialized countries, but rather by the entry of smaller countries, which become niche players. This can be explained by the fact that, like enterprises (Harrison 1997), by linking up with larger partners, smaller countries can reach global markets more quickly or at lower cost than through independent expansion. This creates an opportunity for countries already established in the network to go out beyond the traditional groups and extend the scope of their connections to other countries that have entered the network and also those that are still outside of it. This strategy allows them to create early linkages with newcomers and gain a first-mover advantage. An example of this is the behaviour of the US with respect to, for example, China and India (Nepelski et al. 2011).

This paper has some limitations. First of all, the data used in the study cover only a selection of companies. Second, the richness of information on R&D activities of these companies is also limited. The last point considerably reduces our ability to investigate the intensity and quality of R&D connections between countries.

In conclusion, despite these limitations, the paper provides a number of valuable insights into the structure of the R&D network and the determinants of R&D internationalisation. The results presented here show that the inclusion of network indices, controlling for the position of a country in a global R&D network, are well justified. In addition to the standard explanatory variables, they deliver additional information explaining the existence and intensity of R&D linkages between countries. As a result, it shows how research policy making should be adapted to the new reality of network relationships.

Annex

Table 10: Descriptive statistics

Variable	Mean	SD	Min	Max
Number of R&D centres per country	5,37	10,98	1	102
Number of R&D types per country	8,66	18,75	1	172
Distance (Km)	5942,58	4314,74	173,03	19006,65
Official common language	0,15	0,36	0	1
GDP (current US$)	9,96E+11	2,13E+12	1,01E+09	1,41E+13
Population size (Mln)	96,72	245,01	0,49	1328,02
Number of patents	14373,45	47126,65	1	301229
Number of co-inventions	113,04	220,49	0	1313
In-degree	16,28	11,13	1	41
Out-degree	6,7	4,71	1	19
In-strength	141	218,91	1	955
Out-strength	58	111,83	1	602

Source: Own calculations

Table 11: Pair-wise correlations between variables

		1	2	3	4	5	6	7	8	9	10	11
1	Betweenness centrality	1,00										
2	Closeness centrality	0,496*	1									
3	Clustering coefficient	0,322*	-0,097	1								
4	In-degree	0,796*	0,465*	-0,410*	1							
5	Out-degree	0,628*	0,834*	-0,056	0,680*	1						
6	In-strength	0,931*	0,436*	-0,319*	0,810*	0,573*	1					
7	Out-strength	0,887*	0,601*	-0,230	0,685*	0,756*	0,730*	1				
8	GDP	0,957*	0,534*	-0,247	0,722*	0,670*	0,927*	0,888*	1			
9	Population size	0.283	0.399*	-0.049	0.202	0.446*	0.127	0.616*	0.368*	1		
10	Nr of patents	0,453*	0,341*	-0,222	0,537*	0,453*	0,556*	0,410*	0,519*		1	
11	Co-inventions	0,929*	0,550*	-0,287*	0,802*	0,693*	0,876*	0,842*	0,881*	0,424*		1

Pearson pair-wise correlations.

* Significant at p<0,001 level.

Source: Own calculations

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Abstract
A firm's decision to establish an R&D centre in a specific location creates externalities affecting other firms and, thus, a random distribution of location choices is unlikely. Expecting that the global distribution of R&D centres fulfils the criteria of a complex network, we apply social network analysis to study the locations of international R&D centres and the relationships between the countries owning and hosting them. We analyse the characteristics of the global R&D network and identify its core members. Further, we include network indices in an empirical analysis of the R&D internationalisation determinants. We find that a country's position in the network, which does not necessarily coincide with its geographical or cultural proximity to other countries, has a significant impact on the formation and intensity of R&D linkages between countries. We provide policy implications addressing the challenges emerging from the increasing internationalisation and network of R&D.
Keywords: globalisation of innovation, location of R&D centres, network analysis, gravity model
JEL classification: D8, O32, L23

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