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Abstract

Global innovation networks are emerging as a result of the international division of innovation processes through, among others, international technological collaborations. At the aggregate level, the creation of technological collaboration between countries can be considered as mutually beneficial (or detrimental) and their random distribution is unlikely. Consequently, the dynamics and evolution of the technological collaborations can be expected to fulfil the criteria of a complex network. To study the structure and evolution of the global technological collaboration network, we use patent-based data of international co-inventions and apply the network analysis. In addition, extending the gravity model of international technological collaboration by measures controlling for countries position in the network, we show that that a country's position in the network has very strong impact on the intensity of collaboration with other members of the network.

Keywords: globalisation of technology, technological collaboration, co-invention, network analysis, patent
JEL classification: D8, F23, O14, O30, O57

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1 Introduction

Global innovation networks are 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 form a variety of sources (Sachwald, 2008). In the context of the process of spatial division of innovation activity, corporations seek knowledge sources and opportunities worldwide (Archibugi & Iammarino, 2002; Bartlett & Ghoshal, 1990; Doz, Santos, & Williamson, 2001; Dunning, 1988, 1994). Consequently, today external contacts are decisive for a firm's innovation activities (Asheim & Isaksen, 2002; Cooke, 2002). One form of innovation internationalisation is global technological collaborations (Archibugi & Iammarino, 2002; Narula & Hagedoorn, 1999). At the aggregate level, the result of global technological collaborations is the emergence of knowledge flows between countries. The existence of such flows between any pair of countries creates externalities to other countries. Examples of such externalities might include increased competition for skilled labour or knowledge spillovers (Audretsch & Feldman, 1996; Audretsch & Lehmann, 2005). Hence, the creation of technological collaboration between countries can be considered as mutually beneficial (or detrimental) and a random distribution of technological collaborations is unlikely. Consequently, the dynamics and evolution of the technological collaborations can be expected to fulfil the criteria of a complex network, whose elements and changes are driven by collective actions. Understanding the dynamics of the entire system of global R&D, innovation and technology development seems to be of crucial importance from the innovation policy point of view (Edler & Polt, 2008).. Unfortunately, to our best knowledge, the available research fails to thoroughly capture this perspective.

The objective of the present paper is to create a map of technological collaborations between countries around the world and to analyse the determinants of the formation of technological collaboration relationships between countries. We seek to answer the following questions: What is the structure and the dynamics of the global technological network? What are the workings of network interactions? What positions countries occupy in this network? And, finally, what and how do economic fundamentals affect the formation of technological networks?

To study the global web of technological collaborations as a system of inter-lined activities, we use patent data to obtain measures of international co-inventions. To this aim, we use a comprehensive dataset containing information on a worldwide coverage of patent applications submitted to around 90 patent offices in the world over the last two decades. By applying network analysis, we graphically and analytically study the characteristics and the evolution of the international co-inventions network and the relationships between the actors. In addition, we introduce network measures in a gravity model with the aim of studying how a position of a country in the co-invention network affects the likelihood of formation of links between countries and their intensities.

Despite the fact that the topic of internationalization of innovation has already attracted a considerable amount of attention, there is still relatively little empirical evidence (Carlsson, 2006). Moreover, the existing studies are either based on firm level analysis (Boutellier, Gassmann, & Zedtwitz, 2008; Florida, 1997; Gulbrandsen & Godoe, 2008; Kuemmerle, 1999) or provide case study analysis at a country level (Gassler & Nones, 2008; Pittiglio, Sica, & Villa, 2009). In addition, the available studies focus on developed countries (Niosi, Manseau, & Godin, 2000) and, with some exceptions (Schmiele, 2011), ignore the emergence of the developing countries as a location of inventive activity. Studies that take into account a large group of countries and explain technological collaboration activities between them are scarce as well (Belderbos, Fukao, & Iwasa, 2006; Patel & Pavitt, 1991; Picci, 2010). Thus, not surprisingly, only few studies explicitly investigate innovation internationalization empirically at the system level (Bartholomew, 1997; Niosi & Bellon, 1994). Attempts to study the interdependences between countries are limited to the developed world and are limited too in terms of technology coverage (Bartholomew, 1997; Shapira, Youtie, & Kay, 2011). Consequently, to our knowledge, none of the studies takes a holistic view of the entire system and accounts for the inter-dependencies and externalities that arise in this system of interactions.

Taking into account the gap in understanding the dynamics of the organisation of the global technological collaboration network, the contributions of this paper are: First, we look at the whole system, rather than at individual relationships and interactions. Second, in the analysis of the determinants of international collaborations, we introduce a set of unique variables controlling for a country's position in the network. Overall, we present evidence that helps to better understand the interdependencies present in the process of globalised R&D relations and create a holistic view of the development of the global technological collaboration network.

We acknowledge that studies on knowledge, R&D and innovation networks already exist. Some applications of this type of analysis has been made to, for example, patent (Breschi & Lissoni, 2004; Cantwell & Santangelo, 2000; Chao-Chih, 2009; Han & Park, 2006; Lai, D'Amour, Yu, Sun, & Fleming, 2011; Stefano & Francesco, 2004) and bibliometric data (Glänzel & Schubert, 2005; Glänzel, Schubert, & Czerwon, 1999; Kretschmer, 2004). Our work extends the application of networks to the country level and, by using a comprehensive dataset, maps a global network of inventive collaboration and provides new evidence on the determinants of technological collaboration.

The remaining of the paper proceeds as follows: Section 2 describes the process of designing the global technological collaboration network based on international co-inventions. Section 3 introduces the data and measures used in the study and Section 4 analyses the characteristics of the technological collaboration network and countries' positions in this network. Section 5 formulates a model of formation of collaboration linkages between countries and Section 6 presents and discusses the results of empirical estimations. Section 0 concludes.

2 International co-inventions as a technological collaboration network

Being aware of the limitations of using patents as a measure of international collaboration (Bergek & Bruzelius, 2010), this work uses information included in patent applications to construct measures of international collaboration. Each patent application has a list of inventors, i.e. the people who developed a particular invention, and information about their place of residence. An intuitive way of representing the set of international co-inventions by using patent data as a network is through drawing a line connecting two countries that share a patent developed by their residents. By doing this for the entire pool of international co-inventions, we are able to construct a global network of technological collaborations.

We identify our set of nodes, V, as the countries and the set of arcs, A, as the bilateral relationships that exist whenever a patented invention was developed by at least two inventors residing in different countries (see Annex for a formal definition of a network and network measures). Adding a measure of intensity for each node and each relation permits us to control for the level of internationalisation of each country and the intensity of technological collaboration relationships it maintains with its partners. In other words, each node is weighted by the total amount of inventions developed in join collaboration for each country, which is captured by the vertex value function $P = p_i$, where p_i is the number of patents co-invented be residents of country *i*. This reflects the strength of vertex *i*.

According to Guellec & Van Pottelsberghe de la Potterie (2001), the total number of patents co-invented by residents of country *i* in collaboration with foreign researchers is

$$CoInn_i = \sum_{j \neq i} CoInn_{ij} . \quad (1)$$

Regarding the intensity of technological collaboration relationships between countries, each line is weighted by the total amount of inventive collaboration that takes place between country *i* and country *j*, i.e. the total number of joint patents. Hence, the line value function is $W=w_{ij}$, where *ij* is the link and w_{ij} is the link's weight. Again, according to Guellec & Van Pottelsberghe de la Potterie (2001), this can be defined as $CoInn_{ij}$, i.e. the total number of patents co-invented by residents of country *i* in collaboration with researchers from country *j*.[1]

3 Data

In this paper, we use patent data coming from the European Patent Office (EPO) Worldwide Patent Statistical Database, known as PATSTAT. This database provides a worldwide coverage of patent applications submitted to around 90 Patent Offices in the world. The present analysis is based on indicators built by extracting and elaborating patent application data from the April 2010 release of the PATSTAT database. The analysis takes into account priority patent applications filed at 59 Patent Offices: the EPO itself and 58 National Patent Offices including those of the 27 EU Member States, the US Patent and Trademark Office (USPTO), the Japan Patent Office (JPO) as well as the other most active Patent Offices worldwide, including China and India. The time period taken into account covers from January 1st, 1990 to December 31st, 2007.[2]

Patent applications data provide information on the country of residence of the inventors; therefore patents are attributed to countries using the 'inventor criterion'. This way, our methodology of computing patent statistics for the purpose of this paper follows the most recent approach in literature (de Rassenfosse, Dernis, Guellec, Picci, & van Pottelsberghe de

[1] For an extensive description of the methodology and its application to study internationalization of innovation using patent-based indicators please refer to (G. De Prato, Nepelski, & Stancik, 2011).

[2] Because of the time lag in filling the data, our analysis ends with patent applications submitted by 31.12.2007.

la Potterie, 2011; Turlea et al., 2011).[3] In this paper we use priority patent applications, instead of granted patents. This methodological choice allows taking in account, processing and analysing a much broader dataset than any other methodological choice done before in the domain of patent analysis. Such choice is nowadays supported by a growing scientific literature and generates an increasing amount of relevant results.

According to Table 3-1, there were nearly half a million of patent applications submitted to one of the patent offices considered in 1990. This number continued to grow, on average, nearly 4% per year and reached 777.551 patent applications in 2007. Regarding the results of computing the number of patents and the number of international co-inventions, as defined in section 2, there were only 804 applications that included at least two inventors from different countries in 1990. By 2007, this number grew to over 6.200 patent applications. This represents an average annual increase of 37%, i.e. nearly ten times higher than the growth rate of patent applications. However, as a share in total patent applications, the number of international co-inventions is marginal. For example, in 2007 less than 1% of all patent applications were a result of a collaboration of at least two inventors from different countries. This confirms the results of the findings concerning the low levels of technological internationalisation (Patel & Pavitt, 1991; Picci, 2010). Nevertheless, this part of innovation activity should not be ignored, considering the increasing orientation of large firms to source their technologies from around the world and the fact that not all strategies of R&D internationalisation include developing patentable inventions (G. De Prato, Nepelski, & Stancik, 2011).

Table 3-1. Number of patent and international patent applications, 1990-2007

	1990	1995	2000	2005	2007
Number of priority patent applications	456.425	530.448	666.936	765.175	777.551
Number of international co-inventions	804	2.195	3.912	5.852	6.229
% of international co-inventions in total	0,18	0,41	0,59	0,76	0,80

Source: Own calculations using the inventor criterion based on PATSTAT Database, version 2010

[3] For an extensive description of the methodology and its application to study R&D performance using patent-based indicators please refer to (G. De Prato, Nepelski, Szewczyk, & Turlea, 2011).

4 Characteristics of the global technological collaboration network

4.1 *Network structure*

Our analysis of the global network of co-invention starts with its graphical illustration in two time points, i.e. 1990 and 2007, (Figure 4-1). A first look at Figure 4-1 reveals that, in 1990, the network of international technological collaborations was rather weakly connected. Its centre was formed by the US, Japan and developed European countries. Consequently, as pointed out by early studies, the levels of innovation internationalisation was relatively small (Patel & Pavitt, 1991). However, in 2007, we can clearly see that the number of countries, the linkages between them and their intensity increase at a rapid rate. According to Table 8-1 (see Appendix), in the analysed period, the number of countries involved in global technological collaborations increased from 79 to 125 and the number of links between them nearly quadrupled.

Regarding the general connectivity of the network, the value of the network density parameter started from 0,04 in 1990 and reached the level of 0,06 (Table 8-3, Appendix).[4] Thus, the network is neither regular nor complete. Most of the countries do not have technological collaborations with all the remaining countries, but rather select, or are selected as collaboration partners. Moreover, the distribution of the measure of closeness centrality 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. The value of clustering coefficient is significantly higher than the value of network density. 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.

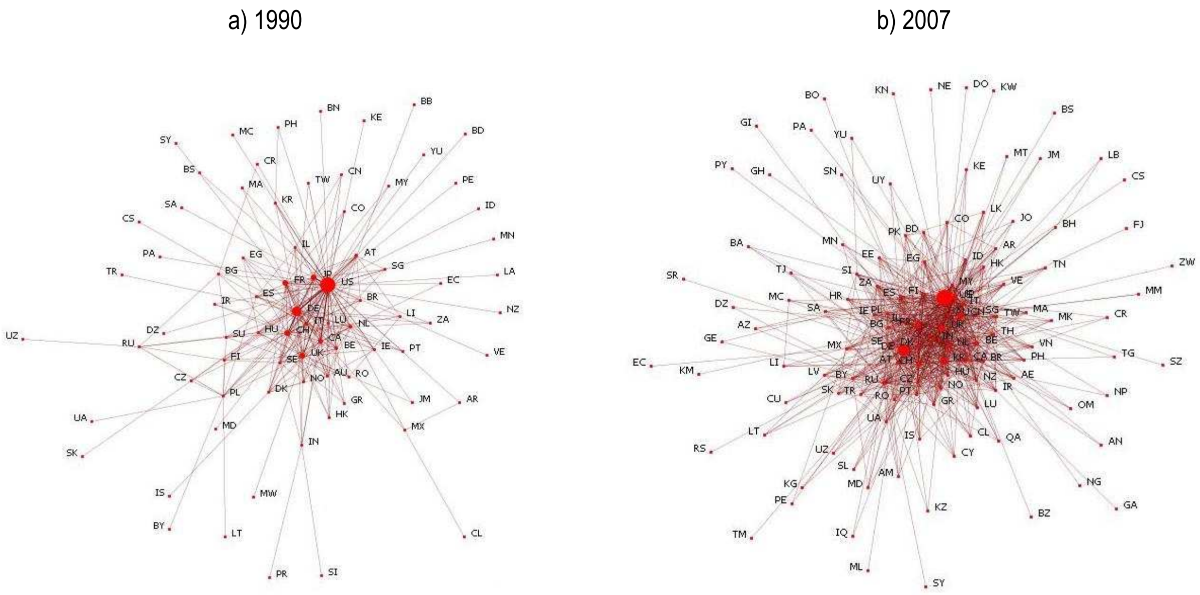
The above analysis of the network indices shows that a number of countries is connected only to the so called 'hubs' of the network and do not hold links with other members of the network. Thus, the network has a clear core-periphery structure. Moreover, it can be said that countries establish technological collaboration relationships with countries that also collaborate with each other. 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

[4] See Appendix 8.1 for formal definitions of network measures.

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.

The above findings contrast the results of network analysis of, for example, international R&D centres and international trade (De Benedictis & Tajoli, 2011; Giuditta De Prato & Nepelski, 2011; Fagiolo, Reyes, & Schiavo, 2007). The straightforward interpretation of this fact is that the production of 'knowledge' in a process of international collaboration is more complex than a mere creation of international R&D centres and that knowledge, as a good, is also less prone to trade and exchange than other material goods or services traded around the world.

Figure 4-1. The evolution of the global technological collaboration network



Source: Own calculations based on PATSTAT Database, version 2010

4.2 *Countries' positions in the network*

Turning to the analysis of countries' positions in the technological collaboration network, we rank countries according to four centrality measures, i.e. degree, strength, closeness and betweenness centrality, in three periods, i.e. 1990, 2000 and 2007 (see Table 8-2, Appendix). One of the most striking finding is that the US appears at the top of each ranking. This confirms the strong position of the US in the network as a source and destination of technological collaboration and, above all, as a central 'hub' of the network. Concerning the degree level, C_i^d, along with the US, Germany, UK, France and Japan play key roles in the network. The case of Japan is also interesting. Although this country is commonly considered as a world innovation power house, e.g. the number of patents submitted by Japanese inventors remains unchallenged, its role in the process of innovation internationalisation and collaboration is relatively weak (G. De Prato, Nepelski, & Stancik, 2011). Regarding the level of strength, s_i , we can see that there is indeed a strong correlation between nodes' degree and strength. Again, developed countries, e.g. the US, Germany, are holding top positions in terms of the output of inventive collaboration. However, also here we can see that over the last two decades the landscape of international collaboration has considerably changed. In particular, a number of Asian countries that were not on the map in 1990 has entered the game and already in 2007 occupied top positions. Here the most prominent examples are China and India.

Whereas, the degree centrality and strength of a node reveals how powerful or influential countries are in the network, closeness centrality, informs how well connected a node is in terms of the shortest paths to others actors of the network. Among the countries included in the collaboration network the US again emerges on the top of the ranking time and again.

The betweenness centrality index, C_i^b , reflects the position of a country as a core or a hub in the network of international technological collaboration. Over the analysed period, the US has held a clear and strong position as a network hub. Although the relative level of its betweenness index has decreased significantly over time, this position is rather unlikely to be challenged in the nearest future. The analysis of the betweenness centrality ranking shows additionally that countries such as the US, Germany, Russia, France and South Korea are likely to play the role of 'regional hubs', due to their the geographic position.

5 The determinants of international technological collaboration

In order to find an explanation of the results presented in the previous sections, we should know what determines international technological collaborations in terms of the structure of the network. Unfortunately, theoretical models dealing with this issue are virtually non-existent and any attempt of dealing with the internationalization of innovation focuses on explaining the pattern and intensity of international innovation activities from the perspective of interactions between individual countries, and do not offer insights about the structure of the whole system.[5] The closest theoretical concept suitable for an empirical analysis of innovation internationalisation is the gravity model of trade, which, except for being widely used in the studies of international trade (De Benedictis & Tajoli, 2011), has already been applied to study this issue (Picci, 2010; Thomson, 2011). This specification allows to formulate prediction concerning the structure of a network, i.e. the existence of trade relationships or technological collaboration between countries. The straightforward form of the gravity equation can be expressed by

$$L_{ij} = \frac{GDP_i \cdot GDP_j}{D_{ij}} \tag{2}$$

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

Taking this theoretical prediction as a starting point, we proceed with formulating a model in which we expect that a country's position in the network of international technological collaborations depends on some of its characteristics. To identify these determinants, we derive a set of factors that are used in studies conceptualising the issue innovation internationalization (Boutellier et al., 2008; Dunning, 1988, 1994; Kuemmerle, 1999; Narula, 2003).

Among the most important drivers of looking for collaboration partners abroad is the access to the resources that, in most cases, are non-transferable and location-specific (Dunning, 1988, 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 technological collaborations 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. Accordingly, the empirical studies of the determinants of the innovation internationalization can be grouped around two main blocks: economic capacity and inventive performance of a country (Dachs & Pyka, 2010; Guellec & Van Pottelsberghe de la Potterie, 2001; Patel & Pavitt, 1991; Picci, 2010). These two elements are expected to reflect the asset exploitation and asset seeking behaviour of companies deciding where to establish their international R&D

[5] 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. Some exceptions can be found, for example, in (Hausmann & Hidalgo, 2009).

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 company.

Our work extends the previous analysis of the determinants of the innovation internationalization by including measures of a country's network position derived in the previous section. The rationale behind it is that as the network evolves, countries take over various functions in the network, e.g. a hub or an intermediary. Performing these functions has further impact on the formation of new ties. This happens due to, for example, the preferential attachment principle, i.e. new countries attach preferentially to countries that are already well connected (Barabási & Albert, 1999). Thus, our function of the intensity of technological collaboration between countries takes the following form:

$$CoInn_{ijt} = f(CommLang_{ij}, Dist_{ij}, GDP_{it}, GDP_{jt}, FDI_{it}, FDI_{jt}, Inv_{it}, Inv_{jt}, N_{it}, N_{jt}, \alpha, \varepsilon_{ijt}) \quad (3)$$

where $CoInn_{ijt}$ represents the count of patented inventions developed by inventors residing in country j and country i formed in $t \in (1990,2007)$. To explain the relationship between the intensity of linkages between countries both 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, and, finally, its position in the network.

Geographical and cultural proximity: 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 $CommLang_{ij}$, which indicates whether two countries share a common official language.[6]

Economic size: Regarding economic size of countries linked through technological collaboration, information on GDP (in current US$) both country i and j in period t is included. Similar situation is with the variables controlling for the inflowing FDI. These measures are supposed to account for the economic attractiveness of both countries. In order

[6] The source of the distance and common language variables is CEPII bilateral trade data (Head, Mayer, & Ries, 2010). For more information please refer to: http://www.cepii.fr/anglaisgraph/bdd/distances.htm

to control for the internationalisation of economic activity, we also include measures of foreign direct investment for each country (in current US$).[7]

Innovative potential: Expecting that not only distance hiders and economic factors facilitate international technological collaborations, we control for the innovation performance of both countries proxied by the total number of patents of country *i* and *j* at time *t*. This has a double interpretation. On the one hand, from the perspective of one country, the measure of its inventive performance indicates the inventive capacity which might attract technological collaboration partners. On the other hand, from the perspective of another country, it might be a proxy of its absorptive capacity. In both cases, 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 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]

A country's position in the network: A vector of network measures included in the above specification, *N*, includes the measures of degree, strength and closeness centrality at time *t*. As explained above, the inclusion of these measures is motivated by the fact that the existence or establishment of bilateral linkages between two countries involving technological collaboration 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 & 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

To estimate the function specified in (3), we run regression with time fixed effects. Table 6-1 reports the results where the dependent variable was the total number of patented inventions

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

[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 (G. De Prato, Nepelski, Szewczyk, et al., 2011).

per link i and j at time t. For gravity model, we report first estimations with variables controlling for geographic and cultural proximity, economic size, and net FDI in-flows. The extended specification includes controls of inventive performance. Finally, we add the network indices as explanatory variables. The network indices refer to country i and j.

All the coefficients of the standard gravity model, i.e. distance, common language and the economy size, have the expected signs, and are significant. The coefficients of the FDI in-flows are not relevant. Regarding the second estimation, we can see that the coefficients related to the number of patents show significant impact on the establishment of technological collaboration between countries. Thus, though to a smaller extent than economic size, inventive capacities of countries positively influence the performance of technological collaboration.

The results reported above confirm that access to the resources that are non-transferable and location-specific are behind factors driving international technological collaboration. Examples of such resources include inputs to R&D activity, e.g. scientists and universities, or the knowledge about customers and markets. Moreover, economic potential of a market additionally increases the incentives to establish a collaborative relationship. These motivations are, however, moderated by geographical and cultural distance. The central issue here seems to be the difficulty to exchange and transfer tacit knowledge. Despite the availability of modern communication technologies, the lack of direct interactions hampers the exchange of knowledge and expertise. Furthermore, differences in national and regional business environments captured by physical and cultural distance might create some incompatibilities or conflict of interests between individuals or organizations from distinct countries. Such sources of incompatibilities include industrial relations, technical and scientific institutions, policies, and many other national institutions that are fundamental to innovative activities (C. Freeman, 1995). For example, differences in institutional arrangements might be an obstacle to the creation of a common framework governing cross-border business activities (Carlsson, 2006). Thus, the combination of the differences and similarities between countries might play a role in stimulating or dampening the progress of technological collaboration across the borders.

Regarding the network indicators, we observe that they are very strong and significant. Whereas a node's degree has a negative impact on the level of output of technological cooperation, the remaining measures, i.e. a node's strength and closeness, show very strong and significant impact on the dependent variable. The negative impact of degree can be interpreted as a decreasing marginal advantage of increasing the degree. This shows some similarities to the observations that were made in the context of international trade, where degree of a country is negatively correlated with its trade volumes (De Benedictis & Tajoli, 2011). If true, it would imply that there is some exclusivity in collaboration ties and a creation of a new connection takes place at the cost of the intensity of existing relationships. Hence, both individuals and organizations face a trade off between increasing the intensity of existing relationships and establishing new ones.

Concerning the strong effect of the closeness coefficient on the intensity of technological collaborations, the results show also that nodes positioned in the centre of the network, i.e. with short geodesic distances to other nodes in the network, tend to have more intense relationships with their partners. This finding might suggest that countries located in the centre of the network, i.e. countries being in the centre of collaborative knowledge and technology creation, are likely to benefit from this position. The central position allows them to get access and to absorb different types of knowledge and technology resources and, hence to leverage inventive performance.

Finally, it is worth noting that the inclusion of network indices has also a considerable impact on the standard gravity variables, which are considered as important drivers of international technological collaboration. For example, the negative impact of distance and the positive one of cultural proximity are weakened. This does not come as a surprise, as the position of a country might be independent from its geographical or cultural positions, 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 inclusion of network indices reduce considerably the role of GDP of both countries involved into a collaboration relationship. This suggests that the economic attractiveness becomes less important when we take into account a country's position in the R&D network, adding some new insights on the drivers of the internationalisation of innovation.

Table 6-1. Estimation results

Number of co-inventions between country *i* and *j*			
	Model 1	Model 2	Model 3
Common Language Dummy$_{ij}$	9,275***	9,217***	8,078***
Log Distance$_{ij}$	-3,124***	-3,120***	-2,498***
Log real GDP$_i$	3,964***	2,665***	1,291***
Log real GDP$_j$	3,999***	2,760***	1,718***
Log FDI In$_i$	0,046	0,355**	-0,269*
Log FDI In$_j$	-0,228	0,033	-0,354**
Log Patent$_i$		0,880***	0,330**
Log Patent$_j$		0,908***	0,406**
Log Degree$_i$			-9,354***
Log Strength$_i$			2,175***
Log Closeness Centrality$_i$			54,692***
Log Degree$_j$			-8,030***
Log Strength$_j$			2,416***
Log Closeness Centrality$_j$			38,716***
Constant	-187,005***	-137,507***	29,355**
N	5414	4916	4916
Pseudo R2	0,275	0,281	0,333

The table reports of the model specified in (3).

Significance levels: * = .90, ** = .95, *** = .99. Year dummies included.

Source: Own calculations based on PATSTAT Database, version 2010

7 Conclusions

We are witnessing the emergence of a global innovation network, a result of companies' decisions concerning the location of their innovation activities and selection of their technological collaboration partners. The increasing internationalisation of innovation let us believe that firms' choices create externalities and that they mutually affect each other. To better understand these interdependencies, we apply network analysis to study the global network of international technological collaborations. Our results show that the inclusion of network indices delivers new insights to the understanding of the formation and intensity of technological collaboration between countries.

The global technological collaboration network is not regular and far from being complete and the network shows signs of "cliquishness". This together with the fact that most of the countries tend to be members of some local or regional groups and that only few countries go beyond these groups suggests strong core-periphery characteristics of the technological collaboration network. In such a network, a number of countries are connected only to the so called 'hubs'. Similar to production networks, the distributions of control and contribution in innovation network are not equal and there are few hubs. The meaning of findings of this work concerning the developments of the global technological collaboration network is not the same for each country participating in the process of innovation internationalisation. Depending on the perspective of a particular country, the implications may be perceived as positive by some countries and negative by others. It is however clear that the bargaining power and a country's attractiveness as a technological collaboration partner will strongly depend on its relative position against the competing countries and, of course, its position in the network.

The main policy implications that can be formulated based on the results are the following: First, when strengthening technological and scientific capabilities with the aim of benefitting from technological collaborations, countries need to take into account broader environment in which there are many countries that both compete and collaborate with each other. Thus, policy makers designing, formulating and executing their innovation and science and technology collaboration policies need to answer such questions as: What position does my country occupy in the network of global technological collaboration? What are the other countries that my country competes/cooperates? How my/their actions will change my/their position in the system of mutual interdependencies? In other words, a clear positioning strategy is required in order to maximise the benefits of international collaboration.

Second, 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. Seeking, exploiting and transferring knowledge across the borders are equally important in the context of increasing collaboration and, hence, dependencies on what other countries produce and absorb. Thus, efforts towards international technology transfer should be strengthen to create a culture and mechanisms, e.g. IP rules and markets, supporting technology transfer and technological collaboration.

Third, 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 an assessment of a country's strengths and mechanisms towards their enhancement with the aim of finding and maintaining a strategic position in the technological space and, hence, in the network.

Lastly, the creation, structure and functioning of the global R&D network challenge the traditional way of research and innovation policy making, usually shaped by one-sided perspective defined by the notion of competition. If this way of organising economic activity in general and innovative activity in particular, becomes dominant in the future, one can expect that the network viability and countries' positions in this network will depend on their ability to develop collaboration mechanisms that support mutual co-dependencies between them.

In conclusion, although the paper provides a number of valuables insights concerning the structure of the technological collaboration network and the determinants of technological collaboration, it suffers from a few limitations. First of all, patent data, despite its richness of information, suffers from its own drawbacks. Second, due to the fact that there is no theoretical foundation explaining the formation and evolution of innovation networks, we do not offer any empirical insights into the development of such a network. Instead, we are forced to stop at including measures identifying the position of a country in the network to explain the intensity of its bilateral collaboration links. Nevertheless, the results presented here show that the inclusion of network indices are well justified. In addition to the standard explanatory variables, they deliver additional information explaining the existence and intensity of technological collaboration between countries. This makes us optimistic about the future of the value of network analysis in the context of internationalisation of innovation.

8 Appendix

8.1 *Definition and characteristics of a network*

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 (lines, relationships), that represent relations between units. A line can be directed – an arc, or undirected – an edge. In a formal way, a network

$$N = (V,L,W,P) \tag{4}$$

consists of a graph $G = (V,L)$, where V is the set of nodes, and $L = E \cup A$ is the set of lines, where A is the set of arcs, if the lines are directed, and E is the set of edges, if the lines are not directed. 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 is the number of edges that is expressed as a proportion of the maximum possible number of connections. It is formally defined as

$$\lambda = \frac{m}{m_{\max}} \tag{5}$$

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, given the same number of nodes.

In order to obtain further information on the structure of a network it is worthwhile to analyse centrality of the network and the nodes, a concept widely adopted in studies of networks (L. C. 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.:

$$C_i^d = \frac{d}{V-1}. \tag{6}$$

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

$$C^d = \frac{\sum_{i=1}^{n} | C_i^d - C_i^{d*} |}{(n-2)(n-1)}, \tag{7}$$

where C_i^{d*} is the highest value of centrality measure in the set of units of a network (L. C. 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).

Regarding 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 connections of vertex *i*. In a formal way, strength is defined as:

$$s_i \equiv \sum_{j \neq i} w_{ij} \tag{8}$$

where w_{ij} represent the intensity of the directed link from V_i to V_j (Squartini, Fagiolo, & Garlaschelli, 2011).

Except for the degree centrality defined in (6), 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). In this paper we use of three additional most commonly applied measures, i.e. closeness centrality and betweenness centrality.

The degree centrality strength of a node reveals how powerful or influential it is in the network. Closeness centrality, on the other hand, informs how powerful a node is in terms of the shortest paths to others actors of the network. 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.:

$$C_i^c = \frac{n-1}{\sum_{j \neq i}^{n-1} \partial_{ij}}. \tag{9}$$

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

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

where C_i^{c*} is the highest value of closeness centrality measure in the set of units of a network (L. C. 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 and it reflects the number of times a node appears on the shortest path between any two other nodes. This property of a network reflects the amount of control that a node exerts over the interactions of other nodes in the network (Yoon, Blumer, & Lee, 2006). The measure of betweenness centrality rewards nodes that are part of communities, rather than nodes that lie inside a community. Therefore, it can be regarded as a measure of gatekeeping and is considered to be a measure of strategic advantage and information control. Formally, the betweenness centrality of V_i can be expressed as:

$$C_i^b = \sum_{j \neq k} \frac{\partial^i_{jk}}{\partial_{jk}}, \tag{11}$$

where ∂_{jk} is the total number of shortest paths joining any two nodes V_k and V_j, and ∂^i_{jk} 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.

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

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

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 & Strogatz, 1998), which reflects the percentage of pairs of node *i* nearest neighbours that are themselves partners. In undirected networks, the clustering coefficient C_i^{cc} of node *i* is defined as

$$C_i^{cc} = \frac{2e_n}{(k_i(k_i - 1))} \tag{13}$$

where k_i is the degree of V_i and e_n is the number of connected pairs between all neighbours of *i* (Barabasi & Oltvai, 2004). The average clustering coefficient of a network is a sum of clustering coefficient values of all nods divided by the total number of nodes in the network. The global clustering coefficient is always a number between 0 and 1, where for a fully connected network *CC=1*.

8.2 *Tables and figures*

Table 8-1. Global technological collaboration network indices

	1990	1995	2000	2005	2007
Number of nodes	79	104	113	124	125
Link count	252	491	651	826	881
Average degree	16,56	30,54	46,14	60,52	63,93
Average degree scaled	0,062	0,049	0,047	0,047	0,046
Average strength	10,30	21,10	34,62	47,20	49,83
Density	0,040	0,045	0,051	0,054	0,056
Closeness centrality	0,016	0,011	0,012	0,011	0,012
Betweenness	0,027	0,031	0,024	0,027	0,024
Clustering centrality	0,420	0,566	0,601	0,630	0,626

Source: Own calculations based on PATSTAT Database, version 2010

Table 8-2. Countries' position in the technological collaboration network

	Degree centrality		Strength		Closeness centrality		Betweenness centrality	
Rank	**Country**	**Value**	**Country**	**Value**	**Country**	**Value**	**Country**	**Value**
1990								
1	US	60	US	207	US	0,804	US	0,604
2	Germany	35	Germany	126	Germany	0,634	Germany	0,141
3	UK	25	Japan	62	UK	0,582	Poland	0,092
4	Switzerland	22	France	55	Switzerland	0,561	UK	0,059
5	France	22	Switzerland	52	France	0,542	Austria	0,056
6	Canada	20	UK	46	Canada	0,542	India	0,051
7	Japan	19	Canada	39	Japan	0,534	France	0,040
8	Italy	18	Belgium	21	Italy	0,534	Switzerland	0,027
9	Netherlands	15	Italy	21	Poland	0,520	Russia	0,027
10	Austria	15	Netherlands	21	Sweden	0,520	Mexico	0,026
11	Belgium	15	Austria	20	Austria	0,520	Czech R.	0,026
12	Sweden	14	Sweden	12	Belgium	0,517	Denmark	0,026
13	Poland	13	S. Korea	9	Hungary	0,513	Hungary	0,021
14	Hungary	12	Poland	9	Netherlands	0,506	Canada	0,017
15	Denmark	11	Israel	7	Spain	0,497	Japan	0,016
2000								
1	US	78	US	896	US	0,767	US	0,298
2	Germany	72	Germany	611	Germany	0,737	Germany	0,210
3	France	52	France	241	France	0,647	Russia	0,139
4	UK	48	UK	239	UK	0,636	France	0,086
5	Russia	48	Japan	207	Russia	0,626	Italy	0,066
6	Japan	45	Switzerland	194	Japan	0,622	Japan	0,057
7	Switzerland	39	Canada	163	Switzerland	0,605	UK	0,038
8	Italy	39	Netherlands	140	Italy	0,596	S. Korea	0,026
9	Canada	35	Belgium	108	Canada	0,589	Spain	0,025
10	Spain	34	Russia	99	Sweden	0,586	Sweden	0,025
11	Sweden	34	Italy	84	Spain	0,583	Taiwan	0,024
12	Austria	32	Taiwan	79	Austria	0,580	Switzerland	0,022
13	Netherlands	30	Austria	77	Netherlands	0,571	Norway	0,021
14	Finland	29	Sweden	73	Finland	0,569	Poland	0,018
15	Belgium	28	China	73	Belgium	0,560	Monaco	0,018
2007								
1	US	164	US	1313	US	0,747	US	0,262
2	Germany	152	Germany	819	Germany	0,721	Germany	0,156
3	France	124	S. Korea	419	France	0,667	Russia	0,102
4	UK	110	France	336	UK	0,639	France	0,091
5	S. Korea	108	UK	318	Netherlands	0,636	S. Korea	0,054
6	Russia	108	Japan	305	Russia	0,633	Spain	0,049
7	Netherlands	106	China	295	S. Korea	0,629	China	0,047
8	Japan	98	Switzerland	262	Japan	0,623	UK	0,039
9	Australia	90	Canada	197	Switzerland	0,611	Italy	0,034
10	China	90	Netherlands	195	China	0,605	Netherlands	0,031
11	Switzerland	90	India	188	Austria	0,605	Japan	0,030
12	Italy	88	Belgium	138	Spain	0,605	Sweden	0,024
13	Spain	88	Russia	136	Italy	0,602	Canada	0,023
14	Sweden	82	Austria	126	Sweden	0,596	Switzerland	0,022
15	India	78	Taiwan	123	India	0,590	Australia	0,020

Source: Own calculations based on the PATSTAT Database, version 2010

Table 8-3. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Distance	10.250	5.491,20	4.575,51	59,62	19.586,18
GDP $_i$	9.762	1.250,00	2.390,00	0,05	14.100,00
GDP $_j$	10.239	1.290,00	2.440,00	0,09	14.100,00
FDI IN $_i$	7.622	29.249,75	50.251,81	-31.670,39	321.276,00
FDI IN $_j$	7.979	30.638,73	52.133,89	-31.670,39	321.276,00
Patent $_i$	10.250	21.623,33	60.374,52	0,00	359.642,10
Patent $_j$	10.250	22.292,00	61.176,10	0,00	359.642,10
Degree $_i$	10.239	31,73	25,35	1,00	164,00
Strength $_i$	10.250	139,34	230,06	0,08	1.313,25
Closeness Centrality $_i$	10.239	0,56	0,09	0,28	0,80
Degree $_j$	10.231	33,04	26,40	1,00	164,00
Strength $_j$	10.250	145,24	238,83	0,08	1.313,25
Closeness Centrality $_j$	10.231	0,56	0,09	0,27	0,80

The table reports descriptive statistics of variables used, pair wise, in the model. GDP denotes gross domestic product in current billion US $ for each country, FDI in refers to the amount of inflowing FDI in current US $. Patent reports the fractional count of priority patent applications in which inventors coming from the country participated. The following three pairs of variables are the main centrality measures coming from the network analysis. Source: Own calculations based on PATSTAT Database, version 2010

Table 8-4. Pair-wise correlations

		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Distance	1												
2	GDP $_i$	0,177	1											
3	GDP $_j$	0,156	-0,139	1										
4	FDI IN $_i$	0,080	0,674	-0,076	1									
5	FDI IN $_j$	0,090	-0,088	0,703	0,031	1								
6	Patent $_i$	0,157	0,493	-0,102	0,084	-0,060	1							
7	Patent $_j$	0,143	-0,076	0,484	-0,042	0,087	-0,071	1						
8	Degree $_i$	0,057	0,632	-0,193	0,600	-0,040	0,295	-0,115	1					
9	Strength $_i$	0,104	0,882	-0,154	0,689	-0,080	0,336	-0,087	0,760	1				
10	Closeness Centrality $_i$	0,053	0,693	-0,231	0,572	-0,129	0,323	-0,129	0,856	0,782	1			
11	Degree $_j$	0,050	-0,195	0,648	-0,035	0,618	-0,125	0,280	-0,109	-0,208	-0,291	1		
12	Strength $_j$	0,090	-0,162	0,883	-0,078	0,715	-0,109	0,321	-0,203	-0,174	-0,253	0,770	1	
13	Closeness Centrality $_j$	0,051	-0,227	0,697	-0,123	0,581	-0,141	0,319	-0,294	-0,253	-0,345	0,847	0,783	1

The table reports pair wise correlations between the variables used in the country-pair models in Table 6-1. All variables are correlated at the significance level of 10%.

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