

The global network of embodied R&D flows

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ABSTRACT

This paper aims to investigate the global R&D network that emerges by mapping the flows of (embodied) R&D expenditures exchanged among industries on a worldwide basis. Through an original combination of the World Input-Output Dataset (WIOD) and OECD data on Analytical Business Enterprise R&D (ANBERD), we build up a longitudinal network of 690 nodes (23 industries in 30 countries) from 2009 to 2013. Drawing on complex network analysis techniques, we examine the relational properties of the industry-country nodes, identify the most central ones, and detect the clusters that they form. While the diffusion of embodied R&D is highly pervasive, the linkages across industries are asymmetric and polarised. The position and role of the industry-country nodes in the network show a high variability both over time and across its network dimensions. Furthermore, except for transportation and ICT related industries, embodied R&D flows are largely confined within national borders. The results of the analysis hint that national systems of innovation might keep a relevance even in the global diffusion of R&D and, arguably, on its absorption and innovative exploitation. Also, changes in the worldwide competition for a centrality leadership of country-industry players in the global R&D diffusion requires policy alertness to take stock of them for innovation development.

KEYWORDS

R&D flows; Input-Output; Global Innovation Network; Complex Network Analysis

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1. Introduction

The advent of the fourth industrial revolution and the digital transformation have increased the extent to which innovations occur and diffuse on a global scale (Tiwari and Buse, 2019). While territories remain crucial milieux of tacit knowledge transfers, their innovation capacity increasingly relies on the local actors' participation to 'global production' (Coe and Yeung, 2015; Landesmann and Stöllinger, 2019) and 'global innovation networks' (Cooke, 2013).

Despite the wide attention these networks have received, both in academic and policy debates, the fact that they are evolving into digital global networks calls for further investigation (Bianchi and Labory, 2018). On the one hand, with the spread of digitalisation, corporate R&D projects are becoming more geographically dispersed and footloose with respect to the headquarters' country of multinational corporations; accordingly, the spectrum of innovative industries is getting less polarised (Hernandez Guevara et al., 2020). On the other hand, digital trade and e-transactions are also extending and reshaping the map of economic flows along which innovation is produced and diffused (OECD, 2019a,b). In the new era of 'digital globalisation', innovation networks are re-configuring themselves and their mapping is therefore important in order to identify the actors and the relationships on which the generation and diffusion of innovation mostly rely.

In the analysis of Global Innovation Networks (Cooke, 2013; Kano, Tsang, and chung Yeung, 2020; Boschma, 2021), an important distinction has to be drawn between networks of interactive innovation relationships and networks of knowledge flows. The former are generated by actors purposely interacting for the sake of an innovative outcome and represent the relationships these actors entertain for that to happen. Networks of this kind are typically built up by the relationships that occur among co-inventors, co-authors of scientific publications and participants of research projects (e.g., Xiang et al., 2013; Protogerou, Caloghirou, and Siokas, 2013). The latter type of networks instead refers to innovative knowledge flows and diffusion (or spillovers) occurring among the economic units that generate this knowledge through some underlying techno-economic relationships. The most investigated networks of this kind

refer to knowledge flows within and across regions and sectors and are mapped either by looking at intersectoral patent citations (e.g. Nomaler and Verspagen, 2008; Lamperti et al., 2020), inter-regional patent citations and R&D collaborations (e.g. Stuck, Broekel, and Revilla Diez, 2016; Bednarz and Broekel, 2019), or at R&D embodied in intersectoral flows of intermediate commodities and goods, that is, R&D-based knowledge that diffuses (spills) from a focal R&D spending industry to (on) other industries, by contributing to the amelioration of the intermediate inputs the latter acquire from the former (e.g. Cerulli and Potì, 2009; Laursen and Meliciani, 2000).

Unlike the networks that emerge through patent-based relationships across industries (e.g., citations), those based on intersectoral flows of embodied R&D – on which we focus in this paper – have been only marginally investigated on a global scale so far. The literature has mainly analysed these networks at the country or, at most, at cross-country (i.e. comparative) level, investigating the characteristics that national and sectoral technological (and innovation) systems reveal in terms of general connectivity, industry centralities, and subsystem components (e.g. Leoncini, Maggioni, and Montresor, 1996; Leoncini and Montresor, 2000, 2005; Montresor and Vittucci Marzetti, 2008, 2009; Guan and Chen, 2009; Soofi and Ghazinoory, 2011; Semitiel-García and Noguera-Méndez, 2012; Shi and Wu, 2019; Taalbi, 2020). International R&D flows of the same sectoral-embodied nature have been rarely integrated into these network analyses. Furthermore, their role has been mainly addressed in aggregated terms by investigating the impact that the stock of indirect sectoral R&D – acquired from other industries and other countries than the focal ones – has on productivity at the industry level (e.g. Frantzen, 2002; Franco, Montresor, and Vittucci Marzetti, 2011). Conversely, comprehensive network analyses of GINs based on intersectoral embodied R&D flows are still missing.

This research gap has been mainly due to the lack of suitable data. On the one hand, a sufficiently high level of industry disaggregation of R&D data has been for long available only with respect to a limited set of developed countries. On the other hand, mapping intersectoral embodied R&D flows across countries has been impeded by the lack of world input-output tables. Indeed, worldwide input-output tables have become available in the form of a structured dataset only recently (Timmer et al.,

2015). This database has been also used to map and investigate the structure of the World Input-Output Network (WION), as it emerges by looking at monetary flows between industries, within and across countries (Cerina et al., 2015). However, the WION does not coincide with the global R&D network we are investigating. While the former can be taken to represent the production substratum of the latter, the configuration and properties of the global R&D network at stake depends also on how R&D expenditures are distributed across countries and industries. Because of this, the global R&D network does not necessarily mimic the properties of the WION and its analysis allows us to explore important additional issues.

Building on existing network analysis studies, the present paper provides a novel investigation of three kinds of characteristics of the global R&D network (for an example taxonomy of network characteristics applied to regional innovation systems see Stuck, Broekel, and Revilla Diez, 2016). First, we look at what emerges from a general overview of this network, by investigating the global distribution of the properties of its nodes and the density of its global relationships. These aspects, and their change over time, are important to understand whether the global (embodied) R&D diffusion is a pervasive and relatively uniform process or if it rather creates core-periphery structures, and whether these structures reflect the boundaries of national economies or rather span within and/or across them. The results of this kind of analysis can contribute future research developments about the globalisation of R&D and innovation (e.g. Lee and Gereffi, 2021) and about the never dormant debate about national technological/innovation systems (Wolff and Nadiri, 1993; Lee, Malerba, and Primi, 2020; Li et al., 2021), shedding new light on the role of national boundaries in the diffusion of embodied innovation.

A second property we investigate is the centrality of the country-industry nodes constituting the global R&D network: that is, the relative importance these nodes exhibit by looking at the different relational dimensions of the network, like the supply rather than the acquisition of embodied innovation, or the hub rather than spokes role of nodes in its diffusion. The identification and evolution over time of these centrality indices are crucial to understand where the leading and lagging poles of the global R&D diffusion are located and how this location can be exploited to spread and acquire

the relative innovative knowledge. What emerges from this second kind of analysis can provide new inputs to further investigations of the structural properties of both national and sectoral (technological) systems of innovation (Fu et al., 2020; Taalbi, 2020), and on the role of global sectors in terms of embodied innovation pervasiveness and dependency (Shi and Wu, 2019).

The third and last aspect on which we provide new evidence is the existence of ‘communities’ within the global R&D network: that is, subnetworks that the relative diffusion process contributes to isolate, by showing within relationships denser than the outside ones. This analysis is important for the detection of clusters in the techno-economic space (Montresor and Vittucci Marzetti, 2008) that, similarly to clusters in the geographical space, can be expected to create synergistic techno-economic relationships among the constitutive nodes, which can increase the benefits of the R&D diffusion process. The geographical (across countries) and functional (across industries) location of these sub-networks is an additional element deserving attention in this analysis. Indeed, these results could contribute the existing and future research on the impact of intersectoral, international R&D spillovers (Franco, Montresor, and Vittucci Marzetti, 2011; Fracasso and Vittucci Marzetti, 2015), for example, by pointing to inter country-industry linkages that could deserve a special weighting in measuring the impact of spillovers, first of all in terms of productivity.

The rest of the paper is organized as follows. After an illustration of the data and the methodology employed to build up the network, a discussion of the network analysis techniques employed to investigate the three main aspects presented above is provided in the following Section 2. The results are discussed in Section 3 and Section 4 concludes and draw some policy and research implications.

2. Methodology

2.1. Data

Our analysis combines two databases: i) the 2016 release of the World Input-Output Database (WIOD) (Timmer et al., 2015), providing the yearly time series, from 2000 to 2014, of world input-output tables and socio-economic accounts for 28 EU coun-

tries and 15 other major countries;¹ ii) the OECD Analytical Business Enterprise R&D (ANBERD) dataset, reporting annual data, from 1987 to 2017, of Research and Development (R&D) expenditures by industry for OECD countries and some selected non-member economies.²

Despite their wide coverage in terms of countries, industries and years, the two datasets are not promptly matchable to obtain a worldwide level network, even along their common time span (i.e. 2000-2014). Unlike WIOD, ANBERD presents several missing values for the R&D expenditure of some countries and industries, especially in its early years. Furthermore, although the datasets are based on the same industrial classification (ISIC Rev. 4), WIOD has a higher level of disaggregation than ANBERD.

This misalignment forced us to adopt some harmonisation procedures that inevitably shrank the temporal span and the country-industry coverage of the analysis. First of all, we excluded the countries for which R&D data are mostly missing, either in time or across industries. Secondly, we aggregated a number of industries to ensure concordance between WIOD and ANBERD classifications.³ Lastly, with respect to countries for which yearly R&D data are available for at least 85% of the industries, we proceeded to a manual imputation of missing country-industry-year observations using the following criteria. If R&D data for a certain industry in a certain country are available, at least, in the two preceding or following years (with respect to the missing year), we imputed the missing one by computing the growth rate of R&D expenditure, for that industry in that country, weighted by the average incidence of such industry's R&D expenditures on its country's total R&D expenditures, in all the other non-missing years. In all the remaining cases, the imputation was performed only according to the simple average rate of growth of the industry's R&D expenditure.⁴

¹Countries other than these are included in a 'rest of the world' region. Data covers about 85% of the world GDP. The database is accessible at <http://www.wiod.org/home>.

²ANBERD provides data on R&D expenditure in the business enterprise sector by industry, where R&D is defined as the set of 'creative and systematic work undertaken in order to increase the stock of knowledge – including knowledge of humankind, culture and society – and to devise new applications of available knowledge', covering three main activities: basic research, applied research, and experimental development. Business R&D expenditures are expressed in Purchasing Power Parity (PPP) million US dollars at 2010 constant prices. The database is available at: <http://www.oecd.org/sti/inno/anberdanalyticalbusinessenterpriseresearchanddevelopmentdatabase.html>.

³The detailed concordance list of aggregated industries is reported in Table A1 in the Appendix.

⁴Although this manual imputation could lead to possible distortions, we are confident that our harmonisation and rigorous imputation procedure should limit any potential bias. Furthermore, it is worth stressing that the imputation involved a very small fraction of the total country-industry-year observations.

The procedure described above allowed us to obtain a full set of country-industry-year R&D and input-output data for 30 countries (Table 1) and 23 industries (Table 2) from 2009 to 2013. As described in the next section, these data were used to obtain a square matrix of order 690 for each year in the period 2009-2013, on which we apply the network analysis indicators described in Section 2.3.

2.2. The matrix of embodied R&D flows

In each period t of our analysis, the global R&D network that we investigate corresponds to a $nm \times nm$ matrix \mathbf{R}_t , where n ($= 30$) is the number of countries and m ($= 23$) the number of industries in each country. This matrix reports the R&D expenditure made in t by each industry in each country, that diffuses to the other industries, of the same as well as other countries, via the correspondent flows of intermediate goods. In formal terms, its generic element $r_{ic,ja}^t$ denotes the R&D performed at time t by industry i in country c , that reaches industry j in country d . For each country c , the cells of \mathbf{R}_t for which $d = c$ identify a squared sub-matrix of R&D expenditure that diffuses domestically, getting embodied in intersectoral (for $i \neq j$) and intrasectoral (for $i = j$) flows of domestically acquired intermediate inputs. Considering the n countries of the world, these sub-matrices constitute the main (matrix) diagonal of \mathbf{R}_t . Still with respect to each country c , the cells of \mathbf{R}_t for each of the other countries $d \neq c$, identify a squared sub-matrix of R&D expenditure that diffuses internationally, getting embodied in intersectoral ($i \neq j$) and intrasectoral ($i = j$) trade of intermediate inputs between c and d . For the $n - 1$ countries other than c , these sub-matrices reflect its dyadic patterns of trade and are located out of the main (matrix) diagonal.

From a conceptual point of view, the construction of \mathbf{R}_t rests on the hypothesis that sectoral R&D expenditure translates into innovation and, in turn, in the supply of ameliorated sectoral intermediate goods and services. The diffusion of innovation would then occur as the extra-value of these ameliorated inputs gets appropriated by the sectors that acquire them (on this embodiment hypothesis and its assumptions, see Leoncini and Montresor, 2000).⁵ Consistently with this hypothesis, \mathbf{R}_t can be defined

⁵In the construction of the matrix we also implicitly assume that the R&D expenditures get embodied in the

Table 1. Country list

Code	Name	Code	Name
AUS	Australia	ITA	Italy
AUT	Austria	JPN	Japan
BEL	Belgium	KOR	Republic of Korea
CAN	Canada	LTU	Lithuania
CHN	China	MEX	Mexico
CZE	Czech Republic	NLD	Netherlands
DEU	Germany	NOR	Norway
DNK	Denmark	POL	Poland
ESP	Spain	PRT	Portugal
EST	Estonia	ROU	Romania
FIN	Finland	SVN	Slovenia
FRA	France	SWE	Sweden
GBR	United Kingdom	TUR	Turkey
HUN	Hungary	TWN	Taiwan
IRL	Ireland	USA	United States of America

Table 2. Industry list

Industry	Description
1	Agriculture, forestry and fishing
2	Mining and quarrying
3	Manufacture of food products, beverages and tobacco products
4	Manufacture of textiles, wearing apparel and leather products
5	Wood, paper, printing and reproduction of recorded media
6	Manufacture of basic pharmaceutical products and pharmaceutical preparations
7	Manufacture of rubber and plastic products
8	Manufacture of other non-metallic mineral products
9	Manufacture of basic metals
10	Manufacture of fabricated metal products, except machinery and equipment
11	Manufacture of computer, electronic and optical products
12	Manufacture of electrical equipment
13	Manufacture of machinery and equipment n.e.c.
14	Manufacture of motor vehicles, trailers and semi-trailers
15	Manufacture of other transport equipment
16	Furniture, other manufacturing and repair and installation of machinery and equipment
17	Electricity, gas and water supply; sewerage, waste management and remediation activities
18	Construction
19	Wholesale and retail trade, repair of motor vehicles and motorcycles
20	Transportation and storage
21	Information and communication
22	Financial and insurance activities
23	Real estate activities; professional, scientific, technical, administrative and support service activities

as follows:

$$\mathbf{R}_t = \hat{\mathbf{r}}_t \mathbf{B}_t \quad (1)$$

where $\mathbf{r}_t = [r_{i_c}^t]$ is the (diagonalised) nm vector of R&D expenditure of each industry i in each country c at time t ,⁶ and $\mathbf{B}_t = [b_{i_c, j_d}^t]$ is a $nm \times nm$ matrix that accounts for intercountry, interindustry intermediate flows of goods and services.

In Eq.1, a crucial role is played by matrix \mathbf{B} , used to distribute R&D expenditures across country-industries. Among the possible specifications of this matrix (on which see Montresor and Vittucci Marzetti, 2009), we hereby assume that sectoral R&D expenditure flows proportionally to direct intersectoral exchanges of intermediate goods and services and adopt the following specification:

$$\mathbf{B}_t = \hat{\mathbf{x}}_t^{-1} \mathbf{Z}_t \quad (2)$$

where $\mathbf{Z}_t = [z_{i_c, j_d}^t]$ is the $nm \times nm$ matrix of intercountry, interindustry transactions, whose generic cell z_{i_c, j_d}^t represents the value of sales made at t by industry i of country c to industry j of country d , and $\mathbf{x}_t = [x_{i_c}^t]$ as the (diagonalised) nm vector of the total output value of each industry j in each country c at t .

By pre-multiplying \mathbf{B}_t by the diagonalised vector \mathbf{r}_t , the generic element of \mathbf{R}_t , r_{i_c, j_d}^t , is equal to the R&D input coefficient of industry i in country c at t ($r_{i_c}^t/x_{i_c}^t$) (the R&D expenditure (in PPP) embodied in each unit value of its sectoral output) multiplied by the value of sales from this industry to industry j in country d .⁷

The matrix \mathbf{R}_t represents the basis of the network analysis we will carry out.

goods of the sectors by which they are performed in the same year in which they are registered, and to a full extent. For a lengthy discussion of these hypotheses see Leoncini and Montresor (2000, 2003), and Montresor and Vittucci Marzetti (2008, 2009).

⁶We adopt the ‘hat’ over a vector to denote the diagonal matrix with the elements of the vector along its main diagonal.

⁷Another possible specification for \mathbf{B} is the one employed by Leoncini and Montresor (2003) and Montresor and Vittucci Marzetti (2008, 2009), who use the operator proposed by Siniscalco (1982) and adopt a description of the production relationships in terms of ‘vertically integrated sectors’. As discussed in Montresor and Vittucci Marzetti (2008), this amounts to assume that the sectoral R&D expenditure flows proportionally to all the production flows that, in all the recursive ‘production rounds’ that link them, industry i of country c provides to industry j of country d at t , in order to satisfy its final demand.

2.3. Network analysis indicators

The global R&D network determined by matrix \mathbf{R} is a weighted directed network (or valued digraph), whose generic node (or vertex) i_c refers to a generic industry i in a generic country c (e.g., manufacture of computer, electronic and optical products in Japan). Each directed link (or arc) (i_c, j_d) between node i_c and node j_d represents the R&D expenditure that flows from i_c (source node) to j_d (target node) embodied in the direct flows of intermediate inputs (e.g., from the manufacture of fabricated metal products in Italy, to manufacture of motor vehicles in Germany). The weight attached to the link represents the value of these embodied innovation flows.

There are several dimensions along which this network can be investigated. In the first exploratory analysis, we focus on three of them and make use of specific indicators, of which we provide a short intuitive definition and an illustration of their meaning in the present application.⁸

2.3.1. Node degree and strength distributions

A first characterisation of the network we are considering can be obtained by looking at how its nodes look like in relational terms. A handy way to do this is by investigating how the nodes distribute with respect to some focal properties, like their degree and strength.

The (*total*) *degree* of a node measures the number of links incident to it and results from two components: the number of outgoing (*out-degree*) and ingoing links (*in-degree*) of the node. In our global R&D network, high out-degree nodes are country belonging industries (hereafter, country-industries) marked by a pervasive number of embodied R&D intersectoral transfers, while high in-degree ones are country-industries with an extended number of acquisitions of it. Looking at both R&D diffusion and acquisition, high total degree nodes are country-industries marked by a large number of connections to the global R&D network.

While the identification of the nodes with a high or low degree is a piece of relevant

⁸For a more technical and formal introduction to concepts, tools and applications of complex network analysis, the interested reader can refer to Newman (2003) and Boccaletti et al. (2006). Vega-Redondo (2007), Jackson (2008) and Easley and Kleinberg (2010) deal in particular with the applications of network analysis to social and economic networks.

information, looking at the in-, out- and total degree distribution of the country-industries provides us with an interesting characterisation of the global R&D network. For example, a distribution in which few country-industries show a high out-degree might signal a core-periphery structure in the global diffusion of R&D, especially if several country-industries reveal, instead, a high in-degree. A right-skewness of the same distribution would be as much telling of this structure. Conversely, left-skewed degree distributions, with the majority of the country-industries showing a high degree, would suggest that the global R&D network is marked by a high level of generic connectivity, in general (total), in the diffusion (out-degree), and in the acquisition (in-degree) of embodied R&D.⁹

Since the global R&D network is a weighted one, a similar distribution analysis can be carried out by considering the *strength* (or *weight*, or *weighted connectivity*) of the network nodes, still in terms of ingoing (*in-strength*), outgoing (*out-strength*), and total links. Such an indicator integrates the information on the number and the weights of links incident to a node by simply calculating their sum. For our global R&D network, out-strength informs us about country-industries marked by an intense (high) or moderate (low) value of intersectoral embodied R&D diffusion. The same does in-strength in qualifying the high or low value of embodied R&D acquisitions by country-industries. Finally, high total strength country-industries reveal pivotal for their conveying (irrespective of the direction) large flows of embodied R&D at the global level. Similarly to the case of degree, the distribution that country-industries reveal in terms of strength is very informative. In particular, this distribution can help us in disentangling whether the kind of connectivity (e.g. core-periphery vs. complete networks) that emerges from the degree distribution is confirmed with respect to R&D flows of different value and whether focusing on large (rather than small) amounts of R&D diffusion or acquisition could reveal the emergence of a variable degree of connectivity among country-industries.

An interesting complement to the previous analyses can be represented by that of

⁹It is worth stressing that, by construction, the presence of a link between two country-industry nodes depend on the underlying existing intercountry, interindustry intermediate flows of goods and services rather than on R&D expenditures as the latter are always strictly positive at the level of aggregation of the data. Nevertheless, we claim that the analysis of the degree and its distribution may still provide valuable information on the overall connectivity of the world R&D network, particularly in comparison to the distribution and dynamics of the weighted connectivity.

the correlations among the nodes' degrees. Through it, the network could be classified as *assortative* – nodes tend to be connected with their connectivity peers (homophily), implying a positive assortativity (correlation) coefficient – or *disassortative* – nodes with a low degree are more likely to be connected with high degree ones so that the relative coefficient is negative – in terms of total-, in- and out-degree. With respect to our global R&D network, positive assortativity would suggest that the diffusion of embodied R&D expenditure across the world occurs in a sort of club manner, with country-industries that connect mainly with peers sharing the diffusion (out-), acquisitions (in-), and exchange (total) of many (few) or more (less) valuable R&D flows. Conversely, a disassortative global R&D network might signal that the diffusion of embodied R&D proceeds in a communicating vessels manner, with country-industries exhibiting few (or less valuable) embodied R&D (total-, in- and out-) flows that are more likely to benefit from connections with country-industries with a large number of (or more valued) R&D flows.

2.3.2. Node centrality, transitivity, and gatekeeping

Having explored the general properties of the global R&D network, additional elements for its characterisation can be obtained by looking at which are the most important nodes in relational terms. Such importance can be ascertained by ranking its constitutive country-industries in different respects, among which we focus on three.

To begin with, we return on the strength of the country-industries of the R&D global network addressed in the previous subsection and rank them in terms of *centrality*.¹⁰ As we said, the most central nodes in out-strength terms denote the country-industries that diffuse the largest amounts (i.e., the highest value) of embodied R&D to the other sectors. Accordingly, their identification enables us to identify the most R&D conductive points of the techno-economic space. Similarly, the nodes with the highest in-strength centrality reveal which are the country-industries that absorb the most of embodied R&D from the other sectors.

Still in terms of centrality, we further qualify the previous analysis and rank the nodes in terms of *hub* and *authority* centrality. A node with a large hub value has more

¹⁰We do not consider and, therefore, removed loops.

outgoing links to nodes with large authority values. In turn, a node with a large authority value receives more links from the nodes with large hub values. Transposed to our global R&D network, country-industries with large hub (authority) scores configure as conducive (recipient) of embodied R&D to (from) the most important receivers (senders).

The second dimension along which we rank the nodes is the so-called *transitivity*, obtained by computing the (weighted directed) local clustering coefficients of the nodes. Still in intuitive terms (for a more formal definition, see Fagiolo, 2007; Clemente and Grassi, 2018), this coefficient measures the extent to which nodes tend to form closed groups (i.e., closed triangles) with a high density of close ties (i.e., with the presence of strong neighbours). In general, the most transitive nodes of a network are those with the highest capacity to create local clusters by exploiting the transitivity property. In the case of our global R&D network, highly transitive nodes are country-industries whose techno-economic neighbourhood dense flows of embodied R&D tend to concentrate: that is, nodes of the techno-economic space that create local patterns in the global diffusion of embodied R&D.

The third and last dimension according to which we order the nodes of the global R&D network is their role of *gatekeeping* within it. In intuitive terms, the gate-keeping score of a node is the higher, the lower the overlap between its own neighbouring nodes and those of the latter.¹¹ In other words, gatekeepers in networks are nodes that hold a position between other nodes that are not directly linked. In our network, country-industries with a higher ‘gatekeeping’ score are relatively more important in intermediating the diffusion of embodied R&D between directly unconnected ones. In other words, these country-industries have a higher capacity to act as boundary-spanners in the global R&D network.¹²

¹¹In formal terms, this amounts to the inverse of Burt’s (1992; 2005) aggregate constraint.

¹²We would like to stress that the amount and direction of the flows considered and the node’s relational attributes do not necessarily entail a qualitative evaluation of the nodes or specific advantages/disadvantages. To illustrate, a high out-strength denotes a country-industry that should be priced for their capacity of diffusing (i.e. selling) embodied R&D flows to other national or global industries. At the same time, a high out-strength, proxying the ability of country-industries to absorb (i.e. acquire), and thus possibly exploit the R&D generated elsewhere, should also be considered valuable.

2.3.3. *Communities*

It is also worth investigating how the global R&D network looks like when we search for *communities* within it: that is, clusters of country-industries for which (the amount and value of) internal embodied R&D interconnections are larger than (the density and strength of) the external ones (i.e. among groups). As discussed in Montresor and Vittucci Marzetti (2008), on a country base, this kind of communities identifies technoeconomic clusters that potentially work as sub-systems of national technological ones. On a global scale, the same communities can also span across national boundaries and involve multi-industry and/or cross-country R&D relationships that potentially point to transnational systems of innovation.

As far as the detection of these communities is concerned, since modularity and similarly-derived algorithms are not well-defined for directed graphs and tend to yield unsatisfactory results in weighted ones, we here apply the MapEquation algorithm put forward by Rosvall and Bergstrom (2008). In intuitive terms, this algorithm takes random walks through the network and identifies a community with the set of nodes for which this random ‘walking’ takes a long time before moving to the other sets of nodes.¹³

3. Results

The results of the global R&D network analysis is presented following the three sets of indicators discussed in Section 2.3. For each of the three dimensions to which these indicators refer, the order of the results will also follow the different sub-dimensions into which we articulated their description.

3.1. *General features of the global R&D network*

As an introduction to the threefold node-distribution analysis of Section 2.3.1, Figure 1 provides a visual representation of the global R&D network in the first and last year

¹³The algorithm, increasingly applied in the economic geography literature (see, among others, Haller and Rigby, 2020), is built on a flow-based, information-theoretic foundation that takes advantage of the duality between finding community structure in networks and minimizing the description length of a random walker’s movements on a network.

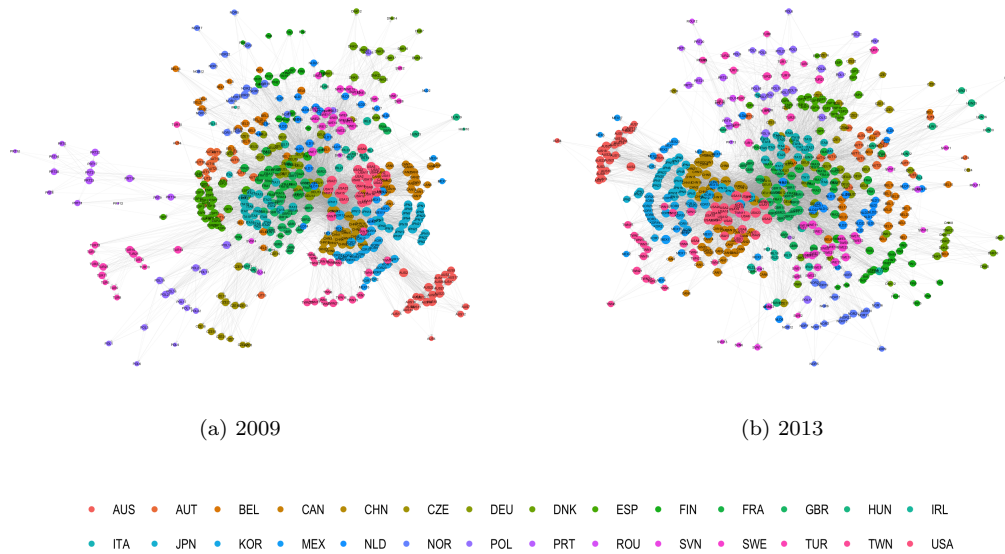


Figure 1. Global network of embodied R&D flows. Nodes are industries within countries and are coloured according to the respective country. Node size is proportional to the (log) total strength. Only links with a weight higher than 1 billion USD are drawn

of our temporal span: 2009 (1a) and 2013 (1b). Nodes with different colours denote industries in different countries, while their size is proportional to the (log) of their total strengths. For the sake of an easier visualization, a filtered version of the network is provided, in which only the links with a weight (R&D flow) of over 1 billion US dollars are reported.

In 2009, the global R&D network presents a core-periphery structure. The core mostly consists of industries from advanced countries (such as US, Germany, France, UK and China) and is surrounded by central European country-industries, around which we find a highly fragmented periphery. The core-periphery structure of the network emerges visually also in 2013, but with some interesting changes. In particular, a number of peripheral country-industries at the beginning of the period moved to the core, whose size is accordingly larger. Although the general structure of the global R&D network remained stable over time,¹⁴ this pattern seems to suggest that the diffusion of embodied R&D has become somehow more globalised.

Further interesting features of the network emerge by looking at the distribution of its nodes, in the three relational respects we presented in Section 2.3.1.

¹⁴Its structure in the intermediate years, available from the authors upon request, is actually very similar.

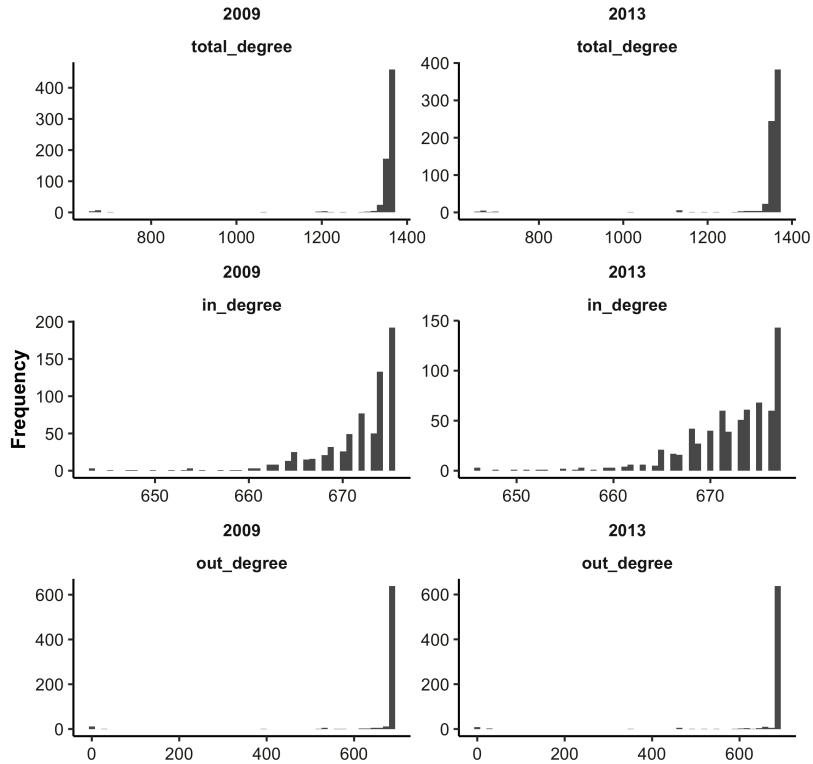


Figure 2. Distributions of total-, in-, and out-degree in 2009 and 2013

Starting with the degree distribution, Figure 2 shows that both at the beginning and the end of the period, all the degree distributions – total-, in-, and out- – are strongly left-skewed: the vast majority of country-industries have a large number of connections, with only a few limitedly connected nodes. This is particularly evident for total- and out-degree, while in-degree is slightly more evenly distributed, although its distribution still exhibits a large negative skewness. On the basis of these distributions, the network appears almost complete (each node is connected with almost all the others) and this result is pretty stable over time. This pattern is commonly observed when dealing with input-output networks and industries are quite aggregated, like in our case (McNerney, Fath, and Silverberg, 2013; Carvalho, 2013; Cerina et al., 2015). Nevertheless, this remains a remarkable result, showing that the diffusion of embodied R&D is truly pervasive and global, as it innervates nearly all the country-industries that constitute the network.

The distributions appear different when we look at the strength of nodes and con-

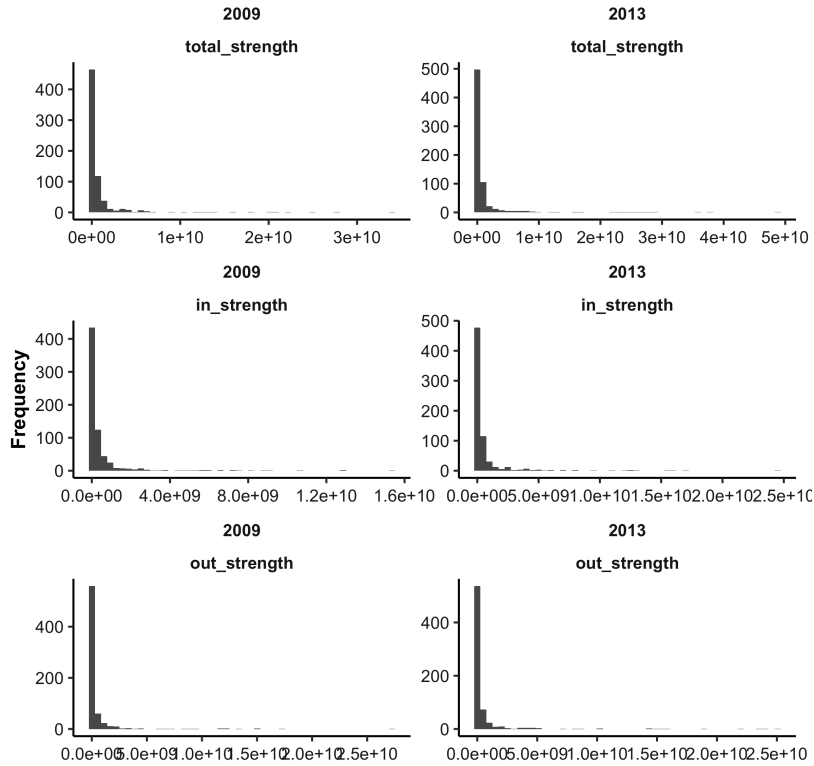


Figure 3. Distributions of total-, in-, and out-strength in 2009 and 2013

sider the value, rather than the number of their links. Figure 3 actually shows that all the relative distributions (in-, out-, and total) are right-skewed this time. The network is characterized by the presence of few country-industries involved in very large incoming and/or outgoing R&D flows, and by many country-industries that instead reveal small inflows and/or outflows of embodied R&D.

The opposite patterns revealed by the degree and strength distributions suggest another interesting feature of the global R&D network: while industries tend to be highly interconnected on a global scale through R&D diffusion, these connections are highly asymmetric in terms of valued flows. In other words, the network appears almost complete but also quite ‘polarised’: nearly all the nodes are involved and connected in the diffusion of R&D, but only a few of them are so in an intense manner. This also seems to be a stable result over time, suggesting that such polarisation is a structural feature of the network.

The final bit of evidence that we report about the global R&D network as a whole,

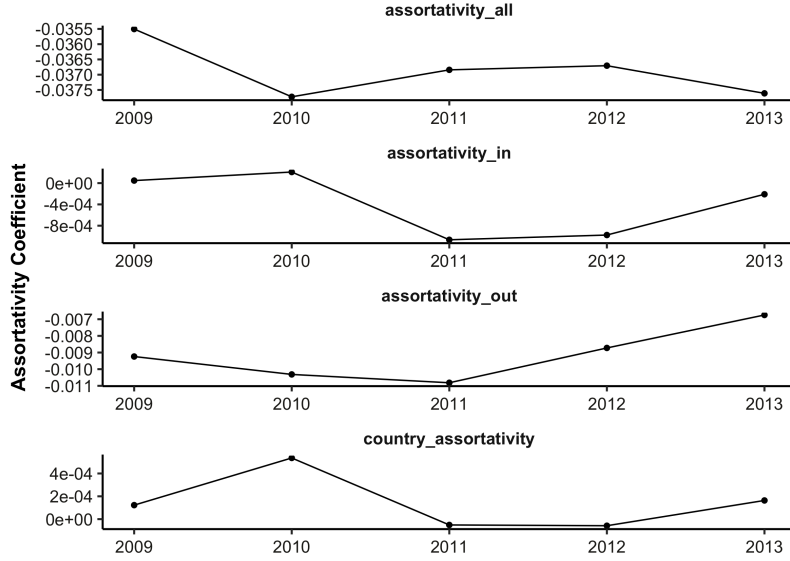


Figure 4. Assortativity coefficients based on total-, in-, out-degree and country from 2009 to 2013

concerns the assortativity (or disassortativity) of its nodes (see Section 2.3.1). In particular, we look at it in total-, in-, and out-degree terms, and we also measure a country assortativity coefficient, based on the country to which each industry belongs. The first three upper panels of Figure 4 reveal that, neglecting the country location of industries, the global R&D network generally shows degree disassortativity (i.e. negative) values. This suggests that, on a global scale, the diffusion of embodied innovation, in addition to being pervasive and polarised, mainly creates connections among asymmetric country-industries, as we said, in a sort of communicating vessels manner. Quite interestingly, when we instead consider the country belonging of industries, the assortativity coefficient is positive (lower panel of Figure 4). In brief, through the diffusion of embodied R&D, industries are more likely to be connected with other industries operating in the same country. This is another important result, hinting at the fact that national technological systems, of which intra-country R&D-based connections can be considered a proxy, keep on to be relevant also in a global scenario.

In concluding this general analysis, let us observe that, unlike the previously identified features, the assortativity-disassortativity one shows a certain variability over time. In- and out-degree assortativity coefficients decrease before 2011, indicating stronger disassortativity, and increase afterwards. A certain variability also applies

to country-assortativity, which follows a similar pattern over time. Overall, the asymmetry between the relational properties of the country-industries that connect in the global R&D network appears a less structural feature than their respective distribution.

3.2. Ranking country-industries in the global R&D network

The role of country-industries in diffusing embodied innovation across the globe is heterogeneous, and their heterogeneity is arguably different when we look at the manifold nature of this role. This expectation seems to be confirmed when we rank the nodes of the global R&D network according to the three relational properties we discussed in Section 2.3.2.

Starting with centrality, Figures 5 and 6 show the ranking of the top 20 country-industries in terms of in-strength (embodied R&D acquiring country-industries) and out-strength (embodied R&D diffusing country-industries), respectively. Looking at the former ranking, the US and China appear to dominate in revealing top industries in terms of in-strength (Figure 5), suggesting that these two large economies host the most important industries in terms of intersectoral acquisitions of embodied R&D. The highest Chinese positions are occupied by construction (CHN18) and by manufacturing sectors related to computer (CHN11), electrical equipment (CHN12), and machinery (CHN13), while the top US industries are services (USA23) and information and communication (USA21). This is an interesting result, which suggests that the dominant (embodied) R&D acquiring role that the US and China reveal on a global scale refers to different functional partitions of their economic systems.

The in-strength centrality ranking does not exhibit significant changes in the considered period, with very few industries entering or exiting the top 20 ranking. However, some interesting cases of rewiring are observable within this group over the five years at stake. In particular, several Chinese industries gain significant positions as embodied R&D absorbers – this is apparently the case of electronics and machinery (CHN12) and, even more sharply, of manufacturing of motor vehicles, trailers and semi-trailers (CH14) – while several US ones fall back in this role – like construction (USA18) and financial and insurance activities (USA22). This is an interesting change, which adds new insights into the interpretation of the manifold technological competitions

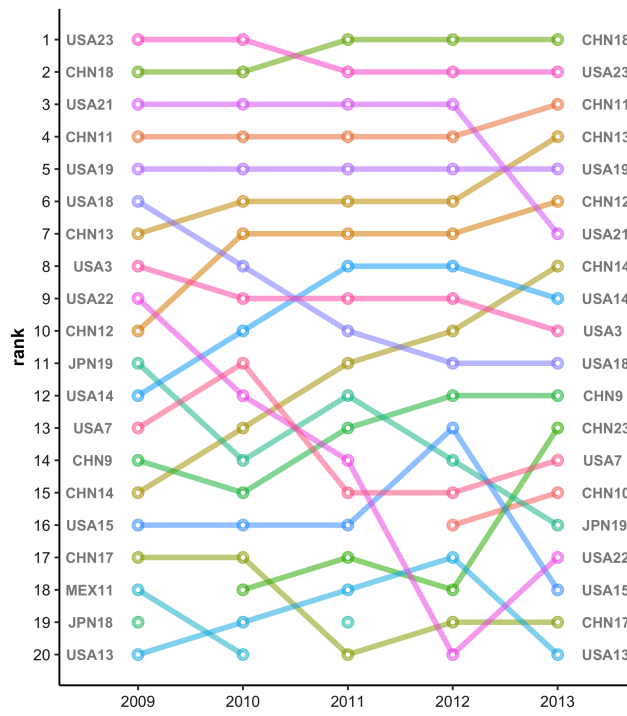


Figure 5. Top 20 country-industries in terms of in-strength from 2009 to 2013

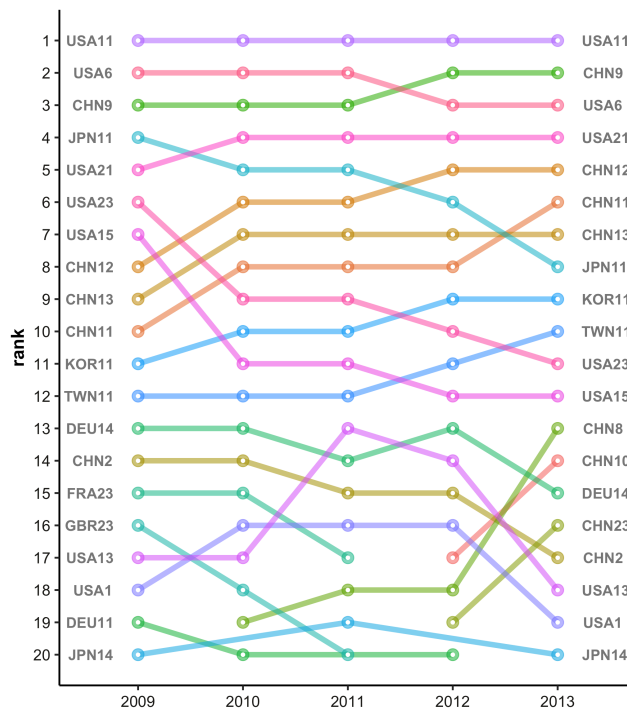


Figure 6. Top 20 country-industries in terms of out-strength from 2009 to 2013

between these two countries.

When we look at the top 20 country-industries in terms of out-strength, their distribution reveals some interesting differences with respect to in-strength (Figure 6). First of all, in 2009 the most embodied R&D diffusing industries across the globe are still US ones, with a top role of manufacturing of computers, electronic and optical products (USA11), and of pharmaceuticals (USA6): different industries from those in the top in-strength club. Chinese industries pervasively populate also this ranking, with a top role of basic metals (CHN9), and show a possibly wider upscale of positions over time than with respect to in-strength. On the other hand, the group of the most central industries in the diffusion of embodied R&D appears more geographically dispersed than those mainly involved in its acquisition. Indeed, it locates also in Japan – like in the case of computers, electronic and optical products (JPN11) – and in some European industries – such as motor vehicles and related manufacturing in Germany (DEU14) and professional-scientific services in France and in the UK (FRA23 and GBR23). This is another interesting result, showing that European countries emerge on a global scale only when their centrality is considered in terms of diffusion, rather than the acquisition of embodied R&D. Furthermore, although some of them appear to lose their central role in 2013, the results about European countries resonate with what we already know about their technological specialisation, which apparently also matters in the diffusion of embodied R&D.

Further insights about the most central country-industries of the global R&D network can be obtained by ranking them in terms of hub and authority scores. Starting with the former, Figure 7 shows that in 2009 the ranking is, again, dominated by US industries, in particular, those related to ICT activities, such as manufacture of computer, electronic and optical products (USA11) and information and communication (USA21), which are joined by the macro-sector of service activities (USA23) and by pharmaceutical (USA6), though its position then declines. Quite interestingly, among the top 20 country-industries in terms of hub score, we detect a diffused presence of ICT related industries of also other countries, namely Asian ones, like China (CHN11), Korea (KOR11), Japan (JPN11) and Taiwan (TWN11). This first picture suggests that the propensity/capacity of diffusing large R&D outflows toward other highly ranked

industries is typical of the manufacturing of computers and other high-tech (electronic and optical) products and somehow invariant to its geographical (country) localisation.

Despite some notable immediate fluctuations, like the sharp increase of CHN12 and the drop of USA16, the ranking remains quite stable over time, especially among the first positions, until 2011-2012. Afterwards, similarly to what we observed along the previous centrality dimensions, we register a rapid position decline of US industries vs. a position increase of Asian industries and the entry of Chinese ones. In the aftermath of these changes, the hub score ranking in 2013 looks quite different from that of 2009. At the end of the period, the ranking is dominated by China and Japan, with almost all the US industries scoring beyond the 20th position (with the exception of USA11, USA21 and USA23, declining from, respectively, the 1st, 2nd and 3rd position in 2009 to the 9th, 10th and 20th in 2013). Overall, a strong R&D diffusion towards strong R&D diffusing nodes emerges as a relatively more volatile feature of the global R&D network and adds interesting evidence with which to look at the comparative evolution of the technological performances of countries over time.

When we focus on the authority scores, Figure 8 shows that, in spite of some changes in their relative position, the ranking of country-industries observed in terms of hub scores is confirmed. Once more, from 2011 onwards, a wide decline of US industries emerge vs. the rise of Chinese ones. In 2013, the most attractive industries all belong to China and the top authority ones refer to the manufacturing of computer, electronic and optical products, electrical and machinery equipment (CHN11, CHN12 and CHN13), followed by construction and manufacturing of basic metals (CHN18 and CHN9). The remaining positions are also occupied by other Asian industries, still in the manufacturing of computer, electronic and optical products (TWN11, KOR11 and JPN11). Pulling the two sets of results together, the country-industry rankings in terms of hub and authority scores point to an important change in the geography of the most important nodes of the global R&D network over the period 2009-2013. Unlike degree centrality, where the change mainly consists of China's uptake of US sectors and leaves the node ranking relatively unchanged, in this case, the shift appears more pervasive, with a greater reshuffling, also involving other Asian economies.

Moving to the second dimension of our node ranking analysis, Figure 9 shows the top

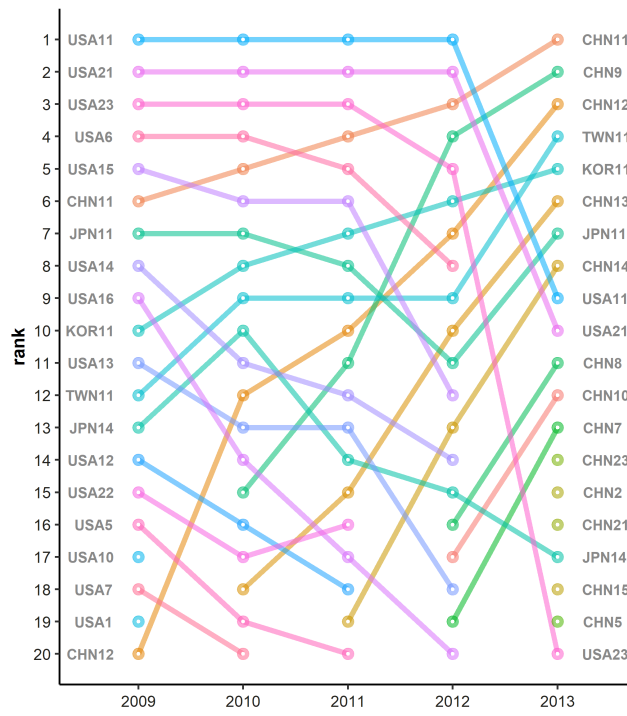


Figure 7. Top 20 country-industries in terms of hub score from 2009 to 2013

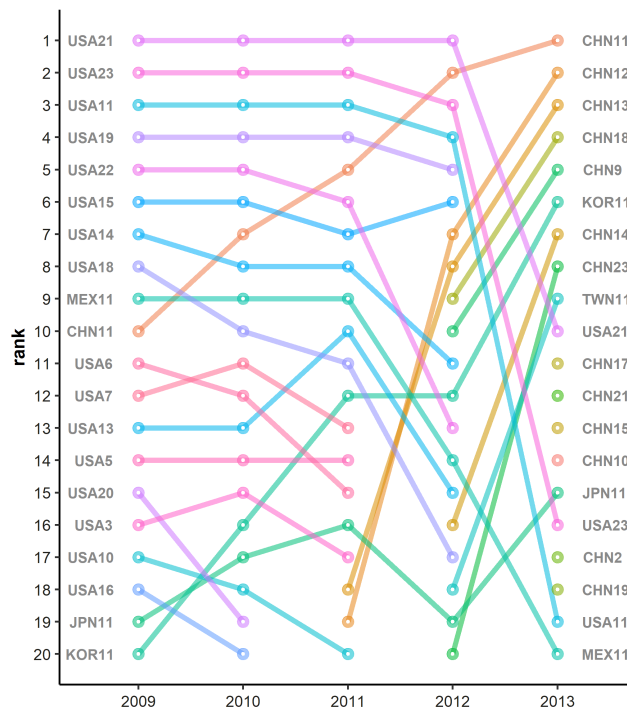


Figure 8. Top 20 country-industries in terms of authority score from 2009 to 2013

20 country-industries in terms of (directed weighted) local transitivity. A first visual inspection shows that both the identity and the evolution of the nodes capable of creating local groups greatly differ from what we observed in terms of centrality (sub-i). In other words, these appear two dimensions in which different country-industries of the global R&D network play the greatest role. The most notable difference concerns the wide presence of European industries among the top 20. The first in the ranking is the financial and insurance activities sector in Hungary (HUN22), which steadily maintains such a dominant position until 2013, followed by the Estonian ‘basic metals’ manufacturing sector (EST9). Crossing the country and the industry identity of these top nodes, another difference emerges. When it comes to the role of industries in clustering the diffusion of embodied R&D, the technological level of the national and sectoral knowledge-base does not appear as crucial as with respect to the ‘simple’ diffusion and acquisition of embodied R&D.

An additional distinguishing feature of the relational property we are investigating is its higher erratic trend over time. As the several dots of Figure 9 reveal, an appreciable number of country-industries stay in the top 20 occasionally and/or discontinuously. Entries and exits are also more numerous with respect to the centrality rankings. In particular, several Austrian industries exit the ranking immediately after 2009, together with a number of other European country-industries (e.g., EST15, FRA18, IRL20), while several Korean industries instead enter the top 20. As a consequence of that, the transitivity ranking greatly changes over the considered period. Indeed, in addition to HUN22 and EST9, only China’s construction sector (CHN18) and Italy’s financial and insurance sector (ITA22) remain in the top 20 group from 2009 to 2013, reaching the 3rd and 7th positions in 2013, from the 10th and 15th ones in 2009, respectively. Quite interestingly, when clustering is considered, European countries somehow substitute the US in its declining trend with respect to China.

The picture that we obtained in terms of transitivity is, in some respects, similar to that emerging from Figure 10 about the most gatekeeping country-industries of the global R&D network. Firstly, the top positions in the ranking reveal the strong boundary-spanning role of two high-tech industries, like pharmaceutical and electrical equipment, in two European countries like Belgium and the Netherlands (BEL7,

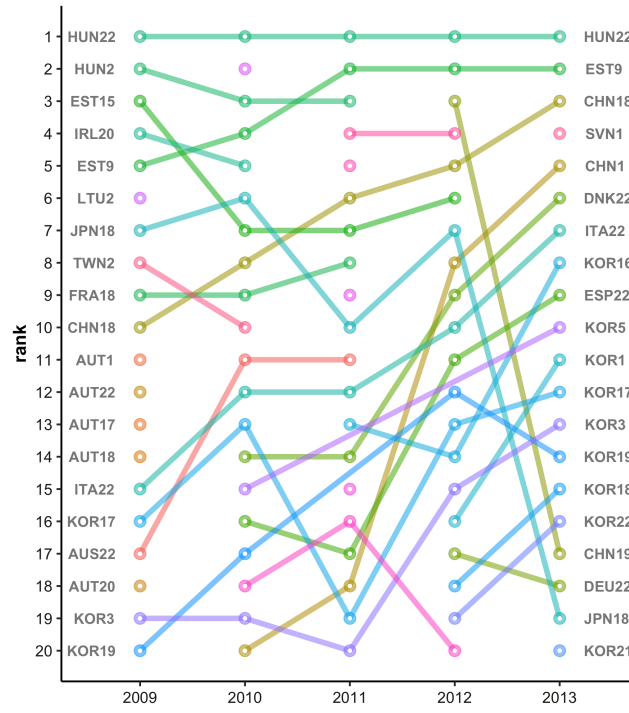


Figure 9. Top 20 country-industries in terms of weighted directed local clustering coefficient from 2009 to 2013

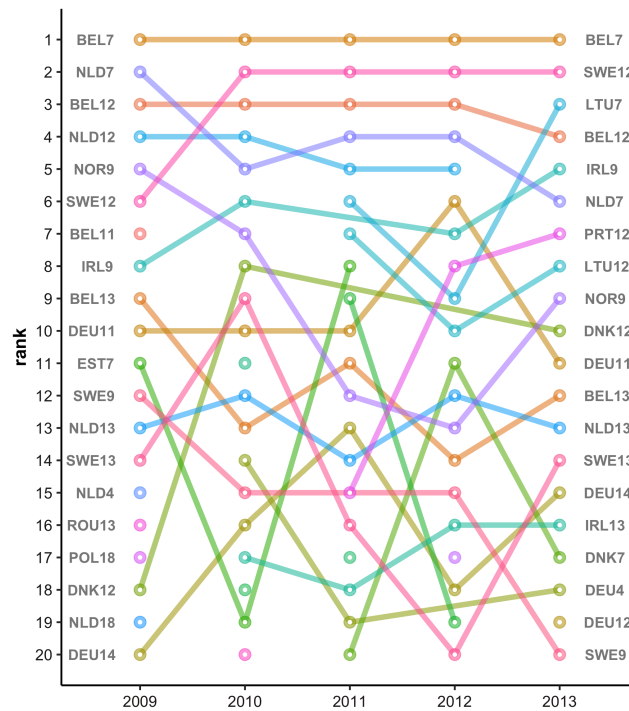


Figure 10. Top 20 country-industries in terms of boundary-spanning score from 2009 to 2013

BEL12, NLD7, and NLD12). Secondly, while these top positions are rather stable, the middle and lower parts of the ranking fluctuate intensively over the considered five years, with several industries rewiring and many new entries and early exits. Lastly, and differently from transitivity, the ranking evolution reveals, on the one hand, the increasing dominance of European industries, with important position advancements of industries from Central and Northern European countries; on the other hand, a low variability of the involved industries that, in addition to pharmaceutical and electrical equipment, mostly concern manufacturing industries related to basic metals, machinery and equipment, and motor vehicles.

In concluding, when two particular relational properties like transitivity and gate-keeping are considered, the most relevant nodes of the global R&D network reveal a different geographical and industrial localisation with respect to those that matter the most by looking at the centrality of R&D diffusion and acquisition. In broad and general terms, the former rankings reveal a more European and less high-tech characterisation, while the latter entail mostly Asian economies and high-tech industries. The former show an intense reshuffling over the considered years, while the latter appear less variable. Quite interestingly, in both the rankings US industries have lost importance over time, although with respect to the increase of country-industries with a different location. Going beyond these general patterns, which represent the key country-industries of the global R&D network in the different respects we have considered has an important informative value per se, Table 3 provides a final synoptic synthesis of these pivotal nodes.

3.3. Mapping communities of country-industries in the global R&D network

In Section 2.3.3, we argue that looking at the communities of country-industries the global R&D network reveals and their changes over time is particularly important to map the presence and evolution of intersectoral clusters in the global techno-economic space.

Figure 11 provides a visual representation of the communities identified through the algorithm described in Section 2.3.3 and of their evolution over time. Country-

Table 3. Top 3 country-industries in terms of centrality, transitivity and gatekeeping dimensions, in 2009, 2011, and 2013

2009						
Rank	In-strength	Out-strength	Hubs	Authority	Clustering	Boundary-span
1	USA23	USA11	USA11	USA21	HUN22	BEL7
2	CHN18	USA6	USA21	USA23	HUN2	NLD7
3	USA21	CHN9	USA23	USA11	EST15	BEL12
2011						
Rank	In-strength	Out-strength	Hubs	Authority	Clustering	Boundary-span
1	CHN18	USA11	USA11	USA21	HUN22	BEL7
2	USA23	USA6	USA21	USA23	EST9	SWE12
3	USA21	CHN9	USA23	USA11	HUN2	BEL12
2013						
Rank	In-strength	Out-strength	Hubs	Authority	Clustering	Boundary-span
1	CHN18	USA11	CHN11	CHN11	HUN22	BEL7
2	USA23	CHN9	CHN9	CHN12	EST9	SWE12
3	CHN11	USA6	CHN12	CHN13	CHN18	LTU7

industries belonging to the same community are grouped along a line with the same colour. The size of these coloured lines is proportional to the importance of the community constitutive nodes and their sorting is increasing (top-down in the figure) according to the relative importance of the cluster. The labels of the communities (country-industry strings) also refer to their most important nodes.

Among the several identified communities, two major ones emerge at the bottom of Figure 11: a US cluster led (in terms of importance in the exchange of embodied R&D) by wholesale, retail and repair (USA19) and real estate and service activities (USA23); and a Chinese cluster led by construction (CHN18) and manufacturing of machinery and equipment (CHN13). Passing through the intermediate size communities led by wholesale, retail and repair in Japan (JPN19) and by manufacturing of motor vehicles in Germany (DEU14), the other clusters stay quite apart from the two major ones in terms of importance. This points to two possibly dominant R&D sub-systems in the global network, which deserve attention.

Quite interestingly, these two major communities are also the only ones characterised by a remarkable evolution over the considered period. Indeed, the other identified community trajectories are quite stable. Almost all the other communities identified in 2009 remain prevalent throughout the whole period and nearly all of them retain a great part of their components over time. Conversely, a first change concerns

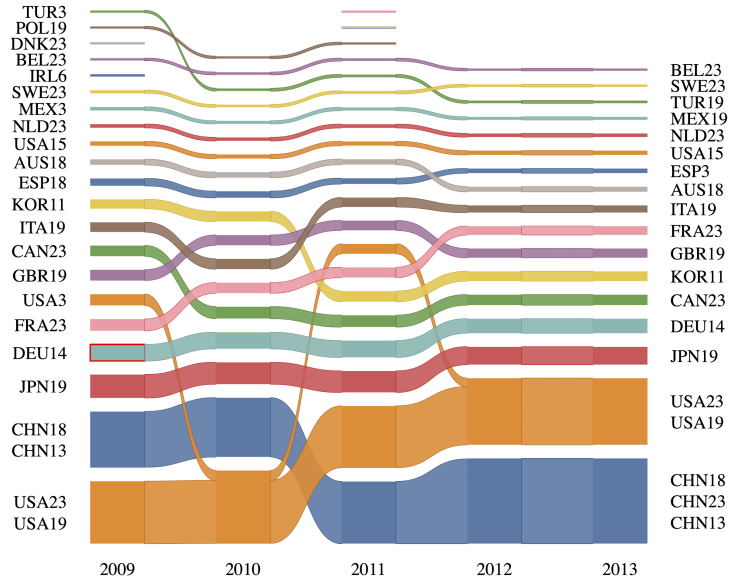


Figure 11. Evolution of communities in the global R&D network from 2009 to 2013

the US major cluster (USA23-USA19) that, in 2010, merges with US food products manufacturing (USA3), before splitting in 2011 and eventually merging again with it from 2012 on-wards. Consistently with our centrality ranking analysis, the major Chinese cluster (CHN18-CHN13) turns from the second to the most important one in 2011 and it increases its dominance in the following years. Overall, the evolution of communities in the global R&D network suggests that R&D flows clusters tend to be highly stable in the short-run and, as we will see in the following, also nationally bounded.

Further elements for the communities analysis of the global R&D network can be obtained by looking at Figure 12, which shows their composition at the beginning (2009) and the end (2013) of the observation period, respectively. Individual industries are arranged by columns, while countries are arranged by rows. Colours identify communities.

The first and most evident result in Figure 12a is that, at the beginning of the period, the identified communities are to a great extent contained in single countries. This somehow contrasts the global nature of the network that we could ascertain by looking at its general features. Although asymmetrically in their connections, the R&D diffusion process actually involves country-industries across the globe. However, the

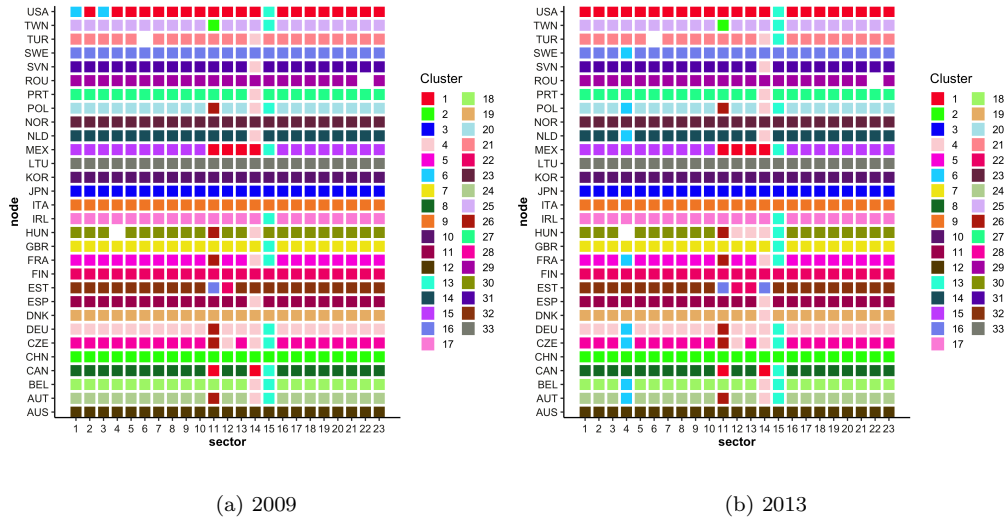


Figure 12. Community detection in the global R&D network

techno-economic clusters that the same diffusion generates among them are, generally, confined within national borders. This suggests, once more, that national technological systems still play a central role in a global context.

Nevertheless, there are a few industries that tend to cluster across countries, pointing to the existence of sectoral technological systems that span the boundaries of different countries. This is the case of the transportation related industries, namely the manufacture of motor vehicles (14) and other transport equipment (15), which constitute almost complete column clusters, thus indicating highly internationalized communities and supporting previous evidence about this industry (Leoncini and Montresor, 2001). Although to a more limited extent, also computer, electronic and optical product manufacturing (11) spans different national borders, mainly clustering across Central and Eastern European countries.

The two highlighted patterns – that is, a country-based composition of communities with few globalised industries – are confirmed and partially strengthened in 2013. In particular, the transportation and storage cluster (20) incorporates new countries, confirming the widening geography of its underlying value chain. In the same vein, the manufacture of textiles, wearing apparel and leather product (4), which was mainly embedded in national communities in 2009, in 2013 gains a more international dimension, forming a new cluster that crosses several countries. Considering the relatively

low-tech nature of this industry, when compared with the transportation sector, this is another interesting result suggesting that globalisation, through the diffusion of embodied R&D, does not necessarily depend on the technological intensity of industries.

4. Conclusions

The transformation of economic systems engendered by the last wave of digitalisation and the so-called fourth industrial revolution has attracted novel attention on the economic role of global networks, especially in the generation and diffusion of innovation on a global scale. In particular, it has become crucial to upgrade our knowledge about how innovation diffuses at the global level, by spanning the boundaries of the industries and of the countries in which R&D investments are undertaken for its generation. How does the global innovation network look like when we map the R&D-based knowledge generated at the country-industry level and the flows of this knowledge embodied in domestic and foreign intersectoral exchanges of goods and services? Which are its main features, and its most important nodes? How do industries of the same and of different countries cluster in this network?

In order to address these research questions, in this paper we have for the first time combined updated data on world input-output tables (WIOD) and R&D expenditures at the country-industry level (ANBERD), and built up a comprehensive and updated matrix of worldwide intersectoral R&D flows for 30 countries and 23 industries from 2009 to 2013. On the basis of this matrix, we have then carried out the analysis of the global network that results from considering as nodes individual industries in each country and, as arcs, the valued directed links represented by embodied R&D flows between them.

Three main sets of findings emerge from our analysis. First, by looking at its general features, as revealed by the distribution of the relational properties of its nodes, we have found that the global R&D network is nearly complete, in terms of connection existence (degree). The intersectoral diffusion of embodied R&D across countries is a really pervasive and highly connecting process at the global scale. However, the linkages of the network appear to be asymmetric and polarised in terms of valued R&D

flows (strength), with only a few country-industries involved in very large incoming and/or outgoing R&D flows. This asymmetry is also reflected in the degree disassortativity of the network, suggesting that the intersectoral diffusion of embodied R&D benefits from heterogeneous connections. Last but not least, industries tend to prioritize connections within their same country, highlighting the still central role played by national technological systems in the global scenario. Overall, these general properties appear quite stable over the relatively short time period that we have considered.

The second set of findings relates to the role of individual country-industries in the global R&D network. Quite interestingly, the identity of the pivotal nodes of the network varies with the focal relational property. The most important country-industries are different in different respects. When we look at the strength (i.e. value and number) of R&D diffusion and acquisition, the most important incoming are initially (in 2009) US and Chinese nodes, with the latter gaining increasing importance in the following years, and arriving to take up the US hegemony at the end of the period (2013). European industries emerge as pivotal in the network when diffusion rather than acquisition flows are considered. A similar pattern is found when looking at R&D hubs and authorities, with greater involvement of Asian industries (e.g., Japan and Korea) other than China. Once more, this picture appears relatively stable over time, but different from the one that emerges by looking at the role of nodes in creating local clusters and in acting as gatekeepers between otherwise unconnected nodes. The analysis reveals a marked dominance of European industries, mainly related to core manufacturing sectors, such as those related to metals, machinery, transportation and pharmaceuticals. Furthermore, results are indeed more volatile than in terms of degree and strength.

The third bunch of results regards the existence and the dynamics of communities, reflecting techno-economic clusters of country-industries in the global R&D network. Results suggest that, among the identified communities, the most important ones are based on some specific sectors in the US and in China. Apart from the change in their relative importance, the trajectories of the other communities are highly stable over time. Furthermore, digging into communities composition, we find that, the increased globalisation notwithstanding, R&D flows are still largely contained within national

borders or geographically close regions, confirming that national technological systems still play a key role in innovation processes. However, there are a few exceptions. In particular, we detect the emergence of two industry-wide clusters, the transportation and ICT related sectors, which form global communities spanning across different countries, highlighting the widening geography of their value chains. Interestingly, in the last year of our sample, we also find an inter-country global cluster around the textiles industry, suggesting that the diffusion of embodied R&D does not necessarily depend on the intrinsic technological intensity of industries.

The evidence gathered from these three sets of results is mainly descriptive. Indeed, our analysis has purposefully refrained from going further in some very tentative and general interpretations of them, especially with respect to the diachronic part of our investigation. Nonetheless, we believe that the knowledge that emerged about the distinguishing features of the global R&D network could have important implications in terms of both academic research and policy-making action. Among the research streams our work contributes to, that on the inter-industry and international R&D spillovers is the most relevant one. The features of the global R&D network could actually help in refining the map of links along which the impact (for example, in terms of TFP) of these spillovers can be expected to occur. The results of our analysis could also importantly contribute geography of innovation studies, especially in providing new evidence about the channels through which national and sub-national economies could open up to external innovative knowledge and specialised into new technologies. The spectrum of the policy applications of our analysis is also wide. Identifying the location of the most diffusing and/or acquiring nodes of R&D-based knowledge, in the geographical and the techno-economic space, could help policymakers in building up dedicated interfaces among industries and in promoting specific trade channels and international relationships to benefit from the same innovative knowledge. In addition, knowing which are the most grouping and boundary spanning industries, and their communities, could support the design of policies aimed at exploiting and benefiting from the synergies that, also along the techno-economic space, clustering phenomena could guarantee.

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Appendix A

Table A1. Concordance list of industry codes

ISIC Rev.4	Description	WIOD	Description
01-03	Agriculture, Forestry and Fishing	A01 A02 A03	Crop and animal production, hunting and related service activities Forestry and logging Fishing and aquaculture
16-18	Wood, Paper, Printing and reproduction of recorded media	C16 C17 C18	Manufacture of wood and of products of wood and cork ex. furniture; manufacture of articles of straw and plaiting materials Manufacture of paper and paper products Printing and reproduction of recorded media
31-33	Furniture; Other manufacturing; Repair and installation of machinery and equipment	C31_C32 C33	Manufacture of furniture; other manufacturing Repair and installation of machinery and equipment
35-39	Electricity, gas and water supply; Sewerage, waste management and remediation activities	D35 E36 E37-E39	Electricity, gas, steam and air conditioning supply Water collection, treatment and supply Sewerage; Waste collection, treatment and disposal activities; materials recovery; Remediation activities and other waste management services
45-47	Wholesale and retail trade; Repair of motor vehicles and motorcycles	G45 G46 G47	Wholesale and retail trade; repair of motor vehicles and motorcycles Wholesale trade, except of motor vehicles and motorcycles Retail trade, except of motor vehicles and motorcycles
49-53	Transportation and Storage	H49 H50 H51 H52 H53	Land transport and transport via pipelines Water transport Air transport Warehousing and support activities for transportation Postal and courier activities
58-63	Information and Communication	J58 J59_J60 J61 J62_J63	Publishing activities Motion picture, video and television programme production, sound recording and music publishing activities; Programming and broadcasting activities Telecommunications Computer programming, consultancy and related activities; Information service activities
64-66	Financial and Insurance activities	K64 K65 K66	Financial service activities, except insurance and pension funding Insurance, reinsurance and pension funding, except compulsory social security Activities auxiliary to financial services and insurance activities
68-82	Real estate activities; Professional, scientific, technical, administrative and support service activities	L68 M69_M70 M71 M72 M73 M74_M75 N	Real estate activities Legal and accounting activities; Activities of head offices; Management consultancy activities Architectural and engineering activities; technical testing and analysis Scientific research and development Advertising and market research Other professional, scientific and technical activities; Veterinary activities Administrative and support service activities