On indirect trade-related R&D spillovers: the "Average Propagation Length" of foreign R&D

Chiara Franco, Sandro Montresor*

Department of Economics, University of Bologna, Strada Maggiore 45, 40125 Bologna, Italy

Giuseppe Vittucci Marzetti

Department of Sociology ad Social Research, University of Milano-Bicocca,
via Bicocca degli Arcimboldi 8, 20126 Milan, Italy

Abstract

The paper estimates the impact on Total Factor Productivity of trade-related R&D spillovers by accounting for the economic distance between countries. The Average Propagation Length foreign R&D covers to reach a domestic country is used in building the foreign available R&D stock and to estimate its TFP impact vs. that of the domestic R&D stock. With respect to 20 OECD countries in the period 1995-2005, the impact on TFP of the available foreign R&D stock is greater than that of the domestic one. Results support the models that recognize indirect trade-related R&D spillovers and provide for them a more accurate interpretation.

Keywords: Average Propagation Length, International R&D spillovers, Total Factor Productivity

JEL Classification: C23, F01, O30, O47

---

*Corresponding author. Address: Department of Economics, University of Bologna, Strada Maggiore 45, 40125 Bologna, Italy, Phone: +39 051 2092651, Fax: +39 051 2092670

Email addresses: `chiara.franco2@unibo.it` (Chiara Franco), `sandro.montresor@.unibo.it` (Sandro Montresor), `giuseppe.vittucci@unimib.it` (Giuseppe Vittucci Marzetti)

The three authors contributed equally to the paper and share Sections 1 and 6. Still, Section 5 could be attributed to Chiara Franco; Section 2 to Sandro Montresor; Sections 3 and 4 to Giuseppe Vittucci Marzetti. The authors are grateful to the participants of the 2009 International Input-Output Conference (San Paulo, Brazil, 13-17 July 2009), of the 50° Riunione Scientifica Annuale della Società Italiana degli Economisti (SIE) (Rome, Italy, 22-24 October 2009), of the 2009 EAEPE conference (Amsterdam, The Netherlands, 6-8 November 2009) and to Erik Dietzenbacher, Francesco Lissoni, Bart Los and Markus Eberhardt, in particular, for their comments on earlier versions of this paper. The authors also thank two anonymous referees for their suggestions. All the three authors gratefully acknowledge financial support by the Autonomous Province of Trento, as the sponsor of the OPENLOC research project. Giuseppe Vittucci Marzetti also gratefully acknowledges the Autonomous Province of Trento for his post-doc scholarship (Grants 2006: FIC). Usual caveats apply.

Preprint submitted to Structural Change and Economic Dynamics *April 20, 2011*

1. Introduction

The role of international trade in conveying technology flows across countries has been both theoretically elaborated and empirically supported. A considerable number of papers on the so called "trade-related Research & Development (R&D) spillovers" has cumulated over the last twenty years (extensive surveys are Keller, 2004; van Pottelsberghe de la Potterie, 1997). A recent development of this research stream is the "indirect" nature of R&D spillovers via-trade. In brief, the idea that these spillovers can occur between two countries also *through* intermediate ones, even if they are not trading partners (Lumenga-Neso et al., 2005). A brief example, adapted from Lumenga-Neso et al. (2005, p.1787), could help in clarifying the point. Suppose we have a simple World of just 3 countries: Belgium, the Netherlands and the US; and that while the Netherlands trade with both Belgium and the US, Belgium does it with the Netherlands only. In the standard R&D spillovers framework, that would entail the US technological knowledge diffuses through trade to the Netherlands only, *directly*. However, some of the US *produced* knowledge would reach Belgium too, *indirectly*, being *available* in the Netherlands.

This idea represents for us an important, although not yet fully recognized, development of the literature on the international diffusion of technology (e.g. Eaton and Kortum, 1999). Not only does such a diffusion depends on the "geographical" distance among countries, as the bulk of the literature retains (e.g. Keller, 2002). But it also depends on what we call the "economic" distance between them, in terms of "trade-rounds". This adds a further dimension to the manifold notion of "proximity" in economic studies (Boschma, 2005). Indeed, technology diffusion between two geographically close countries, could be weakened (or magnified) by the fact that they are distant (or close) economic partners.

The aim of the paper is to provide a measurement of this economic distance between countries, and to evaluate its impact on the international diffusion of R&D through trade. In order to do that, we refer to the input-output idea of *Average Propagation Length* (APL) (Dietzenbacher et al., 2005) – of a final demand or value added shock – and we extend it from its original, domestic intersectoral setting to an inter-country, aggregate one. More precisely, a country-by-country APL matrix is built up by drawing on their bilateral imports. Such a matrix is then used to weigh the domestic R&D expenditures which become *available* abroad and to obtain a more accurate measurement of the relative stock. Finally, the impact on Total Factor Productivity (TFP) of this available R&D stock is estimated for 20 OECD countries over the decade 1995-2005, and compared with that of the R&D stock produced by them domestically and by their direct partners only.

The paper is organized as follows. Section 2 reviews the literature on trade-related R&D spillovers and distinguishes direct from indirect foreign R&D spillovers. Section 3 re-frames the notion of "indirect" R&D spillovers and defines the inter-country APL as a measurement of the economic distance between countries. Section 4 discusses the econometric model and its empirical specification. Section 5 presents the econometric results. Section 6 concludes and illustrates some future research lines.

2. Trade-related R&D spillovers: direct vs. indirect

Trade-related R&D spillovers are technology flows which diffuse across countries through their import-export relationships. For this reason they are retained an "embodied" kind of flows. In brief, by investing in R&D, exporting firms introduce in traded commodities ameliorations and improvements, which are "embodied" in them and make the related knowledge circulate across countries. What is more, the exporting firms are unable to fully charge the importing firms for this incorporated knowledge, thus allowing them for a "rent R&D spillover" (Griliches, 1979, 1992).

Trade-related R&D spillovers are inherently diverse from those occurring through Foreign Direct Investments (FDI) (van Pottelsberghe de la Potterie and Lichtenberg, 2001). By making R&D investments abroad, Multi-National Corporations (MNC) create new technological knowledge which partially spillovers on the firms of the host-country. This occurs even in the absence of an underlying market transaction between MNC and local firms (as different from a simple interaction): that is, in a "disembodied" way. The fact that knowledge is non fully appropriable is enough to have "pure knowledge" spillovers.[2]

International R&D spillovers have been investigated also with respect to other disembodied flows. Following the method proposed by Jaffe (1986), pure knowledge spillovers have been mapped by looking at the technological similarity between sectors, as captured by cross-patent citations in technology-flow matrices (e.g. Verspagen, 1997). Patent citations have been also used to investigate the role of geographic distance in driving the impact on TFP of domestic vs. international spillovers (e.g. Jaffe et al., 1993), controlling for the absorptive capacity of the recipient country (Mancusi, 2008), the origin of R&D funding (Guellec and van Pottelsberghe de la Potterie, 2004), and other characteristics of the institutional set-up. Recently, increasing attention has being devoted to the role of information technology in international R&D spillovers and productivity growth (Tang and Koveos (2008), for example, use international telephone traffic as means of disembodied R&D flows). A survey of the massive literature

---

[2] One might just think of those spillovers which pass through "demonstration effects" of the new technology by the MNC to the local firms, or through the "employment effects" related to the local workforce training and mobility. Different is instead the case of those spillovers which pass through the vertical (both backward and forward) and horizontal linkages MNC have with the domestic suppliers-clients and competitors, respectively. In the presence of an underlying market transaction, the disembodied flows actually combine with embodied, rent ones. A certain combination can be traced also with respect to trade, where disembodied spillovers can add to embodied ones by considering that international trade can simply "expose" the foreign knowledge to the importing country (van Pottelsberghe de la Potterie and Lichtenberg, 2001). Still, unlike trade-based, FDI-based R&D spillovers should be considered for us disembodied flows (e.g. Kim and Lee, 2004), rather than embodied ones, as some authors claim (e.g. Tang and Koveos, 2008).

on the topic is out of this paper's reach (for a review see Saggi, 2002). However, overall it seems to us that, at least in the OECD area, bilateral trade is still an important channel for international R&D spillovers, especially versus FDI, whose impact is instead relatively small (Zhu and Jeon, 2007, p.955). Accordingly, trade-related R&D spillovers deserve more careful investigation (Bitzer and Geishecker, 2006), a research stream along which this paper places.

Once identified as an important channel of international technology diffusion, trade is also a potential driver of economic growth (e.g. Jacob and Los, 2007). In particular, it enables innovation to flow across countries, for example via the increase in the number and quality of intermediate inputs (Grossman and Helpman, 1991; Peri, 2005). Accordingly, the foreign R&D stock of a country can be expected to impact on its TFP as well as its domestic one.

The issue then becomes an empirical one, in which an accurate index of the foreign trade-related R&D capital stock (hereafter foreign R&D stock) has to be worked out. This is a research question which Coe and Helpman (1995) (CH hereafter) for first addressed by suggesting to equate the foreign R&D stock of a certain country to the import-weighted sum of the domestic R&D capital of its trade partners. In so doing, they found that the foreign R&D stock actually had a significant impact on the TFP of a number of OECD countries over the period 1970-1990.

This seminal work stimulated a lot of reactions and extensions. On the one hand, a number of papers have tried to extend the original setting, by including additional explanatory variables – in particular, human capital (Engelbrecht, 1997) and the institutional set-up (Coe et al., 2009) – and by enlarging the data coverage (Madsen, 2007). In general, these extensions confirm the CH results on the role of international trade in diffusing knowledge. On the other hand, less confirming is a thread of papers which focus on the sensitivity of the results to the measurement of foreign R&D. Lichtenberg and van Pottelsberghe de la Potterie (1998) (LP hereafter), for example, identified in CH an "aggregation-bias" due to mergers among foreign countries. Accordingly, they suggested to correct the original weighting scheme of foreign R&D and divided its weights by the GDP of the exporting country.[3] Along this thread, the work by Keller (1998) is particularly important. Not only because did he not obtain worse results than CH by weighing their foreign R&D data with allegedly *random*, rather than with observed trade shares (Coe and Hoffmaister (1999) actually showed them not being actually random). But also and above all because he got an even better outcome by equating the foreign R&D of each country to the simple sum of the domestic R&D produced by all the other countries.

As Lumenga-Neso et al. (2005) (LOS hereafter) argued, rather than a supposed proof of the trade irrelevance in conveying technological knowledge, Keller's application might point to a different concept of foreign R&D stock, which they call *available*. Indeed, by importing from a foreign country, not only does a

---

[3] As we will see, casting doubts on the economic interpretation of this operation, Lumenga-Neso et al. (2005) instead suggest to refer to the GDP of the importing country.

domestic one benefit from the R&D investments of the former – *direct* foreign R&D spillovers. But also from those R&D investments made by *other* foreign countries, with which the initial foreign country only has traded, while the domestic one has not – *indirect* foreign R&D spillovers. LOS' contribution adds a further important piece to the "mosaic" of the productivity impact of foreign R&D stock.

The distinction between direct and indirect trade-related spillovers appears to us extremely interesting and appealing. As we will argue in the next section, it brings to the front the "economic" distance which separates countries in terms of trade rounds. This distance, we claim, affects the extent to which domestic countries can actually access the foreign R&D stock available abroad and the extent to it impacts on their TFP.

3. Indirect foreign R&D and economic distance: the "Average Propagation Length"

Following LOS, R&D spillovers (trade-related will be omitted hereafter) are indirect as they are embodied in commodities which go from the foreign to the domestic country through at least one intermediate country. In the example we made in the introduction (Section 1), this is the case of Belgium, which intermediates the R&D from the US to the Netherlands. However, the intermediation could be represented by two or more countries. In the same example, the Netherlands could benefit from the R&D of Japan, if the US in turn imports from it. And this is so even if neither the Netherlands, nor Belgium trade with Japan. The Japanese R&D spillovers available to the Netherlands are still indirect, but evidently not as indirect as the US ones. While the latter go through one "trade round", the former require two trade rounds to become available to the Netherlands.[4] In our opinion, an appropriate measurement of the foreign R&D available to a domestic country should take this into account, and more explicitly than LOS do.

First of all, let us clarify what in our framework *trade-round* means. One generic country j normally satisfies another country i's demand of imports, m_{ij}, by processing commodities it also imports from other countries, such as, for example, country k: m_{jk}. m_{jk} is thus a function of m_{ij}, and we can write $m_{jk}(m_{ij})$.[5] To satisfy this demand, country k, in turn, may require commodities

---

[4] We must warn the reader that the example is in terms of binary (on/off) trade relationships just to make the point clearer. The methodology and the application are instead closer to trade reality and developed in terms of value relations. Indeed, also because of the high level of aggregation of our empirical application, simply referring to the binary international trade does not make too much sense since this is almost complete and therefore uninformative (almost every country trades something with every other). On this point see also footnote 8.

[5] How much of country k's commodities will actually enter in the production of country j's commodities can be defined only by moving at a sectoral level of disaggregation. The same disaggregation would be necessary to account for the fact that only intermediate commodities are transformed to produce those final and capital goods which are then traded. Although at the price of some inaccuracy, for the sake of simplicity, we provide only the intuition of this

from another generic country z, so that we can write $m_{kz}(m_{jk}(m_{ij}))$, and the same might hold true for z with respect to another trade partner, s, of it, that is $m_{zs}(m_{kz}(m_{jk}(m_{ij})))$, and so on. Hence, country i adds to its direct imports from j, m_{ij}, the indirect ones required after the first step trough each generic country k, $\sum_k m_{jk}(m_{ij})$, those after the second step trough each generic country z, $\sum_{k,z} m_{kz}(m_{jk}(m_{ij}))$, and so on. In this framework, therefore, a trade-round is a step of a global production process which occurs at the inter-country level.

The sequence of these trade-rounds between two countries defines a *trade-chain* along which we can identify a particular kind of distance between them. As it is determined by the international structure of production and by the countries' specialization patterns, this distance is *economic* rather than geographic. Taking into account the role of transportation costs, this distance may be related to a standard geographical one: close economic partners in terms of trade could be expected to be geographically close too, and the trade-chain to have a correspondent spatial dimension. However, especially in a world trade network (De Benedictis and Tajoli, 2009) which is much "flatter" than it used to be in the past (Friedman, 2007; Stiglitz, 2007), this cannot be taken for granted. For instance, two countries such as Belgium and the Netherlands, which are geographically close, could be distant in economic terms if their specialization patterns are in commodities which require a lot of trade-rounds between them.[6] Finally, let us note that, unlike the geographical distance, the economic distance is not symmetric, cause the economic distance from country i to country j is not necessarily the same from that separating j from i.

The sequence of trade-rounds which constitutes the trade-chain between countries obviously takes (real) time to be covered, and would thus require a dynamic model to be investigated. However, even in a static framework, in which all the trade-rounds are assumed to occur simultaneously with respect to the real time, each of them can be retained in a different logical time. Furthermore, as shown by the input-output based literature on product-embodied R&D diffusion (e.g. Papaconstantinou et al., 1998; Sakurai et al., 1997), different sectors have different propensity to rely on their own R&D, rather than on that of other sectors: the distinction between manufacturing and services in this last respect is crucial. Similarly, different sectors have different propensity to acquire and diffuse embodied R&D abroad, rather than domestically: for example, ICT is emerging as the most acquired sector in the OECD area. On this basis, trade-rounds for foreign R&D among countries should be taken to have sector specific sequences and length. An accurate account of their TFP impact would thus require us to measure such a kind of rounds along intersectoral trade

---

argument and in the following we remain at the country level.

[6] This kind of economic distance should not be confused with that which, starting from the seminal paper by Patel (1964), economists have elaborated in order to account for the economic dependence among countries and for its growth impact (e.g Conley and Ligon, 2002). Furthermore, although a relationship could be envisaged, the same economic distance differs from the technological one the North-South trade models and developing studies usually refer to (e.g. Fukuchi and Satoh, 1999).

diagrams, as suggested by Wixted (2009). However, while making the analysis more accurate, adding an intersectoral dimension to the inter-country (bilateral) one would have strongly reduced the country and time coverage of the empirical analysis because of the lack of consistent data. In the present paper the trade off is resolved choosing an aggregate level of analysis so to increase data coverage. This choice also improves the comparability of our results with the other studies derived from CH's seminal work.

3.1. Economic distance between countries and international technology diffusion

The literature on the impact geographic distance has on the international diffusion of technology is quite large (Keller, 2002, 2004; Mancusi, 2008). In spite of some apparent contradictory results, the effects foreign R&D has on the domestic productivity seems to decline with the geographic distance between countries. To the best of our knowledge, which effect the economic distance between countries (the way we define it) has on the international diffusion of technology, instead, has not received great attention yet. While the literature on the world trade network (e.g. De Benedictis and Tajoli, 2009; Fagiolo et al., 2009) has recently moved important steps in understanding the structure of indirect trade relationships, the analysis of their role in the issue at stake is still among its potentialities.

By combining these two streams of literature, in the paper we assume that the economic distance between the sender and the recipient country exerts on the transmitted R&D a "decay rate" similar to the geographic one. But for different reasons. First of all, the longer the economic distance between two countries – that is the higher the number of trade-rounds between them – the lower the rent the recipient country can benefit from the R&D of the supplier. By getting repeatedly embodied in an increasing number of countries, such a rent spreads among an increasing number of appropriation sources, and thus diminishes. Second, considering the economic distance as a component of the wider social one between two countries, the longer it is, the larger the frictions which make the received knowledge progressively less consonant to the transmitted one (as it happens in the classic word-of-mouth game). In both respects, in the static framework we assume, the decay-rate is naively instantaneous. In a dynamic framework, instead, with the passage of time, a longer economic distance increases the possibility that the recipient country develops more efficient domestic, technological knowledge before the foreign knowledge reaches it, thus becoming the latter obsolete.[7]

---

[7] Although the previous arguments support it in more than one respect, the assumption we make needs further discussion and empirical support. In particular, one should be able to reject the alternative hypothesis of a positive relationship between economic distance and the productivity impact of foreign knowledge. An hypothesis that could be supported by thinking of the synergies and super-additive effects trade intermediation might have. Although we do not think this is the case, in the empirical application we will control for this possibility.

3.2. The Average Propagation Length of foreign R&D

In trying to measure the economic distance between countries, we exploit an interesting analogy with the ideas of production-round and Leontief multipliers developed within the Input-Output (IO) analysis.[8]

This analogy appears evident when we formalize our account of direct and indirect trade relationships (Section 2) and apply it to R&D as a proxy of technological knowledge. Following LOS, we can state that the total R&D *available* in each country (S^t) is the sum of the R&D *produced* domestically (S^d) and the R&D *available* in its trading partners weighted by the correspondent bilateral import-GDP ratios:

$$S^t = S^d + \mathbf{M}S^t \tag{1}$$

where $\mathbf{M}$ is the matrix of country-by-country import/GDP ratios, S^d is the column vector of domestic R&D stocks and S^t the column vector of R&D stocks available in each country.[9].

Solving the previous equation for S^t yields:

$$S^t = (\mathbf{I} - \mathbf{M})^{-1}S^d = (\mathbf{I} + \mathbf{M} + \mathbf{M}^2 + \mathbf{M}^3 + ...)S^d \tag{2}$$

where $\mathbf{I}$ is the identity matrix.

Being the difference between S^t and S^d, the foreign R&D stock is thus given by:

$$S^f_T = (\mathbf{I} - \mathbf{M})^{-1}S^d - S^d = [(\mathbf{I} - \mathbf{M})^{-1} - \mathbf{I}]S^d = (\mathbf{M} + \mathbf{M}^2 + \mathbf{M}^3 + ...)S^d \tag{3}$$

The effect that an increase in the countries' domestic R&D (ΔS^d) has on the foreign R&D available (ΔS^f_T) is therefore:

$$\Delta S^f_T = (\mathbf{M} + \mathbf{M}^2 + \mathbf{M}^3 + ...)\Delta S^d \tag{4}$$

Equation (4) transposes in analytical terms the step-wise process we have discussed in Section 3. The R&D produced by a country j (ΔS^d_j) gets "embodied" into the goods another country i imports from it, which benefits from it proportionally to the incidence of these imports on its GDP. The share of ΔS^d_j which

---

[8] Other useful analytical tools seem those provided by complex network analysis. Nonetheless, despite the many progresses made recently in the analysis of *valued networks* under the heading of "complex weighted network analysis" (see, for instance, Barthélemy et al., 2005), most of the tools developed so far can be used only to analyze *binary networks*. Therefore, the trade network is sometimes reduced for analytical convenience to a binary one (e.g. De Benedictis and Tajoli, 2009; Fagiolo et al., 2009). However, once "binarized" with no strictly positive threshold, this network becomes almost complete, given that it is not so common that two economies do not trade at all, and this leads to trivial results. For a discussion of the problems entailed in choosing the threshold see, for instance, Montresor and Vittucci Marzetti (2009). An analysis of intersectoral "embodied" R&D flows by means of both IO analysis and network analysis is in Montresor and Vittucci Marzetti (2008).

[9] To be sure, LOS initially refer to bilateral import shares. As it poses analytical problems, we use import/GDP ratios as weights. As we will see, this does not affect substantially the meaning of indirect trade related flows.

reaches country i through direct imports, and thus "feeds" its available foreign R&D stock ($\Delta S^f_{T,i}$) is thus weighted according to m_{ij} in the matrix $\mathbf{M}$. Consistently, taking into account intermediate trade-rounds, the R&D which takes an intermediate country to the same destination is weighted according to $[\mathbf{M}^2]_{ij}$; that going through two intermediate countries, according to $[\mathbf{M}^3]_{ij}$; and so on and so forth.

Equation (4) is pretty similar to that through which standard IO analysis deals with the effects of a demand pull occurring in sector j ($\Delta\mathbf{f}$) on the total sectoral output of i ($\Delta\mathbf{x}$). By neglecting the round-zero effects – amounting to the initial demand-led increase of output ($\Delta\mathbf{x} = \Delta\mathbf{f}$) – the direct and indirect effects of $\Delta\mathbf{f}$ on $\mathbf{x}$ in the subsequent production rounds can be written as:

$$\Delta\mathbf{x} = (\mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + ...)\Delta\mathbf{f} \tag{5}$$

where $\mathbf{A}$ is the input coefficient matrix, whose generic element is $a_{ij} = x_{ij}/x_j$, x_{ij} are the input deliveries of sector i to sector j and x_j its total output.

As is well known, the production rounds Equation (5) refers to are those needed to produce the inputs required to produce $\Delta\mathbf{f}$ (round 1), the inputs for these latter inputs (round 2), and so forth, in a recursive way.

Quite interestingly, Equations (4) and (5) – from both of which round 0 effects have been dropped[10] – are conceptually identical, and this fact can be exploited to find the measurement of inter-country economic distance we are looking for. Our suggestion is that of extending to direct and indirect inter-country linkages of trade-embodied R&D flows the matrix of Average Propagation Lengths ($\mathbf{V}$) Dietzenbacher et al. (2005) (DRB hereafter) have defined with respect to direct and indirect production flows between sectors.

Intuitively, in the standard IO Leontief model, the generic element of this matrix, v_{ij}, can be defined as the average of the different (and infinite) production rounds – that is 1, 2, 3, ... – linking sector i to sector j, weighted by their correspondent "production importance" (see AppendixA for a formal derivation).[11]

Extending this idea to indirect foreign R&D spillovers, the APL between two countries, v^*_{ij}, can be defined as the average number of trade rounds the R&D of a foreign country j (S^d_j) takes to affect the R&D available to a domestic country i through trade ($S^f_{T,i}$). By extending the analytical procedure developed by DBR, v^*_{ij} can be defined as:

$$v^*_{ij} = \frac{1 \times m_{ij} + 2 \times [\mathbf{M}^2]_{ij} + 3 \times [\mathbf{M}^3]_{ij} + ...}{l^*_{ij} - \delta_{ij}} = \frac{h^*_{ij}}{l^*_{ij} - \delta_{ij}} \tag{6}$$

where δ_{ij} (= 1 if $i = j$ and 0 otherwise) is the Kronecker delta, l^*_{ij} is the generic

---

[10] The IO round-zero effect is actually correspondent to the domestic R&D stock of a certain country.

[11] As Dietzenbacher et al. (2005) argue, these production rounds do not have a temporal but rather a logical connotation.

element of $\mathbf{L}^*$:

$$\mathbf{L}^* = (\mathbf{I} - \mathbf{M})^{-1} \tag{7}$$

and h^*_{ij} the generic element of $\mathbf{H}^*$:

$$\mathbf{H}^* = (\mathbf{L}^* - \mathbf{I})\mathbf{L}^* \tag{8}$$

where the previous matrix is simply the correspondent of the matrix $\mathbf{H}$ in the original intersectoral framework (Equation (A.3)). The two differs only because the matrix $\mathbf{H}$ has been transposed for consistency, since in the original IO framework the row indicates the source of the flow (i.e. the sector where the inputs come from), whereas here it is the column that indicates the source of the flow (i.e. the country where the imports come from).

On the basis of the previous arguments, a matrix $\mathbf{V}^*$ can be obtained, whose elements proxy the economic distance between countries.[12] Accordingly, the foreign R&D stock available in each country can be obtained by using them as weights for the R&D produced in the foreign countries.

It should be noticed that the method we suggest to weigh foreign R&D is only apparently similar to that put forward by LOS. Rearranging their own Equation (4), their available foreign R&D stock can be written as follows:

$$S^f_T = (\rho\mathbf{M} + \rho^2\mathbf{M}^2 + \rho^3\mathbf{M}^3 + ...)S^d \tag{9}$$

where $\mathbf{M}$ is, in their account, the matrix of bilateral import shares ($m_{ii} = 0$ and $\sum_j m_{ij} = 1$), $\mathbf{I}$ the identity matrix and ρ a parameter of *absorption capacity* of foreign knowledge, defined on the domain $[\,0, 1\,]$ (being $\rho = 0$ the case of no absorption capacity, and $\rho = 1$ that of perfect absorption).

In spite of the similarity with our Equation (4), this specification suffers from some problems. The first one is conceptual: defining ρ in terms of absorptive capacity does not seem completely adequate. The innovation literature deals with absorptive capacity as a specific characteristic of the individual countries involved in the knowledge diffusion process (e.g. Lall, 1992). The ρ LOS use instead seems a characteristic of the knowledge *exchange* between the countries, and of its frictions in particular. Only with this meaning, we claim, ρ can be modeled as a country-invariant parameter, as they do in Equation (9).

With this interpretation, ρ takes a meaning which is close to our APL between countries: the higher the number of trade rounds, the lower the amount of foreign-knowledge available domestically, as with $0 < \rho < 1$ we have that $\rho > \rho^2 > \rho^3 > \ldots$. However, unlike our APL, which is calculated on the basis of a (hopefully) sound economic argument, the value of ρ to be used in their TFP regressions is rather estimated. More precisely, ρ is identified by looking through grid-search the value that maximizes the fitness (R^2) of the different specifications of their model. In so doing, two further problems emerge. First

---

[12] This should be actually retained only as a second-best solution due to the existence of data constraints in the empirical application. Indeed, a complete extension of the concept of APL in this framework would have required a full multi-country multi-sector model.

of all, estimated values of $\rho > 1$ (which actually emerge in their estimates) do not found a conceptual counterpart in their framework, even by treating ρ as a parameter of a friction exchange.[13] Second, as they are estimated, the frictions of knowledge diffusion among countries might appear irrelevant even if they are simply small.

4. Empirical application

The empirical application we carry out is intended to illustrate the implications of our proposal in terms of impact on TFP of foreign R&D. In particular, in a comparative way with respect to other methodologies which have been put forward in dealing with the same issue.

By using bilateral trade data for 90 OECD countries, we estimate the TFP impact of the domestic and foreign R&D capital stocks of 20 of them, over the period 1995-2005. Although not very large, at the end, once compared with other works in the same literature, such a dataset draws on extensive intermediate information. Furthermore, it is simultaneously the longest and the most updated one can refer to by relying on officially available data, and for which data inaccuracy is thus minimized (see AppendixB).

The model we estimate is quite standard in the literature and use the following log-linear specification:

$$\log TFP_{c,t} = \alpha_c + \beta^d \log S^d_{c,t} + \beta^f \log S^f_{c,t} + \epsilon_{c,t} \tag{10}$$

where $TFP_{c,t}$ is the Total Factor Productivity of country c at time t, α_c a country dummy, $S^d_{c,t}$ the domestic R&D capital stock, $S^f_{c,t}$ the foreign R&D stock and $\epsilon_{c,t}$ an error term.

Following Section 3.1, we construct our own account of the foreign R&D stock:

$$S^f_{FMV} = \mathbf{W} S^d \tag{11}$$

In defining S^f_{FMV}, the domestic R&D (of the exporting countries) (S^d) is weighted by using the matrix $\mathbf{W}$, defined as:

$$\mathbf{W} = [w_{ij}] = \left[\frac{l^*_{ij} - \delta_{ij}}{v^*_{ij}} \right] \tag{12}$$

where l^*_{ij} is the generic element of the matrix $\mathbf{L}^*$ (Equation (7)) and v^*_{ij} the APL between country j and country i (Equation (6)).

In this formulation, the APL between two countries has a negative impact on the extent to which the domestic R&D of the former turns into the foreign R&D

---

[13] How could country i absorb more than the R&D available in country j? Furthermore, the case of perfect absorption capacity is actually ruled out as $\rho = 1$ would make the matrix $(\mathbf{I} - \rho\mathbf{M})$ of Equation (9) singular and thus non invertible: a problem that, as they themselves suggest, can be overcome by using country-by-country import/GDP ratios as we do in Equation (4).

of the latter through trade. This is consistent with our hypothesis (Section 3.1) of a "decay-rate" effect induced by the economic distance between countries.

In order to control for the soundness of this hypothesis, we also allow for a more flexible impact of the APL on the international technology diffusion, and use for $S^f_{c,t}$ the following weighting scheme:

$$\mathbf{W} = [w_{ij}] = \left[(v^*_{ij})^{\gamma}(l^*_{ij} - \delta_{ij})\right] \tag{13}$$

In particular, the opposite hypothesis that trade-rounds increase the productivity impact of the transmitted knowledge is tested by performing a grid-search on γ. By making it span from $\gamma = -5$ up to $\gamma = 5$, with $\Delta\gamma = 0.005$, we search for the value that maximizes the fitness of the regression. An estimated value of $\gamma > 1$ would of course contradict our hypothesis, while a $\gamma < 1$ would support it.

Following CH, and unlike LOS, we do not lag the stock of foreign R&D. First, because we found no evidence of endogeneity of R&D stocks.[14] Second, because the different time-lags needed in equilibrium for the foreign R&D stocks to affect TFP are already captured by the APL in our specification.

For the sake of comparison, in addition to our own, we estimate Equation (10) with respect to other five specifications in which, *ceteris paribus*, $S^f_{c,t}$ is built up according to the alternative methods put forward in the literature (see Section 2 and Table 1 for a summary of the different measures of foreign R&D stock).

In the first of them, we replicate the seminal approach of CH and construct the foreign R&D stock as $S^f_{CH} = \mathbf{M}S^d$, where $\mathbf{M}$ is the matrix of bilateral imports over each and every country's total imports.

In the second one, we instead use the approach LP suggested to solve the problem of aggregation bias detected in CH, and weight foreign R&D with bilateral imports divided by the GDP of the exporting country (S^f_{LP}).[15]

---

[14] We test the endogeneity of foreign R&D stock by using as instruments one and two year lagged values of the variable. The null hypothesis of exogeneity is never rejected at the 10% significance level.

[15] With respect to the aggregation bias, we must warn the reader that both LOS measures and ours suffer from some form of bias produced by country aggregation, even when $\mathbf{M}$ elements are bilateral import/GDP ratios. This is similar to what happens in IO analysis in case of sectoral aggregation (see Miller and Blair, 2009, p.165-167). So, for instance, although the authors do not analyze it, in LOS the aggregation bias is equal to:

$$\mathbf{b} = \left[(\mathbf{I} - \rho\mathbf{M}^*)^{-1} - \mathbf{I}\right]\mathbf{T}S^d - \mathbf{T}\left[(\mathbf{I} - \rho\mathbf{M})^{-1} - \mathbf{I}\right]S^d = \left[(\mathbf{I} - \rho\mathbf{M}^*)^{-1}\mathbf{T} - \mathbf{T}(\mathbf{I} - \rho\mathbf{M})^{-1}\right]S^d$$

where $\mathbf{M}^*$ is the matrix of import/GDP ratios of the aggregated system and $\mathbf{T}$ is the *aggregation matrix* (Miller and Blair, 2009, p.161). The total aggregation bias vanishes if and only if:

$$(\mathbf{I} - \rho\mathbf{M}^*)^{-1}\mathbf{T} = \mathbf{T}(\mathbf{I} - \rho\mathbf{M})^{-1}$$

that is if and only if:

$$\mathbf{TM} = \mathbf{M}^*\mathbf{T}.$$

A condition almost certain not to be met since countries have different bilateral import/GDP ratios.

Table 1: Measures of foreign R&D stock

Authors	Formula	Weight
Coe & Helpman (1995)	$S^f_{CH} = \mathbf{M}S^d$	Bilateral import share: $m_{ij} = IMP_{ij}/\sum_j IMP_{ij}$
Lichtenberg & van Pottelsberghe de la Potterie (1998)	$S^f_{LP} = \mathbf{M}S^d$	Bilateral export intensity: $m_{ij} = IMP_{ij}/GDP_j$
Keller (1998)	$S^f_K = (\mathbf{1} - \mathbf{I})S^d$	No weight: sum of domestic R&D stocks of other countries
Lumenga-Neso, Olarreaga & Schiff (2005)	$S^f_{LOS} = [(\mathbf{I} - \rho\mathbf{M})^{-1} - \mathbf{I}]S^d$	Total adjusted flows using bilateral import shares: $m_{ij} = IMP_{ij}/\sum_j IMP_{ij}$ $0 < \rho < 1$
	$S^f_{LOS2} = [(\mathbf{I} - \rho\mathbf{M})^{-1} - \mathbf{I}]S^d$	Total adjusted flows using import/GDP ratios: $m_{ij} = IMP_{ij}/GDP_i$ $\rho > 0$
Franco, Montresor & Vittucci Marzetti	$S^f_{FMV} = \mathbf{W}S^d$	APL weighted total flows: $w_{ij} = v^{*-1}_{ij}(l^*_{ij} - \delta_{ij})$ v^*_{ij}: APL from j to i $l^*_{ij} - \delta_{ij} = \left[(\mathbf{I} - \mathbf{M})^{-1} - \mathbf{I}\right]_{ij}$ $m_{ij} = IMP_{ij}/GDP_i$

In the third specification, following Keller, we define the foreign R&D stock of each and every country (S^f_K) as the simple sum of the correspondent rest of the world's R&D stock.

In the fourth specification, as in LOS, we calculate the total foreign R&D stock (S^f_{LOS}) according to Equation (9) by using the best fitting estimated value of ρ.

In the fifth specification, as also done by LOS, we calculate the total foreign R&D stock (S^f_{LOS2}), still according to Equation (9), but by defining $\mathbf{M}$ as the matrix of bilateral import/GDP ratios.[16]

As far as the econometric strategy is concerned, at the outset, we estimated a fixed effects model and run some diagnostics tests on it. In particular, we checked for homoskedasticity, using the modified Wald test, and controlled for zero serial correlation, using the Wooldridge test (Wooldridge, 2002). As shown in Table 3, tests confirm the presence of both heteroskedasticity and serial correlation, forcing us to estimate the models using a Feasible Generalized Least Square (FGLS) estimator.

We also checked for the presence of nonstationarity in our series by running

---

[16] In both these last specifications, ρ is estimated by means of a grid search for that value which maximizes the overall fitness of the regression (R^2). In the first one, the search is carried out starting from 0 and increasing it by discrete changes of 0.005, up to 0.999. In the second one, the search is carried out in a larger range ($[0, 3]$), allowing for the possibility that it can be greater than 1, with $\Delta\rho = 0.005$. Enlarging the set further would have produced negative estimates of the foreign stock.

two panel unit root tests. A standard procedure in this last respect is that suggested by Levin et al. (2002), which assumes that all panels display the same autoregressive parameter, that is a cross sectional common unit root is present.[17] However, as the variable of domestic R&D displays some missing values, it is not possible to run such test, which requires strongly balanced panels. Accordingly, we rather run Fisher-type tests (Choi, 2001) which, unlike the case of the previous test, allow for the autoregressive parameter to be panel specific: in this way we are also able to make robustness checks. As Table 2 shows, all the tests reject the null hypothesis of the presence of a unit root in our series, confirming that variables are stationary.

5. Results

Table 3 reports the estimation results of Equation (10), carried out by using the Feasible Generalized Least Square (FGLS) estimator.

The measurement of foreign R&D stock capital we propose (S^f_{FMV}, column (vi)) turns out significant in affecting TFP and with the expected positive sign. Furthermore, the point estimates of the correspondent coefficients recognize to foreign R&D (.0437) a larger impact than to the domestic one (.0138). This is a first important outcome, which confirms after one decade the seminal result CH obtained for the period 1971-1990: trade matters in conveying foreign technological knowledge to the OECD countries.

To be sure, once replicated with respect to our most recent period – 1995-2005 – in the original CH specification, the foreign R&D stock (S^f_{CH}, column (i)) turns out non significant. Relying on direct R&D spillovers only, as CH do, thus appears currently more severe than in the past in attenuating the TFP impact of foreign technological knowledge. The increasing complexity and integration of trade at the worldwide level might have a role in accounting for this result. In the same vein can be interpreted the results of the Keller specification, whose foreign R&D stock (S^f_K, column (iii)) is also non significant, but possibly as an overestimation of the indirect R&D spillovers LOS point to.

The only other exception to the TFP significance of foreign R&D is that of the first LOS specification (S^f_{LOS}, column (iv)). On the one hand, this is apparently surprising, as LOS share the same indirect logic as ours. On the other hand, however, unlike our own approach, but like CH, this specification uses bilateral import shares as weights. As we noticed in the previous Section, although substantially equivalent, this choice might entail methodological problems.[18]

---

[17] This test is recommended especially when the size of the panel is moderate, like in our case.

[18] The way bilateral import flows are turn into ratios might have a role also in accounting for the results of the LP specification, where they are divided by the GDP of the exporting countries. While the positive TFP impact of the foreign R&D stock is confirmed (S^f_{LP}, column (ii)), that of the domestic one is exceptionally significant but negative. A result which is difficult to accommodate, even by retaining the different temporal span of the current

Table 2: Unit Root tests

	Fisher-ADF without trend	Fisher-ADF with trend	LLC without trend	LLC with trend
$\log TFP$	52.5819*	105.4099***	-1.9127**	-5.1370***
$\log S^d$	52.9093*	183.0894***		
$\log S^f_{CH}$	79.6840***	197.4404***	-4.0676***	-12.1027***
$\log S^f_{LP}$	85.6235***	288.6916***	-18.6994***	-33.1653***
$\log S^f_{K}$	76.6267***	319.5257***	-15.1712***	-9.3217***
$\log S^f_{LOS}$	85.7136***	313.9497***	-94.4951***	-16.6229***
$\log S^f_{LOS2}$	84.8434***	237.6793***	-2.4747***	-2.3e+02***
$\log S^f_{FMV}$	82.7288***	348.4505***	-4.6670***	-2.8e+02***

In all the tests, the null hypothesis is non stationarity.
Reported statistics: Fisher-ADF test: inverse χ^2; Levin test: bias adjusted t (t^*_δ).
Significance levels : * 10%; ** 5%; *** 1%.

Table 3: FGLS estimation results (pooled data 1995-2005 for 20 countries; dependent variable: log TFP)

	(i) CH	(ii) LP	(iii) Keller	(iv) LOS	(v) LOS2	(vi) FMV
$\log S^d$	0.0219*	-0.0176**	0.0056	-0.0137	0.0125**	0.0138**
	(0.0115)	(0.0085)	(0.0050)	(0.0206)	(0.0050)	(0.0055)
$\log S^f_{CH}$	0.0139					
	(0.0159)					
$\log S^f_{LP}$		0.0436***				
		(0.0098)				
$\log S^f_{K}$			0.0942***			
			(0.0184)			
$\log S^f_{LOS}$				0.0225		
				(0.0225)		
$\log S^f_{LOS2}$					0.0427***	
					(0.0070)	
$\log S^f_{FMV}$						0.0437***
						(0.0079)
Cons	4.1794***	4.3792***	3.0786***	4.2419***	3.9684***	3.9496***
	(0.2328)	(0.0789)	(0.2903)	(0.3546)	(0.1108)	(0.1231)
Obs.	219	219	219	219	219	219
Wald χ^2	4.91*	22.10***	28.61***	1.38	39.06***	32.58***
Wald test	6924.3***	6019.6***	3568.6***	5089.5***	8135.9***	5110.2***
Wooldridge test	52.31***	144.50***	62.80***	51.56***	53.56***	54.53***

Estimation robust to heteroskedasticity and first order serial correlation.
Null hypothesis: Wald test: no heteroskedasticity; Wooldridge test: no serial correlation.
Standard errors in parenthesis. Significance levels : * 10%; ** 5%; *** 1%.

Looking for the specifications with the highest fitness, still referring to FGLS, those are our own FMV and LOS2, with only a marginal difference in the tests between them (see the Wald χ^2). This is an interesting, although somehow ambivalent result. On the one hand, as expected, the relevance of indirect R&D spillovers through trade is double confirmed: while considering only direct trade flows, as done by CH, underestimates the productivity impact of foreign R&D, retaining direct and indirect trade flows indistinguishably, as in Keller, actually overestimates the same impact. On the other hand, our own approach might seem not to add much to LOS2, at least in terms of econometric outcomes. However, what we got is actually more than a simple confirmation of the LOS2 approach, but rather an important specification of it. If indirect trade-related R&D spillovers matter, as they also find, this is so in spite of the economic distance which separates countries, rather than in spite of their imperfect absorptive capacity, as they argue. Indeed, the grid search we performed on the weighting scheme with γ returned a value $\gamma^* = -0.145$, thus supporting the hypothesis that an increasing APL makes spillovers decrease. Also in the estimates carried out with LOS and LOS2 (columns (iv) and (v)), the grid search for the most fitting ρ returns a value lower than one (0.65 and 0.895, respectively). However, such parameter appears significantly invariable across countries. As in the first application by LOS, also in our estimates, allowing for asymmetric deviations from the most fitting ρ value to account for its variability across countries, or groups of countries (e.g. developed and developing countries), does not improve the fitness. This would amount to say, paradoxically and counterfactually, that all the investigated countries have the same (imperfect) capabilities to absorb and retain foreign technological knowledge from international trade.

In contrast to this odd interpretation, it seems to us what LOS actually found is that the "estimated" frictions which affect knowledge diffusion across-countries are country-invariant. Or, alternatively, that the amount of "estimated" foreign knowledge which remains available to countries is the same, although the economic distance between them (captured by the matrix $\mathbf{V}$) is inherently diverse.

The fact that the *estimated* differences across countries in the foreign knowledge available are significantly negligible, would seem to allow one to conclude that negligible are also the *calculated* differences in the economic distances between countries. However, this is not so, as S^f_{LOS2} and S^f_{FMV} are conceptually and substantially different. First of all, as the trade-related diffusion of technology across countries is imperfect, S^f_{FMV} appears preferable as it encapsulates a measurement of the prime motive of this imperfection, rather than its estimated consequences. Second, S^f_{FMV} is also more accurate from an applied perspective given that it does not rely on any grid search.

---

application, unless by invoking the methodological problems LOS saw in the LP approach.

6. Conclusions

International trade is an extremely important means of technology transfer. By importing from a foreign country, a domestic one can have a twofold technological benefit (Lumenga-Neso et al., 2005). First of all, the latter gains from the R&D investments of the former, whose outcomes get embodied in the commodities it sells abroad, that is in terms of *direct* foreign R&D spillovers. Second, the domestic country also benefits from the R&D investments made by other foreign countries, with which the initial one has traded in turn, in terms of *indirect* foreign R&D spillovers.

Although the idea of *indirect* foreign R&D spillovers has been defined and measured by retaining direct and indirect trade flows, an accurate approach to it requires to consider that the same flows identify a very particular kind of distance, which we call *economic distance*. The analysis of the nature and effects of this distance in terms of international trade is the first value added of the paper.

By extending an argument originally developed in the Input-Output (IO) analysis, this economic distance can be proxied by calculating the average length trade takes in "propagating" knowledge flows across countries: in brief, the Average Propagation Length (APL), which is the second value added of the paper. Finally, this APL can be used to define an original notion of the foreign R&D capital stock available to a certain country, and to estimate the impact it has on TFP along with the domestic R&D capital stock and other standard controls. Indeed, in so doing, we can incorporate in this kind of standard exercise the novel, although quite intuitive idea, that foreign R&D gets through a decay rate because of the economic distance which separate two countries. On the one hand, because the rent the recipient country can benefit from the R&D of the supplier becomes "thinner". On the other hand, because the frictions which make the received knowledge progressively less consonant to the transmitted one also increase.

Our empirical application, carried out with respect to 20 OECD countries over the period 1995-2005, show that the approach we put forward confirm, at least to a certain extent, the results obtained by other alternative approaches with respect to the same dataset. However, it provides for them a different and more accurate interpretation.

More precisely, one decade later Coe and Helpman's (1995) seminal contribution, trade still matters in conveying foreign technological knowledge to the OECD countries. However, the TFP impact of the foreign R&D capital stock is in general significant, providing indirect trade flows are retained in transmitting foreign knowledge across countries.

Once compared with the previous models, our own seems to perform better than those which either neglect indirect R&D spillovers or simply pull them together with the direct ones indistinguishably. As expected, our model performs as well as those which incorporate indirect R&D spillovers, by discounting the decay rate trade imposes on international technology diffusion. However, we claim that, as the APL represents the prime reason of such decay, our approach should be retained conceptually and empirically more accurate.

Finally, the idea of APL of R&D across countries has a number of interesting possible extensions. The most direct one draws on the IO framework underpinning the APL idea, and consists of retaining an intersectoral specification for it. Using the recent developments in the constructions of IO tables at the worldwide level, and combining them with recent empirical work on trade cluster networks (e.g. Wixted, 2009), one could try to measure the different APL different sectors have (in particular, ICT vs. other low- and medium- tech sectors). In so doing, an important interpretation to the evidence of the sector-specific TFP impact of foreign R&D could be provided.

References

Barthélemy, M., Barrat, A., Pastor-Satorras, R., Vespignani, A., 2005. Characterization and modeling of complex weighted networks. Physica A 346, 34–43.

Bitzer, J., Geishecker, I., 2006. What drives trade-related R&D spillovers? decomposing knowledge-diffusing trade flows. Economics Letters 93 (1), 52 – 57.

Boschma, R. A., 2005. Proximity and innovation: a critical assessment. Regional Studies 39 (1), 1–14.

Choi, I., 2001. Unit root tests for panel data. Journal of International Money and Finance 20, 249–272.

Coe, D., Helpman, E., 1995. International R&D spillovers. European Economic Review 39, 859–887.

Coe, D. T., Helpman, E., Hoffmaister, A. W., 2009. International R&D spillovers and institutions. European Economic Review 53 (7), 723–741.

Coe, D. T., Hoffmaister, A. W., February 1999. Are there international R&D spillovers among randomly matched partners? A response to Keller. Working Paper 18, International Monetary Fund.

Conley, T., Ligon, E., 2002. Economic distance and cross-country spillovers. Journal of Economic Growth 7 (2), 157–187.

De Benedictis, L., Tajoli, L., 2009. The world trade network. The World Economy forthcoming.

Dietzenbacher, E., Romero, I., Bosma, N., 2005. Using average propagation lengths to identify production chains in the Andalusian economy. Estudios de Economía Aplicada 23, 405–422.

Eaton, J., Kortum, S., 1999. International technology diffusion: Theory and measurement. International Economic Review 40 (3), 537–570.

Engelbrecht, H.-J., 1997. International R&D spillovers, human capital and productivity in OECD economies: An empirical investigation. European Economic Review 41 (8), 1479–1488.

Fagiolo, G., Reyes, J., Schiavo, S., 2009. The evolution of the world trade web: A weighted-network analysis. Journal of Evolutionary Economics 10, 1–36.

Friedman, T. L., 2007. The world is flat: A brief history of the twenty-first century. Picador.

Fukuchi, T., Satoh, M., 1999. Technological distance between Indonesia and Brazil: a comparative study of technical input structure. Developing Economies 37 (3), 253–274.

Griliches, H. Z. (Ed.), 1992. Output Measurement in the Service Sectors. Vol. 56 of NBER Studies in Income and Wealth. University Of Chicago Press, Chicago.

Griliches, Z., 1979. Issues in assessing the contribution of research and development to productivity growth. The Bell Journal of Economics 10 (1), 92–116.

Grossman, G. M., Helpman, E., 1991. Innovation and Growth in the Global Economy. MIT Press, Cambridge, MA.

Guellec, D., van Pottelsberghe de la Potterie, B., 2004. From r&d to productivity growth: do the institutional settings and the source of funds of r&d matter? Oxford Bulletin of Economics and Statistics 66, 353–378.

Jacob, J., Los, B., 2007. Absorptive capacity and foreign spillovers: A stochastic frontier approach. In: Frenken, K. (Ed.), Applied Evolutionary Economics and Economic Geography. Edward Elgar, Cheltenham UK, pp. 121–144.

Jaffe, A., Trajtenberg, M., Henderson, R., 1993. Geographic localization of knowledge spillovers as evidenced by patent citations. Quarterly Journal of Economics 63, 577–598.

Jaffe, A. B., 1986. Technological opportunity and spillovers of R&D: Evidence from firms' patents, profits, and market value. The American Economic Review 76 (5), 984–1001.

Keller, W., 1998. Are international R&D spillovers trade-related? analyzing spillovers among randomly matched trade partners. European Economic Review 42 (8), 1469–1481.

Keller, W., 2002. Geographic localization of international technology diffusion. The American Economic Review 92 (1), 120–142.

Keller, W., 2004. International technology diffusion. Journal of Economic Literature 42, 752–782.

Kim, J. W., Lee, H. K., 2004. Embodied and disembodied international spillovers of R&D in OECD manufacturing industries. Technovation 4, 359–368.

Lall, S., 1992. Technological capabilities and industrialization. World Development 20 (2), 165–186.

Levin, A., Lin, C. F., Chu, C. S. J., 2002. Unit root tests in panel data: Asymptotic and finite-sample properties. Journal of Econometrics 108, 1–24.

Lichtenberg, F. R., van Pottelsberghe de la Potterie, B., 1998. International R&D spillovers: A comment. European Economic Review 42 (8), 1483 – 1491.

Lumenga-Neso, O., Olarreaga, M., Schiff, M., 2005. On indirect trade-related R&D spillovers. European Economic Review 49, 1785–1798.

Madsen, J., 2007. Technology spillover through trade and TFP convergence: 135 years of evidence for the oecd countries. Journal of International Economics 72 (2), 464–480.

Mancusi, M., 2008. International spillovers and absorptive capacity: A cross-country cross-sector analysis based on patents and citations. Journal of International Economics 76 (2), 155–165.

Miller, R. E., Blair, P. D., 2009. Input-Output Analysis: Foundations and Extensions, 2nd Edition. Cambridge University Press, Cambridge.

Montresor, S., Vittucci Marzetti, G., 2008. Innovation clusters in technological systems: A network analysis of 15 OECD countries for the mid-1990s. Industry and Innovation 15 (3), 321–346.

Montresor, S., Vittucci Marzetti, G., 2009. Applying social network analysis to input-output based innovation matrices: An illustrative application to six OECD technological systems for the middle 1990s. Economic Systems Research 21 (2), 129–149.

Papaconstantinou, G., Sakurai, N., Wyckoff, A., 1998. Domestic and international product-embodied r&d diffusion. Research Policy 27, 301–314.

Patel, S., 1964. The economic distance between nations: its origin, measurement and outlook. The Economic Journal 74 (293), 119–131.

Peri, G., 2005. Determinants of knowledge flows and their effect on innovation. Review of Economics and Statistics 87 (2), 308–322.

Saggi, K., 2002. Trade, foreign direct investment, and international technology transfer: A survey. World Bank Research Observer 17 (2), 191–235.

Sakurai, N., Papaconstantinou, G., Ioannidis, E., 1997. Impact of R&D and technology diffusion on productivity growth: empirical evidence for 10 OECD countries. Economic Systems Research 9, 81–109.

Stiglitz, J. E., 2007. Making globalisation work. W.W. Norton & Co.

Tang, L., Koveos, P. E., 2008. Embodied and disembodied R&D spillovers to developed and developing countries. International Business Review 17, 546–558.

van Pottelsberghe de la Potterie, B., 1997. Issues in assessing the effect of interindustry R&D spillovers. Economic Systems Research 9, 331–356.

van Pottelsberghe de la Potterie, B., Lichtenberg, F., 2001. Does foreign direct investment transfer technology across borders? Review of Economics and Statistics 83 (3), 490–497.

Verspagen, B., 1997. Measuring intersectoral technology spillovers: Estimates from the European and US patent office databases. Economic Systems Research 9 (1), 47–65.

Wixted, B., 2009. Innovation System Frontiers: Cluster Networks and Global Value. Springer, Berlin.

Wooldridge, J. M., 2002. Econometric Analysis of Cross-section and Panel-data. MIT Press.

Zhu, L., Jeon, B., 2007. International R&D spillovers: Trade, FDI, and information technology as spillover channels. Review of International Economics 15 (5), 955–976.

AppendixA. Average Propagation Length in the Input-output model

According to DRB, in the standard Leontief model, where $\Delta\mathbf{x} = \mathbf{L}\Delta\mathbf{f}$ (with $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$), the generic element of the matrix $\mathbf{V}$ (v_{ij}) can be seen as a weighted average of the different (and infinite) production rounds linking sector i to sector j: round $1, 2, \ldots$ More precisely, each round is weighted according to the share of the correspondent total effect on output ($l_{ij} = [\mathbf{L}]_{ij}$) conveyed in it, that is: the share a_{ij}/l_{ij}, in round 1; the share $[\mathbf{A}^2]_{ij}/l_{ij}$, in round 2; and so on.

By dropping the round 0 effects, which are independent from the industrial structure, and referring to $l_{ij} - \delta_{ij}$, where δ_{ij} ($= 1$ if $i = j$ and 0 otherwise) is the Kronecker delta, rather than to l_{ij}, the generic element of the APL matrix $\mathbf{V}$ is:

$$v_{ij} = \frac{1 \times a_{ij} + 2 \times [\mathbf{A}^2]_{ij} + 3 \times [\mathbf{A}^3]_{ij} + \ldots}{l_{ij} - \delta_{ij}} \tag{A.1}$$

After some matrix algebra, the previous expression can be re-written as:

$$v_{ij} = \frac{h_{ij}}{l_{ij} - \delta_{ij}} \tag{A.2}$$

where h_{ij} is the generic element of the matrix:

$$\mathbf{H} = \mathbf{L}(\mathbf{L} - \mathbf{I}) \tag{A.3}$$

As DRB shows, APL is the same in a cost-push IO model, where it measures the weighted average number of steps it takes a cost-push in industry i to affect the price of product j.

AppendixB. Data appendix

The database used in the paper covers 20 OECD countries (Australia, Austria, Belgium-Luxembourg, Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Japan, Korea, Netherlands, Portugal, Spain, Sweden, United Kingdom, United States) plus Slovenia over the decade 1995-2005.[19] It results from the matching of three different datasets.

The first one is the EU KLEMS Database (2008),[20] from which we have drawn the country TFP.

The second dataset is the IMF's Direction of Trade Statistics, from which we have obtained the value of bilateral imports (c.i.f.) in US dollars. Because, when indirect foreign R&D is considered, imports from countries not in the previous group can nevertheless convey indirect flows, as done by Lumenga-Neso et al. (2005), we built up the $\mathbf{M}$ matrix enlarging the sample and here including 90 countries. Still as in Lumenga-Neso et al. (2005), we considered two alternative ways of building $\mathbf{M}$: in the first, the elements of the matrix are calculated as the share of bilateral imports in total imports of each country, while, in the second, we considered the share of imports on the GDP of the importing country. In the latter case, the value of the GDP in US dollars is taken from the World Development Indicators of the World Bank.

The third dataset is the OECD Main Science and Technology Indicators (2008), from which we have taken the Gross Domestic Expenditures on R&D (GERD) – valued at Purchasing Power Parities in constant 2000 US dollars – for all the OECD countries plus some non OECD ones, that is: Argentina, China, Israel, Romania, Russian Federation, Singapore and Slovenia. Following CH and LOS, missing R&D values have been made equal to 0, as in the majority of the cases they refer to countries with relatively negligible total R&D expenditure. As a consequence, out of the 90 countries of the $\mathbf{M}$ matrix, only 35 have been retained to be source of produced R&D. From these data, we calculated the correspondent R&D capital stocks by using the perpetual inventory model (Griliches, 1979; Coe and Helpman, 1995). We assumed a 5% depreciation rate, and estimated the average annual logarithmic growth of R&D expenditures by

---

[19] Due to the lack of disaggregated data, we considered Belgium and Luxembourg as a single country, adding up trade data and using GDP, R&D and TFP of Belgium.

[20] Marcel Timmer, Mary O'Mahony and Bart van Ark, *The EU KLEMS Growth and Productivity Accounts: An Overview*, University of Groningen and University of Birmingham; downloadable at `www.euklems.net`.

using the data for the whole period for which R&D data were available (1981-2005). 1981 was the benchmark year for the calculation of the stock for many countries in our sample.