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The impact of R&D offshoring on the home knowledge production of OECD investing regions

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Abstract

We investigate the effect of research and development (R&D) offshoring from high-income regions to prominent emerging economies. Specifically, we examine whether there is a complementary relationship between a region's home and foreign investments in R&D that affects home's regional knowledge production. Using a theoretical framework based on economic geography and the literature on international knowledge sourcing, we conjecture that high-income regions would have a comparative advantage in high-tech R&D, while emerging economies would have an advantage in medium/low R&D. Complementarity should obtain when the comparative advantages of the geographical areas are utilized. We find overall empirical support for this prediction.

Keywords: R&D offshoring, knowledge production, complementarity, emerging countries
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1. Introduction

Since the 1990s, organizations increasingly have seen offshoring as an important means of achieving competitive advantage. The volume and rate of growth of offshored activities to lower-wage foreign countries have increased hugely (Trefler, 2005). However, compared to offshoring of tangible commodities, research and development (R&D) outsourcing to lower-income countries is a recent phenomenon (Lewin et al., 2009). The increasing internationalization of economic activities is being accompanied by changes to the location of overseas innovative activities (UNCTAD, 2005) with significant proportions of R&D going to developing Asia (Beausang, 2004)—to countries that have emerged as new technology producers (Athreye and Cantwell, 2007).

This development could be considered problematic by the developed regions (see for instance, Manning et al., 2008). The economic geography literature considers R&D and innovation as the main explanations of differences in regional development and growth (e.g. Crescenzi et al., 2007; Frenken et al., 2007; Lehto, 2007) and suggests that regional, geographically bound R&D positively impacts on regional level economic development since knowledge spillovers appear to decay rapidly with geographical distance (see also, Bode, 2004; Ó hUallacháin and Leslie, 2007; Rodríguez-Pose and Crescenzi, 2008; Paci and Usai, 2009). On the other hand, the literature on international knowledge sourcing shows that multinational enterprises (MNEs) increasingly are exploiting R&D internationalization to tap into the technological capabilities of specific host locations in order to improve their own abilities to combine knowledge for innovation (e.g. Cantwell, 1995; Patel and Vega, 1999; Santangelo, 2002; Verspagen and Schoenmakers, 2004; Fifarek and Veloso, 2010).

The work on regional development and R&D does not address the international division of labour in knowledge production and, with the exception of Fifarek and Veloso (2010), the literature on international knowledge sourcing considers only cases where MNEs engage in home-base augmenting investments in other developed regions. Hence, little is known about how offshoring R&D activities to fast-growing emerging economies affects knowledge generation in the home region. Fifarek and Veloso (2010), in the context of rare earth catalyst and magnet technologies, examine how foreign (including fast-growing emerging economies) and home innovative activities co-evolve as a result of offshoring. They analyse changes to the geographical dispersion of innovative activities in USA, Europe and Asia, before and after 1990 when offshoring had become prominent in this area, but not the effects on knowledge production at home of R&D offshoring to fast-growing emerging economies.

The present article contributes to both the literatures referred to by investigating whether and how R&D offshoring to fast-growing emerging economies affects knowledge creation in the OECD investing regions. We focus on R&D offshoring to fast-growing emerging economies, including Brazil, Russia, India, China, Singapore and Taiwan (BRICST), since the empirical evidence suggests that this group receives the lion's share of R&D investment from the advanced regions (UNCTAD, 2005; Belderbos and Sleuwaegen, 2007). We focus also on the type of R&D offshoring and what Kotabe and Murray (2003, 9) call 'offshore subsidiary sourcing' and others (e.g. Kedia and Mukherjee, 2008; Lewin et al., 2009) refer to as 'captive outsourcing'. That is, we examine R&D activities offshored by MNEs headquartered in the OECD region, to subsidiaries in BRICST countries. We use the terms offshoring and internationalization interchangeably. We investigate whether R&D offshoring complements home R&D with respect to knowledge production by the investing region, measured by patent applications. Following Milgrom and Roberts (1995, 181), complementarity among activities obtains if 'doing (more of) any one of them increases the returns to doing (more of) the others'.

While it is possible that offshoring might stifle innovative activity in the home region (see for instance, Teece, 1987; Manning et al., 2008) it is possible also that R&D offshoring to emerging economies will complement and enhance the value of the R&D conducted at home (Kotabe, 1990; Verspagen and Schoenmakers, 2004). Mudambi (2008) suggests that advanced country firms are finding that value-added increasingly is concentrated in the upstream (R&D) and downstream (marketing) ends of the value chain. Thus, firms prefer to focus on these activities at home and to offshore mid value chain activities (manufacturing and standardized services). Following Lewin et al. (2009), we propose that, in addition to offshoring activities in the middle of the value chain, parts of the R&D activity could be offshored. We argue that this should not reduce the efficiency of the home region R&D base.[1]

1 Note that an observed complementarity effect between offshored and home region R&D in home region production of knowledge implies that investment in offshored R&D makes home region R&D more

We assume that: (i) firms in the advanced regions tend to have comparative advantage in R&D in the most advanced technologies; (ii) less complex technologies are easier to codify and transfer across borders and (iii) modular technologies require coordination at the organizational and knowledge levels, which may be managed better within MNEs (as opposed to being traded on the market) and, also, that these technologies are easier to transfer across borders. Based on these assumptions, we propose that offshored R&D that: (i) is not high-technology intensive and, therefore, is also less complex and (ii) is related to modular technologies, should complement R&D conducted in the more advanced home regions. That is, we posit that R&D offshored to BRICST countries is complementary if it is dissimilar to and less complex than the R&D carried out in the home region (e.g. medium/low technology-intensive R&D activities) and requires systemic integration and is easier to transfer across borders (e.g. R&D in software and knowledge-intensive services). Based on this logic, we also posit that there will be no complementarity effect between offshored R&D in high-technology sectors and home region R&D, in terms of knowledge production in the home region.

Our sample comprises 221 large OECD regions for which we have data on patenting activity, socio-economic indicators and R&D offshoring investments in BRICST countries. The regional focus is in line with the regional systems of innovation (RSI) literature (e.g. Cooke et al., 1997; Asheim and Gertler, 2005) and the distributed or open innovation approach (von Hippel, 1988; Chesbrough, 2003). The *meso* level (as opposed to country-level which is a too aggregated unit of analysis) allows us to capture the systemic and 'open' aspect of knowledge production (Braczyk et al., 1998).

The article is organized as follows. Section 2 revisits the theoretical debate on the effects of home and offshored R&D on home innovation activity, and the notion of complementarity. Section 3 examines firms' location advantages in relation to R&D offshoring; Section 4 presents the arguments related to our theoretical expectations. Sections 5 and 6 describe the data and sample, and the model, and Sections 7 and 8 discuss the complementarity, and the spatial econometric issues. Section 9 provides an exploratory analysis and Section 10 presents the results of the econometric analysis. The discussion in Section 11 concludes the article.

2. The theoretical debate

The RSI approach is based on the idea that regional (as opposed to national) borders define the creation of innovation by strongly interrelated local actors (Asheim, 1996; Braczyk et al., 1998; Cooke, 2005). The empirical significance of geographical proximity—consistent with the RSI approach—is confirmed in the work on knowledge spillovers (Jaffe et al., 1993; Feldman, 1994; Audretsch and Feldman, 1996) and clusters (Porter, 1990; Beaudry and Breschi, 2003; Iammarino and McCann, 2006), and research highlighting the problems related to knowledge codification, which can hamper knowledge transmission across large geographical distances (Anselin et al., 1997; Bode,

effective for producing innovation, reflected in home region patents (and vice versa). However, it provides no information on whether or not offshored R&D is associated with higher (lower) investment in home region R&D *per se*. If a complementary effect is identified, it could be argued that there is a stronger incentive to invest in home region R&D for a given region where firms offshore R&D compared to regions where firms make no such investment. For a formal representation of how to test complementarity, see Section 7.

2004; Crescenzi et al., 2007; Rodríguez-Pose and Crescenzi, 2008; Paci and Usai, 2009). Some researchers see the globalization of R&D and innovation as possibly eroding the R&D-based strengths of advanced regions, and predict an incremental shift in R&D activities towards the emerging economies, where scientific and engineering talents are increasing (Manning et al., 2008). However, Cantwell (1995), Patel and Vega (1999) and Le Bas and Sierra (2002) show that although large firms typically retain the largest share of their R&D in their home countries, a substantial part is conducted in foreign locations, aimed ultimately at sourcing new complementary knowledge.

This might be seen as challenging the RSI approach, but Verspagen and Schoenmakers (2004, 24) argue that the tendency to perform R&D abroad rather implies support for this notion. They argue that the existence of specific skills and competencies in people who are not perfectly mobile means that the technological capabilities of specific RSI cannot be exploited easily at a distance (Morgan, 2004) and that MNEs that want to make use of specific knowledge need to achieve some sort of physical presence in the region, an argument echoed by Cantwell and Iammarino (2001). However, as already pointed out, almost all of these contributions consider cases where MNEs engage in home-based research augmenting activity, conducted in other developed regions.

Drawing on the theoretical notion of complementarity, in this article, we examine how offshoring of R&D to fast-growing emerging economies can affect the efficiency of knowledge production in the home region. As noted above, complementarity arises when the marginal return to one element (practice or activity of the firm, industry or region) increases as the volume of another element increases. This notion has achieved prominence in modern economics through the work of Milgrom and Roberts (1990, 1995), who drew on the work of Topkis (1978) and mathematical lattice theory to model complementarities. There is a large empirical literature on complementarities—for a comprehensive review of the complementarity literature applied to management research, see Ennen and Richter (2010). A part of this literature addresses the various complementarities involving firms' external linkages related to innovative activities. In this context, and in a much cited empirical paper, Arora and Gambardella (1990) find four external knowledge sourcing strategies used by chemical firms that are complementary. Cassiman and Veugelers (2006) show that firm-internal and outsourced R&D investments are complementary in affecting product innovation outcomes, and in the geography literature, Mancinelli and Mazzanti (2009) analyse potential complementarities between levels of internal R&D and external networking activities in small and medium sized enterprises. We employ a similar empirical methodology to that employed in the latter two articles. Our main claim is that complementarity effects will emerge in relation to geographical technological specialization and reverse knowledge transfer (i.e. from foreign subsidiary to parent company), so that the home region technological knowledge will increase if the home region firms are strong R&D performers and outsource R&D activities to BRICST countries.[2]

2 Note that we do not check for complementarities between specific technologies. If technological complementarities are very strong, theory and evidence would suggest that the technologies should be kept within the same firm and perhaps at the same geographical location (see, Nesta and Saviotti, 2005).

3. Location advantages of R&D offshoring

Offshoring is part of the global disaggregation of the value chain, and as Mudambi (2008) points out, is a critical interface between the interconnected issues of geography and MNE activity. This disaggregation is the result of firms combining the comparative advantages of different geographic locations with in-house resources and competencies, to create and sustain competitive advantage (Dunning, 1977; Kogut, 1985; McCann and Mudambi, 2005). The interplay between comparative and competitive advantage determines the optimal location of value chain components (i.e. offshoring decisions). Differences in factor costs have strong implications for where firms locate parts of their value-added chains (Kogut, 1985) and indicate that they will choose regions and countries that offer comparative advantages. Because regions and countries differ in terms of numbers and quality of production factors, which eventually are reflected in factor costs, and because the intensity of factor use varies along the value chain, the distribution and type of value adding activities between regions and countries will differ. A key driver of offshoring is related to the implied increased division of labour it allows, which enables the offshoring firm to focus on higher value activities in the home region and to outsource lower value activities to emerging developing countries, typically at lower cost (Stopford and Wells, 1972; Ramamurti, 2004; Doh, 2005; Mudambi, 2008).

The empirical evidence on R&D offshoring suggests that it is enabled by advances in information and communication technology (ICT), which allow information exchange and interaction over larger distances (Howells, 1995; Manning et al., 2008).[3] The transfer of knowledge over large geographical distances is non-trivial, even when facilitated by modern ICT (Bulte and Moenaert, 1998; Morgan, 2004), but this discussion is beyond the scope of the present article.

We posit that location of R&D in emerging countries produces location-specific advantages. An important advantage is that offshore locations offer specific high-quality R&D services at low cost. Also, the regional science and technological base varies 'from country to country and from region to region [and] is said to constitute the location-specific supply base of technological and knowledge externalities that firms draw upon for their competitiveness' (Amin and Cohendet, 2005, 467). Examples are India's supply of engineers and strengths in software development, and Taiwan's strengths in computer hardware. According to Lewin et al. (2009, 920): 'Asian countries such as India and China, and certain countries in Eastern Europe and Latin America, are becoming recognised as suppliers of highly qualified engineering and science talent'. Related to this is evidence of increased clustering of R&D activities in emerging economies (see, e.g. Chen, 2004; Arora and Gambardella, 2005; Tan, 2006), which is allowing MNEs to exploit these science and technology systems through subsidiary location choices.

3 Note there are several mechanisms that allow MNEs to transfer tacit knowledge, including communities of practice and knowledge enablers (see, Gertler, 2003).

4. Complementarity between the home region and offshored R&D

While it is clear that emerging countries' location advantages can benefit MNEs, the effect on knowledge production in the MNE's home region is less clear. R&D offshoring activity could detract from the home base by reducing the effectiveness of knowledge production in the home country. Alternatively, R&D offshoring activity might be 'home-base augmenting' and might increase the efficiency of domestic R&D investment for knowledge production in the home country. It is plausible also that there will be no effect on knowledge clusters in advanced countries and regions and that what they offer will continue to be very high value (Doh, 2005; Manning et al., 2008; Lewin et al., 2009). To our knowledge, there is very little empirical evidence on these issues.

In this article, we posit that complementarity effects will emerge due to geographical technological specialization, and reverse knowledge transfer. First, if the R&D activities in the home region are mostly dissimilar to the offshore offerings, MNEs can focus on retaining certain types of R&D in-house and offshoring others. Quinn (1992, 37) notes that 'virtually all staff and value chain activities are activities that an outside entity, by concentrating specialists and technologies in the area, can perform better than all but a few companies for whom that activity is only one of many'. Certainly, R&D offshoring will favour an increased focus on core competencies in the home region, and offshoring some activities may allow the firm to increase managerial attention and resource allocation to those tasks that it does best in the home country, relying on management teams in other locations to oversee tasks where the offshoring firm offers relative advantage. Given the shortage of engineers and scientists in most advanced countries, there are good reasons for a focus on only some R&D activities in the home region.

Secondly, knowledge developed in offshore locations by foreign affiliates may be 'reverse' transferred to the parent (Mansfield and Romeo, 1984). The international business and management literature shows that MNEs rely increasingly on this less conventional type of knowledge transfer—from subsidiary to parent company—in order to source new complementary knowledge from distant locations (Ghoshal et al., 1994; Mudambi and Navarra, 2004; Rabbiosi, 2011). Strong embedding of the parent firm in the home RSI facilitates the exchange of knowledge and mutual learning in the home country, through trust-based local relationships (Andersson et al., 2002; Forsgren et al., 2005). Thus, offshore knowledge is fed into and enhances home region knowledge production. Reverse knowledge transfer, which is based on the relationship between internal R&D and external knowledge sourcing, is further strengthened by the recent trend towards open innovation (Chesbrough, 2003). The focus of firms' knowledge strategies is changing from more closed to more open innovation and exploitation of knowledge from a range of external actors to develop and commercialize new technology (Chesbrough, 2003). The transfer of knowledge developed in offshore locations can be seen as part of this trend towards open innovation and accessing external sources of knowledge through deliberate location choices. It allows the firms in a given region to focus on specialized knowledge production while being open to variously located external sources of knowledge—including emerging economies—to promote innovation production.

To assess the complementarity between home and offshored R&D we need to consider the nature and technological intensity of R&D offshoring. We assume that firms in the advanced regions have comparative advantage in R&D in the most advanced technologies, and would not expect a complementarity effect between offshored R&D in high-technology sectors and home region R&D, on knowledge production in the investing home region ('Expectation No. 1'). Although, in principle, the offshoring of R&D in these sectors might benefit from relative cost advantages, research suggests that the fast-growing emerging economies need to complete their technological upgrading (Athreye and Cantwell, 2007), meaning that their real contribution to the production of knowledge in high-technology sectors in advanced locations may be limited.

However, we expect offshored R&D in medium/low technology-intensive ('Expectation No. 2') to complement home region R&D activity, for two reasons. First, medium/low technology-intensive activities are likely to be dissimilar to home region technological activity. Advanced regions tend to have comparative advantage in R&D in the most advanced technologies, while offshore locations will likely have comparative advantage in medium/low technology-intensive R&D activities. The knowledge production of advanced regions will be enhanced because scarce factors of production can be directed towards areas of comparative advantage (involving the most advanced R&D activities) for the firms in those regions. Secondly, and related, the innovation literature shows that less complex (e.g. medium/low) technologies are easier to transfer from the offshore location to the home region because they are easier to codify than the most advanced technologies (Cantwell and Santangelo, 1999).

Finally, we expect offshoring in software and knowledge-intensive services sectors will complement home region R&D activity ('Expectation No. 3'). The innovation literature shows that modular technologies (e.g. software and knowledge-intensive services) are easier to transfer (Kotabe et al., 2007) and to integrate with other technologies (Brusoni and Prencipe, 2001). In turn, the relatively lower costs of transferring and integrating technologies developed offshore to promote the production of knowledge in the home region, increases the probability of a complementarity effect between offshored and home region R&D activities in home production of knowledge. However, whether software and knowledge intensive services technologies are fully modular, or display degrees of interdependence with other technologies when applied in the same product, is debateable. For instance, the development of advanced robotics hardware is likely to be strongly interdependent with the development of the advanced software required to control it. Similarly, there is no consensus that the emerging economies have a clear comparative advantage in software and knowledge-intensive services (Arora and Gambardella, 2005).

5. Data and sample

Our sample includes 221 regions in 21 OECD countries, with R&D investments in BRICST. We constructed a data set for these regions using data from the OECD REGPAT database (version January 2010), fDi Market database and OECD Regional Database (RDB).

OECD REGPAT collects patent applications filed under the Patent Cooperation Treaty (PCT), on which the European Patent Office (EPO) is the designated office. The PCT provides an alternative route to direct application to national/regional patent offices. It enables application for patent rights in multiple countries via one application in one language, although only the designated national (e.g. the US Patent and Trademark Office) or regional (e.g. the EPO) patent office has the authority to grant a patent. The PCT process is considered important internationally because it is not biased towards any particular country (Le Bas and Sierra, 2002; Khan and Dernis, 2006). PCT applications in the OECD REGPAT database are 'regionalized', a process that links inventor and applicant addresses to regional codes. Its regionalization covers 42 countries (Maraut et al., 2008), 30 of which are OECD members (see Appendix A for the OECD countries included). The sub-national units are OECD Territorial Grids (OECD, 2008). According to this system, the regions in OECD member countries are classified at two hierarchical levels: Territorial levels 2 and 3 (TL2 and TL3) include 335 and 1679 regions, respectively. This study uses the more aggregated TL2. For most European countries, the TL corresponds to Eurostat (NUTS) classifications (see Appendix B for details of the NUTS Classification). REGPAT provides information on the technological content of patents. Drawing on International Patent Classification (IPC, version 8) codes, we can assign each patent's technological field to one of the following technological groups (Schmoch, 2008): (i) Electrical Engineering, (ii) Instruments, (iii) Chemistry, (iv) Mechanical Engineering and (v) Other.

The fDi Market database relies on media sources and company data, and collects detailed information on cross-border greenfield and expansion investments worldwide (available from 2003). fDi Market data are based on investment announcements, and provide daily updated data. For each foreign direct investment (FDI) project, fDi Market reports information on the investment (e.g. the leading industry sector), the home and host countries and regions and cities involved, and the investing company (e.g. location). For the present analysis, we converted the fDi Market database sectors to offshoring investments based on the OECD classification (Hatzichronoglou, 1997) of sector R&D intensity (i.e. High-technology, Medium-high technology, Medium-low technology and Low technology). Due to the very small number of offshoring investments in the Medium-low and Low technology industries, we aggregated these sectors with the Medium-high group, labelling it Medium/low. Also, since offshoring investment occurs in knowledge-intensive services, we exploit the EUROSTAT (2006) classifications. The OECD and EUROSTAT classifications are based on NACE Rev. 1.1. Table 1, column 1 lists the fDi Market sectors with Standard Industry Classification (SIC) sectors in parentheses; column 2 contains the relative OECD and EUROSTAT sectors with NACE Rev. 1.1 codes in parentheses; column 3 reports the three sectoral aggregations adopted in our analysis, that is, high (H), medium/low (M) and knowledge-intensive services, including software (KS).

One of the limitations of the fDi Market database is that it collects planned (future) investments. Some projects are never realized or are realized in a different form from originally announced. However, we believe that the percentage of these projects is negligible since the database is a source of FDI project information used for the UNCTAD World Investment Report and is used by the Economist Intelligence Unit. Finally, we rely on the OECD RDB, which collects socio-economic indicators for the OECD regions (e.g. demographic statistics, regional accounts, regional labour market, innovation indicators, social indicators).

We combined the three data sources drawing on information in fDI Markets on the investing firm's location. In particular, we matched each investing firm's location with

Table 1. fDi Market, OECD and EUROSTAT sectoral breakdown, and the sectoral aggregation adopted

fDi market aggregations (SIC codes in parentheses)	OECD/EUROSTAT (NACE Rev. 1.1 codes in parentheses)	Aggregations adopted
	High-technology	High (H)
Aerospace (372)	Aerospace (35.3)	
Biotechnology (2836, 8731)	Computers, office machinery (30)	
Business machines and equipment (357)	Electronics-communications (32)	
Communications (366, 482, 483, 484, 489)	Pharmaceuticals (24.4)	
Consumer electronics (363, 365, 386)	Scientific instruments (33)	
Electronic components (362, 364, 3671, 3672, 3677, 3678, 3679, 369)		
Medical devices (384, 385)		
Pharmaceuticals (2834, 2835, 8731, 8734)		
Semiconductors (3674, 3675, 3676)		
	Medium-high-technology	Medium/low (M)
Automotive components (3714)	Motor vehicles (34)	
Automotive OEM (3711, 3713, 551, 552, 553, 75)	Electrical machinery (31)	
Chemicals (281, 2833, 284, 285, 286, 287, 289, 8731)	Chemicals (24–24.4)	
Engines and turbines (3517)	Other transport equipment (35.2 + 35.4 + 35.5)	
Industrial machinery, equipment and tools (352, 353, 354, 355, 356, 358, 359, 3617, 382)	Non-electrical machinery (29)	
Non-automotive transport OEM (373, 374, 375, 379, 3715, 3716, 555, 556, 557, 558, 559)		
Plastics (282)		
	Medium-low-technology	
Alternative/renewable energy (2819, 2869)	Rubber and plastic products (25)	
Building and construction materials (17, 324, 327, 5032, 5033, 5039, 5211)	Shipbuilding (35.1)	
Coal, oil and gas (12, 13, 29, 554)	Other manufacturing (36.2 through 36.6)	
Consumer products (387, 391, 393, 394, 395, 396, 399, 523, 525, 526, 527, 537, 563, 569, 57, 59, 76)	Non-ferrous metals (27.4 + 27.53/54)	
Metals (10, 33, 34)	Non-metallic mineral products (26)	
Rubber (30)	Fabricated metal products (28)	
	Petroleum refining (23)	
	Ferrous metals (27.1 through 27.3 + 51/52)	

(continued)

Table 1. Continued

fDi market aggregations (SIC codes in parentheses)	OECD/EUROSTAT (NACE Rev. 1.1 codes in parentheses)	Aggregations adopted
	Low-technology	
Beverages (208)	Paper printing (21 + 22)	
Food and tobacco (01, 02, 07, 08, 09, 201, 202, 203, 204, 205, 206, 207, 209, 21, 54)	Textile and clothing (17 through 19)	
Paper, printing and packaging (26, 27)	Food, beverages and tobacco (15 + 16)	
Textiles (22, 23, 31, 561, 562, 564, 565, 566)	Wood and furniture (20 + 36.1)	
Wood products (24, 25)		
Business services (731, 732, 733, 734, 735, 736, 738, 81, 82, 871, 872, 8732, 8733, 874)	Water and Air Transport (61, 62)	Knowledge-intensive services (KS)
Financial services (60, 61, 62, 63, 64, 67)	Post and telecommunications (64), Financial intermediation, insurance, pension funding and other auxiliary activities (65, 66, 67), Real estate activities (70), Renting of machinery and equipment, etc. (71), Computer and related activities (72), Research and development (73), Other business activities (74), Education, Health and social work, recreational, cultural and sporting activities (80, 85, 92)	
Software and IT services (737)		

Source: Authors' elaboration on Hatzichronoglou (1997), EUROSTAT (2006) and fDi Market database.

1 of the 221 TL2 regions in REGPAT and the OECD RDB.[4] This allowed us to link each R&D investment to the home region's patenting activity and socio-economic indicators.

6. The model

6.1. The main variables

To model regional knowledge production we use Griliches's (1979) and Jaffe's (1989) knowledge production function (KPF) framework, which models the functional relationship between knowledge production process inputs and output, that is, economically useful new technological knowledge. It takes the form of a two-factor Cobb–Douglas production function, which relates a knowledge output measure to input measures. Studies using the KPF framework mostly focus on R&D expenditure and university research as input measures, and firms (Griliches, 1979) and geographical locations of firms (countries or sub-national territorial entities) (Jaffe, 1989) as the unit of analysis. In line with our research objectives, we follow Jaffe (1989) and the literature that developed from his work (e.g. Anselin et al., 1997; Acs et al., 2002; Bode, 2004; Fritsch and Slavtchev, 2011), and adopt TL2 regions as the unit of analysis. We consider R&D expenditure and R&D offshored to BRICST as inputs. Thus, the regional knowledge production function (RKPF) we estimate analytically is expressed as

$$\log(K_{rt}) = \alpha + \beta \log(\text{R\&D}home_{rt-1}) + \gamma \log(\text{R\&D}off_{rt-1}) + \delta \log(Z_{rt-1}) + \varepsilon_r \quad (6.1)$$

where K is a proxy for the knowledge of region r at time t, *R&Dhome* is regional R&D, *R&Doff* is R&D from region r to BRICST and Z typically includes a measure of the innovation-related interactions within region r. The last three terms refer to $t-1$. The parameters β, γ and δ are output elasticities. Positive and significant coefficients of β, γ and δ indicate the positive effects of different regional knowledge sources on regional knowledge production.

Innovation counts or patents are used traditionally to measure regional knowledge (Jaffe, 1989; Anselin et al., 1997, 2000; Baptista and Swann, 1998; Acs et al., 2002; Bode, 2004). Although patents have several shortcomings (Griliches, 1979), we use number of patents as an indicator of regional innovation. We take the fractional count of PCT applications aggregated by the region r of residence of the inventor in year 2006–2007 (2-year average) and transform it in logarithm ($logK_{rt}$). Note, that, if more than one inventor is named on a patent, it is shared equally. Therefore, for each region we count the share of the inventors resident in that region. No regions have zero patents. The fractional counts render the dependent variable more similar to a continuous than a discrete variable. Also, the transformation in logarithm of the dependent variable helps alleviating the censoring problems that can arise when dealing with patents, since the skewness and kurtosis values of the transformed variable are

4 To check that R&D investment was made by the headquarters (subsidiary investment is considered rare), we traced headquarters and TL2 regional locations using Hoovers online (http://www.hoovers.com) database and other web sources. We matched headquarters location to 1 of the 221 TL2 regions, which is consistent with a new R&D unit set up in BRICST by another corporate unit ultimately reporting to the corporate headquarters. In 4% of the R&D in our sample, the R&D investment was not made by the headquarters.

close to a normal distribution (skewness 1.66 and kurtosis 6.07). To proxy for regional R&D we follow Jaffe (1989) and used regional average R&D expenditure (US PPP) for the period 2003–2005. To account for R&D offshoring to BRICST from region *r*, we adopt the average number of R&D offshoring investments made by firms headquartered in region *r* in the period 2003–2005.

6.2. Controls

Taking region as the unit of analysis, we account for the systemic regional characteristics of knowledge production, which emerge as a result of firms not innovating in isolation and are affected by several spatially bounded elements (Lundvall, 1992). To control for these elements, we introduce a set of exogenous variables calculated for the period 2003–2005 and expressed in logarithms.

Following prior studies (e.g. Sterlacchini, 2008; Usai, 2011), we control for regional population density (*DEN*) to proxy for inter-firm relationships, under the assumption that interaction and collaboration among firms in agglomerations are stronger. To capture a primary city effect, we introduce a binary variable (*CAP*) that takes the value 1 if the region hosts the country capital. R&D laboratories and firms' headquarters frequently are located in capital cities,[5] to be proximate to government research centres and other large R&D actors, among other reasons (Feldman, 2003). To control for the local presence of financial institutions, we use share of employment in financial intermediation (*FIN_SHARE*). The more localized these financial institutions, the closer they are to the needs of innovative firms (Cooke et al., 1997). Also, Lundvall (1992) highlights the significance of R&D organizations in innovation systems. In the past, knowledge production relied mainly on internal R&D laboratories; contemporary knowledge production increasingly is the result of a more open process (Chesbrough, 2003) characterized by inter-firm collaboration, firm–university partnerships, start-ups and science networks. These collaborations for innovation often have a cross-border dimension, as shown by the rise in international technological partnerships (e.g. Narula and Hagedoorn, 1999). Therefore, we control for international inter-regional collaboration by considering the share of patents with multiple inventors, at least one of whom is located in a different country (*INTERNATCOOP*). In addition to Lundvall's (1992) elements, we consider the role of education and training, as suggested by Freeman (1987), and include the share of labour force with tertiary level education (*HK_SHARE*) as a proxy for human capital. In line with the large literature on the contribution of industry and universities to regional knowledge production (e.g. Anselin et al., 1997; Acs et al., 2002), we include two additional variables—for regional shares of industry (*R&D_BUS*) and university (*R&D_UNI*) R&D expenditure. Although the TL2 classification accounts for the regional geographic dimension and population size, it is based primarily on existing institutional divisions. Therefore, TL2 regions vary in dimension and, especially, population size. We account for differences in region size by controlling for number of inhabitants (*POP*) (Bode, 2004). To account for the effect on regional knowledge creation of R&D investment from region *r* to non-BRICST countries in H, M and KS, we include a binary variable (*R&D_FDI*). We draw on the UNCTAD (2008) database and control also for the international attractiveness of the

5 We thank a reviewer for suggesting this argument.

home country by considering the net value of the stock of inward FDI (*FDI*), calculated as a dummy that takes the value of 1 if FDI inward stock minus FDI outward stock is positive.

To consider the different propensities among regions to patent across technologies (Scherer, 1983; Arundel and Kabla, 1998), we introduce revealed technological advantage (RTA), which accounts for regional relative specialization in each of the five groups of technologies based on the patent IPC codes ($adjRTA_j$ where $j = 1, 2, 3, 4$ and 5). Thus, RTA is calculated as:

$$RTA_{rj} = \frac{P_{rj}/\Sigma_j P_{rj}}{\Sigma r P_{rj}/\Sigma_{rj} P_{rj}} \tag{6.2}$$

where P_{rj} is the number of patents in region r in the technology group j. Thus, this index gives the share of patents in region r in the technology group j (numerator), weighted by the share of patents in all the regions in technology group j, on all the patents in the sample (denominator). Since this index takes values between 0 and $+\infty$, we normalize it to constrain its variation between -1 and $+1$, as follows:

$$adjRTA_{rj} = \frac{RTA_{rj} - 1}{RTA_{rj} + 1} \tag{6.3}$$

Values close to $+1(-1)$ represent comparative technological advantage (disadvantage) of region r in the technology group j.

We use a set of controls for the destination countries of R&D investments in H, M and KS to account for the idiosyncrasies of the emerging economies considered, e.g. weak intellectual property rights regime, which might affect the FDI location choice (Lall, 2003), and MNE technology strategy (Zhao, 2006). We include dummies for home regions in Western Europe (EU15 plus Norway), and Canada and USA (*WESTEUROPE* and *NORTHAMERICA*, respectively). Table A1 reports the variables included in the analysis and related data sources and descriptive statistics.

7. Supermodularity of the RKPF

We want to test whether home (*R&Dhome*) and offshore (*R&Doff*) R&D are complementary, in relation to the production of knowledge in the investing region. Although *R&Dhome* and *R&Doff* are continuous variables, the latter shows a very skewed distribution with many regions showing zero investments and—among investing regions—~83% recording fewer than 10 R&D investments. Skewness and kurtosis values for R&D offshoring distribution are 11.19 and 146.57, well above the expected values for a normal distribution. The distribution remains skewed when *R&Doff* is calculated for each of the sectors H, M and KS. The *R&Doff* distribution for sector H is particularly skewed (equal to 11.19) and kurtosis is 146.57. Skewness and kurtosis values are 4.05 and 19.46 for *R&Doff* for sector M, and for KS *R&Doff* skewness is 13.45 and kurtosis 192.20. Since these values are well above those in a normal distribution, *R&Doff* can be regarded as a rare event, and the presence of one investment a sign of R&D offshoring activity. This feature of the variable forced us to work with discrete variables to test for complementarity, which means that we cannot introduce an interaction term in the regression framework to test for the sign of the interaction parameter (as done by, for instance, Laursen et al., 2012). Instead, we derive an inequality constraint as implied by the theory of supermodularity and test whether the constraint is accepted by the data.

As discussed above, the concept of complementarity refers to the simultaneous presence of certain elements which are mutually reinforcing. More formally, following Milgrom and Roberts (1990), complementarity can be defined as follows:

Definition: *Let* A *and* B *be two activities. Each activity can be performed (*$A=1$*) or not performed (*$A=0$*). The function* F*(*A, B*) is* supermodular *and* A *and* B *are said to be* complements *only if:*

$$F(1,1) - F(0,1) \geq F(1,0) - F(0,0) \tag{7.1}$$

The right-hand side of Equation (7.1) defines the marginal increase from performing only activity A [$F(1,0)$] rather than neither activity [$F(0,0)$]. The left-hand side describes the marginal increase from performing both activities [$F(1,1)$] rather than only B [$F(0,1)$]. Therefore, the equation states that the marginal increase of adding one activity (i.e. A), when already performing the other (left-hand side), is higher than the marginal increase from performing only one activity (right-hand side).

7.1. Testing for complementarity

One way to test for complementarity is through the adoption (indirect) approach, which tests whether the two activities, A and B, are correlated based on the correlation of the residuals in the reduced-form equations (Arora and Gambardella, 1990). However, this approach suffers from the omission of exogenous variables that bias the correlation among residuals (see Arora, 1996; Athey and Stern, 1998). An alternative approach is the productivity (direct) approach, where testing the complementarity between regional R&D and R&D offshored to BRICST from the focal region, is a direct test of whether the RKPF of Equation (6.1) is supermodular, that is, whether the inequality constraint in Equation (7.1) is satisfied (Milgrom and Roberts, 1990; Mohnen and Roller, 2005; Belderbos and Sleuwaegen, 2007). This approach has been shown to be more conclusive (Athey and Stern, 1998). Also, given the setting of our analysis, the productivity approach does not suffer from the complexities related to the existence of more than two activities (Lokshin et al., 2011).

To implement this test, we generated two dummy variables, $HOME$ and $OFF_{H,M,KS}$. The first accounts for the level of the region's R&D at home and takes the value 1 if *R&Dhome* is greater than the sample median. The second dummy variable accounts for the 49 regions with offshore R&D (i.e. 22% of the sample), and takes the value 1 if the region has at least one R&D offshore investment in the given sector H, M or KS. Using $HOME$ and $OFF_{H,M,KS}$ we construct all possible combinations between R&D at home and R&D offshoring in the three sectors:

- *HOMEOFF_H* equals 1 if $HOME=1$ and at least one R&D offshoring investment in sector H has departed from the region (i.e. $OFF_H=1$)
- *HOMEOFF_M* equals 1 if $HOME=1$ and at least one R&D offshoring investment in sector M has departed from the region (i.e. $OFF_M=1$);
- *HOMEOFF_KS* equals 1 if $HOME=1$ and at least one R&D offshoring investment in sector KS has departed from the region (i.e. $OFF_{KS}=1$);
- *ONLYOFF_H* equals 1 if $HOME=0$ and at least one R&D offshoring investment in sector H has departed from the region (i.e. $OFF_H=1$);

– *ONLYOFF_M* equals 1 if $HOME = 0$ and at least one R&D offshoring investment in sector M has departed from the region (i.e. $OFF_M = 1$);
– *ONLYOFF_KS* equals 1 if $HOME = 0$ and at least one R&D offshoring investment in sector KS has departed from the region (i.e. $OFF_{KS} = 1$);
– *ONLYHOME* equals 1 if $HOME = 1$ and at no R&D offshoring investment has departed from the region (i.e. $OFF_{H,M,KS} = 0$);
– *NOHOMEOFF* equals 1 if $HOME = 0$ and no R&D offshoring investment has departed from the region (i.e. $OFF_{H,M,KS} = 0$).

The RKPF of Equation (6.1) can then be refined as follows:

$$\log(K_{rt}) = \alpha + \theta C_{crt-1} + \delta \log(Z_{rt-1}) + \varepsilon_r \tag{7.2}$$

where c refers to the eight combinations of $HOME$ and the offshoring variables accounting for the sector of the offshoring investment. $C_{crt\ -\ 1}$ measures the combination of complements of region r at time $t-1$. θ is the vector of the coefficients of the combinations $C_{crt\ -\ 1}$.

The test of complementarity is based on the following null hypothesis:

$$\theta_{11} - \theta_{10} \geq \theta_{01} - \theta_{00} \tag{7.3}$$

where the first subscript refers to $HOME$ and the second subscript refers to each of the three types of offshoring investment ($OFF_{H,M,KS}$). The test is a Wald χ^2 one-sided test performed in two steps. The first step tests the null hypothesis of equality; if the null is rejected, then the second step tests the null of submodularity versus supermodularity (i.e. complementarity). Thus, a significant Wald χ^2 one-sided test in the second step reveals the existence of complementarity since the test rules out that performing only one of the two R&D activities ($HOME$ and $OFF_{H,M,KS}$) has a lower effect on regional knowledge production than performing both.[6]

8. Spatial econometric issues

To obtain efficient estimates of Equation (7.2) we need to apply a spatial econometric framework (Acs et al., 2002; Moreno et al., 2005) because we are dealing with cross-sectional data for geographically close units of observation. It is very likely that the innovation output of each unit will be affected positively by innovation performed in neighbouring regions, meaning that the error terms are correlated across observations. Spatial autocorrelation renders the OLS estimator inefficient, although it leaves the coefficients unbiased (Anselin, 1988). To deal with this problem, we test for the presence of misspecification by means of a Moran's I test with a binary contiguity matrix, in which the contiguity matrix takes the value 1 if the pair of regions share a border, and 0 otherwise. We constructed the binary contiguity matrix manually to include islands[7] and to take account of regions which, although not sharing a border, are separated by only few kilometres width of sea- or lake-water (e.g. the French region of Calais and the British region of Dover, and US and Canadian states along the Great

6 We test the inequality constraints in STATA following the procedure described at http://www.stata.com/support/faqs/stat/oneside.html.
7 These regions include: Prince Edward Island in Canada; Sicily, Sardinia, Corsica, the Greek Archipelago and the Balearic Islands in the Mediterranean Sea; and Åland in Finland.

Lakes). This way of proceeding was motivated by the argument that the spatial weight matrix should be chosen on the basis of the structure of dependence, rather than on a simple pre-packaged description of the spatial relation (Anselin, 1988). Therefore, although we use the simplest spatial matrix to account for spatial dependence, we want also to account for obvious geographical proximity between regions without a common border. Moran's index of spatial correlation rejects the null hypothesis that patents from contiguous regions are independent ($p < 0.01$ level of significance). Therefore, we need to control for spatial dependence in the models. We searched for the most appropriate functional form to model spatial dependence using a set of Lagrange Multiplier tests on the OLS results. The two forms of spatial autocorrelation that are most relevant in applied empirical work are so-called substantive dependence, or dependence in the form of a spatially lagged dependent variable, and nuisance dependence, or dependence in the regression error term. Given the inefficiency of OLS in the case of spatial correlation, we use the ML estimator and run two Lagrange Multiplier tests (i.e. the LM-LAG and the LM-ERR) using the binary contiguity matrix in order to identify the most appropriate functional form. The spatial lag model estimated can be expressed as:

$$\log(K_{rt}) = \alpha + \theta C_{crt-1} + \delta \log(Z_{rt-1}) + \rho W \log(K_{rt}) \varepsilon_r \tag{8.1}$$

where $Wlog(K)_{rt}$ is the spatially lagged dependent variable for the weight matrix W and ρ is the spatial autoregressive coefficient. A positive and significant effect of this coefficient suggests that the knowledge production of region r is influenced by the knowledge production in neighbouring regions. The second form of spatial dependence is often expressed as a spatial autoregressive process for the error term in a regression model. Analytically, this can be reported as:

$$\log(K_{rt}) = \alpha + \theta C_{crt-1} + \delta \log(Z_{rt-1}) + \varepsilon_r \tag{8.2}$$

with

$$\varepsilon_r = \lambda W \varepsilon_r + u_r \tag{8.3}$$

where λ is the spatial autoregressive coefficient and u_r is the spherical error term. W is the weight matrix. The LM tests do not show remarkable difference between the lag and the error model. We decided to adopt the lag model [Equation (8.1)] because it gives additional information about the impact of neighbouring regions' patents through the coefficient ρ. For reasons of space, the OLS estimates and LM tests are not presented here, but are available upon request.

9. Exploratory analysis

As a preliminary analysis, we explored the world R&D FDI trends during the period under analysis. Figures 1 and 2 show numbers of R&D FDI by home and host countries, respectively.

OECD countries are still major investors in R&D abroad. Specifically, the bulk of R&D FDI in 2003–2005 departed from USA (which confirms its investor leadership). Germany and Japan follow, although with much lower numbers of investments. The UK, France, Switzerland and South Korea are also major investors. The trend is markedly different for countries hosting R&D FDI in the same period. In particular,

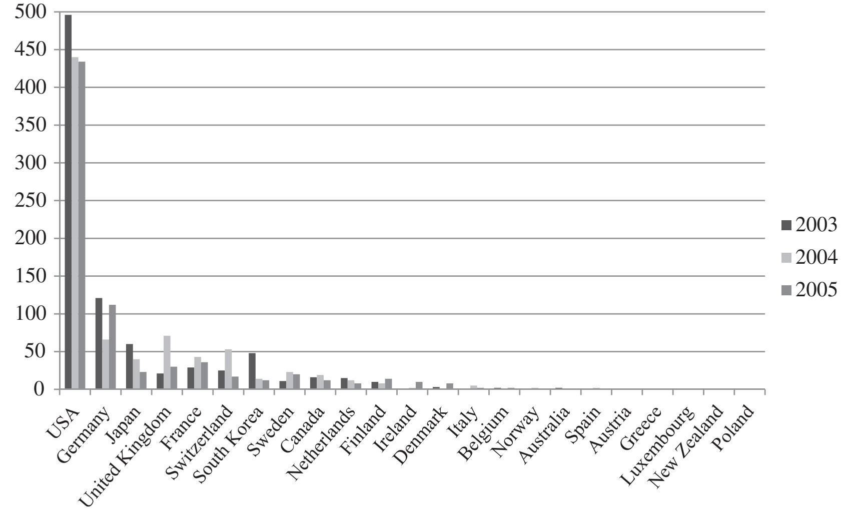

Figure 1. R&D FDI by home country (number of investments), 2003–2005.

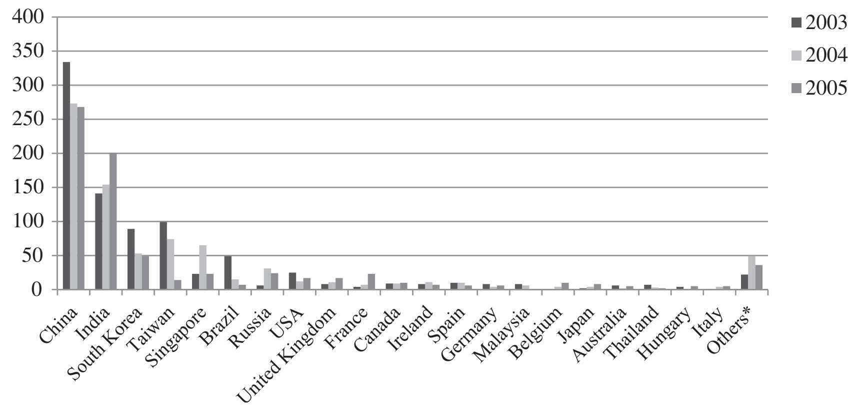

Figure 2. R&D FDI by host country (number of investments), 2003–2005. *Denmark, Sweden, Austria, Poland, Czech Republic, Romania, Israel, Mexico, Colombia, Finland, Netherlands, New Zealand, Morocco, Philippines, Portugal, Vietnam, Bulgaria, Hong Kong, Qatar, Slovakia, South Africa, Switzerland, UAE, Ukraine, Armenia, Chile, Ecuador, Estonia, Latvia, Lebanon, Nigeria, Norway, Pakistan, Peru, Turkey.

BRICST are the top six non-OECD host countries for R&D FDI. China and India lead with China hosting the largest number of investments in each of the 3 years under analysis. Taiwan, Singapore, Brazil and Russia follow with Taiwan and Singapore attracting more investments than Brazil and Russia. All OECD countries, which traditionally host the bulk of R&D FDI, are lagging behind. South Korea is ranked third as a recipient of R&D FDI after China and India.

We also consulted the mapping of the two key independent variables—R&D at home and R&D offshore—in the three technological sectors. Figure 3 shows the regions that are above and below the R&D expenditure median for the whole sample (i.e. *HOME*).

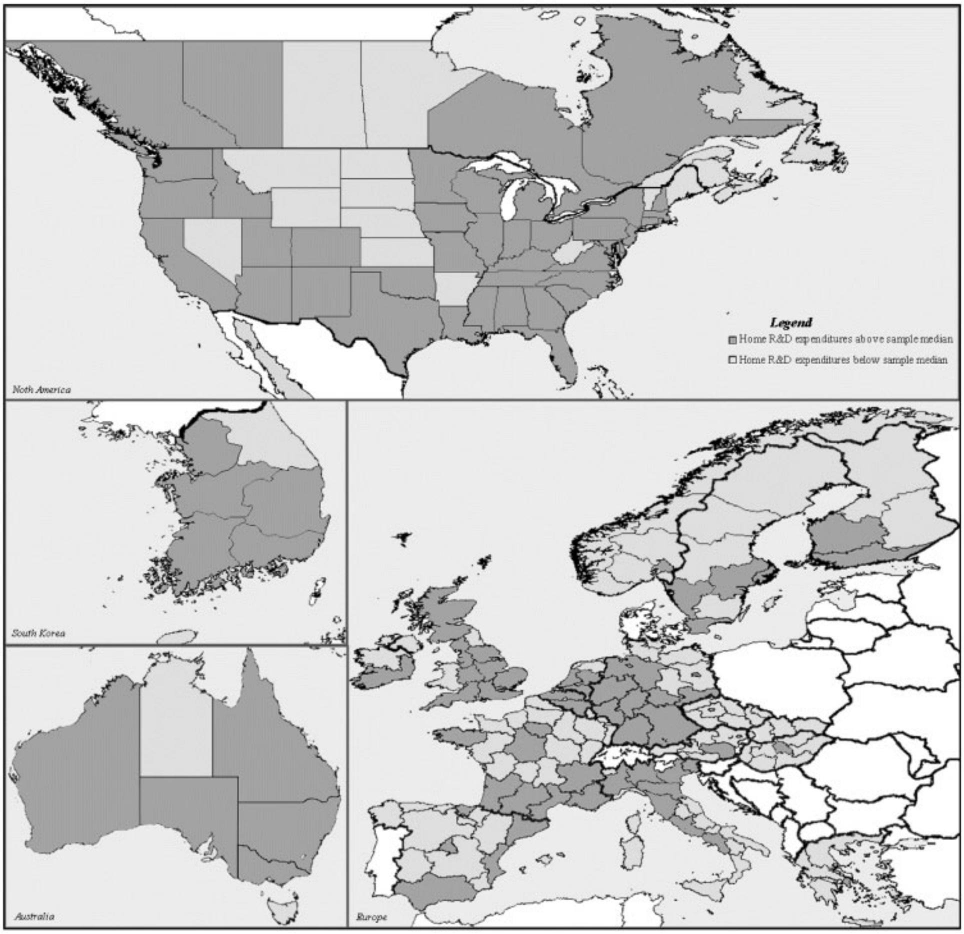

Figure 3. OECD regions standing above and below R&D expenditures sample median, 2003–2005.

Luxembourg and Slovakia are the only OECD countries with no regions that have above the sample median R&D expenditure. In some small EU countries (i.e. Czech Republic, Greece, Hungary, Ireland, Norway), only the capital region has levels of R&D expenditure above the sample median. Germany has the highest number of regions (10 *länder*) with above the median R&D expenditure in Europe, while USA is the OECD country with the highest number of R&D intensive regions (i.e. 39 of the 49 states in the sample). The majority of regions in South Korea and Australia have above the sample median R&D expenditure.

Figure 4 depicts the distribution of regions investing in R&D in H, M and KS, in BRICST (i.e. $OFF_{H,M,KS}$).

In Europe, it is mainly English-speaking, central European and Scandinavian regions that offshore R&D to BRICST, and—especially in the case of German regions—primarily medium/low technology-intensive R&D. US and Canadian investment is mostly in high technology-intensive R&D and knowledge-intensive service R&D. This applies to Eastern and North-eastern USA, and Washington, Texas and California.

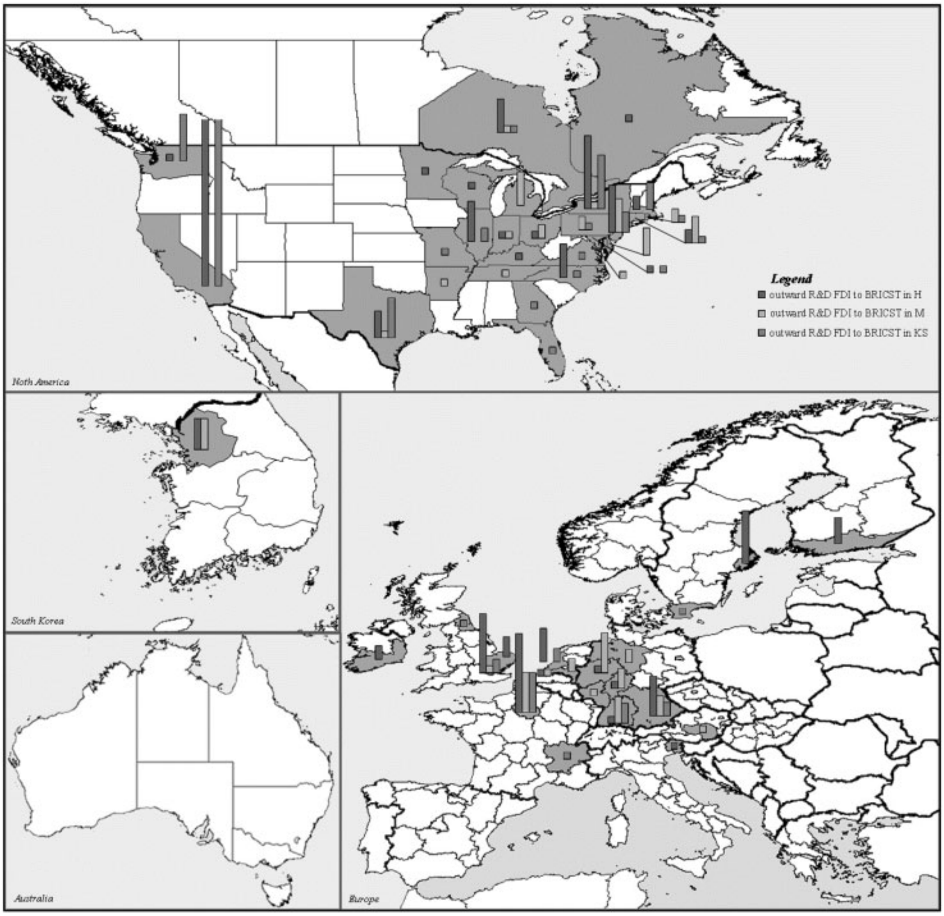

Figure 4. Number of R&D offshoring investments departing from OECD home regions, by technology-intensive sector, 2003–2005.

California is the top investing OECD home region in BRICST for both total and sectoral R&D FDI. Australia has no investments in any of the three sectors, while South Korea's capital region offshores only high and medium/low technology-intensive R&D to BRICST.

Table 2 shows the absolute numbers and percentages of regions for the categories $HOME$ and $OFF_{H,M,KS}$ combined (columns 1 and 2) and the average numbers of patents and standard deviations (columns 3 and 4). The mean of patents in the $HOMEOFF_{H,M,KS}$ categories is always higher than in the categories $ONLYOFF_{H,M,KS}$ and $ONLYHOME$. This can be interpreted as an initial sign of complementarity, suggesting that regions engaged in both home and offshore R&D are highly innovative.

We conduct an additional exploratory analysis to look at the unconditional correlations between the complements $HOME$ and $OFF_{H,M,KS}$. We test the null hypothesis of independent pairs of decision variables (Miravete and Pernias, 2006). Table 3 shows the pair-wise Spearman's correlations for $HOME$ and $OFF_{H,M,KS}$. All the coefficients are positive and significant at $p < 0.01$, another indication of complementarity (Cassiman and Veugelers, 2006).

Table 2. Distribution of regions and patents

	Regions	Patents	
	Number (%)	Mean	SE
High			
$HOMEOFF_H$	29 (13)	2226.1	2213.0
$ONLYOFF_H$	2 (1)	107.1	0.2
$ONLYHOME_H$	81 (37)	484.0	415.8
$NOHOMEOFF_H$	109 (49)	64.1	64.6
Tot. $OFF_H=1$	31 (14)	2089.4	2202.4
Medium/low			
$HOMEOFF_M$	23 (10)	1918.3	1406.5
$ONLYOFF_M$	2 (1)	82.4	34.8
$ONLYHOME_M$	87 (39)	685.5	1296.6
$NOHOMEOFF_M$	109 (49)	64.5	64.7
Tot. $OFF_M=1$	25 (11)	1771.4	1439.4
Knowledge-intensive services			
$HOMEOFF_{KS}$	24 (11)	2231.5	2358.0
$ONLYOFF_{KS}$	1 (0)	148.9	–
$ONLYHOME_{KS}$	86 (39)	583.7	659.1
$NOHOMEOFF_{KS}$	110 (50)	64.1	64.1
Tot. $OFF_{KS}=1$	25 (11)	2148.2	2345.7

Table 3. Spearman correlation

	HOME
OFF_H	0.353***
OFF_M	0.301***
OFF_{KS}	0.330***

***$p<0.01$.

10. Econometric results

Table 4 reports the estimations of the RKPF in Equation (8.1). Columns 1–3, respectively, present the results for the model by H, M and KS sectors.

In all the models the coefficients of the spatially lagged dependent variable reported at the bottom of the table are statistically significant, showing that regional knowledge production is influenced by neighbouring regions' patenting activities. Similarly, all the models show that *HOMEOFF* and *ONLYHOME* are statistically significant; *ONLYOFF* is never significant (NOHOMEOFF was dropped due to collinearity).[8] These results are consistent with complementarity, the coefficients of *HOMEOFF* are

8 A possible solution to the collinearity problem would be to drop the constant in the models estimated. However, the spatreg STATA command used here does not allow this option. Consequently, our complementarity test is performed on 3 ($HOMEOFF_{H,M,KS}$, $ONLYOFF_{H,M,KS}$ and *ONLYHOME*) of the

Table 4. Econometric results

Dep. variable Explanatory	Model 1 H K Coef. (SE)	Model 2 M K Coef. (SE)	Model 3 KS K Coef. (SE)
HOMEOFF	0.997 (0.269)***	0.853 (0.320)***	0.913 (0.353)***
ONLYOFF	0.374 (0.393)	−0.528 (0.479)	0.417 (0.600)
ONLYHOME	0.533 (0.109)***	0.477 (0.110)***	0.563 (0.111)***
Controls			
DEN	−0.122 (0.034)***	−0.128 (0.035)***	−0.135 (0.036)***
CAP	−0.367 (0.178)**	−0.260 (0.174)	−0.087 (0.190)
FIN_SHARE	9.554 (1.640)***	10.54 (1.644)***	9.547 (1.668)***
INTERNATCOOP	−0.298 (0.062)***	−0.309 (0.063)***	−0.292 (0.063)***
HK_SHARE	0.446 (0.123)***	0.496 (0.125)***	0.471 (0.126)***
R&D_BUS	0.488 (0.071)***	0.522 (0.073)***	0.496 (0.073)***
R&D_UNI	−0.103 (0.057)*	−0.112 (0.058)*	−0.139 (0.058)**
POP	0.651 (0.055)***	0.700 (0.055)***	0.706 (0.056)***
R&D_FDI	0.335 (0.117)***	0.059 (0.115)	−0.088 (0.172)
FDI	−0.234 (0.109)**	−0.256 (0.111)**	−0.284 (0.112)**
adjRTA1	0.355 (0.204)*	0.348 (0.210)*	0.305 (0.212)
adjRTA2	0.395 (0.162)**	0.368 (0.166)**	0.350 (0.166)**
adjRTA3	0.304 (0.240)	0.165 (0.242)	0.211 (0.251)
adjRTA4	−0.084 (0.241)	−0.300 (0.248)	−0.130 (0.255)
BR	0.358 (0.369)	−0.407 (0.419)	0.028 (0.816)
RU	−0.089 (0.332)	0.054 (0.250)	0.370 (0.561)
IN	−0.136 (0.225)	0.118 (0.251)	−0.092 (0.315)
CN	−0.068 (0.217)	0.005 (0.299)	0.308 (0.257)
SG	−0.188 (0.211)	0.153 (0.342)	−0.322 (0.365)
TW	0.218 (0.243)		0.091 (0.400)
WESTEUROPE	0.501 (0.131)***	0.511 (0.134)***	0.499 (0.134)***
NORTHAMERICA	−0.403 (0.164)**	−0.376 (0.169)**	−0.402 (0.169)**
Constant	−3.883 (0.700)***	−4.409 (0.700)***	−4.283 (0.727)***
Rho constant	0.009 (0.004)**	0.007 (0.004)	0.012 (0.004)***
Sigma constant	0.507 (0.024)***	0.516 (0.024)***	0.521 (0.024)***
Number of obs.	221	221	221
Complementarity test: $HOMEOFF_{H,M,KS} \geq ONLYOFF_{H,M,KS} + ONLYHOME_{H,M,KS}$			
Wald χ^2 (one-sided)	0.04	4.92***	0.02

***$p<0.01$, **$p<0.05$, *$p<0.10$.

highly significant and large, the other coefficients are smaller and less significant. The last row in Table 4 reports the direct Wald χ^2 one-sided test of complementarity for each of the three models, and its significance. In line with Expectation No. 1, in the H model, the test does not reject the null of equality. Thus, regions that both offshore

four categories, according to the following rule:

$$\theta_{11} - \theta_{10} \geq \theta_{01} \tag{7.3*}$$

However, if we take NOHOMEOFF as the benchmark for the other three dummies, $\theta_{00} = 0$. Accordingly, the inequality tests involving four [Equation (7.3)] and three [Equation (7.3*)] dummies are equivalent.

R&D activities in high technology-intensive sectors to BRICST and conduct R&D at home above the sample median, do not show a level of knowledge production greater than regions that only offshore R&D activity to BRICST, or only conduct high-level R&D at home. Our expectations are confirmed in relation to regions offshoring R&D in medium/low technology-intensive sectors because for the M model the one-sided Wald χ^2 test detects complementarity (Expectation No. 2). In particular, the null of equality and submodularity is rejected at $p < 0.01$. This implies that regions that both offshore R&D in medium/low technology-intensive sectors to BRICST and carry out above median level R&D at home, produce more knowledge than regions that either only offshore R&D in medium/low technology-intensive sectors to BRICST, or only conduct above median R&D at home. However—and contrary to Expectation No. 3—the Wald χ^2 one-sided test of complementarity yields insignificant results for regions' offshoring R&D in KS.

A number of controls produce statistically significant results. In particular, regional population density exerts a negative effect on innovation (statistically significant at $p < 0.05$). Surprisingly, heavily populated regions seem to be at a disadvantage in knowledge production. Hosting the primary city has a negative effect on the innovative activity of regions offshoring R&D in high knowledge-intensive sectors and has no effect on the innovative activity of regions offshoring in M and KS sectors (*CAP* is statistically negatively significant at $p < 0.05$ in the H model). This result is most likely due to a preference for locating R&D laboratories and firm headquarters in regions other than the more expensive capital region. Financial institutions play a role in enhancing regional knowledge production (*FIN_SHARE* is statistically positive and significant at $p < 0.01$) as suggested by the innovation system literature (Lundvall, 1992). Despite the documented beneficial effects of a more open innovation model and an increase in international collaborations (Narula and Hagedoorn, 1999; Chesbrough, 2003), we find a negative effect of cross-country collaboration on patenting activity (*INTERNATCOOP* is negative and statistically significant at $p < 0.01$). The share of educated labour force (*HK_SHARE)* is positive and statistically significant at $p < 0.01$, which confirms that human capital is a main determinant of innovation (e.g. Usai, 2011). In addition, we find that industry R&D has a positive effect on regional innovative activity (*R&D_BUS*; $p < 0.01$), while our results show a negative effect of university R&D (*R&D_UNI* at $p < 0.10$ in the H and M models, and $p < 0.05$ in the KS model). This finding is consistent with studies that show a clear dominance of private R&D over university research on regional patenting activity (e.g. Acs et al., 2002).

Region size positively affects regional knowledge production (*POP* is statistically positively significant at $p < 0.01$). *R&D_FDI* in non-BRICST countries is a driver of regional innovative activity, but only if the investment is related to high technology-intensive sectors. This result is consistent with the international business literature, showing that international knowledge sourcing primarily targets advanced countries with greater expertise in cutting-edge technologies (Cantwell, 1989). Country attractiveness for FDI hampers home region patenting activity (*FDI* is negative and statistically significant at $p < 0.05$). Regions specialized in electrical engineering and instrument technology are higher knowledge producers ($adjRTA_1$ is positive and significant at $p < 0.05$ in the H and M models and $adjRTA_2$ is positive and statistically significant at $p < 0.05$ in all three models). This may be because this specialization is more likely to produce new knowledge in the current information economy. Finally, the home region dummies are significant and show that among Western European regions, knowledge production is higher in all three models, and lower for North American regions. In relation to host country controls, we find that host country conditions do not affect investment in specific sectors.

10.1. Robustness checks

To check the robustness of our result, we estimate Equation (8.1) for the sub-sample of US and Western European regions, which accounts for 80% of the regions in our sample, in order to rule out that our results are driven by a few outliers. Table 5 reports the estimations for the KPF for our sub-sample of R&D offshored in H, M and KS (columns 1–3, respectively).

The results confirm our main findings related to complementarity. The coefficients of HOMEOFF are significant and large; the other coefficients are all smaller. The Wald χ^2 one-sided test shows statistically significant results for the M model, revealing that regions that both offshore in M sectors and conduct high quality R&D at home, produce more knowledge than regions engaging in only one of these activities. *HOMEOFF* and *ONLYHOME* are statistically significant in all models. Similar to the main results, *ONLYOFF* is never significant (again, *NOHOMEOFF* was dropped due to collinearity).

The findings for the controls are generally the same as for the main results, but there are a few exceptions. Unlike the main results, regional population density is not statistically significant in the H model. In these estimations, a negative primary city effect is detected for the M and KS models—in addition to the negative effect in the H model. In none of the models is the significant effect of human capital on innovation replicated. Similarly, unlike our main results, country attractiveness of FDI is not statistically significant; probably as a result of the higher homogeneity of countries in this sub-sample. Other differences between these estimations and the main findings relate to regional technological specialization in electrical engineering ($adjRTA_1$), where the significant effect in the main findings for H and M disappear. Finally, in relation to the home country controls, all other things being equal, Scandinavian regions are high knowledge producers and US regions do less well.

11. Discussion and conclusion

We began by observing that the trend in global offshoring from advanced regions to emerging countries is no longer confined to the offshoring of tangibles. At least parts of the R&D function are offshored. Based on insights from economic geography and the literature on international knowledge sourcing, we conjectured that complementarity should obtain between home region R&D and offshored R&D if the offshored R&D is dissimilar to the type of (presumably) high-technology R&D conducted in the home region. We hypothesized that offshored R&D would improve the efficiency of home R&D if the R&D in these two locations was of different technological intensity. When we split offshored R&D into three categories (high-technology, medium/low technology and knowledge-intensive services sectors), complementarity applies only to medium/low technology R&D. This is in line with our theoretical expectations (Expectations No. 1 and No. 2). For knowledge-intensive services sectors, however, and contrary to our expectation (Expectation No. 3), we find no complementarity. Our theoretical framework hints at some explanations for this finding. First, while it is fairly evident

Table 5. Robustness checks on subsample (US and Western European regions)

Dep. variable Explanatory	Model 4 H K Coef. (SE)	Model 5 M K Coef. (SE)	Model 6 KS K Coef. (SE)
HOMEOFF	0.779 (0.254)***	0.790 (0.302)***	0.737 (0.385)*
ONLYOFF	0.457 (0.363)	−0.475 (0.446)	0.583 (0.591)
ONLYHOME	0.391 (0.109)***	0.322 (0.113)***	0.427 (0.115)***
Controls			
DEN	−0.078 (0.048)	−0.092 (0.051)*	−0.092 (0.051)*
CAP	−0.583 (0.189)***	−0.428 (0.188)**	−0.430 (0.204)**
FIN_SHARE	10.12 (1.836)***	11.46 (1.911)***	11.24 (1.915)***
INTERNATCOOP	−0.238 (0.079)***	−0.232 (0.081)***	−0.230 (0.082)***
HK_SHARE	0.097 (0.154)	0.136 (0.159)	0.142 (0.162)
R&D_BUS	0.406 (0.079)***	0.438 (0.083)***	0.405 (0.083)***
R&D_UNI	−0.223 (0.075)***	−0.229 (0.078)***	−0.257 (0.078)***
POP	0.790 (0.059)***	0.853 (0.060)***	0.842 (0.063)***
R&D FDI	0.351 (0.116)***	0.018 (0.113)	−0.162 (0.171)
FDI	0.024 (0.117)	0.016 (0.121)	0.005 (0.123)
$adjRTA_1$	0.275 (0.212)	0.264 (0.220)	0.213 (0.227)
$adjRTA_2$	0.364 (0.185)**	0.317 (0.190)*	0.318 (0.193)*
$adjRTA_3$	0.198 (0.261)	0.097 (0.267)	0.050 (0.284)
$adjRTA_4$	−0.184 (0.261)	−0.362 (0.275)	−0.266 (0.283)
BR	0.611 (0.394)	−0.163 (0.389)	−0.159 (0.757)
RU	0.111 (0.310)	−0.009 (0.253)	0.405 (0.530)
IN	−0.146 (0.219)	−0.093 (0.238)	−0.179 (0.359)
CN	−0.081 (0.202)	−0.108 (0.278)	0.202 (0.267)
SG	−0.262 (0.213)	0.165 (0.319)	0.188 (0.418)
TW	0.137 (0.234)		0.026 (0.377)
SCAN	0.799 (0.162)***	0.844 (0.165)***	0.807 (0.171)***
US	−0.729 (0.155)***	−0.704 (0.161)***	−0.724 (0.165)***
Constant	−3.929 (0.780)***	−4.599 (0.791)***	−4.416 (0.834)***
Rho constant	0.237 (0.042)***	0.223 (0.043)***	0.240 (0.043)***
Sigma constant	0.437 (0.023)***	0.450 (0.023)***	0.458 (0.024)***
Number of obs.	177	177	177
Complementarity test: $HOMEOFF_{H,M,KS} \geq ONLYOFF_{H,M,KS} + ONLYHOME_{H,M,KS}$			
Wald χ^2 (one-sided)	0.03	6.09***	0.30

$^{***}p<0.01$; $^{**}p<0.05$; $^{*}p<0.10$.

that high-income regions generally have a comparative advantage in R&D in the most advanced technologies, and emerging economies have a comparative advantage in R&D in medium/low technologies, it is less clear that, in the period studied, emerging economies have equal comparative advantage in software R&D and other knowledge-intensive services (Arora and Gambardella, 2005). Similarly, it is not a given that high-income countries are at an unambiguous disadvantage for developing these technologies. For instance, much state-of-the-art software continues to be developed in California. Secondly, it is not a given that software and other knowledge-intensive services are as straightforward to co-develop (as we have assumed) over large geographical distances as other technologies. It is possible that there is a high degree of interdependence between software and other advanced technologies when these technologies are applied in the same products. This high interdependence may make geographical separation of their development activities less feasible.

Our findings have a number of implications. The first refers to the debate on whether the RSI notion is challenged by R&D offshoring. Within the economic geography literature, our results are in line with those of Verspagen and Schoenmakers (2004) in the sense that, with reference to R&D offshoring in emerging countries, the tendency to perform R&D abroad implies a strengthening of the notion of RSI rather than the reverse. Similarly, within the literature on international knowledge sourcing (Cantwell, 1995) our findings confirm the beneficial effect of R&D internationalization on home innovative activities, including when R&D is offshored to emerging economies. For MNEs, investing in R&D in these countries improves the effectiveness of the production of knowledge in the home region. We suggest that these results are related to specialization advantages combined with reverse knowledge transfer from the emerging countries, within the more general trend towards open innovation. Another related implication concerns the 'systemic' nature of knowledge production underlined in the RSI tradition. Although in our case we addressed the issue of cross-fertilization between region-internal and region-external knowledge, our analysis complements the theoretical contribution to the economic geography literature, of Bathelt et al. (2004), who argue for a combination of knowledge-related 'local buzz' and 'global pipelines' for regional development. Our findings confirm that regional development (in our case knowledge production) to some extent is dependent on the interaction between knowledge development within and outside the region.

Our analysis has a major policy implication. Policy-makers in the advanced economies are fearful of a hollowing-out effect on home R&D activity from R&D offshoring to emerging countries. However, our findings indicate that R&D offshoring in emerging countries may yield potential gains for advanced home locations. Policy-makers in high-income regions should design structural policies that take account of the international division of labour in knowledge production. From the point of view of these advanced economies, exploiting the benefits of division of labour requires vast effort and expertise in high-tech sectors within the home regions.

This study contributes to the economic geography and international business literatures; it is the first systematic investigation of the effect of offshored R&D to fast-growing emerging economies, on the level of knowledge production in advanced home regions. It advances traditional economic geography research by challenging the view that more information-intensive activities and facilities are to be found solely in advanced locations. The article contributes also to the international business research by considering the effects of reverse knowledge transfer from home-base augmenting activities in emerging economies. Finally, the study responds to a number of calls for research that combines insights from the economic geography and international business literatures (McCann and Mudambi, 2005; Beugelsdijk et al., 2010).

The analysis in this article has some limitations, the most important being that we cannot break down home region R&D into different classes associated with different degrees of knowledge intensity; this is only possible for offshored R&D. Such a break-down would require more detailed regional R&D statistics. Also, our analysis is only able to address the issue of in-house or captive offshoring. Future research should try to analyse the complementarity/substitutability of outsourced offshore R&D (in addition to captive offshoring). Also, our data do not allow us to analyse subgroups of technologies since we have information only on the industry of the R&D investment.

This is clearly an important area for future research. Despite these limitations, we hope that this article will prompt more research on the relationship between regional and extra-regional knowledge production.

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Appendix A

The OECD members are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, South Korea, Luxemburg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, UK and USA. Because of missing regional data we excluded Japan, Turkey, Mexico, Iceland, Denmark, Switzerland, New Zealand, Poland and Portugal, and nine regions (two Canadian regions, two Spanish autonomous regions and the Canary Islands, two Italian autonomous provinces and Alaska and Hawaii in USA).

Appendix B

The Nomenclature of Territorial Units for Statistics (NUTS, from the French 'nomenclature d'unités territoriales statistiques') was developed by the EU to enable a uniform geographical breakdown for statistical and policy-making purposes. NUTS comprises three levels. NUTS divisions do not always correspond to national administrative divisions. REGPAT TL classification relies on the July 2007 NUTS version. However, differences exist between TL and NUTS regions for some EU countries. Since Belgium, Greece and the Netherlands are small countries, the NUTS 2 level corresponds to TL3. For the UK, NUTS 1 corresponds to TL2. For Denmark, which has no NUTS two divisions, TL2 corresponds to the TL3/NUTS3 regions.

Table A1. Variable definitions and descriptive statistics[a]

Variable	Description	Source	Period	Mean	SD
K	PCT applications which have designated EPO at the international phase by inventor's residence and fractional count. 2-year average.	REGPAT	2006–2007	4.96	1.694
DEN	Regional population density.	RDB	2003–2005	4.364	1.548
CAP	Dummy equal 1 if the region hosts the country capital city, 0 otherwise.	RDB	2003–2005	–	–
FIN_SHARE	Share of employment in financial intermediation.	RDB	2004[b]	0.126	0.041
INTERNATCOOP	Share of patents with multiple inventors in which at least one inventor is not resident in the same country of region *r*.	REGPAT	2003–2005	1.890	0.624
HK_SHARE	Share of labour force with tertiary education (ISCED 5–6).	RDB	2003–2005	3.195	0.338
R&D_BUS	Share of industry R&D expenditure.	RDB	2003–2005	3.917	0.582
R&D_UNI	Share of university R&D expenditure.	RDB	2003–2005	3.121	0.791
POP	Regional population.	RDB	2003–2005	7.651	1.068
R&D_FDI$_{H,M,KS}$	Dummy equal to 1 for regions investing in R&D FDI in non-BRICST countries by sector H, M and KS.	fDi Market	2003–2005	–	–
FDI	Dummy equal to 1 if net value of FDI inward stock is positive.	UNCTAD	2003–2005	–	–
adjRTA$_1$	Index of Reveal Technological Advantage of Electrical Engineering technological group.	REGPAT	2003–2005	−0.236	0.268
adjRTA$_2$	Index of Reveal Technological Advantage of Instruments technological group.	REGPAT	2003–2005	−0.099	0.233
adjRTA$_3$	Index of Reveal Technological Advantage of Chemistry technological group.	REGPAT	2003–2005	−0.031	0.211
adjRTA$_4$	Index of Reveal Technological Advantage of Mechanical Engineering technological group.	REGPAT	2003–2005	0.077	0.227
BR$_{H,M,KS}$, RU$_{H,M,KS}$, IN$_{H,M,KS}$, CN$_{H,M,KS}$, SG$_{H,M,KS}$, TW$_{H,M,KS}$	Dummy equal to 1 for each destination BRICST country of OECD R&D investments by sector H, M and KS.	fDi Market	2003–2005	–	–
NORTHAMERICA	Dummy equal to 1 for investing North American (USA and Canada) regions, 0 otherwise.	fDi Market	2003–2005	–	–
WESTEUROPE	Dummy equal to 1 for investing EU15 regions and Norwegian regions, 0 otherwise. (Excluded from European OECD regions are regions in Hungary, Czech Republic and Slovakia).	fDi Market	2003–2005	–	–

[a]All variable are transformed in logarithm, but are dummy variables.
[b]For Germany, the available year is 2003.