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Research collaboration and regional knowledge production in Europe

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Research collaboration and regional knowledge production in Europe

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Abstract. The focus of this study is on regional knowledge production in Europe, with special emphasis on the interplay between intra- and inter-regional research collaboration. The objective is to identify and measure effects of research collaboration on knowledge production at the level of European regions. We use a panel data spatial Durbin model (SDM) relationship for empirical testing. The European coverage is achieved using 228 NUTS-2 regions covering all pre-2007 EU member states except Cyprus, Greece and Malta. The dependent variable, regional knowledge production, is measured in terms of fractional patent counts at the regional level in the time period 2000-2008, using patents applied at the European Patent Office (EPO). The independent variables include an agglomeration variable, reflecting intra-regional research collaboration, measured in terms of employment in knowledge intensive sectors, and a network variable, reflecting extra-regional research collaboration, measured in terms of a region's collaboration activities in the EU Framework programmes (FPs), weighted by R&D expenditures in network partner regions. We implement a panel version of the standard SDM that controls for spatial autocorrelation as well as individual heterogeneity across regions, and allows for the estimation of spatial spillovers from neighbouring regions. The estimation results confirm the prevalence of agglomeration effects for regional knowledge production, and, by this, the importance of co-location of R&D actors. Furthermore, the study provides evidence that inter-regional R&D collaborations in the FPs significantly contribute to regional knowledge production.

JEL Classification: R11, O31, C21

Keywords: Regional knowledge production, Agglomerations effects, R&D networks, European Framework Programmes, panel spatial Durbin model

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1 Introduction

Today it is widely recognised that interactions and research collaborations among organisations are essential elements of knowledge production processes (see, for instance, Powell and Grodal 2005). Organisations must collaborate more actively and more purposefully with each other in order to cope with converging technologies, and increasing market pressures due to changing patterns of demand in a globalising world (see, for instance, Fischer 2001). In particular, firms have expanded their knowledge bases into a wider range of technologies (Granstrand 1998), requiring more diverse knowledge, so firms must learn how to integrate new knowledge into existing products or production processes (Cowan 2004). It may be difficult for a firm to develop this knowledge alone or acquire it via the market. Thus, firms aim to form co-operative arrangements with other firms, universities or research organisations that already have this knowledge to get earlier access to it.

In the recent past, organisations seem to have expanded the spatial range of their collaboration activities, referred to as local buzz vs. global pipelines or the local-global duality in the process of knowledge creation (see, for instance, Bathelt et al. 2004). On the one hand, as a consequence of the globalisation process, knowledge production becomes increasingly interconnected and internationalised. The network of interactions between R&D actors rises considerably. On the other hand, R&D activities remain bounded within a relatively narrow geographic area. Taking regions – defined as subnational spatial units – as essential sites of knowledge creation (see, for instance, Lagendijk 2001), this local-global duality is reflected by the co-existence of, on the one hand, the co-location of actors producing knowledge inducing geographically localised, mostly intra-regional knowledge spillovers (see, for instance, Fischer et al. 2006), and, on the other hand, of global, more far-reaching research collaborations tapping specific pieces of region-external knowledge (see, for instance, Varga et al. 2010).

In a policy context, it is notable that regional, national and supranational Science, Technology and Innovation (STI) policies as well as regional innovation policies have shifted attention to supporting research collaborations between various organisations, in particular among firms and

universities (see Caloghirou et al. 2002, among others)¹. Policy makers have to balance between two types of policies: on the one hand, policy that leads to economies of scale in knowledge production by supporting further regional specialisation, and on the other hand, policy that promotes cross-regional R&D collaboration and accelerates inter-regional knowledge diffusion particularly to regions where given knowledge is not available (Pontifakis et al. 2009). While regional and national policy programmes mainly address collaborative knowledge production within one region or country, at the supranational level, such as the EU, more far-reaching, large-distance collaboration is encouraged. The prime examples at the European level are the European Framework Programmes (FPs) for Research and Technological Development (RTD). They support pre-competitive R&D projects, creating a pan-European network of actors performing joint project-based R&D (see, for instance, Scherngell and Lata 2012).

Up to now, there is only little empirical evidence on the local-global duality in knowledge creation at the regional level. In this study we take a regional perspective to address this question drawing on novel data sets providing information on project based networking activities in the FPs. The objective is to identify and measure effects of intra- and interregional research collaboration on knowledge production at the level of European regions. We use a panel data spatial Durbin model (SDM) for empirical testing. The European coverage is achieved using 228 NUTS-2 regions covering all pre-2007 EU member states except Cyprus, Greece and Malta. The dependent variable, regional knowledge production, is measured in terms of fractional patent counts at the regional level in the time period 2000-2008, using patents applied for at the European Patent Office (EPO). The independent variables include an agglomeration variable, reflecting intra-regional research collaboration, measured in terms of employment in knowledge intensive sectors, and a network variable, reflecting extra-regional research collaboration, measured in terms of a regions' collaboration activities in the EU Framework programmes (FPs), weighted by R&D expenditures in network partner regions. By this we are able to estimate the distinct effects of network participation and agglomeration on regional knowledge production. In

¹ This policy focus has been mainly triggered by various considerations in theoretical and empirical literature of Economics of Innovation, Economic Geography, Regional Science and Management Science (see Fagerberg and Verspagen 2009 for an overview). In particular, two arguments are essential in this respect: First, innovation, knowledge creation and the diffusion of new knowledge are the key vehicles for sustained economic growth of firms, industries or regions, and, thus, are essential for achieving sustained competitive advantage in the economy (see, for example, Romer 1990). Second, as mentioned above, interactions, research collaborations and networks of actors are crucial for successful innovation (see, for instance, Fischer 2001).

estimating the effects, we implement a panel version of the standard SDM that controls for spatial autocorrelation as well as individual heterogeneity across regions. The specification incorporates a spatial lag of the dependent variable as well as spatial lags of the independent variables. This allows for the estimation of spatial spillovers of agglomeration and network effects from neighbouring regions by calculating scalar summary measures of impacts.

The paper is organised as follows. **Section 2** sheds some light on the theoretical background for the study, focusing on regional knowledge production and the importance of extra-regional research collaboration for gaining access to external knowledge sources. **Section 3** outlines the econometric framework, specifying the empirical model in form of a panel version of the SDM relationship to be estimated. **Section 4** comprises a detailed description of the empirical setting, presenting the data and the dependent and independent variables as well as some descriptive statistics. **Section 5** presents the estimation results and their interpretation, before **Section 6** concludes with a summary of the main results and an outlook for future research.

2 Theoretical background

The importance of research collaborations for generating new knowledge² is nowadays widely accepted (see, for instance, Powell and Grodal 2005). The motives and drivers for organisations to engage in R&D collaborations with firms, research organisations and universities are manifold; one of the most striking arguments is the increasing complexity of innovation processes, most notably in the context of converging and rapidly developing technologies (see, for instance, Pavitt 2005). Consequently, the absorption and integration of new knowledge from various sources as well as a permanent search for novel combination opportunities of complementary knowledge bases is the key to sustainable innovative capability.

As noted by Granstrand (1998), innovating organisations have expanded their knowledge bases into a wider range of technologies which requires the integration of a more diverse set of external

² Knowledge can be seen as a process, embedded in employees and firms' routines (Fischer and Froehlich 2001). For the purpose of this study, it is useful to distinguish between two types of knowledge - tacit and codified (see, among others Polanyi 1967, Nonaka and Takeuchi 1995, Fischer 2001). Tacit knowledge is embodied in a person and can be obtained by experience. It requires rather interpersonal contact to diffuse, and, thus, is conditional on geographical proximity (Fischer 2001, Varga et al. 2010). On the contrary, codified (explicit) knowledge is stated in an explicit form, can be stored and transmitted easily over long distances almost frictionless (Bathelt et al. 2004).

knowledge pieces. Collaborative arrangements create incentives for interactive organisational learning which leads to faster knowledge diffusion and stimulates the creation of new knowledge or the combination of pieces of existing knowledge in a new way. Such collaborations are particularly useful in an environment characterised by uncertainty and complexity such as knowledge production processes. Collaborating reduces the degree of uncertainty and provides faster access to different kinds of knowledge, in particular tacit knowledge (see, for example, Kogut 1988)³.

The fundamental importance of research collaborations for knowledge production is also reflected in the various systems of innovation concepts (see Lundvall 1992 among many others). In this conception the sources of new knowledge are often established between firms, universities, suppliers and customers. In the concept of the *regional innovation system*, it is further assumed that innovating actors are embedded in a regional innovation system – where the region is defined as a subnational spatial unit – benefiting from spatial proximity to other actors (see Asheim and Gertler 2005). Spatial proximity is considered to be of particular importance since knowledge is in part tacit; Krugman (1991) argues that knowledge flows are restricted with geographical boundaries due to cost of (especially tacit) knowledge transmission, which in contrast to costs for the transmission of information, rises with geographical distance. The distance decay pattern of knowledge externalities has been confirmed in various empirical studies, beginning with the pioneering study of Jaffe et al. (1993), followed by Autant-Bernard (2001), Maurseth and Verspagen 2002, Fischer und Varga (2003), Fischer et al. (2006), LeSage et al. (2007) or Fischer et al. (2009). Audretsch and Feldman (1996) provide evidence that in industries, for which knowledge diffusion is particularly important, innovative activity tends to be more spatially concentrated. It implies that knowledge flows are encouraged by a spatial proximity of different R&D actors including firms, public and private research institutes,

³ Incentives to cooperate and advantages arising from R&D collaborations may also be identified using other theoretical arguments (Hagedoorn et al. 2000, Caloghirou et al. 2003). From the perspective of transaction costs, firms and organisations entering into collaborative arrangements can avoid high costs of internalising R&D activities. Industrial organisation theory argues that R&D collaborations are suitable strategies to capture external knowledge. In addition, the managerial perspective highlights an ability of a firm to learn from cooperation, thereby adopting new skills and abilities, and, thus, improving its own competitive position after all. Both, managerial and industrial organisation views, implicitly include further advantages arising from R&D collaborations, such as R&D costs sharing, economies of scale and scope, risk pooling or access to complementary resources. Close interactions build trust and reduce the uncertainty and thus the complexity of production.

universities etc. Such organisations are taking advantage of their co-location. These gains are also referred to as agglomeration economies or external economies of scale⁴ (Rosenthal and Strange 2004).

However, key players of the regional innovation systems, such as universities and large knowledge-intensive firms do not only benefit from the local knowledge base, but increasingly are compelled to search for knowledge sources that are geographically located further away in order to keep pace in the global innovation competition (see, for example, Maggioni et al. 2007, Scherngell and Barber 2009 and 2011, Wanzenböck et al. 2012). Such region-external knowledge sources are tapped via region-external research collaboration activities – for instance in the form of joint R&D projects, joint assignment of patents or joint conduction of scientific publications – and/or labour mobility. These knowledge sources may be explicitly valuable for such organisations to gain contact with less familiar pieces of knowledge that may be important for their long-term development (see Maskell et al. 2006).

In a policy context, the importance of research collaboration has also been affirmed by the common vision of the EU to develop the European Research Area, intended to integrate national science, technology and innovation (STI) policies (European Commission 2000), and to support international research collaboration across Europe. The main instrument to reach this goal are the EU Framework Programmes (FPs) for Research and Technological Development (RTD) that are funding programmes created to support and stimulate R&D projects⁵ between European organisations in order to boost technological competitiveness on the one hand, while to ensure cohesion on the other hand. By this, the FPs provide a significant channel for organisations to tap region-external knowledge sources, and may represent an example of geographically dispersed R&D collaborations⁶. Furthermore, increasing inter-regional connectedness that may be viewed

⁴ Two types of agglomeration economies may be specified. Localisation economies (called also intra-industry externalities) emerge from the spatial concentration of economic activity within one single industry, hence from the scale of the industrial specialisation (Marshall 1920, Arrow 1962, Romer 1986). Urbanisation economies (intra-industry externalities) arise from the industrial diversification, region-size (Jacobs 1969).

⁵ See, for instance, Breschi and Cusmano (2002) for a preliminary view on the emergent pan-European network of firms, public research organisations, universities, consultants and government institutions jointly collaborating on projects across different research areas.

⁶ The geography of R&D collaborations within the FPs has attracted increasing attention in the recent past. The study of Constantelou et al. (2004) confirms significant collaborative activity among clusters of neighboring

as an alternative explanation of regional knowledge production in addition to conventional agglomeration economies, may provide regions with rather weak agglomeration characteristics an opportunity to be highly productive in case of being well inter-linked to inter-regional R&D collaboration networks (Varga et al. 2010). The focus of this study is to test the interdependencies between region-internal research collaboration – proxied by regional agglomeration effects – and region external research collaboration – proxied by regional participation in the FPs. By this, the study contributes to the literature on the local-global duality of knowledge production processes from a regional perspective.

3 The empirical model

In order to estimate the relationship between regional knowledge production and region-internal and region-external research collaboration, we use a panel version of the Spatial Durbin Model (SDM) as introduced by Elhorst (2003). This is an appropriate way to deal with the problem of spatial autocorrelation, and to estimate the influence of spatial spillover effects. The panel version of the standard SDM model controls not only for spatial autocorrelation but also for individual heterogeneity across regions (see LeSage and Fischer 2012). Denoting our set of regions by $i = 1, \dots, N$ and our time periods by $t = 1, \dots, T$, the empirical model to estimate the relationship between research collaboration and regional knowledge production is given by

$$y_t = \rho W y_t + \delta_1 a_t + \delta_2 W a_t + \gamma_1 k_{t-2} + \gamma_2 W k_{t-2} + \eta_t \quad i = 1, \dots, N; t = 1, \dots, T; \quad (1)$$

with

$$\eta_t = \mu + \varepsilon_t \quad (2)$$

countries. Autant-Bernard et al. (2007) find that relational distance by means of the firms' position within a network matters more than their geographical location. Maggioni et al. (2007) suggest that a region's knowledge production is mainly influenced, besides by regions that are located close in geographical space, also by regions that are close in relational space. The study of Schnerngell and Barber (2009) provides evidence that geographical factors matters for interregional collaboration intensities, whereas the effect of technological proximity prevails. Schnerngell and Barber (2011) further show that geographical factors are less significant for public research networks in comparison with the greater impact of geography on patterns of industrial R&D collaboration networks.

where y_t is the N -by-1 vector of observations on regional knowledge production in N regions at time t . a_t denotes the N -by-1 vector of observations on the agglomeration variable at time t , capturing intra-regional research collaborations, while k_{t-2} is the N -by-1 vector reflecting the observations on the network variable at time $t-2$ ⁷, measuring inter-regional research collaboration activities. δ_1, γ_1 are scalar parameters to be estimated.

W is the N -by- N matrix of spatial weights reflecting the spatial configuration of the regions with elements

$$w_{ij} = \begin{cases} 1 & \text{if } s_{ij}^{(1)} \leq s_{ik(i)}^{(1)} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where $s_{ij}^{(1)}$ measures the geographical distance between two given regions i and j . $k_{(i)}$ indicates the k nearest neighbouring of region i . Following previous empirical research, we set $k = 5$ (see, among others, LeSage and Pace 2008, Scherngell and Lata 2012).

As a consequence, Wy_t denotes the N -by-1 vector representing the spatial lag of regional knowledge production in k nearest neighbours at time t . Its coefficient ρ measures the strength of spatial dependence. Similarly, N -by-1 vectors Wa_t and Wk_{t-2} denote the average of observations on the agglomeration and the network variable in k nearest neighbours at time t and $t-2$, respectively. δ_2, γ_2 are the associated scalar parameters to be estimated.

$\varepsilon_t = (\varepsilon_{1t}, \dots, \varepsilon_{Nt})'$ is the N -by-1 vector of disturbances for time period t which is independently and identically distributed with zero mean and variance σ_ε^2 . $\mu = (\mu_1, \dots, \mu_N)'$ is the N -by-1 vector representing random spatial specific effects, i.e. μ is treated as a random element and is assumed to be independently and identically distributed with zero mean and variance σ_μ^2 ⁸. Since

⁷ Following previous empirical studies (Furman et al. 2002, Varga et al. 2010), we decide to impose a lag of two years on the network variable, as it takes some time between the inputs translate into measurable outputs. In case of the agglomeration variable, time lag is not necessary, as the variable varies only slightly over the analysed period.

⁸ The model with random effects is more appropriate in case of our sample data, because variables that do not change or change only slightly over time periods cannot be estimated using the model with fixed effects, since they are eliminated in estimation process (Elhorst 2010b). Such a variable in our model is the agglomeration variable and its spatial lag. Moreover, the model with fixed effects can be estimated consistently only when the time domain T is sufficiently large (Elhorst 2010b). As our sample comprises a relatively small number of time periods $T = 9$ as compared to the number of cross sectional observations $N = 228$, the model with random effects is more suitable.

space-specific time-invariant effects are likely to have an impact on the dependent variables, their omission could lead to a biased and inconsistent estimation result (Elhorst 2010b).

Inclusion of lags of both dependent and independent variables allows to account for spatially autocorrelated omitted variables that are likely to be correlated with the included explanatory variables (LeSage and Pace 2009). Furthermore, the SDM model specification offers great analytical opportunities. Having the unconstrained SDM model as an initial model enables us to follow the general-to-simple model selection rule by testing whether the model can be simplified (Fischer and Wang 2011). The SDM model nests a spatial lag (SAR) and a spatial error (SEM) model as special cases. Even when one of these models is the true data generating process, the SDM model provides unbiased estimation results (LeSage and Pace 2009). When $\delta_2 = \gamma_2 = 0$, the model is reduced to the SAR model and comprises only a spatial lag of the dependent variable. By setting $[\delta_2 \gamma_2] + \rho [\delta_1 \gamma_1] = 0$, the SDM model is simplified to the SEM model⁹. However, this restriction is only correct when there are no omitted variables correlated with the included explanatory variables (LeSage and Fischer 2008). In order to find an appropriate model specification, a likelihood ratio test is carried out. The double difference between the values of log-likelihood function for the SDM model and a model with a restriction is chi-squared distributed with a number of degrees of freedom reflecting the number of imposed restrictions.

An additional specific advantage of using the SDM in the context of our research focus is the possibility to measure the scale of intra- and inter-regional spillovers, or so called direct and indirect effects (LeSage and Pace 2008)¹⁰. Besides direct impacts of a change of independent variables a_i and k_i on knowledge production measured by means of patents y of their respective region i (direct effects), we can additionally observe the effect of changes of these variables in other regions j on region i (indirect effects). Such partial derivatives represent possible spillover impacts from all other regions $N-1$. Since we consider changes in each $j = 1, \dots, N-1$ region including changes in the own region, these results can be expressed by means of N -by- N matrices

⁹ There is also a possibility to derive a model where only independent variables exhibit spatial dependence and observations of dependent variable are assumed to be spatially independent ($\rho = 0$). Finally, the restrictions $\rho = 0$ and $\delta_2 = \gamma_2 = 0$ would result in a standard OLS model (Fischer and Wang 2011).

¹⁰ Taking only the parameter estimates δ_1 and γ_1 for the agglomeration and network variables into account would be an incorrect interpretation of the model, since they do not include the effect of so called feedback loops that arise as a result of impacts passing through neighboring regions and back to the regions themselves (LeSage and Pace 2009).

for both independent variables:

$$S_a(W) = \partial y / \partial a = (I_N - \rho W)^{-1} (I_N \delta_1 + W \delta_2) \quad (4)$$

$$S_k(W) = \partial y / \partial k = (I_N - \rho W)^{-1} (I_N \gamma_1 + W \gamma_2) \quad (5)$$

The matrices $S_a(W)$ and $S_k(W)$ of all partial derivatives are correct measures of local (direct) and spillover (indirect) impacts arising from changes in the independent variables a and k of each region i on the dependent variable y of the respective region and all other regions (LeSage and Pace 2009, Elhorst 2011). The off-diagonal elements represent cross-partial derivatives, which can be summarised into scalar measures representing indirect impacts using the average of either the row-sums or column-sums of the matrix elements excluding the diagonal. The average summary measure of direct effects is defined as the average of the sum of the own partial derivatives on the main diagonal of the matrices. The average total scalar measure is represented by the sum of direct and indirect effect averages (LeSage and Pace 2009).

4 Data and variables

In this study, European coverage is achieved using $N = 228$ NUTS-2 regions (revision 2003) covering all pre-2007 EU member states except Cyprus, Greece and Malta. The choice of NUTS-2 regions is motivated by the fact that they have an appropriate size to catch sub-national characteristics (see, for instance, LeSage and Fischer 2012). The time domain comprises $T = 9$ time periods from 2000 to 2008.

To measure regional knowledge production we use fractional counts of patent applications to the European Patent Office sorted by the by priority year (date of application) derived from Eurostat¹¹. We use fractional counts, i.e. we count patents based on the number of inventors listed on a patent application, dividing the number of inventors by the number of different

¹¹ As inventions have to be novel, non-trivial and commercially applicable in order to be protected by a patent, patents can be recognised as quantitative indicators of inventions. Nevertheless, the use of patents has some limitations. Not all inventions that could be patented are actually patented, because patenting is a voluntary strategic decision. Further, not all inventions are allowed to be patented, for example a program code (OECD 1994).

regions in which they are located. For a patent with three different inventors in three different regions we count 1/3 for each region so that the total sum of counts for one patent equals to 1 (Eurostat 2007).

As introduced in the previous section, our independent variables consist of the *agglomeration variable* and the *network variable*. We use employment in knowledge intensive sectors derived from Eurostat as a proxy for agglomeration effects (see, for instance, Varga et al. 2010) By knowledge intensive sectors, we understand high- and medium-high-technology manufacturing, high-technology knowledge intensive services, knowledge intensive market services, financial services as well as the education and the health sector, as defined by Eurostat.

Table 1. Descriptive statistics

	2000	2001	2002	2003	2004	2005	2006	2007	2008
Regional knowledge production									
Mean	223.8	222.2	222.2	228.1	238.2	243.9	247.5	245.9	208.2
Std.	410.3	420.1	403.0	410.2	425.9	423.1	426.0	420.2	354.2
Min	0.3	0.3	0.5	0.2	0.3	0.2	0.4	0.9	0.5
Max	2913.5	2922.6	2792.5	3098.4	3317.7	3019.0	3073.5	3087.4	2689.1
Agglomeration variable									
Mean	295.6	303.5	307.3	312.4	317.3	322.8	331.2	340.3	345.5
Std.	264.6	272.1	275.7	273.1	282.4	288.7	293.9	301.1	307.3
Min	2.0	2.9	2.7	2.7	2.9	2.3	2.2	5.0	2.6
Max	2387.3	2473.4	2474.6	2404.8	2414.7	2470.3	2444.2	2516.4	2562.1
Network variable									
Mean	3121.3	2817.8	3427.7	4155.5	5055.5	5265.1	7186.4	7638.3	8194.4
Std.	4921.0	4358.2	5380.2	6473.6	7923.3	8209.4	11759.5	12646.5	13788.6
Min	0	0	0	0	1.2	0	0	0	0
Max	45617.7	40613.2	51987.3	61428.1	76191.6	79236.3	119005.1	129465.8	140499.7

The *network variable* is measured in terms of the number of regional EU Framework programme (FPs) participations, weighted by R&D expenditures in partner regions. Thus, the measure is defined as a product of an N -by- N collaboration matrix (see Scherngell and Barber 2009 and 2011), and an N -by-1 vector of total regional R&D expenditures for each time period. The data on regional R&D expenditures come from Eurostat. For the construction of the collaboration matrix we use data from the EUPRO database that contains information on research

collaborations of participating firms and organisations within the FPs. The time period 1998 to 2006 covers the fifth (1998-2002) and the sixth (2002-2006) FP. For each time period, the collaboration matrix contains the number of linkages in terms of joint project participations between all (i,j) -region pairs, given $i = 1, \dots, N$ regions in the rows and $j = 1, \dots, N$ regions in the columns. Since the network variable acts as a proxy for extra-regional research collaboration, we do not consider intraregional knowledge flows.

Table 1 presents some summary statistics on the three model variables. It can be seen that for the dependent variable, that is regional knowledge production, as well as for the agglomeration, we cannot observe a time trend concerning mean knowledge production – as captured by regional patenting – and mean degree of agglomeration – as captured by employment in knowledge intensive sectors. In contrast, for the network variable – captured by regional participation in the FPs weighted by R&D expenditures in network partner regions – we can observe a sharp increase in mean regional FP participation intensity between 2000 and 2008.

5 Estimation results

In this section we present and discuss our empirical findings. All variables in the model are defined in log form. *Table 2* presents the parameter estimates of the SDM model. Furthermore, we report model specification tests that confirm the choice of the SDM specification with random effects. Using a likelihood ratio test we can reject the restriction of the model to the SAR model, which includes only a spatial lag of the dependent variable (284.26, $p=0.000$). A Breusch-Pagan test statistic validates the significance of the random effects (4721.03, $p=0.000$). All parameter estimates of the independent variables in the SDM model specification are highly significant. However, these estimates cannot be interpreted as marginal effects of changes in the agglomeration and network variables on the knowledge production variable. As mentioned in *Section 3*, the parameters estimates differ from direct effect estimates that contain also feedback effects arising partly due to the coefficient of spatially lagged dependent variable, which we find highly statistically significant, and partly due to the highly significant coefficients of spatially lagged independent variables (Elhorst, 2010a). It is also important to remark that highly significant spatially lagged variables do not imply significant indirect effects of the respective

variables (see *Table 3*). The spatially lagged variables indicate just impacts of nearest neighbouring regions as defined by the spatial weight matrix W .

Table 2. Parameter estimates from the SDM with random effects (Nobs = 2052)

Variable	Coefficient	Standard error	p-value
Agglomeration variable (δ_1)	0.523	0.058	0.000
Network variable (γ_1)	0.075	0.011	0.000
Spatially lagged variables			
Knowledge production (ρ)	0.413	0.028	0.000
Agglomeration variable (δ_2)	-0.244	0.062	0.000
Network variable (γ_2)	0.059	0.015	0.000
Model specification tests			
Log Likelihood	-1807.91		
LR test for spatial lag	284.26 ($p = 0.000$)		
BP test for random effects	4721.03 ($p = 0.000$)		

Notes: The dependent and the independent variables are defined as given in the text. LR denotes the Likelihood Ratio test for the spatial lag specification, while BP denotes the Breusch-Pagan test for the random effects specification.

Table 3 reports the average summary measures along with 95% credible intervals indicating that the direct, indirect and total effects of the explanatory variables, except the indirect effect of the agglomeration variable, are different from zero based on the credible intervals. If we consider the average direct impacts, it is important to note that they are close to the SDM model coefficient estimates reported in *Table 2*. Differences between these two measures represent feedback effects that arise from induced effects in the neighbours of the neighbours of region i , successively in the neighbours of those neighbours, and continuing throughout the whole system, including some feedback effects to the region i itself.

The direct effect of the agglomeration variable that is highly significant appears to be 0.519. Since the coefficient estimate is equal to 0.523, the feedback effect of this variable amounts to -0.004 or 0.8% of the direct effect. Similarly, the feedback effect of the network variable is the difference between the highly significant direct effect 0.082 and the parameter estimate 0.075, that is 0.007 or 8.5% of the direct effect. Thus, the feedback effect turns out to be relatively small and negative for the agglomeration variable. The feedback effect of the network variable,

although still relatively small, shows much stronger and positive impact than in the previous case.

Table 3. Average scalar summaries from the SDM

Variable	0.05 level	Mean	0.95 level
Agglomeration variable			
Direct impact	0.402	0.519* (0.055)	0.622
Indirect impact	-0.170	-0.047 (0.063)	0.079
Total impact	0.401	0.472* (0.035)	0.538
Network variable			
Direct impact	0.062	0.082* (0.010)	0.102
Indirect impact	0.108	0.147* (0.021)	0.188
Total impact	0.192	0.229* (0.035)	0.269

Note: *significant at the 0.001 significance level; standard errors in brackets

Direct effect estimates show in both cases a positive impact, i.e. a change of the independent variable in region i on the knowledge production in that region. This impact is much higher in magnitude in case of the agglomeration variable (0.519). It confirms the importance of co-location of R&D actors. The direct impact of the network variable, i.e. a region's own collaboration activity with other regions, is lower as compared to the agglomeration variable (0.082). However, the results confirm the direct impact of research collaborations within the EU FPs on regional knowledge production, when considering patents as an output of knowledge production, though the agglomeration characteristics of a region play a much more prominent role.

Indirect effects of the agglomeration variable are not significant suggesting that the employment in knowledge intensive sectors has only a local impact, in other words, it influences only its own region. On the contrary, the indirect impact estimate for the network variable indicates considerable average spillover effect to other regions (0.147). The indirect effect of a change in the network variable appears to be 1.8 times the magnitude of the direct effect of the same variable. Thus, this result suggests that regions with less developed R&D infrastructure may

profit from collaborations with other regions. The total impacts of both independent variables on knowledge production are positive and highly significant (0.472 and 0.229). A 10% increase in the agglomeration variable increases regional production by 4.72%. Similarly, a 10% increase in the network variable results in a 2.29% increase in regional knowledge production.

6 Conclusions

Research collaborations are nowadays to be seen as one of the most essential elements for the knowledge production of firms, universities and research organisations. The focus of this study has been on regional knowledge production in Europe, devoting special emphasis to the question how research collaborations contribute to knowledge production processes from a regional perspective. We have employed a spatial Durbin model (SDM) relationship to test whether region-internal and region-external research collaboration contribute to regional knowledge production, using 228 NUTS-2 regions of Europe as our spatial framework, and accounting for spatial spillovers between our system of spatial units. Regional knowledge production has been proxied by using information on regional patenting for the years 2000-2008, while region-internal research collaboration has been measured by means of an agglomeration variable that is defined by the share of a region's employment in knowledge intensive sectors, and region-external research collaboration by regional participation in the EU Framework Programmes (FPs) that have been specifically designed to foster international research collaboration across Europe.

The study produces promising results in the context of the literature dealing with the local-global duality of knowledge production, also referred to as the local-buzz vs. global pipelines in the process of knowledge creation. The estimation results confirm the prevalence of agglomeration effects for regional knowledge production, and, by this, the importance of co-location of R&D actors. However, the most important outcome of the study is that it provides statistical evidence that inter-regional R&D collaborations in the FPs significantly contribute to regional knowledge production, i.e. knowledge flows via such global knowledge pipelines – often corresponding to large-distance collaborations of key players of the regional innovation system – significantly contribute to the overall regional knowledge production output in form of regional patents.

The results are also important in a policy perspective, as this study is one of the first few studies that provides systematic statistical evidence on the positive contribution of participation in the FPs to knowledge production across Europe, and that such FP collaborations may indeed induce knowledge flows between regions that are located further away, complementing intra-regional inputs to the knowledge production process. Further, the results imply that considerable benefits may arise from R&D collaborations for lagging regions.

Some ideas for a future research agenda come to mind. *First*, alternative measurements of research collaboration may be considered, in particular for extra-regional research collaborations, having in mind that research collaborations in the FPs constitute only a very small and specific subsample of total research collaborations. *Second*, other model specifications may be considered, for instance models for dynamic spatial panels (see Elhorst 2011), in order to be able to disclose and characterise dynamic effects in the relationship between regional knowledge production and intra-regional vs. extra-regional research collaboration.

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Note: Online links validity checked on 29th June 2012

Appendix: List of regions

In this study we use 228 NUTS-2 regions (revision 2003) covering all pre-2007 EU member states except Cyprus, Greece and Malta. In addition, the list does not include the Spanish North African territories of Ceuta y Melilla, the Portuguese non-continental territories Azores and Madeira, and the French Departments d'Outre-Mer Guadeloupe, Martinique, French Guayana and Reunion.

<i>Austria:</i>	Burgenland, Kärnten, Niederösterreich, Oberösterreich, Salzburg, Steiermark, Tirol, Vorarlberg, Wien
<i>Belgium:</i>	Prov. Antwerpen, Prov. Brabant-Wallon, Prov. Hainaut, Prov. Limburg (B), Prov. Liège, Prov. Luxembourg (B), Prov. Namur, Prov. Oost-Vlaanderen, Prov. Vlaams-Brabant, Prov. West-Vlaanderen, Région de Bruxelles-Capitale / Brussels Hoofdstedelijk Gewest
<i>Czech Republic:</i>	Jihovýchod, Jihozápad, Moravskoslezsko, Praha, Severovýchod, Severozápad, Střední Morava, Střední Čechy
<i>Denmark:</i>	Danmark
<i>Estonia:</i>	Eesti
<i>Finland:</i>	Åland, Etelä-Suomi, Itä-Suomi, Länsi-Suomi, Pohjois-Suomi
<i>France:</i>	Alsace, Aquitaine, Auvergne, Basse-Normandie, Bourgogne, Bretagne, Centre, Champagne-Ardenne, Corse, Franche-Comté, Haute-Normandie, Île de France, Languedoc-Roussillon, Limousin, Lorraine, Midi-Pyrénées, Nord - Pas-de-Calais, Pays de la Loire, Picardie, Poitou-Charentes, Provence-Alpes-Côte d'Azur, Rhône-Alpes
<i>Germany:</i>	Arnsberg, Berlin, Brandenburg, Braunschweig, Bremen, Chemnitz, Darmstadt, Dessau, Detmold, Dresden, Düsseldorf, Freiburg, Gießen, Halle, Hamburg, Hannover, Karlsruhe, Kassel, Koblenz, Köln, Leipzig, Lüneburg, Magdeburg, Mecklenburg-Vorpommern, Mittelfranken, Münster, Niederbayern, Oberbayern, Oberfranken, Oberpfalz, Rheinhessen-Pfalz, Saarland, Schleswig-Holstein, Schwaben, Stuttgart, Thüringen, Trier, Tübingen, Unterfranken, Weser-Ems
<i>Hungary:</i>	Dél-Alföld, Dél-Dunántúl, Észak-Alföld, Észak-Magyarország, Közép-Dunántúl, Közép-Magyarország, Nyugat-Dunántúl
<i>Ireland:</i>	Border, Midland and Western; Southern and Eastern
<i>Italy:</i>	Abruzzo, Basilicata, Calabria, Campania, Emilia-Romagna, Friuli-Venezia Giulia, Lazio, Liguria, Lombardia, Marche, Molise, Piemonte, Puglia, Sardegna, Sicilia, Toscana, Trentino-Alto Adige, Umbria, Valle d'Aosta/Vallée d'Aoste, Veneto
<i>Latvia:</i>	Latvija
<i>Lithuania:</i>	Lietuva
<i>Luxembourg:</i>	Luxembourg (Grand-Duché)
<i>Netherlands:</i>	Drenthe, Flevoland, Friesland, Gelderland, Groningen, Limburg (NL), Noord-Brabant, Noord-Holland, Overijssel, Utrecht, Zeeland, Zuid-Holland

<i>Poland:</i>	Dolnośląskie, Kujawsko-Pomorskie, Lubelskie, Lubuskie, Łódzkie, Mazowieckie, Małopolskie, Opolskie, Podkarpackie, Podlaskie, Pomorskie, Śląskie, Świętokrzyskie, Warmińsko-Mazurskie, Wielkopolskie, Zachodniopomorskie
<i>Portugal:</i>	Alentejo, Algarve, Centro (P), Lisboa, Norte
<i>Slovakia:</i>	Bratislavský kraj, Stredné Slovensko, Východné Slovensko, Západné Slovensko
<i>Slovenia:</i>	Slovenija
<i>Spain:</i>	Andalucía, Aragón, Cantabria, Castilla y León, Castilla-La Mancha, Cataluña, Comunidad Foral de Navarra, Comunidad Valenciana, Comunidad de Madrid, Extremadura, Galicia, Illes Balears, La Rioja, País Vasco, Principado de Asturias, Región de Murcia
<i>Sweden:</i>	Mellersta Norrland, Norra Mellansverige, Småland med Öarna, Stockholm, Sydsverige, Västsverige, Östra Mellansverige, Övre Norrland
<i>United Kingdom:</i>	Bedfordshire & Hertfordshire; Berkshire, Buckinghamshire & Oxfordshire; Cheshire; Cornwall & Isles of Scilly; Cumbria; Derbyshire & Nottinghamshire; Devon; Dorset & Somerset; East Anglia; East Riding & North Lincolnshire; East Wales; Eastern Scotland; Essex; Gloucestershire, Wiltshire & North Somerset; Greater Manchester; Hampshire & Isle of Wight; Herefordshire, Worcestershire & Warwickshire; Highlands and Islands; Inner London; Kent; Lancashire; Leicestershire, Rutland and Northamptonshire; Lincolnshire; Merseyside; North Eastern Scotland; North Yorkshire; Northern Ireland; Northumberland and Tyne and Wear; Outer London; Shropshire & Staffordshire; South Western Scotland; South Yorkshire; Surrey, East & West Sussex; Tees Valley & Durham; West Midlands; West Wales & The Valleys; West Yorkshire