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## Inter-regional betweenness centrality in the European R&D network: Empirical investigation using European Framework data

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# **Inter-regional betweenness centrality in the European R&D network: Empirical investigation using European Framework data**

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**Abstract.** Given the great current interest in European R&D networks, in which organizations from the science and the industry sectors perform joint R&D, we investigate knowledge flows in the European R&D network, as inferred from Framework Programme (FP) data. We make use of the concept of edge betweenness centrality, which assesses the power of a relation based on the load placed on the corresponding network edge. Edges with high betweenness centrality have the greatest load, are strategically positioned, and potentially can act as bottlenecks for the flows. We use this idea to evaluate knowledge flows between organizations in the European R&D network, considering several ways to relate the betweenness centrality at the level of FP project participants to knowledge flows at the NUTS2 regional level. We do so by aggregating betweenness centrality values calculated using bipartite graphs linking organizations to the FP projects in which they participate, condensing inter-organizational centralities to inter-regional betweenness centralities. We determine the most central inter-regional knowledge flows, and consider the implications for knowledge flows in European R&D networks. We model the betweenness centrality by means of spatial interaction models, estimating how geographical, technological, and social factors influence the centralities. The results have meaningful implications to European R&D policy, in particular concerning which region pairs become bottlenecks in the flow of knowledge.

**JEL Classification:** L14, O31, R12

**Keywords:** European R&D networks, social network analysis, betweenness centrality, Framework Programmes, knowledge flows, bottlenecks

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## 1 Introduction

Today it is widely recognized that innovation – the heart of technological change – is the primary engine for (regional) economic development. The innovation process depends upon the accumulation and diffusion of new knowledge. Certainly, the individual firm plays an essential role for the development of specific innovations, but the knowledge production process now involves a complex web of interactions among a range of firms, universities and other research institutions. This is often explained by the increasing complexity of technological knowledge needed for the production of innovations, leading to a situation where in-house innovative capabilities of firms are insufficient for developing such innovations (see, for instance, Fischer 2001). Thus, firms collaborate with other firms, universities or research organizations that already have this knowledge to more rapidly access it. The study of Hagedoorn and van Kranenburg (2003) confirms the rise of strategic R&D alliances during the 1990s.

From this perspective, knowledge diffusion processes in R&D networks have received much recent attention in the theoretical and empirical research of different scientific disciplines. In a regional science context, the investigation of the geographical dimension of R&D collaborations has been one major research stream over the past few years<sup>1</sup>. A recent empirical contribution is the study of Scherngell and Barber (2009) focusing on the geography of R&D collaborations across European regions by using data on joint research projects of the fifth EU Framework Programme (FP5) as a proxy for cross-region collaboration activities. The study provides evidence that geographical distance significantly affects patterns of cross-region R&D collaborations in Europe<sup>2</sup>.

In light of the importance of R&D networks, we are motivated to investigate European R&D collaborations using methods of network analysis. Previous applications of network analysis have revealed interesting facets of European R&D collaborations at the regional level. We note two in

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<sup>1</sup> Theoretical considerations of New Growth Theory assume that geographical space is crucial for innovation. These theoretical considerations have been followed by empirical studies. The pioneering study of Jaffe et al. (1993) produces evidence for the localization hypothesis of knowledge diffusion. The following years of empirical research have been characterized by the development of new indicators and the integration of new econometric and statistical techniques (see, for instance, Maurseth and Verspagen 2002, Fischer et al. 2006).

<sup>2</sup> Other recent contributions that investigate geographical aspects of R&D collaborations involve the studies of Constantelou et al. (2004), Autant-Bernard et al. (2007b), Maggioni et al. (2007) Maggioni and Uberti (2007) and Hoekman et al. (2009).

particular. *First*, Barber and Scherngell (2012) examined community structures in FP5 identifying thematically differentiated communities whose geographical properties showed pronounced differences from those of FP5 as a whole. *Second*, Wanzenböck et al (2012) focus on the embeddedness of regions in the European network of R&D cooperation within the FPs from a social network analysis perspective.

In this paper, we focus – using network analysis techniques – on a very important question in the context of the literature on the so-called local-global duality of knowledge production: assuming that knowledge production is not only geographically localized, knowledge flows increasingly also depend on knowledge sources located further away in geographical space (see, e.g., Bathelt et al. 2004). This is also referred to as the local buzz vs global pipelines in the process of knowledge creation. The objective of the study is to explore possible bottlenecks for knowledge flows between 255 NUTS-2 regions, which may constitute such global knowledge pipelines, using the concept of betweenness centrality, a ranking of network constituents based on how necessary they are for efficient flows in the network. In contrast to the study by Wanzenböck et al. (2012), we focus on what betweenness centrality reveals about the inter-regional flows, rather than applying the betweenness centrality to rank the regions themselves. In calculating inter-regional betweenness centrality, we use data on joint R&D projects constituted under the FPs. Further, the geographical structure of observed inter-regional edge betweenness is investigated by means of Poisson spatial interaction models, disclosing the influence of geographical factors on inter-regional betweenness centrality. It may be assumed that geographical factors play only a minor, in particular as compared to the FP5 network as a whole.

## **2 Measuring inter-regional bottlenecks**

In social network analysis, the importance of constituent members of the network is frequently assessed in terms of centrality. Centrality measures are computed from the linkage structure of the network, with various measures defined to reflect properties of interest in the network. Centrality then condenses a complex network structure into a more easily interpretable ranking of the network nodes or links, with the highest ranks indicating a more central position and, presumably, a greater importance to the structure and function of the network.

Betweenness centrality  $g(v)$  for a node  $v$  is calculated using the shortest paths in the network. Its value is

$$g(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}} \quad (1)$$

where  $\sigma_{st}$  is the number of shortest paths with nodes  $s$  and  $t$  as their endpoints, while  $\sigma_{st}(v)$  is the number of those shortest paths that include node  $v$ . The betweenness centrality increases with the number of nodes in the network, so a normalized version is often considered with the centrality values scaled to between 0 and 1. A related edge betweenness centrality is also defined, ranking the network links based on the number of shortest paths that flow through them. Nodes with high betweenness centrality have a high load placed on them, lending them importance in the network. They are responsible for effective flows through the network, placing them in the role of gatekeepers, able to impede flows. Analogously, edges with high edge betweenness centrality also have high loads, which position them as bottlenecks.

In this work, we would like to use the above concepts to characterize knowledge flows between European regions due to FP projects. The corresponding network consists of organizations linked by project co-participation. The organizations are geographically rooted and thus make sense as nodes in the network, while the projects provide a medium for interactions between the organizations, and thus would naturally be the basis for links in the network.

However, projects generally link more than two organizations, unlike links in a simple network. This more complex form of linkage constitutes a hypergraph, which offers an equivalent representation as a bipartite network with the organizations and projects constituting the two parts of the network and links between organizations and the projects in which they participate. To assess the nature of knowledge flows between organizations, we are thus motivated to consider the betweenness centrality of the project nodes in the bipartite network. In this fashion, we can build on the conceptual and computational foundation of the standard betweenness centrality, modifying the calculation only by separately normalizing the centrality scores for the two parts of the network, thus ranking the significance of the projects with a value between 0 and 1.

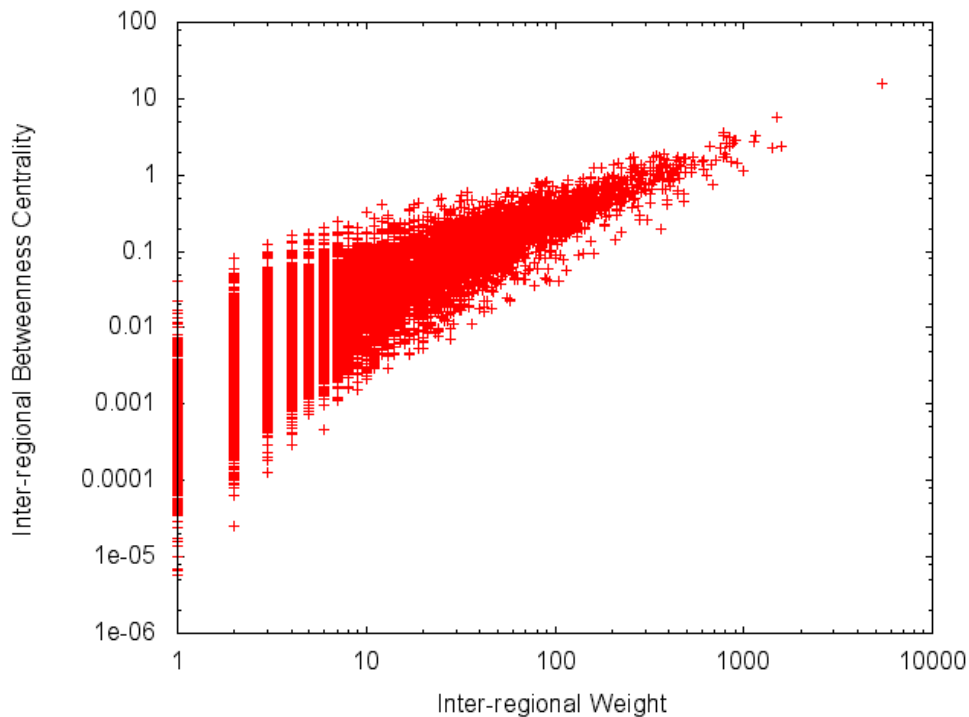
As we are interested in bottlenecks in inter-regional knowledge flows, rather than inter-organizational knowledge flows, we still must address how to aggregate the betweenness centralities of the projects into a form of inter-regional betweenness centrality  $g_{ij}$ . Here, we build on the approach used by Scherngell and Barber (2009) to determine inter-regional flow weights  $w_{ij}$  from similar bipartite networks derived from FP data. They considered each pair of organizations

in the network as providing a contribution to the flow between the regions in which they are located, said contribution being equal to the number of projects in which both organizations take part. The total inter-regional weight is then the sum of all contributions from organizations located in the regions. Here, we take a pair of organizations as contributing to the appropriate inter-regional betweenness centrality  $g_{ij}$  an amount equal to the sum of the betweenness centralities of all projects in which both organizations take part, with the total inter-regional value again being the sum of all contributions from organizations in the regions.

### 3 Characterization of inter-regional bottlenecks

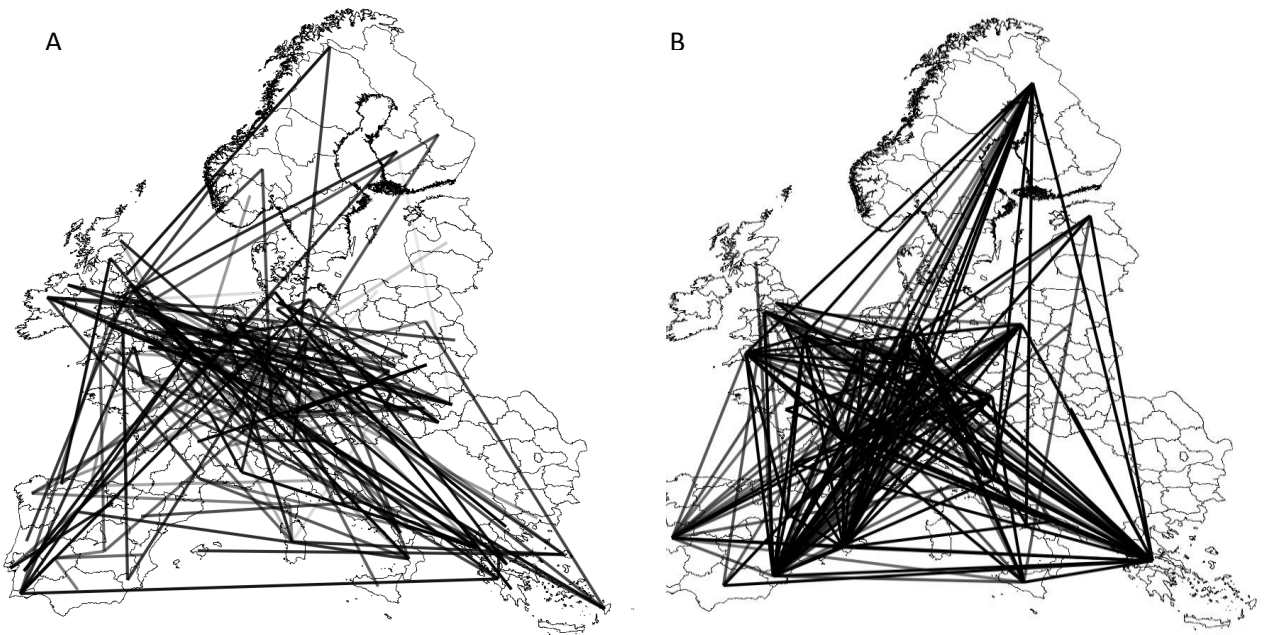
In this section, we characterize the inter-regional betweenness centrality in Europe. We present results for R&D networks derived from FP5, aggregated to the NUTS-2 level. We additionally considered FP6, but do not show the results as they are similar. We turn first to the distribution of centralities. In Figure 1, we see that the centrality  $g_{ij}$  strongly correlates with the weight  $w_{ij}$ , both of which vary over several orders of magnitude in FP5. Given this correlation, the ratio  $r_{ij}=g_{ij}/w_{ij}$  of the inter-regional betweenness centrality to the inter-regional weight is more likely to be interesting, in particular with high values indicating region pairs that tend to produce bottlenecks.

**Figure 1:** Correlation of Inter-regional betweenness and inter-regional weights (FP5)



To compare the high- $r_{ij}$  links to the low- $r_{ij}$  links, we select those links and visualize the resulting subnetworks. In Figure 2, we show subnetworks derived from the 1% of inter-regional links with the lowest  $r_{ij}$  (Figure 2A) and the 1% of inter-regional links with the highest  $r_{ij}$  (Figure 2B), respectively. Links in the figures are shown with opacity proportional to the maximal  $r_{ij}$  in the corresponding subnetwork.

**Figure 2:** Links with high and low ratios of inter-regional betweenness centrality to weight



Notes: Map A shows the network of the 1% of FP inter-regional links with the lowest ratio of inter-regional betweenness to weight; Map B shows the network of the 1% of FP inter-regional links with the highest ratio of inter-regional betweenness to weight

The two networks reveal marked differences: the high-ratio subnetwork shows a hub-like structure with numerous nodes (regions) having high degree (number of incident links), while this structure is absent in the low-ratio subnetwork. Of the 161 regions linked in the low-ratio subnetwork, the greatest degree is a mere 11, while 12 of the 54 regions linked in the high-ratio network have a degree at least that large, reaching a maximum of 34 incident links.

In Table 1, we present the largest hubs, here taken as those regions from the high-ratio subnetwork which have degree ten or more. These hubs differ strongly from the regions more usually constituting hubs base on flow strengths, e.g., Île-de-France or Oberbayern.

**Table 1:** Central hubs of bottlenecks

<b>NUTS-2 Code</b>	<b>Region</b>	<b>Degree (# of incident links)</b>
<b>ES62</b>	Región de Murcia	34
<b>GR24</b>	Stereia Ellada	30
<b>DE26</b>	Unterfranken	23
<b>ES53</b>	Illes Balears	23
<b>FR72</b>	Auvergne	18
<b>UKK4</b>	Devon	15
<b>PT16</b>	Centro (P)	14
<b>PL41</b>	Wielkopolskie	14
<b>FI1A</b>	Pohjois-Suomi	14
<b>UKH3</b>	Essex	12
<b>DE14</b>	Tübingen	12
<b>ITG1</b>	Sicilia	11
<b>DEA4</b>	Detmold	10
<b>AT31</b>	Oberösterreich	10
<b>ES24</b>	Aragón	10
<b>UKD2</b>	Cheshire	10
<b>ITE3</b>	Marche	10

Notes: Included here are the regions which form hubs in the subnetwork formed from the 1% of FP5 links with the highest centrality-weight ratios  $r_{ij}$  (see Figure 1). We include those regions which have degree of at least ten.

We next generalize this idea by varying the fraction of the high- or low-ratio inter-regional links. Rather than presenting numerous maps, we instead introduce a measure of the concentration of the degrees of the regions; this is especially advantageous as the fraction increases, because the increasing number of links tends to obscure interesting features of the visualized subnetworks. We use the normalized Herfindahl index  $H^*$  as the concentration measure. Denoting the degree (number of incident links) of region  $i$  as  $d_i$ , we define the share  $s_i$  as

$$s_i = \frac{d_i}{\sum_i d_i} \quad (2)$$

The standard Herfindahl index  $H$  is then



$$H = \sum_i s_i^2 \quad (3)$$

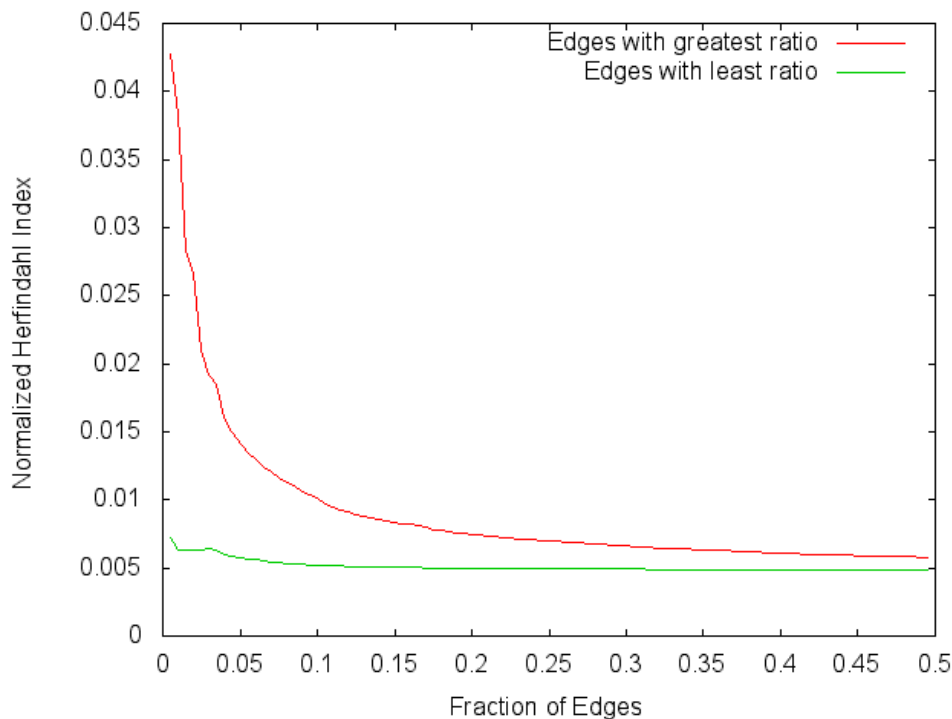
and the normalized Herfindahl index  $H^*$  is

$$H^* = \frac{H - 1/N}{1 - 1/N} \quad (4)$$

where  $N$  is the number of regions with non-zero degree.

In Figure 3, we show the variation in  $H^*$  with the fraction of high- $r_{ij}$  and low- $r_{ij}$  inter-regional links. We see that the links most likely to be high centrality bottlenecks are concentrated in relatively few regions, but that this concentration exponentially diminishes as we include more links in the subnetwork. The subnetworks derived from low-ratio links do not show this concentration.

**Figure 3:** Regional concentration of bottlenecks



Notes: The inter-regional links with the highest ratio of inter-regional betweenness to weight are concentrated in comparatively few regions. As an increasing fraction of high-ratio links are included, the degree distribution in the networks becomes more uniform, indicated by the decreasing Herfindahl index. In contrast, the low-ratio links show no such regional concentration, having a greater diversity and correspondingly low Herfindahl index throughout.

## 4 Prediction of inter-regional bottlenecks

In this section, we focus on the question on how we can explain the structure of inter-regional betweenness centrality. As mentioned in the previous section, we can speak of regional bottlenecks for region pairs that show a comparably high betweenness, i.e. these edges are important bottlenecks for knowledge flows across Europe, also over large distances. In the context of the literature on global knowledge-pipelines (see, e.g., Maskell et al. 2006), the development that key players of the innovation systems—such as universities and large knowledge-intensive firms—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 with the global innovation competition (see Wanzenböck et al. 2012). Such region-external knowledge sources may be explicitly valuable for such organizations to gain contact with less familiar pieces of knowledge that may be important for their long-term development.

The question that arises at this point is how the spatial structure of inter-regional betweenness centrality differs from observed inter-regional collaboration patterns as a whole. The study of Scherngell and Barber (2009) shows that geographical factors – including geographical distance, country border effects or neighboring region effects – are important determinants of inter-regional R&D collaboration intensities in FP5, but the effect of technological proximity is stronger. Inter-regional R&D collaboration intensities here simply refer to the number of joint R&D projects between two organizations located in two different NUTS-2 regions. It is to be hypothesized – given the literature on the local-global duality of knowledge production, also referred to as the local buzz vs. global pipelines in the process of knowledge creation (see, e.g., Bathelt et al. 2004, Maskell et al. 2006) – that geographical factors play a minor role in explaining inter-regional betweenness centrality, in particular when taking the centrality as proxy for such global knowledge pipelines that are assumed to be geographically de-localised.

To test this hypothesis, we simply take the approach of Scherngell and Barber (2009) to estimate the impact of geographical factors on cross-region R&D collaborations, applied to inter-regional betweenness centrality  $g_{ij}$  between two regions  $i$  and  $j$ . In this sense, we employ a spatial interaction modeling perspective to model our inter-regional betweenness centrality dependent on some origin function, some destination function, and some separation including geographical factors and some control variables. We describe the modeling approach formally in compact form. Our general model is given by

$$G_{ij} = A_i B_j S_{ij} + \varepsilon_{ij} \quad i, j = 1, \dots, n \quad (5)$$

with

$$A_i = A(a_i, \alpha_1) = a_i^{\alpha_1} \quad i, j = 1, \dots, n \quad (6)$$

$$B_j = B(b_j, \alpha_2) = b_j^{\alpha_2} \quad i, j = 1, \dots, n \quad (7)$$

$$S_{ij} = \exp \left[ \sum_{k=1}^K \beta_k d_{ij}^{(k)} \right] \quad i, j = 1, \dots, n \quad (8)$$

where  $G_{ij}$  denotes a stochastic dependent variables that is realized by the observed betweenness centrality  $g_{ij}$  for region  $i$  and region  $j$ .  $A_i$  denotes the origin function,  $B_j$  the destination function, while  $S_{ij}$  represents a separation function, and  $\varepsilon_{ij}$  some disturbance about the mean. The  $a_i$  and  $b_j$  are measured in terms of the number of organizations participating in EU FP5 projects in the regions  $i$  and  $j$ , and are simply employed here to control for size effects.  $\alpha_1$  and  $\alpha_2$  are scalar parameters to be estimated.

The  $d_{ij}^{(k)}$  are  $K$  separation measures, the  $\beta_k$  are corresponding parameters to be estimated that will show the relative strengths of the separation measures including our geographical factors. For comparison purposes with the study of Scherngell and Barber (2009), we focus on  $K=6$  separation variables:  $d_{ij}^{(1)}$  measures the great circle distance between the economic centers of two regions  $i$  and  $j$ .  $d_{ij}^{(2)}$  is a country border dummy variable that takes a value of zero if two regions  $i$  and  $j$  are located in the same country, and one otherwise, while  $d_{ij}^{(3)}$  is a language area dummy variable that takes a value of zero if two regions  $i$  and  $j$  are located in the same language area, and one otherwise<sup>3</sup>.  $d_{ij}^{(5)}$  and  $d_{ij}^{(6)}$  are dummy variables that take a value of one if the regions  $i$  and  $j$  are direct neighbors<sup>4</sup> or are located in neighboring countries, respectively, and zero otherwise.  $d_{ij}^{(4)}$

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<sup>3</sup> Language areas are defined by the region's dominant language (see LeSage et al. 2007). However, in most cases the language areas are combined countries, as for instance Austria, Germany and Switzerland (one exception is Belgium, where the French speaking regions are separated from the Flemish speaking regions).

<sup>4</sup> We define two regions  $i$  and  $j$  as neighbors when they share a common border.

captures technological distance between two regions – measured in form of the dissimilarity of two regions’ patent portfolios<sup>5</sup> – in order to isolate geographical from technological effects.

In estimating the parameters  $\alpha_1 = \alpha_2$  and  $\beta_k$ , we specify a Negative Binomial spatial interaction model that allows for overdispersion in the data, as is often the case for flows between discrete units in geographical space (see, e.g., Fischer et al. 2006). Furthermore, we can directly compare our results with those of Scherngell and Barber (2009) using the same regional setting and having in mind that the parameters can be interpreted as elasticities. The Negative Binomial density distribution in our case is given by

$$f(G_{ij}) = \frac{\Gamma(g_{ij} + \delta^{-1})}{\Gamma(g_{ij} + 1)\Gamma(\delta^{-1})} \left( \frac{\delta^{-1}}{A_i B_j S_{ij} + \delta^{-1}} \right)^{\delta^{-1}} \left( \frac{A_i B_j S_{ij}}{A_i B_j S_{ij} + \delta^{-1}} \right)^{g_{ij}} \quad (9)$$

where  $\Gamma(\cdot)$  denotes the gamma function and  $\delta$  is the dispersion parameter. Model estimation is done by Maximum Likelihood procedures (see Long and Freese 2001).

Table 2 presents the sample estimates of the spatial interaction model, with standard errors given in brackets. The left column reports the results for modeling FP5 edge betweenness centralities across our set of European regions, while the right column reports the results from Scherngell and Barber (2009) for total FP5 inter-regional collaboration activities. The model results are quite interesting in the context of the literature on European R&D networks on the one hand, and in the context of the literature on the local-global duality of knowledge production processes. Comparing the results for the betweenness centrality model with those of total FP5 collaboration intensities, it is clearly shown that geographical factors play a minor role for explaining the structure inter-regional betweenness centrality in comparison to the total collaboration patterns in FP5. The negative effect of geographical distance is much lower for the inter-regional betweenness centrality than for the overall collaboration intensity between two regions. Other geographical factors, such as county border effects, language area effects as well as neighboring region and neighboring country effects

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<sup>5</sup> We measure technological distance by using regional patent data from the European Patent Office (EPO). The application date is used to extract the data for each year of our time frame. We follow Moreno et al. (2005) and construct a vector for each region  $i$  that contains region  $i$ ’s share of patenting in each of the technological subclasses of the International Patent Classification (IPC). Technological proximity between two regions  $i$  and  $j$  in time period  $t$  is given by the uncentered correlation between their technological vectors.

are even insignificant in predicting inter-regional bottlenecks as proxied by inter-regional edge betweenness, while these factors are all significant for predicting total FP5 collaborations.

**Table 2:** Estimation Results of the Negative Binomial spatial interaction model [65,025 observations, asymptotic standard errors given in brackets]

	Predicting FP5 edge betweenness	Total FP 5 collaborations (Scherngell and Barber 2009)
<i>Origin variable</i> [ $\alpha_1$ ]	0.894 <sup>***</sup> (0.002)	0.973 <sup>***</sup> (0.002)
<i>Destination variable</i> [ $\alpha_2$ ]	0.892 <sup>***</sup> (0.002)	0.974 <sup>***</sup> (0.002)
<i>Geographical distance</i> [ $\beta_1$ ]	-0.051 <sup>*</sup> (0.021)	-0.228 <sup>***</sup> (0.005)
<i>Country border effects</i> [ $\beta_2$ ]	0.032 (0.006)	-0.048 <sup>**</sup> (0.017)
<i>Language area effects</i> [ $\beta_3$ ]	0.137 (0.005)	-0.119 <sup>***</sup> (0.015)
<i>Technological distance</i> [ $\beta_4$ ]	-0.705 <sup>***</sup> (0.105)	-0.677 <sup>***</sup> (0.071)
<i>Neighbouring region</i> [ $\beta_5$ ]	-0.146 (0.152)	0.256 <sup>***</sup> (0.022)
<i>Neighbouring country</i> [ $\beta_6$ ]	0.083 (0.071)	0.080 <sup>***</sup> (0.009)
<b>Constant</b>	-11.798 <sup>***</sup> (0.435)	-6.131 <sup>***</sup> (0.077)
<b>Dispersion parameter</b> ( $\delta$ )	12.354 <sup>***</sup> (2.421)	4.271 <sup>***</sup> (0.051)
<b>Log-Likelihood</b>	-11,725.43	-126,729.12
<b>AIC</b>	11,745.11	253,603.61
<b>Sigma Square</b>	4.123	8.823

Notes: The dependent variable and independent variables are defined as given in the text. Note that we tested the residual vector for the existence of spatial autocorrelation which could be a problem in the context of interaction data (see, e.g., Scherngell and Lata 2012). However – as to be expected for the edges betweenness – the respective test statistics are insignificant. \*\*\* significant at the 0.001 significance level, \*\* significant at the 0.01 significance level, \* significant at the 0.05 significance level

This supports the hypothesis that a high betweenness between two regions – assumed to be a proxy for important, often large distance knowledge channels between bottleneck regions – is not or only to a low degree influenced by geography, but relies significantly on technological distance between regions and other unobserved factors as reflected by the comparably high dispersion parameter  $\delta$ . By this, the results provide – at least to our knowledge – the first systematic empirical evidence on

the local-global duality of knowledge production, and the different spatial range and spatial characteristics of local vs. global knowledge production activities.

## 5 Conclusions

We have explored bottlenecks for knowledge flows between NUTS-2 regions using the concept of betweenness centrality. We first introduced a measure of inter-regional betweenness centrality using the structure of networks derived from organizational participation in Framework Programme projects. Using this measure to investigate FP5, we found that a relatively small set of regions were more likely to form highly central links to other regions, giving a hub-like structure. These hubs appear to constitute major bottlenecks in European knowledge flows.

We further explored the bottlenecks using a spatial interaction model, with the inter-regional betweenness centrality in the role of the modeled flows. Thus, geographical determinants of these “flows” are actually determinants of the bottlenecks in the knowledge flows. Model results show at most a minor influence from geographical factors, but a strong effect from technological distance between linked regions. The results thus provide empirical support for the local-global duality of knowledge production.

Some ideas for future research come to mind. *First*, other measures for aggregating inter-organizational betweenness centrality to the regional level may be considered. *Second*, the study motivates a deeper investigation of the regions that form the hubs for the bottleneck links, concerning their geographical, economic and technological structure.

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