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Knowledge flows across European regions

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Abstract

The recent resurgence of growth studies has clearly established that technological progress and knowledge accumulation are among the most important factors in determining the performance of regional and national economic systems. Nonetheless, few empirical studies have tried to analyse the flows of technology and knowledge across regional economies in Europe due to the lack of adequate indicators.

In this paper we propose new evidence on the characteristics of knowledge flows across European regions based on a statistical databank, set up by CRENoS, on regional patenting and citations at the European Patent Office spanning from 1978 to 2004 and classified by ISIC sectors (3 digit). We consider 175 regions of 17 countries in Europe assigning each patent a region according to the place of residence of the inventors; then, we examine in- and out-flows of patent citations as a proxy of knowledge connections, while looking also at their sectoral differences and dynamics through time.

The econometric analysis is based on a model where the transmission and exchange of knowledge across regions is mainly affected by geographical distance together with a set of spatial dummy variables. Moreover, we make several controls to check for the robustness of our results with respect to the inclusion of other characteristics of the origin and destination regions (production structure, economic conditions and technological efforts) as well as different estimation methods.

The main result is that knowledge flows decrease as the geographical distance between the origin and the destination region increase. Furthermore, knowledge flows tend to be higher among contiguous regions and areas within the same country.

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1. Introduction

Different studies have attempted to analyse the mechanics of knowledge exchange and transmission across nations and regions. In particular, starting from the seminal paper by Griliches (1979), many economists have sought to find evidence of the existence of knowledge spillovers either embodied in R&D exchanges, in bilateral trade flows, in capital goods acquisition or in external direct investment. However, since the beginning this research line has suffered from the lack of adequate indicators, as these interactions are hard to appraise, especially when tacit knowledge plays an important role. In fact, Krugman (1991) observed that knowledge flows are invisible and cannot be measured and tracked. This view was opposed by Jaffe et al. (1993) who suggested that indeed knowledge spillovers may leave a "paper trail" in the form of patent citations[1], which can be easily measured and therefore used to obtain information on several dimensions of the technological transmission mechanism.

Citations of previous patented innovations are collected for legal reasons, since they limit the property right (and therefore the monopoly power) awarded to proponents of new patents. More specifically, the cited patent is acknowledged as a previous piece of existing knowledge upon which the new invention is built. The linkage between cited and citing patents may therefore be a reasonable way to detect knowledge flows. If such knowledge flows are expressed as a measure of geographical space (for example using inventors' place of residence) then one may have an adequate proxy for interregional or international flows of technologies.

By now, a growing body of empirical studies have used citations as measures of knowledge exchange. A seminal contribution on patent citations was developed at NBER by Jaffe et al. (1993), based on data

[1] There are two ways patent citations have been used by economists. In the first instance, a *citation* represents a "paper trail" left by a technological spillover: when a firm cites a previous patent, it acknowledges a debt to the knowledge embodied in it. Secondly, a *citation* can be used as an indirect indicator of the significance of the innovation contained in the cited patent and hence the number of citations may be a proxy of the economic potential value attached to a patented innovation. In the present contribution we focus mainly on the former use of citations.

provided by the United States Patent Office (USPTO). The wide availability of this source has given rise to several studies on knowledge flows based on USPTO dataset (see Jaffe and Trajtenberg, 1999, 2002 and Hall et al., 2001 among others). Other contributions have tried to combine this dataset with the one provided by the European Patent Office (EPO), like Lukatch and Plasmans (2003) or Criscuolo and Verspagen (2006). Finally, there are some contributions, principally based on EPO data, such as Maurseth and Verspagen (2002) and Le Sage et al. (2007) that attempt to measure knowledge flows across regions in Europe.

This is also the aim of the present contribution, which proposes original evidence on the characteristics and the determinants of knowledge flows across 175 European regions, based on a databank of patents citation at EPO spanning from 1978 to 2004 and classified by 3 digit ISIC sectors set up by CRENoS. The main hypothesis to be tested is that knowledge has a local nature, and its diffusion may be hindered by geographical distance. Since the contribution of Marshall (1920), spatial proximity is believed to ease the process of firm interaction and information sharing thus helping knowledge diffusion (Audretsch and Feldman, 1996; Rallet and Torre, 1999; Paci and Usai, 1999; Maskell and Malmberg, 1999). An econometric model is estimated to pursue the aim of assessing the strength and robustness of the relationship between knowledge exchanges and geographical distance. In particular, econometric analysis allows to test whether geographical distance and spatial contiguity influence, the former negatively and the latter positively, the transmission of knowledge across regions in Europe. Furthermore, we extend the model by including other measures of "distance" (economics, production structure and technology) between the regions of origin and destination which may affect knowledge flows.

The paper is structured as follows. The second section provides a description of the main characteristics of the database together with a comprehensive picture of the citation phenomenon in Europe across regions, sectors and time. Section three presents the basic econometric estimates, while in section 4 several extensions and some robustness exercises are discussed. The last section briefly summarises the main results and suggests some improvements and research issues to be tackled.

2. Database and descriptive analysis

2.1 The database on citations

Following the original idea by Jaffe et al. (1993), we use patents citations as a proxy for knowledge flows among the European regions. The database was set up by CRENoS using data from the EPO, selecting patents granted to inventors resident in 17 European countries (15 UE pre-2005 members plus Switzerland and Norway) and ignoring the country which applies for the patent. We consider patents granted instead of patent applications because the administrative procedure followed by the EPO specify that the citations list is completed by the examiner during the granting procedure.[2] On this issue, it is worth remarking that the wide role of the examiners in the EPO procedure (according to Criscuolo and Verspagen, 2006, almost 90% of EPO citations are traced by the examiners[3]) makes citations a noisy indicator of localized knowledge spillovers (Jaffe et al., 2000). Nonetheless, when aggregate citations are used as a proxy of knowledge interactions among regions in a broader sense, as in this paper, this issue becomes less compelling (Breschi and Lissoni, 2006).

Our temporal analysis of patent citations is limited by two technical reasons: firstly, citations can only refer to those cohorts of patents which are already accessible and for which, as a result, embodied knowledge has really become available; secondly, patents are granted by EPO with a delay of several years with respect to the application date. Consequently, although the series on granted patents is available from 1978 to 2004, we select the year 1990 as a first point in time for the analysis, in order to grant inventors an adequate period of time to become aware of the new patented inventions (i.e. the period 1978-1990). We choose the year 1998 as a second point in time, since an average lag of 5 years is estimated to process the majority of patent applications. In this latter case we consider citations which refer to EPO patents over the whole period 1978-1998.

As far as the territorial breakdown is concerned, patents and citations have been attributed to regions according to the inventor's

[2] As far as the USPTO is concerned, the duty of candour applies, which implies that the inventor and his/her lawyer are obliged to provide a list of reference describing the state of the art. The EPO has no similar requirement.

[3] According to Thompson (2006) the corresponding proportion for a sample of USPTO patents is around 40% due to the presence of the duty of candour.

residence using postal codes.[4] We have followed the classification provided by EUROSTAT referring to NUTS (Nomenclature des Unités Territoriales Statistiques) while trying to select in each country those geographical units characterized by an adequate degree of administrative and economic control. As a result, we consider 175 national and sub-national units which are a combination of NUTS 0, 1 and 2 levels (see appendix for details).

As for the industrial classification, patents and citations are recorded for administrative purposes using the International Patent Classification (IPC) system, which categorizes inventions by product or process based on technological categories which can not be directly related to industrial sector. This association is needed if one wants to know which particular sector of the economy is responsible for the invention or its subsequent use. For this reason patent data, originally classified by means of the IPC, have been converted to the manufacturing industry thanks to the Yale Technology Concordance, which uses the probability distribution of each IPC or product code across manufacturing industries in order to attribute each patent proportionally to the different sectors where the innovation may have originated.[5]

2.2 Aggregate distribution

In order to perform the analysis on knowledge flows within the EU, we selected from the whole set of citations only those patents granted to inventors resident in our group of 17 European countries (around 77,000 and 73,000 citations in 1990 and in 1998, respectively). In particular, we considered only citations towards patents which: (i) have at least one inventor resident in one of the 17 countries in our sample; (ii) have been granted by the EPO. Only for this subset it is possible to obtain all useful information on knowledge flows: that is, information on their technological content, their geographical origin and destination. Table 1 shows that this subset represents around 15% of total citations both in 1990 and in 1998. Even though decreasing over time (from 46%

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[4] In the case of patents with more than one inventor resident in different regions, a proportional attribution has been computed.

[5] We have also employed the conversion table proposed by Schmock et al. (2003) but the results have not changed and therefore in this paper we present only the results based on the Yale concordance.

to 33%), a high proportion of total citations still refers to citations of patents granted by national patent offices within Europe. These citations cannot be directly considered in our analysis since the geographical and sectoral information required are available only through a very costly inquiry to each national office.[6] Finally, it is worth noting that a high and, most importantly, growing portion of citations is directed to the US (25% and 30% in 1990 and 1998, respectively) whereas the increasing share of the rest of the world is 4% to 11% of total citations.

Our focus on the spatial distribution of knowledge flows at the regional level implies that rather than concentrating on the relationship between "cited patent – citing patent", we focus on the pair "cited region – citing region". In light of this, Table 2 explores the main geographical features at the regional level of the subset of citations used in this paper: about 11,500 in 1990 and 10,600 in 1998. It is worth remarking that in 1990 a significant share of citations was referred to inventions generated within the same region (29%) whilst a higher portion (47%) was directed towards other countries. In 1998, a significant change appears in the geographical network of citations, with a clear reduction of intraregional flows (down to 22%) and a simultaneous increase in international knowledge flows (up to 52%). Citation flows directed to contiguous regions and to regions within the national borders are, on the contrary, quite stable: around 9% and 15% of total flows, respectively. At a first glance, this picture seems to indicate an increase in the spatial scope of knowledge diffusion which goes in the direction proposed in the literature under the label of "death of distance" (Cairncross, 1997).

This aggregate picture is completed by Table 3 which illustrates the geographical flows of citations for each country. National performances appear quite varied. In 1990, for example, intra-regional flows show a minimum value of just 17% in Sweden and at a maximum of 43% in the Netherlands. At the same time, international citations range from a minimum of 36% in Germany up to a maximum of almost 77% in Sweden. These variations may depend, on the one hand, on physical reasons related to the geographical distribution and the number of regions considered within each country; or, on the other hand, on

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6 Recently, a very useful equivalence table to link EPO and National Patent Offices data was built by Webb et al (2005) and was kindly provided to us by the authors. For the purpose of our work, however, this table allows us to add only a very small number of citations and therefore we have preferred, at this stage of the work, to consider only EPO data.

technological reasons associated with different patterns of knowledge dynamics within and outside each country. The case of Finland and Sweden, with a high share of international citations, implies a very open innovation system, probably due to their specialization in high-tech industries where global competitiveness is pervasive. This representation appears stable for most countries throughout the nineties, except for the fact that, in 8 out of the 11 countries reported in the table, international flows increase and again in 8 out of 11 countries, intra-regional flows decrease. The Netherlands offer a very interesting case, where citations within the region go from a maximum of 43% in 1990 to 24% in 1998 while international citations in the same period increase from 46% to 66%. In conclusion, the aggregate picture highlights a growing process of internationalization of knowledge flows which goes together with the increasing role of multinational firms and the international diffusion of R&D laboratories.

2.3 Regional distribution

Map 1 shows the distribution of citations across regions, revealing that the areas which are more involved in citation flows, both in 1990 and 1998, are Germany, Switzerland, the Northern part of France and Italy, Southern UK. This picture confirms previous analyses which show the existence of a deep gap between the core area situated in the central-northern Europe, where more than almost half of European patents and citations is concentrated, and the periphery in the North and especially in the South.

Table 4 lists the twenty most prolific regions in terms of citations. It is immediately evident that, at the regional level, German regions are the most numerous, with 8 and 11 regions out of 20 in the 1990 and in the 1998, respectively. Nonetheless, the French capital region of Ile de France is at the top of the ranking in both periods. Among the top regions we also find British, Swiss, Italian, Dutch and Belgian regions. The absence of Scandinavian regions, which are usually among the top when it comes to patent and R&D activity, is noticeable. This peculiar pattern is probably related to the fact that most citations of these countries are made abroad (as shown in table 3) and they are not available in our database since the destination is outside our set of countries.

If one compares the rankings in the two periods a few interesting cases emerge. It is interesting to notice that Ile de France, for example, while being able to attract more than 800 citations in both periods, makes almost 200 fewer citations in 1998 with respect to 1990. This implies that Ile de France starts as a net exporter of citations (with a negative balance of 34 between citations made and received) and becomes a net importer (with a balance of 163 citations). Among the regions which lose some ground along the nineties it is worth noting the case of the British South-East region, which goes from the 8th ranking position with 343 citations to the 19th with only 153 citations. Unlike the Ile de France, however, this region maintains its characteristic as a net exporter of knowledge with a positive balance of almost 100 citations in the two years.

Finally, one may note that the number of cited or citing regions is quite variable, the highest numbers being 105 cited regions in 1990 and 122 citing regions in 1998. Both cases refer to the Ile de France region. This indicator tells us that the number of regions which are involved in the citation process as an origin and as a destination is increasing in time. It can further suggest that the scope of the diffusion process is getting wider. This first impression is confirmed by the statistics on geographical concentration reported in Table 5. Gini and Herfindhal concentration indices, for citations by region of origin and destination, are almost identical and corroborate the evidence of a decreasing trend from the early to the late nineties. Again this result suggests that geographical agglomeration of knowledge exchange, although still relevant, tend to decrease over time.

2.4 Sectoral distribution

Finally, we shift our attention from knowledge flows across regions referred to the whole economy to flows across sectors. Since the process of technology creation and diffusion is characterised by considerable differences at the industrial level, this may prove a particularly fruitful exercise. In particular, one may expect a more localised pattern of technology diffusion in the case of traditional activities, while a higher degree of internationalisation should characterise high-tech industries (see Paci and Batteta, 2003, Criscuolo et al., 2005). In order to assess these issues, we consider the sectoral distribution of citations converted from the IPC classification to the ISIC industrial classification.

Table 6 shows that the share of citations for both origin and destination are extremely differentiated across sectors, going in 1990 from 27% in Chemicals to almost nothing in Tobacco and from 25% in Machinery to 0,2% in Tobacco in 1998. It is also clear that there have been some interesting changes along the years in the relative significance of sectors with respect to the ability to originate and attract citations. Among the most interesting performances one may note that of Machinery, the share of which goes from around 20% in 1990 to 25% in 1998. This positive dynamics has its counterpart in the performance of Chemicals which goes from 27% to around 18%. These results can be explained by the changes in the production and technological structures where the chemical trajectory is becoming less pervasive.

Table 6 reports also the share of citations directed to the same sector which has originated the patent (i.e. within sector citations). Such a share is extremely heterogeneous since it goes from a maximum of 72,6% in Chemicals (a technology that is highly self contained) to a minimum of 2,6% in Recycling in 1990. Ten years later this picture has not changed much: the maximum share is 66% again referred to Chemicals and the minimum 2,5% in the Recycling sector. Moreover, the spread of citations across sectors, on average, increases in time since the mean share of citation within the same sector decreases from 38% to 33%. This is a very interesting result as it indicates that production, and hence technology, is becoming more complex and requires increasing exchanges with other sectors.[7] Obviously the degree of interdependence and cross fertilisation of technology varies considerably across sectors and this has important implications on knowledge production and diffusion (Moreno et al., 2006, Criscuolo et al. 2005 and Balconi et al., 2004).

A useful characteristic of the network of citations is that one can measure the distance covered by these knowledge flows. In Table 7 we report, for the entire economy and for some selected sectors, the geographical distribution of citations together with the average distance measured in kilometres. The first noticeable result is that the average distance covered by knowledge increases from 516 km in 1990 to 570 km in 1998. This seems to confirm the general view that modern technologies, especially those related to information and communication, are favouring a wider diffusion of ideas and knowledge over space. This pattern is common to all sectors considered, except for Footwear. This is not the only difference across sectors which is worth noting. Footwear, an example of traditional sector, shows also the lowest average length of flows (290 km in 1998). This is due to the fact that in this sector

[7] In the literature the advantages of sectoral diversity and technological cross fertilisation have been originally suggested by Jacobs (1969).

knowledge flows are mostly referred to firms within the region (the quota of such flows over the total reaches 47% in 1998). At the other extreme, it is worth emphasising the case of the high-tech industry of computing, where knowledge exchanges are the most far reaching and are getting more so along time (from 549 km in 1990 to 625 km in 1999).

These results confirm that knowledge interactions are locally bounded, but that their spatial scope differs widely across sectors: it is quite limited in the more traditional sectors and relatively larger in high tech industries. Furthermore, this difference seems to be getting wider.

3. Econometric analysis

The previous descriptive analysis on the spatial distribution of patent citations among European regions shows the existence of a deep disparity between the central-northern part of Europe, which represents the core of technological innovation and knowledge exchanges, and the southern periphery, characterized by low levels of technological development. The analysis clearly reveals that there are important differences across countries, regions and sectors with respect to the geographical pattern and extent of the technological diffusion process, as far as this can be measured by patent citations.

The purpose of this section is to elaborate a useful framework, which takes into account this evidence, in order to identify those factors which influence the configuration and the implementation of the complex network of knowledge flows within Europe. Therefore, this paper, on the one hand, integrates previous contributions mainly focussed on knowledge production across European regions (Bottazzi and Peri, 2003, Moreno et al, 2005, 2006). On the other hand, it seeks to build upon the only other contribution on this very same research line, the one by Maurseth and Verspagen (2002), by means of a greater sample of regions and a particular attention to how the phenomenon under study changes over time.

At the same time, the present paper complements the analysis by Le Sage et al. (2007) who address the same objective of assessing knowledge flows across regions in Europe by focusing only on the high-tech sector.[8] Finally, we should mentioned the existence of a parallel line

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[8] Their main original contribution lays in the use of a special procedure to test for spatial autocorrelation by using Poisson estimation procedures while the matrix of observations is of an origin-destination nature.

of analysis on knowledge flows, measured through relational data other than patent citations (see Maggioni et al. 2006 and Acosta and Coronado 2003 among a few others).

The main hypothesis we would like to test is that knowledge linkages are localized in space and, therefore, that geographical distance and contiguity influence knowledge flows across regions. Moreover, the use of country and regional dummies aims to take into account other potential influences coming from institutional and cultural differences, and other aspects which are not specifically incorporated in the model.

Let us now briefly describe the variables included in the estimated equation.

Dependent variable: patent citations (C). The dependent variable of our model is represented by knowledge flows proxied by the number of citations in each possible pair of the 175 European regions considered. As a result a matrix 175x175 is created where the generic element C_{ij} represents the number of citations originated from patents granted by EPO to inventors resident in the citing region i and directed to patents granted by EPO to inventors resident in the cited region j. Following previous literature (Maurseth and Verspagen, 2002 and Malerba et al., 2003) in order to reduce the problem of firm self-citations, we have preferred to exclude those 175 cells for which $i = j$ and which represent citations referred to patents within the same region. We end up with a matrix of 30,450 observations and a total of around 8,200 citations for each of the two years under examination. The model was estimated for two different periods, 1990 and 1998, to assess if there have been significant changes in the pattern of knowledge diffusion along the nineties.

Geographical distance (GD). This is the key variable in the analysis of knowledge flows since it aims at testing the hypothesis that a higher distance has a negative impact on the strength of knowledge flows. One expects that increasing geographical distance would reduce technological exchanges among regions, signalling that knowledge flows are bounded in space and characterized by a spatial declining effect due to the presence of spatial transaction cost in knowledge exchange. The geographical distance matrix is a 175x175 matrix whose generic element GD_{ij} represents the distance, in hundreds of kilometres, between the centres of the citing region i and the cited one j.

Dummy contiguity (DC). This indicator aims at further testing the hypothesis that geographical contiguity, that is physical proximity between regions which share a common border, may have a major impact on knowledge linkages, irrespective of distance measured in *GD*. Therefore, we include a dummy variable which takes value one when citing and receiving regions share a border (even in different countries) and zero otherwise. We expect a positive sign since geographical proximity should facilitate technological exchanges.

Dummy Nation (DN). It is well known that migration and commercial flows are greater among regions belonging to the same country. Furthermore, our descriptive analysis on the geographical direction of knowledge flows has shown that, although the bulk of international citations has increased over time, a strong component of citations does not cross national borders, denoting a potentially important role played by each country's peculiarities. One can, therefore, hypothesize that knowledge flows take place more frequently among regions located in the same nation, because language, cultural and institutional homogeneity may facilitate such exchanges.[9] The estimated equation, therefore, includes a dummy nation *DN* which consists of a 175x175 matrix, whose generic element is equal to 1 if the citing region *i* and the cited one *j* belong to the same nation, and equal to 0 elsewhere.[10] We expect this variable to positively influence the amount of the citations flows, thus implying that knowledge spreads with greater ease within the same country and that national innovation systems may still be at work.

Dummy region (DR). A set of 175 fixed effects for each region *i* is inserted into the model in order to allow for some idiosyncratic regional factor which is not appropriately measured by the whole set of variables specified above.

The regression to be estimated is a linear regression model where knowledge flows among regions are explained by the geographical distance between each pair of regions, in order to assess whether knowledge exchanges tend to be locally bounded. The spatial elements are also controlled for by the inclusion of the contiguity dummy, while national and regional characteristics are taken into account with two specific dummies. Consequently, our estimated equation is:

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[9] We have also tried to introduce a variable to take into account same language regions that belong to different countries. However, results were not significant because the nation dummy already controls for this aspect.

[10] Another way to control for these national effects is the introduction of a national dummy for each country (as in Maurseth and Verspagen, 2002). This was also done and results are not significantly different, while not all dummies are significant.

$$(1) \qquad C_{ij} = \beta_1 GD_{ij} + \beta_2 DC_{ij} + \beta_3 DN_{ij} + \gamma_i DR_i + \varepsilon_{ij}$$

where *i* indicates the region from which the citations originate and *j* the region of destination.

The main estimation results are reported in Table 8 which reveals that all coefficients are statistically significant with the expected sign. In particular, geographical distance exerts a negative impact on knowledge diffusion, given that flows of citations (and therefore knowledge embodied in them) among regions get weaker as geographical distance increases.

A second interesting result is that knowledge interactions occur most often between origin-destination regions that belong to the same country and share a common border. The contiguity dummy is positive and significant, implying that technological flows between neighbouring regions tend to be higher. At the same time, national borders seem to constitute an obstacle to knowledge leakages, since citations flows between any couple of regions are, *ceteris paribus*, more likely when the two territorial entities are within the same nation. In other words, technological flows among firms and inventors are favoured when they share the same language, culture and institutional setting. This result can be interpreted as indirect evidence that in Europe national systems of innovation (Nelson, 1993; Cantwell and Iammarino, 2003) still play a major role with respect to a single, unified European system.

Table 8 so far confirms previous results in the literature. There is however something new which is worth remarking: the relationships under examination are changing with time. In particular, we see that the importance of distance becomes more substantial in 1998 compared to 1990. Such result is in contrast with the dynamics of the coefficient for the contiguity, which becomes smaller. The same applies to the coefficient of the national dummy.

In conclusion, spatial distance is still alive and kicking while its impact grows in time, even though national and contiguity borders somewhat loose their role. These results obviously require some robustness check, which is provided in the next section.

4. Robustness checks and extensions

In this section we extend the basic model presented above while testing the robustness of the main results.

As a first robustness test, we attempt to control for the presence of a high number of zeros, i.e. pairs of regions without citation flows. This control can be performed either by using Poisson or Negative Binomial procedures[11]. In this paper the Poisson method is applied but results are similar using the Negative Binomial procedure. The robustness of the previous results is shown in the first two columns of Table 9 where all estimated coefficients are still significant with the expected sign.

The second robustness exercise consists in the estimation of the model with the inclusion of the 175 intra- regional citation flows. This means that we now consider also the citations originated and received by the same region, which may also include some intra firm citations. We can see from columns 3 and 4 in Table 9 that results do not change: geographical proximity still play a positive role on technological flows. This result is also strengthen by the positive significance of the dummy "within region" (*DW*) which controls for the case where regions *i* and *j* coincide.[12]

The extensions of the model regard the inclusion in the estimated equation of other variables which differentiate origin and destination regions and thus may affect inter-regional knowledge flows: heterogeneous specialization patterns, economic conditions and technological efforts. In the rest of this section we describe each new variable and present the estimation values resulting from their inclusion in the basic equation.

Structural distance (SD). A first extension of the basic model regards the inclusion among the explanatory variables of the difference in the production structure between regions. The idea is that the exchange of knowledge occurs with greater intensity, irrespective of geographical distance, between regions with comparable production structures, that is, regions specialized in similar sectors. This is due to the fact that researchers are expected to benefit more from other researchers who work in the same or related sectors (Bode, 2004). There are different ways to measure structural distance (see the critical review

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[11] The former is used in Le Sage et al. (2007) whilst the latter is used in Maurseth and Verspagen (2002).

[12] Note that, based on the Hausman test, we report the model either with Fixed Effects or with Random Effects to take into account for regional idiosyncratic factors.

by Los, 2000). One method is based on input-output tables (Verspagen, 1997) where technology diffusion works through purchases of intermediate goods or through sales to other industries. However, due to the lack of input-output data for our 175 regions, it is not possible to use this approach. Therefore, we employ an alternative method based on the sectoral distribution of patenting activity, following the original suggestion by Jaffe (1986). More precisely, in order to measure structural heterogeneity between two regions we have first considered for each region the distribution of patents applications across 23 sectors. Then, we have computed a 175x175 matrix whose generic element SD_{ij} is defined as:

$$(2) \qquad SD_{ij} = 1 - P_{ij} = 1 - \frac{\sum_{k=1}^{K} f_{ik} f_{jk}}{\sqrt{(\sum_{k=1}^{K} f_{ik}^2 \sum_{k=1}^{K} f_{jk}^2}}$$

where the correlation index P_{ij} measures the degree of similarity between the citing region *i* and the cited region *j* and f_{ik} represents region *i* patents share in sector *k* with respect to the total patents[13]. The index *SD* ranges between zero (minimum distance: identical sectoral structure between the two regions) and one (maximum distance: the production structures are orthogonal). We expect to find a negative coefficient for this variable if knowledge flows are more intense among two regions specialized in similar sectors.

Results reported in columns 5 and 6 confirm expectations and corroborate previous results in Maurseth and Verspagen, 2002. They show that the flows of citations are negatively influenced by structural mismatches between the originating and the receiving regions and thus by the differences in the pattern of sectoral specialization between each pair of regions. In other words, interregional knowledge flows follow particular technological trajectories, and occur most often between regions that are closely located not only in the geographical but also in the technological space. This result suggests that working on a future extension on this relationship at the sectoral level may be a very promising avenue for further research. Finally, it is important to observe that the inclusion of this variable does not affect previous results.

[13] For the Greek regions with no patents in the two periods the index has been set equal to zero.

Economic distance (ED). We also try to control for the effects on knowledge flows generated from a variety of aspects which are reflected by the difference in the economic conditions between each pair of regions. The idea is that regions which are more similar in terms of economic performances (i.e. richer and larger areas) are supposed to have higher exchanges of technological information, other factors held constant. Economic distance is represented by a 175x175 matrix where the generic element ED_{ij} is computed as the absolute value of the gap in GDP over population (*POP*) between the origin and the destination region:[14]

$$(3) \qquad ED_{ij} = \left| (GDP/POP)_i - (GDP/POP)_j \right|$$

From column 7 and 8, one can see that, as expected, knowledge flows are influenced negatively by the economic distance between regions while all other variables remain unchanged.

Technological effort (TE). In the descriptive analysis we observed that the amount of citations originated from and received by each region reflects the level of its technological activity: regions with high patenting activity are also those with most intense knowledge exchanges. One, therefore, may suggest that citation flows among regions depend, *ceteris paribus*, on the magnitude of the innovative activity which characterizes both the destination and origin regions. In order to take into account such a feature, we have included in the model a measure of technological effort of the region of origin (TE_i) and of destination (TE_j) calculated as the shares of R&D expenditure in the business enterprise sector on GDP.[15] The inclusion of these two variables for origin and destination regions together with the distance variable makes the estimated equation a gravity model.[16]

From columns 9 and 10 we detect a positive and significant coefficient for the technological efforts in both the origin and

[14] Data come from the Cambridge Econometrics database, 2000.

[15] Due to the lack of complete annual series for the 175 regions considered, R&D expenditures refers to 1989-1992 and 1997-2000 respectively for the year 1990 and 1998.

[16] Gravitational models are a useful tool for empirical analysis since the sixties, and have been mainly applied in international trade studies. An interesting application of gravitational model in a setting similar to this paper is provided by Maggioni et al. (2006) based on a series of relational data to study knowledge flows across a selected sample of regions in Europe.

destination regions which confirms the hypothesis that more knowledge exchanges occur among regions which are characterized by a high rate of innovative activity.[17] Also in this case, the other variables maintain their sign and significance.

General specification. Finally, we estimate the following equation where all the explanatory variables are included together:

$$(4) \qquad C_{ij} = \beta_1 \, GD_{ij} + \beta_2 \, DC_{ij} + \beta_3 \, DN_{ij} + \beta_4 \, SD_{ij} + \beta_5 \, ED_{ij} + \beta_6 \, TE_i + \beta_7 \, TE_j + \gamma_i DR_i + \varepsilon_{ij}$$

Columns 11 and 12 in Table 9 show that all variables keep the expected sign and are significant.

5. Concluding remarks

In this paper we have examined knowledge flows among 175 regions in Europe using as a proxy citations in patents granted by the EPO. The main aim of the analysis was to assess the influence of geographical distance and spatial proximity on knowledge transmission. The results achieved with the econometric analysis confirm that geographical distance represents an obstacle to the circulation of knowledge. Furthermore, regions which share borders are more likely to mutually cite respective patents. We have also shown that citations flows are higher when the two regions belong to the same country; national borders constitute an obstacle to knowledge flows and the national systems of innovation still play a role compared to a unified European system. We have performed some robustness exercises which have confirmed the results in terms of expected signs and statistical significance of the estimated coefficients.

Moreover, the basic model has been extended with the inclusion of other factors which may affect the transmission of knowledge between each pair of regions, namely: the production structure, the economic conditions and the innovative effort. The results of the extended model show that the diffusion of technological exchanges improves when the origin and destination regions are similar in terms of the production structure, since specialization in related sectors helps

[17] As an alternative measure for technological levels we have also used the number of patents demanded to EPO by the citing and the cited regions obtaining similar results.

inventors to exchange new ideas. At the same time, regions which are similar in terms of economic conditions and allocate more resources to innovative activities are more likely to exchange technological innovations.

Most importantly, previous results are maintained also in the extended model. Knowledge flows are bounded in space and characterized by a spatial declining effect due to the presence of spatial transaction cost in knowledge exchange.

These results encourage us to proceed further along the current research line. The analysis of knowledge flows at the sectoral and firm level and the application of more advanced procedures for the econometric analysis of spatial data are the most likely future prospects. With these two main developments, the research promises to carry interesting potential for the design of innovative policies for European regions.

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Appendix. Regions and NUTS level

Country	N. regions	NUTS
Austria	9	2
Belgium	3	1
Denmark	1	0
Finland	6	2
France	22	2
Germany	40	2
Greece	13	2
Ireland	2	2
Italy	20	2
Luxembourg	1	0
Netherlands	4	1
Norway	7	2
Portugal	5	2
Spain	15	2
Sweden	8	2
Switzerland	7	2
United Kingdom	12	1

Table 1. International flows of patent citations
(only patents granted by EPO to inventors resident in the 17 European countries)

	1990	1998
Patents granted	19,987	18,659
Citations	77,463	72,804
Citations to patents granted by:	**% shares**	**% shares**
EPO	24.2	24.3
17 countries	*15.0*	*14.6*
other countries	*9.3*	*9.7*
European national patent offices	45.7	33.7
USA	25.6	30.8
Rest of the world	4.4	11.3
Total	**100.0**	**100.0**

Table 2. Geographical distribution of patent citations

	1990	1998
Citations by EPO to EPO (17 countries)	11,589	10,606
Geographical flows	**% shares**	**% shares**
Intraregional	28.6	21.9
National interregional		
- contiguous regions	9.3	9.7
- not contiguous regions	15.4	16.2
International interregional	46.7	52.1
Total	**100.0**	**100.0**

Table 3. Geographical distribution of patent citations in selected countries
(% shares on total citations made)

Nation	no of regions	1990 intraregional flows	1990 international flows	1998 intraregional flows	1998 international flows
Austria	9	18,3	72,1	21,0	70,1
Belgium	3	31,3	56,1	36,4	56,3
Switzerland	7	29,2	53,8	27,6	54,3
Germany	40	27,0	36,8	17,5	44,9
Spain	15	22,2	72,1	19,3	76,9
Finland	6	19,8	70,3	19,0	71,5
France	22	30,7	51,8	30,6	48,7
Italy	20	27,4	58,8	30,6	54,3
Netherlands	4	43,7	46,7	24,3	66,7
Sweden	8	17,9	76,6	14,9	77,9
United Kingdom	12	28,8	48,7	16,4	65,3

Table 4. Top 20 regions by origin of citations

Nuts	Region	Citations made		Citations received		N. cited regions	N. citing regions
		num.	rank	num.	rank		
1990							
FR1	Ile De France	857	1	823	1	105	112
DE71	Darmstadt	581	2	579	3	99	98
DE21	Oberbayern	565	3	589	2	94	98
DEA1	Duesseldorf	513	4	533	4	88	93
DEA2	Koeln	473	5	515	5	82	94
DE11	Stuttgart	375	6	355	7	80	83
IT2	Lombardia	345	7	297	11	75	78
UKJ	South East	343	8	457	6	73	89
FR71	Rhone-Alpes	336	9	297	12	82	88
NL4	Zuid-Nederland	318	10	335	8	73	75
DEB3	Rheinhessen-Pfalz	311	11	273	15	76	84
NL3	West-Nederland	292	12	291	13	81	79
DE12	Karlsruhe	291	13	274	14	78	84
CH03	Nordwestschweiz	239	14	304	10	64	66
UKH	Eastern	217	15	311	9	62	78
CH04	Zurich	202	16	189	17	67	73
BE2	Vlaams Gewest	182	17	176	18	66	58
DE25	Mittelfranken	161	18	165	19	64	63
DE13	Freiburg	161	19	140	21	62	59
UKD	North West	156	20	208	16	54	67
1998							
FR1	Ile De France	675	1	838	1	102	122
DE11	Stuttgart	497	2	440	4	102	98
DE21	Oberbayern	481	3	468	2	101	98
DEA1	Duesseldorf	473	4	431	5	97	102
DE71	Darmstadt	385	5	462	3	96	103
DEA2	Koeln	338	6	331	7	96	91
IT2	Lombardia	285	7	358	6	88	100
FR71	Rhone-Alpes	281	8	287	8	86	93
DE12	Karlsruhe	246	9	226	10	90	86
NL3	West-Nederland	244	10	187	16	83	79
DEB3	Rheinhessen-Pfalz	224	11	195	15	83	76
BE2	Vlaams Gewest	208	12	225	11	68	66
DE13	Freiburg	174	13	147	20	71	69
CH03	Nordwestschweiz	173	14	200	14	59	72
DE14	Tuebingen	170	15	106	26	78	64
CH04	Zurich	168	16	203	13	71	74
DEA5	Arnsberg	160	17	138	21	72	75
IT4	Emilia-Romagna	159	18	163	18	57	69
UKJ	South East	153	19	241	9	67	86
DE27	Schwaben	137	20	101	29	73	57

Table 5. Concentration indices across 175 regions

Concentration indices	Citations made		Citations received	
	1990	1998	1990	1998
CR 5	0.26	0.24	0.26	0.25
CR 10	0.41	0.37	0.41	0.38
CR 20	0.60	0.53	0.61	0.56
Gini	0.72	0.68	0.73	0.70
Herfindhal	0.025	0.021	0.026	0.023

Table 6. Sectoral composition of citations

	Sectors	1990		1998	
		Shares (%)	Citations within sector (%)	Shares (%)	Citations within sector (%)
1	Food, beverages	1.0	47.4	0.8	32.3
2	Tobacco	0.0	39.1	0.2	51.2
3	Textiles	1.0	9.7	1.2	9.3
4	Wearing apparel	0.2	2.8	0.3	3.7
5	Footwear	0.3	51.3	0.3	48.1
6	Wood products	0.9	4.0	0.8	3.9
7	Paper	0.8	12.4	1.0	14.7
8	Printing, publishing	0.3	6.8	0.3	7.0
9	Coke, petroleum products	2.1	12.3	1.3	10.6
10	Chemicals	27.3	72.6	18.4	66.5
11	Rubber and plastic	2.2	12.4	2.6	14.8
12	Non metallic mineral products	2.1	14.1	2.2	13.5
13	Basic metals	0.6	12.8	0.9	15.0
14	Fabricated metal products	6.3	21.0	8.0	20.9
15	Machinery	20.0	37.4	25.7	40.4
16	Computing, office	1.5	7.7	1.7	7.4
17	Electrical machinery	8.6	27.2	8.8	28.2
18	Radio, tv, communication equipment	6.2	30.8	4.9	26.5
19	Medical, precision instruments	7.7	22.4	6.8	18.4
20	Motor vehicles, trailers	3.9	19.0	5.3	17.3
21	Other transport equipment	3.1	6.6	3.4	6.9
22	Furniture and other	3.6	11.4	4.7	14.2
23	Recycling	0.3	2.6	0.4	2.5
	Total / average	100.0	37.9	100.0	33.1

Table 7. Geographical distribution of patent citations in selected sectors

Sectors	Within the region	Towards contiguous regions	Within the nation	Towards other countries	Total	Average distance of citations, Km
1990						
Footwear	32.7	9.5	3.4	54.4	100.0	339
Machinery	28.3	8.8	15.3	47.7	100.0	542
Computing, office	31.7	7.0	15.2	46.1	100.0	549
Total citations	28.6	9.3	15.4	46.7	100.0	516
1998						
Footwear	47.5	9.2	10.8	32.5	100.0	290
Machinery	23.8	9.1	16.6	50.5	100.0	573
Computing, office	22.2	8.1	16.7	52.9	100.0	625
Total citations	21.9	9.7	16.2	52.1	100.0	570

Table 8. Determinants of knowledge flows

Dependent variable: citation flows from region i to region j (exclude i=j)
Estimation method: OLS
Number of observations = 30450
Standard errors in parentheses
Level of significance: ***=1%; **=5%; *=10%

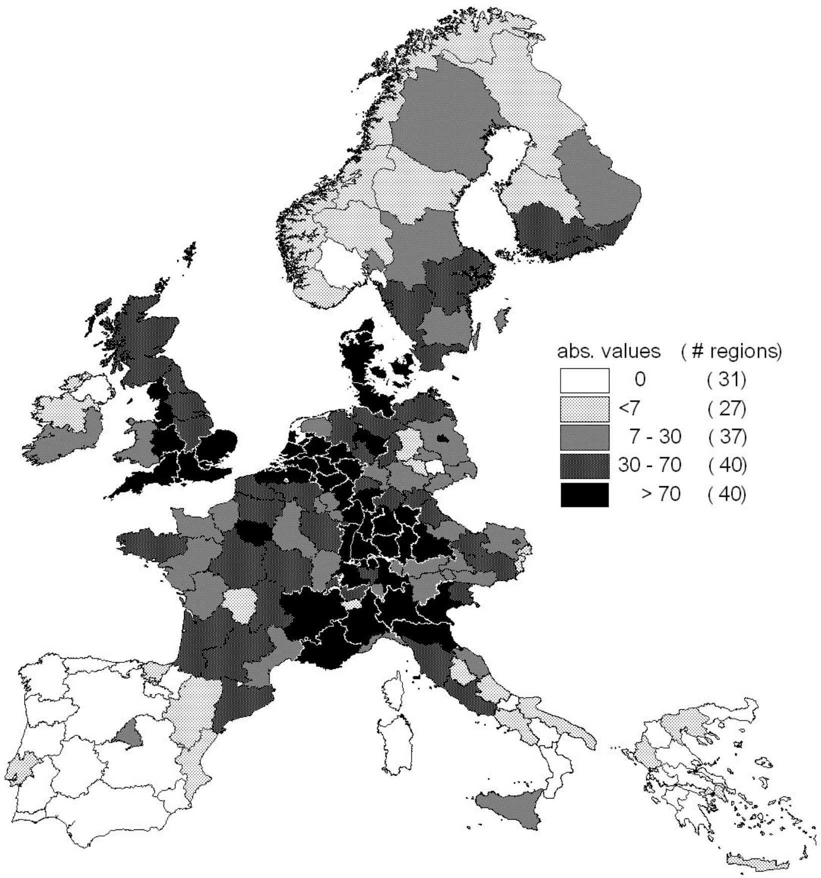
	1990	1998
Geographical Distance (GDij)	-1,252	-1,349
	(0.105)***	(0.089)***
Dummy Contiguity (DCij)	0,835	0,735
	(0.048)***	(0.040)***
Dummy Nation (DNij)	0,290	0,269
	(0.026)***	(0.022)***
Dummies 175 Regions (DRi)	yes	yes
Adj. R^2	0,14	0,16

Table 9. Robustness control and extensions
Dependent variable: citation flows from region i to region j (include i = j only in Reg 3-4)
Standard errors in parentheses
Level of significance: ***=1%; **=5%; *=10%

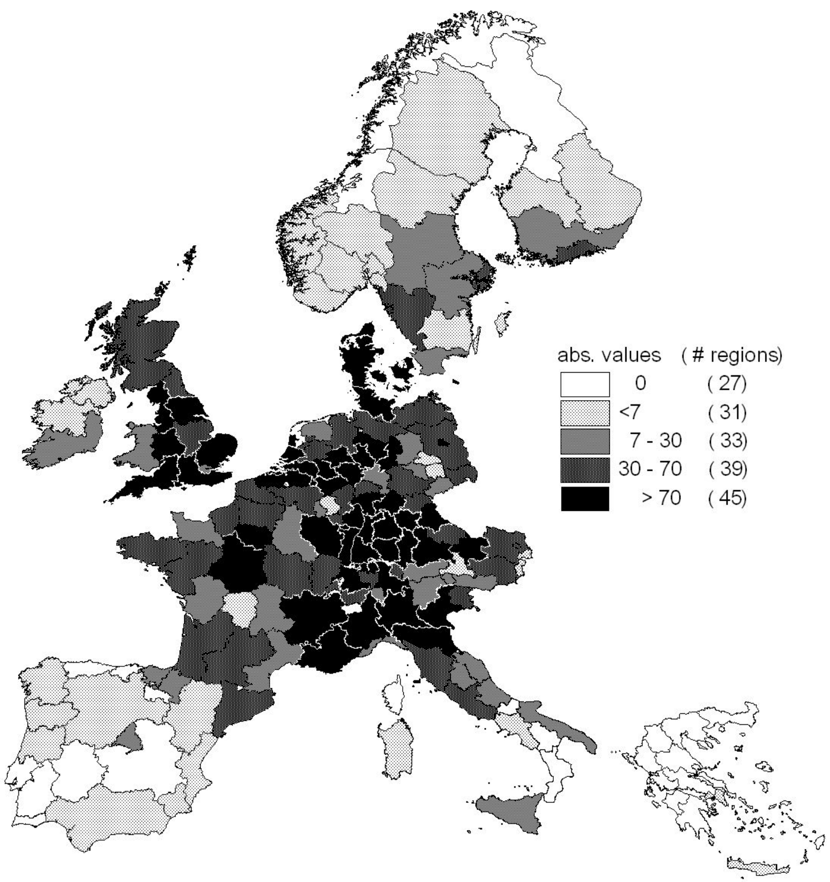
	Reg 1	**Reg 2**	**Reg 3**	**Reg 4**	**Reg 5**	**Reg 6**	**Reg 7**	**Reg 8**	**Reg 9**	**Reg 10**	**Reg 11**	**Reg 12**
Estimation year	1990	1998	1990	1998	1990	1998	1990	1998	1990	1998	1990	1998
Number of observations	30450	30450	30625	30625	30450	30450	30450	30450	30450	30450	30450	30450
Estimation method	Poisson with f.e.	Poisson with f.e.	random eff.	random eff.	fixed eff.	fixed eff.	fixed eff.	fixed eff.	random eff.	random eff.	random eff.	random eff.
Geographical Distance (GDij)	-0.953	-1.008	-0.852	-1.013	-1.048	-1.170	-1.176	-1.257	-0.554	-0.885	-0.344	-0.709
	(0.021)***	(0.021)***	(0.313)***	(0.221)***	(0.107)***	(0.091)***	(0.106)***	(0.090)***	(0.104)***	(0.087)***	(0.107)***	(0.087)***
Dummy Contiguity (DCij)	0.536	0.449	0.304	0.747	0.833	0.733	0.827	0.729	0.845	0.740	0.832	0.734
	(0.034)***	(0.034)***	(0.081)***	(0.103)***	(0.048)***	(0.040)***	(0.048)***	(0.041)***	(0.047)***	(0.039)***	(0.047)***	(0.039)***
Dummy Nation (DNij)	0.304	0.197	0.853	0.287	0.300	0.278	0.286	0.266	0.354	0.308	0.353	0.309
	(0.027)***	(0.026)***	(0.147)***	(0.056)***	(0.026)***	(0.022)***	(0.026)***	(0.022)***	(0.026)***	(0.021)***	(0.026)***	(0.021)***
Dummy Within region (DWij)			20.4	14.0								
			(0.287)***	(0.201)***								
Structural Distance (SDij)					-0.445	-0.389					-0.218	-0.205
					(0.046)***	(0.039)***					(0.045)***	(0.038)***
Economic Distance (EDij)							-0.006	-0.005			-0.009	-0.005
							(0.001)***	(0.000)***			(0.001)***	(0.000)***
Technological effort origin (TE_i)									0.153	0.214	0.153	0.211
									(0.018)***	(0.025)***	(0.018)***	(0.025)***
Technological effort destination (TEj)									0.160	0.222	0.161	0.219
									(0.004)***	(0.006)***	(0.004)***	(0.006)***
Adj. R^2			0.18	0.19	0.14	0.17	0.14	0.16	0.17	0.20	0.17	0.20

Map 1 Distribution of patent citations by region of origin

1990



1998



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