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Abstract

In this paper, we investigate a new approach for the measurement of spillovers. The concept of spillovers is central in many theories of geography, innovation and growth, particularly at the regional level. We evaluate the impact of size and intensity of knowledge production, as observed in publications and patents at the sub-regional level, on the efficiency of manufacturing activity. We employ nonparametric and robust conditional measures in efficiency analysis to a unique dataset at the sub-regional level (province) for Italy. We find that most Italian provinces are located in a region of absence or extremely low impact of knowledge spillovers. Nevertheless, a few provinces with maximum volume in both patents and publications and some medium-sized provinces with high knowledge intensity show knowledge spillovers.

Keywords: knowledge spillovers, manufacturing industry, growth, efficiency analysis, conditional efficiency, robust nonparametric estimation.
JEL Classification: C14, D20, L60, L23, O30, R50

1. Introduction

After approximately three decades of intense research, the concept of knowledge spillover, while extremely powerful in theory, continues to be elusive in empirical analysis. In this study, we show the usefulness of a recently developed estimation technique, that is, robust conditional efficiency analysis (Daraio and Simar 2005, 2007), in addressing some of the most controversial empirical issues. In particular, although earlier studies have been motivated by the need to estimate the magnitude of knowledge spillover effects under the theoretical assumption of their positive impact, recent studies have shown the existence of regions with zero or negligible impact. We explore the role of absolute size (volume of knowledge), relative size (intensity of knowledge) and complementarity between public and private knowledge production, as measured by scientific publications and patents, on the technical efficiency of the manufacturing industry at the province level.

More specifically, the paper will address the following research questions:

- Does the size of the territory matters? Are spillover effects larger in larger provinces and cities or do they exist beyond a given threshold?
- Is knowledge intensity a substitute for knowledge size? In other words, do provinces with high intensity but small size benefit from large spillovers?
- Is there a dichotomy between patenting and publishing for Italian provinces? Which provinces experience large knowledge spillovers?
- Is there a complementarity between publications and patents in terms of the production of spillovers?

We employ an original dataset at the sub-regional level, which refers to the Italian provinces, instead of the regional level, which has been considered in most of the extant literature on the subject.

The remainder of the paper is organized as follows. In Section 2, we briefly discuss the theoretical status of the concept of spillovers and existing econometric approaches to measure spillover effects. In Section 3, we introduce the notion of conditional robust nonparametric efficiency and illustrate its main concepts. In Sections 4 and 5, we present the data and the main results, respectively. In Section 6, we discuss our findings in light of the most recent studies and outline further developments.

2. Knowledge spillovers: Role in economic theories and estimation issues

The measurement of knowledge spillovers is important because it plays a crucial role in several streams of economic research. Spillovers are positive externalities generated by agents who invest in certain activities and cannot prevent other agents from benefitting from these activities. More specifically, knowledge spillovers refer to the fact that firms can benefit from the knowledge generated by others, particularly (but not exclusively) during R&D activities (i.e. by other firms, including rival firms, or public institutions in the same industry, territory or elsewhere), without having to pay for it. Knowledge spillovers take various forms: collaboration among researchers, mobility of researchers and technicians from academia to industry and *vice versa* or within the industry, informal exchanges of ideas, unintended information disclosure, reverse engineering of easily available rival products and availability of better and cheaper components due to the R&D activity of suppliers. In all these cases, knowledge cannot be considered a production factor *stricto sensu* because companies do *not* pay for it. They may benefit from the knowledge that is produced elsewhere and is accessible without the need to pay the full cost, although some positive cost of absorption is necessary.

Undoubtedly, according to extant literature, spillovers are relevant in many areas of economic theory. In the *market failure* argument, which were put forward in the classical papers of Nelson (1959) and Arrow (1962), owing to the non-appropriability of knowledge (Foray 2004), spillover effects are the primary cause of the discrepancy between the private and social rates of return of investment in knowledge production. In theories of growth, particularly in the *endogenous growth theory* (Romer 1986; 1990) and *neo-schumpeterian theories* (Aghion and Howitt 1992; 1998; Jones 1995), the concept of spillover is used to argue that knowledge, as opposed to other factors of production, is not subject to diminishing returns and to explain the persistence of high growth rates in advanced countries.

In the *economics of innovation,* the interest for knowledge spillovers follows several streams:

- Analysis of the impact of public sector research on industry, through personnel mobility (Almeida and Kogut 1999; Saxenian and Hsu 2001), and personal interaction between researchers and managers (Jaffe et al. 1993; Zucker and Darby 1996; Zucker, Darby and Armstrong 1999), particularly under co-location in the same geographic area (Mansfield 1980; Jaffe 1989; 1996; Anselin, Varga and Acs 1997; Varga, 1998; Cohen, Nelson and Walsh 2002);

- The role of intermediate goods as inputs, new production technologies, or inter-industry flows of knowledge (Scherer 1982; Link 1983; Griliches and Lichtenberg 1984; Bernstein and Nadiri 1988; 1989);
  - The role of foreign direct investments and multinational corporations as sources of spillovers, with flows of knowledge *from* multinational companies to host countries and vice versa (Blomstrom and Kokko 1998; Barrell and Pain 1999; Aitken and Harrison 1999; Cantwell and Iammarino 2001), particularly through human capital mobility (Fosfuri et al. 2001), and flows of knowledge *within* multinational companies (Almeida 1996; Gupta and Govindarajan 2000; Frost 2001; Szulanski 2006) or generally within companies (Blazek and Sickles 2010);
- The role of international spillovers as one of the main sources of growth for less developed countries, particularly for those engaged in catching up (Kokko 1994; Coe and Helpman 1995; Kokko et al. 1996; Gwanghoon 2005).

Finally, the idea of spillover is also central to *new economic geography* (Krugman 1990, 1991) and the theory and empirics of *geographical agglomeration* of industry (Ottaviano and Puga 1998; Rosenthal and Strange 2004) and innovative activities (Feldman 1994; Audretsch and Feldman 1996; Jaffe et al. 1993; Breschi 2000; Autant-Bernard 2001; Carrincazeaux et al. 2001; Bagella and Bechetti 2002; Orlando 2004).

More recently, several authors have attempted to review and summarize the literature to examine the main results and to develop theory-based frameworks for analysis. Given the multiplicity of the mechanisms through which knowledge spillovers occur, in some cases, the survey is specialized.[1] To the best of our knowledge, Ghinamo (2012) is the most recent survey on academic knowledge spillovers; this study is based on a meta-regression methodology. His most important results are that spillovers are

[1] Thus, for example Breschi and Lissoni (2001), Audretsch and Feldman (2004), and Doring and Schnellenbach (2006) review the literature on spatial knowledge spillovers; Rothaermel et al. (2007) review the studies on university entrepreneurship; Fritsch (2013) surveys the literature on the creation of new firms; Cincera and van Pottelsberghe de la Potterie (2011) examine international spillovers, whereas Kaiser (2002) critically examines various econometric techniques used to estimate spillovers.

indeed geographically bounded and selective. The measures of spillover are significantly larger in studies that assume a restricted geographic area and focus on particular scientific and technological specializations, with an impact on a subset of manufacturing and service sectors. Moreover, there are several geographic areas in which the spillover is absent (see also Liy et al. 2011, for similar results). Existing literature has used numerous estimation techniques, which are briefly discussed before the introduction of the methodology.

An important stream of literature derives the magnitude of spillover effects from the difference between private and social rates of return in R&D investments (for a survey, see Dowrick 2003; Wieser 2005), following an *indirect estimation approach*. Most published case studies show that there is significant difference between the two rates of return and this is taken as sufficient evidence of the existence of spillovers. The typical range of private rates of return (20–30%) in most studies does not exceed, to a great extent, the average rate of return from physical assets, adjusted for risk. This confirms that although investment in R&D is economically sound, it is not exceedingly attractive. On the contrary, the social rate of return is usually very high (50% or above), implying a large positive externality for society. If these values were to be considered at face value, they would imply that the magnitude of knowledge spillover effects is approximately the same as that of appropriable benefits.

Numerous previous studies on the subject are based on *field surveys* and these studies directly seek evidence of knowledge spillovers (Mansfield 1980; 1991; 1998; Beise and Stahl, 1999; Wieser, 2005). These studies may encounter problems of memorization, ex-post rationalization, and categorization on the part of respondents, thereby distorting the measure. Although this approach explains the microfoundations of spillovers, it is difficult to generalize and develop an estimate at the aggregate level.

By a large margin, the most commonly used econometric approach has been including spillover effects *directly* in the specification of equations, usually in the production function, as *cross-effects*. Thus, besides the regressor representing R&D expenditure at time t for firm i, the expenditure of all other firms in the same industry, other industries, other regions or local systems are directly included in the equation. The direct approach requires the ex-ante specification of the direction of impact of spillovers to include the cross effect among the variables of the equations. Moreover, it involves the introduction of numerous additional variables in the equation. Recent studies that have employed this approach have attempted to develop the independent variables associated to knowledge by operationalizing it not only in terms of expenditure (input) but also in terms of intermediate outputs of the expenditure (such as publications, patents or licenses), whereas the dependent variable is occasionally defined in terms of final output, such as the launch of new products (Landry et al. 2007; Lang 2009; Nelson 2009; Shen and Li 2009).

Another important stream of analysis has indicated that the possibility of firms purchasing intermediate products that incorporate technical progress for which the firms have not paid is also a source of knowledge spillover. Therefore, the structure of *input-output flows* (at the level of industries) or that *of international trade* (at the level of countries) can be used to approximate the structure of flows of knowledge.

Undoubtedly, a crucial dimension of spillovers is the spatial dimension. Knowledge produced in local area A may reach firms in region B, with a probability and/or intensity that is inversely proportional to the distance. Among many others, Autant-Bernard (2001), Audretsch et al. (2005), Del Barrio Castro and Quevedo (2005), Woodward et al. (2006) and Ellison at al. (2010) provide evidence of the role of knowledge spillovers as agglomeration forces. To consider these effects, previous studies have developed techniques for disentangling *spatial dependence* from other effects (Anselin 1988; Abreu et al. 2004).[2]

The analysis of previous literature reveals a fundamental problem in the conceptualization and estimation of knowledge spillovers: Is knowledge a production factor? In the traditional knowledge

[2] These techniques make the spillover effect a function of the distance matrix between any pair of points in the geographic space, which are associated with a series of distance functions that may reflect various effects. The estimates are much more precise and robust this way. With respect to the previous approach, spatial dependence models leave open the direction of the impact of spillovers, observing the effects ex-post instead of modelling interaction effects ex-ante.

production function approach, assuming that knowledge is a direct productive factor by using proxies, such as R&D expenditure or R&D stock, has several advantages (Griliches 1992). From the empirical perspective, this approach suffers from two weaknesses: First, once a firm assumes the role of an imitator, the magnitude of the effect of R&D on growth is not as large as posited by the theory (Jones 1995, Comin 2002). Second, the measure of knowledge stock (as proposed by Griliches 1979; see also Adams 1990, 1993) is heavily dependent on time horizon and the rate of depreciation, and there is no way to normalize these variables.

At a more fundamental level, is knowledge an input to or output of the production process, or both? If one admits that knowledge is both an input and an output, then the conventional production function approach becomes completely inadequate.

From a methodological perspective, the approach to knowledge spillover is subject to a dilemma.

The survey-based technique is the most reliable technique for obtaining a precise result regarding the spillover mechanism; moreover, it is almost impossible to obtain an aggregate estimate for the spillover mechanism.

On the other hand, the overall effect of knowledge spillover can only be determined by including various proxies of knowledge production *directly* into the equation. However, by doing so, we are compelled to accept that spillover effect is generated only when the source of the spillover is a production factor.

The crucial point is that many relevant sources of spillover are *not* production factors. They are neither consumed during production nor substituted by investment decisions. The sources of spillover may influence the productivity of firms without being channelled through production factors or by the purchase of intermediate goods incorporating technical progress generated in other industries. This creates a difficult dilemma, one that, to the best of our knowledge, remains unresolved in the literature.

We suggest an alternative approach, based on robust nonparametric efficiency techniques (Daraio and Simar 2005, 2007), that permits us to treat knowledge as an *external factor.* This may influence the technical efficiency of productive units (in our case provinces), without the need to specify ex-ante whether knowledge is an input or output. [3]

3. A conditional efficiency technique to estimate knowledge spillovers

Efficiency analysis techniques rely on the basic and intuitive idea of efficiency as the best use of resources (i.e. the use of the lowest amount of inputs x) to produce the maximum feasible amount of outputs (y). The efficiency score of a production unit (in our case, the province) is assessed by measuring its distance from an estimated efficient frontier. Nonparametric efficiency analysis, which does not assume any functional form for the efficient frontier, has a long history in the area of productivity analysis. However, the application of nonparametric efficiency analysis to the economics of growth is more recent[4]. This could be attributed to the fact that conventional nonparametric techniques, such as Data Envelopment Analysis (DEA, Charnes et al. 1978), suffered from various methodological shortcomings, including the influence of outliers (given that the efficient frontier is estimated by enveloping all data points, including the most extreme values), the *curse* of dimensionality[5] and the unrealistic assumptions made for introducing external factors in the estimation. The new developments, discussed at length in Daraio and Simar (2007), solve most of these issues and deliver a flexible and powerful set of tools.[6] In this paper, we employ robust or *partial* frontiers, termed order-m frontiers (Cazals et al. 2002). Instead of defining the efficient frontier according to the highest technically achievable outputs, outliers are permitted to lie above a 'robust' or 'partial' frontier. We adopt the output-oriented framework, in which the goal of the province is to maximize the quantity of outputs, given the available inputs.[7]

[3] See Bonaccorsi and Daraio (2004) for a detailed comparison between production functions and production frontiers in the analysis of R&D systems.
[4] See Jerzmanowski (2007) and van Beveren (2012) and the literature cited in these studies.
[5] This is shared by most nonparametric estimators, see more details in Daraio and Simar (2007, p. 48).
[6] Bonaccorsi and Daraio (2007) illustrate the potential of these methods in the microbased analysis of universities.
[7] In this context, an efficiency score equal to one means that a province is on the estimated efficient frontier, an efficiency score higher than one means that a province is inefficient (i.e. it could expand its level of outputs given the inputs used) and an efficiency score lower than one means that a high performing province lies outside the estimated efficient frontier.

One of the main areas for the development of robust techniques is the so-called conditional efficiency analysis. The central idea is to reformulate the deterministic production process in a probabilistic setting to *condition* the production activity to the impact of external factors. Any external variable can be introduced in the analysis, and this variable will take the conventional label of 'Z factor'. This can be done without assuming ex-ante the sign of the impact itself. If external factors do not exert any impact, the *conditional* measure of efficiency will be equal to the *unconditional* measure. Then, a central role in conditional efficiency analysis is played by the *ratio* between conditional and unconditional efficiency scores, denoted as Q_m^z. The ratio of a province that uses *p* inputs $(x \in R^p)$ to produce *q* outputs $(y \in R^q)$ and whose production process might be affected by *r* external factors $(z \in R^r)$ can be defined as

$$Q_m^z = \frac{\lambda_m(x,y|z)}{\lambda_m(x,y)}, \tag{1}$$

where $\lambda_m(x,y)$ is the *unconditional* order-m output efficiency score that can be computed by the following univariate integral:[8]

$$\lambda_m(x,y) = \int_0^{\infty}[1-(1-S_{Y|X}(uy|X \leq x))^m]du, \tag{2}$$

where $S_{Y|X}(.)$ is the following probability: Prob$(Y \geq y|X \leq x)$; and $\lambda_m(x,y|z)$ is the *conditional* order-m output efficiency score defined as[9]

$$\lambda_m(x,y|z) = \int_0^{\infty}[1-(1-S_{Y|X,Z}(uy|X \leq x, Z = z))^m]du, \tag{3}$$

where $S_{Y|X,Z}(.) =$ Prob$(Y \geq y|X \leq x, Z = z)$.

Roughly speaking, the idea behind equation (2) is to take the expectation of the best output performance among *m* peers, randomly drawn from the population of provinces using lesser resources than its level of inputs (x), as a benchmark for evaluating the efficiency of a province. Since the benchmark is set against an average of the best output performance obtained from *m* peers, the

[8]A consistent nonparametric estimator and an alternative Monte Carlo algorithm is introduced and discussed in Daraio and Simar (2005, 2007).

[9]A consistent nonparametric estimator and an alternative Monte Carlo algorithm is introduced and discussed in Daraio and Simar (2005, 2007).

corresponding efficient frontier (the set of points where $\lambda_m(x, y) = 1$) is less extreme than the full frontier that envelops all points.[10] When provinces face external conditions, $Z \in R^r$, which are neither inputs nor outputs but might influence their production process, we introduce the *conditional* order-m measure in equation (3) by conditioning every random event described in equation (2) to $Z = z$.

For each province, the ratio Q_m^z takes a numerical value. If the value exceeds one, it means that external factors influence productive efficiency. As shown in Daraio and Simar (2005, 2007), the scatterplots of these ratios and a smoothing nonparametric regression offer an intuitive and useful representation. The plot may, however, exhibit irregular shapes, fully considering individual cases and local effects. Scatter diagrams that represent the impact of Z can be interpreted as follows. The vertical axis shows the ratios between conditional and unconditional efficiency scores (Q_m^z). The horizontal axis represents the value of the external variable Z. A line is drawn for representing the nonparametric regression of the ratios of individual units over the Z variable, and it can be read as a local average approximation. Daraio and Simar (2005, 2007) show that an increasing pattern of this nonparametric regression line indicates a *positive* effect of the external factor Z on the performance of the analyzed provinces. A decreasing pattern of the nonparametric regression line indicates a *negative* effect of the external factor Z. A flat region in the nonparametric regression line indicates *no effect* of the external factor Z. The technique also permits an investigation of the effect of multivariate external factors taken separately or jointly. In the latter case, the three dimensional plot enables us to capture partial and interaction effects.

4. Empirical analysis

The main empirical strategy of the paper is to measure the knowledge spillover effect as the *combined impact* of innovative and scientific activities on the efficiency of the production process conducted at local level (province).

[10] In the application that follows, we set m = 35 to leave outside the frontier 5% of the most extreme provinces.

Italy is an interesting case study for the analysis of spillovers, because Italian provinces are highly heterogeneous in terms of all the indicators of growth and innovation. More specifically, most manufacturing activity does not occur in large metropolitan areas, but rather in mid-sized provinces located in the Northern and Central regions (occasionally called Third Italy). Furthermore, public research is concentrated not only in a few large metropolitan areas, but also in numerous mid-sized provinces that do not have a strong manufacturing tradition. Thus, the geography of science does not overlap with the geography of innovation. Therefore, Italy is the ideal test bed for estimation approaches, such as conditional efficiency, which permits the estimation of local effects and the complementary effects of external variables.

We use an original dataset, which was disaggregated at the Italian territorial level of province and was developed by combining several sources. There are a total of 109 provinces in Italy. From these, we excluded some recently created provinces for which data for the analyzed period (2001–2003) was not available. Moreover, relevant data was not available for some other provinces and therefore these were also eliminated. Finally, our sample comprised 92 observations.[11]

A description of the variables is presented in Table 1.

[11] The analysed Italian provinces are as follows: Agrigento, Alessandria, Ancona, Aosta, Arezzo, Ascoli Piceno, Asti, Avellino, Bari, Belluno, Benevento, Bergamo, Bologna, Bolzano, Brescia, Brindisi, Cagliari, Caltanissetta, Campobasso, Caserta, Catania, Catanzaro, Chieti, Como, Cosenza , Cremona, Cuneo, Enna, Ferrara, Firenze, Foggia, Forlì, Frosinone, Genova, Gorizia, Grosseto, Imperia, La Spezia, L'aquila, Latina, Lecce, Livorno, Lucca, Macerata, Mantova, Massa, Carrara, Matera, Messina, Milano, Modena, Napoli, Novara, Nuoro, Padova, Palermo, Parma, Pavia, Perugia, Pesaro, Pescara, Piacenza, Pisa, Pistoia, Potenza, Ragusa, Ravenna , Reggio Calabria, Reggio Emilia, Rieti, Roma, Rovigo, Salerno, Sassari, Savona, Siena, Siracusa, Sondrio, Taranto, Teramo, Terni, Torino, Trapani, Trento, Treviso, Trieste, Udine, Varese, Venezia, Vercelli, Verona, Vicenza and Viterbo.

Role	*Variable*	*Description*
Input (X_1)	ULA IND	No. of employees in manufacturing industries at the province level (source: ISTAT - Italian National Statistical Office, *Conti pubblici provinciali*). Average 2001-2003. Thousand units.
Input (X_2)	IP	Proxy of the infrastructural stock at the province level (Picci 2002).
Input (X_2')	DPM	Alternative proxy of the infrastructural stock at the province level (Di Palma and Mazziotta 2002).
Input (X_2'')	KPUB	Share of public capital stock, allocated in proportion to total value added. Year 2001 (Picci 2002).
Input (X_2''')	KPUB1	Share of public capital stock, allocated in proportion to number of employees (ULA). Year 2001 (Picci 2002).
Input (X_3')	KPRIV	Share of private capital stock, allocated in proportion to total value added. Year 2001 (Picci 2002).
Input (X_3'')	KPRIV1	Share of public capital stock, allocated in proportion to number of employees (ULA). Year 2001 (Picci 2002).
Output (Y)	VA IND	Added value of manufacturing industries at the province level (source: ISTAT - Italian National Statistical Office, *Conti pubblici provinciali*). Average 2001-2003. Million current euro.
External factor (Z_1)	PAT TOT	Cumulative number of EPO (European Patent Office) patents, 1999-2003 (source: Unioncamere).
External factor (Z_2)	PUB TOT	Cumulative number of ISI publications, produced by universities and other research institutions at the province level, 1990-2000 (source: elaboration on ISI data from CRUI).
External factor (Z_3)	PUB TECH TOT	Cumulative number of ISI publications in the Engineering and Technology fields of science, produced by universities and other research institutions at the province level, 1990-2000 (excluding construction engineering).
External factor (Z_4)	PAT INT	Patent intensity: No. of EPO patents (PAT TOT) per million of inhabitants.
External factor (Z_5)	PUB INT	Total publication intensity: Cumulative number of ISI publications (PUB TOT) per million inhabitants.
External factor (Z_6)	PUB TECH INT	Engineering and technology publication intensity: Cumulative number of ISI publications in the Engineering and technology fields per million inhabitants, 1990-2000 (excluding construction engineering).

Table 1. Variables used in the analysis.

Tables 2 and 3 in the Appendix contain descriptive analyses of inputs, outputs and external factors. Moreover, the Appendix offers a detailed cartography of knowledge production at the province level in Italy. The province-level analysis permits a fine-grained observation of spillover effects. Clearly, the smaller the geographic size of the unit of analysis, the larger the spillover from activities that are not located in the same area, but in the neighbourhood. To consider this possibility, we model spatial dependence in patents and publications by assigning its own unique number plus the numbers of all other provinces weighted by the ratio of one divided by the distance (in km) to each province. This operationalization is consistent with most literature on geographic spillovers.

We study how the availability of several sources of knowledge at the province level influences the efficiency of the production activity of the manufacturing industry. We consider units of labor and physical infrastructure as inputs, and industrial value added as output. We condition the efficiency of the production process to the operation of the sources of spillovers: industrial innovation activity, as measured by patent applications, and research activity, as measured by international scientific publications. These two sources of knowledge, industrial innovation activity and research activity, can be read, with some crude approximations, as coming from the private and the public sectors, respectively.[12] Therefore, the estimation strategy measures knowledge spillovers as the combined impact of these two sources of knowledge on the technical efficiency of production.

Following the literature and given the important role played by manufacturing in the Italian economy, we select the manufacturing industry as the main target for knowledge spillover flows.[13] The main interest is not to develop new theories of knowledge spillovers, but rather to leverage on the existing contributions (mainly on specific channels for knowledge flows) and estimate a global effect at a sufficiently disaggregated territorial level to capture all relevant factors. Owing to the omnipresence of data constraints, most literature on spillovers deals with data at the regional level. At this aggregation level, however, it is difficult to attribute the estimated effects to the channels that are usually discussed

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[12] Although this characterization is not necessarily valid in general, it holds well for the case of Italy, a country in which, owing to the specialization model and historical factors, few academic and research institutions produce patents, and very few companies publish scientific articles.

[13] The importance of the Manufacturing sector is also highlighted in the document 'Manufuture: a vision for 2020 – assuring the future of manufacturing in Europe', European Commission, Publications Office, November 2004: 'The manufacturing activity in Europe represents today approximately 22% of the EU GNP. It is estimated that in total 75% of the EU GDP and 70% of today employment in Europe is related to manufacturing. This means that each job in manufacturing is linked to two jobs in manufacturing related services […]'.

in the literature, because the latter are concerned with various forms of labour mobility, personal information flows and face-to-face interaction, which usually take place at the infra-regional level. We believe that using province-level data is the most appropriate.

Moreover, we use data on publications at the province level, enabling the identification of the effect of local presence of universities and research centers. Following the concept that the impact on productivity and growth of scientific research has a longer time lag than industrial research, as witnessed by patents, we consider a longer time series (1990–2000) for publications than that for patents (1999–2003). The geographic referentiation of publications does not create noise in data because academic and research affiliations usually refer to the laboratory, department or institute and not to the headquarters. As is well known, this is not true for patents, the ownership of which is located at the headquarters (assignee), irrespective of the site of generation of the novel idea (inventor).[14] In fact, only a few multi-plant firms in Italy develop patents in different sites and locate their ownership at the headquarters. Hence, owing to larger coverage, the European Patent Office (EPO) patents data are used in this study.

Using the variables described in Table 1, we estimate several simple models with an exploratory purpose. In particular, we use the IP stock proposed by Picci (2002) as a proxy for infrastructural stock; this proxy employs the permanent inventory technique to reconstruct the infrastructural index of the province. Alternatively, we compare the results obtained by using the DPM infrastructural index, proposed by Di Palma and Mazziotta (2002), which is based on the stock in physical terms. The obtained results (using IP or DPM as a proxy of the infrastructures of the provinces) are very similar; therefore, in the following section, we report those obtained using as input the IP index.

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[14] To address this issue, we compared two sets of data. First, we extracted data on the location of inventors from US Patent Office (USPTO) patents. These data are fine grained with respect to the invention stage, but cover mostly large firms patenting in the United States. Second, we used the time series published by Unioncamere, which instead use EPO patents and then locate assignees, not inventors. Although this data has a larger coverage, it does not provide any information regarding the locus of invention. We run the models and found that the overall effect is not affected. However, the position of a few provinces were modified slightly and we should consider this in the positioning of individual units.

By examining the geographic distribution of patents, one stylized fact is immediately evident: although there is only one large inventive area (Milano) and only two large provinces (Bologna and Torino), there are many provinces where the cumulative patent activity is small (less than 1,000) but the density is very high. These provinces (Modena, Vicenza, Reggio Emilia, Parma, Treviso, Bergamo and Como) are all located in Northern Italy and are medium sized, and their economies are largely based on a strongly competitive mechanical engineering industry. A very different picture comes to light for publications. Here, there are two large agglomerations (Milano and Roma) and a few provinces with a significant volume of scientific activity that are centered around large cities (Napoli, Torino, Genova, Firenze, Padova and Bologna). However, the star provinces in terms of publication intensity are small to medium-sized research-oriented cities, such as Trieste, Pisa and Pavia. These cities neither have particularly strong manufacturing activities nor intense patenting activities. This finding is confirmed, with only a few variations, for publications in Engineering and Technology.

Figure 1 combines the two dimensions of knowledge production in terms of intensity. As a measure of intensity, we consider the ratio between the number of patents and publications and the total resident population, that is patents per million of inhabitants (PAT INT) and publications per million of inhabitants (PUB INT). Although the data refers to different periods (1990-2000 for publications, 1999-2003 for patents), they are cumulated and the overall comparison is appropriate, given the expected longer time lag for spillovers from scientific research. It is evident that a few provinces are specialized in both scientific and inventive activity, confirming the interest in the Italian case for empirical analysis. In particular, a certain dichotomy is found between provinces rich in science but relatively poor in patents (Pisa, Trieste, Padova, Pavia, Firenze, Siena, Genova and Ferrara) and provinces that follow the opposite pattern.

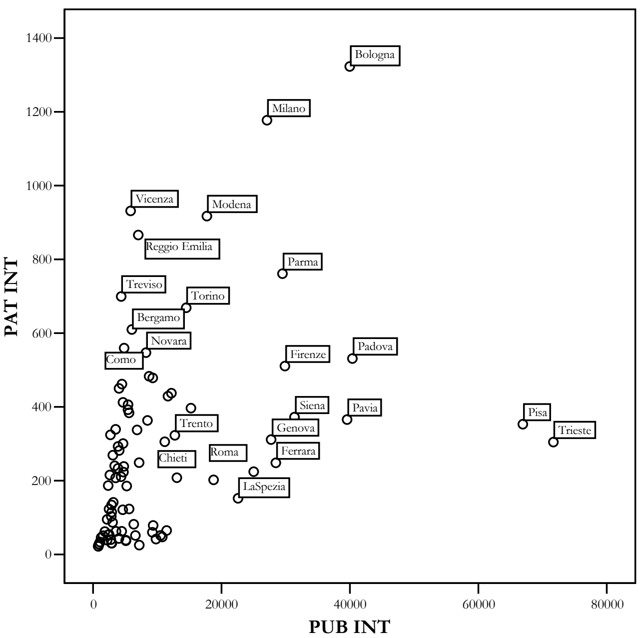

Figure 1. Plot of Publication intensity (PUB INT) versus Patent intensity (PAT INT) of Italian provinces.

Given this pattern, it is interesting to investigate the existence and measure the magnitude of spillover effects on production activity.

5. Main results

The first group of models introduce external factors in absolute value. In particular, we explore how the efficiency of manufacturing is influenced by the presence of the following external knowledge factors in the same province:

(a) PAT TOT: cumulative number of EPO patents at the province level (1998-2003);

(b) PUB TOT: cumulative number of ISI scientific publications at the province level (1990-2000);

(c) PUB ENGTECH: cumulative number of ISI scientific publications in engineering and technology fields (1990-2000).[15]

[15] Besides patent activity, we also investigated the effect of scientific publications in engineering and technical fields. For the sake of brevity, we have omitted the figures and reported only the findings; these figures are available from the authors upon request. The impact of the intensity of engineering publications (PUB ENGTECH INT), when associated with patent intensity, is similar to the general case. This suggests that the bulk of the effect of scientific activity in a given territory is captured by the engineering and technical fields.

By introducing these variables in absolute terms, we are interested in investigating size effects or the impact of the overall size of knowledge production activity, as indicated by patents or publications, on production activity.

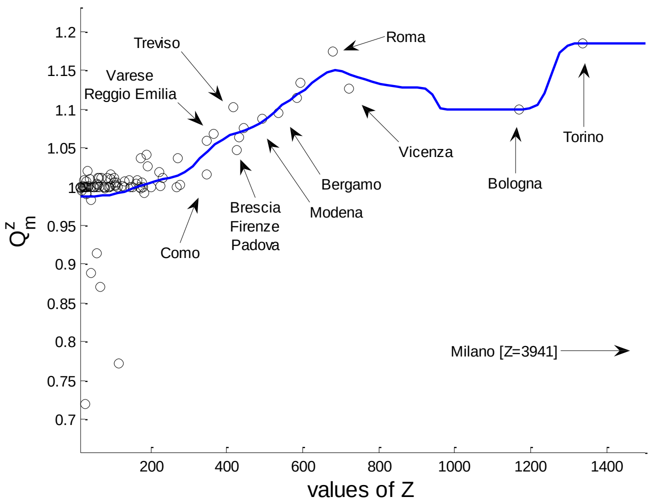

Figure 2. Impact of absolute size (volume) of patent activities on the production efficiency of Italian provinces. *Inputs: X1 = Number of employees (ULA IND), X2 = Infrastructural stock (IP), X3 = Share of private capital stock (KPRIV), Outputs: Y = Added value of manufacturing industries (VA IND), External factors: Z = Patent size (PAT TOT).*

Figure 2 shows the variation of the ratios of robust conditional and unconditional efficiency measures (Q^z_m) in relation to the total volume of patents at the province level. Here, for purposes of illustration, we include the labels of a few individual provinces (not repeated subsequently). There are several effects of interest. First, as witnessed by the upward slope in the initial region, the overall effect is positive, reaching a peak value of 1.5 for the outlier province of Milan and values from 1.05 to 1.2 for many provinces. Second, most provinces are located in the initial region (or cloud of points) of the plot in which the total volume of patent activity is small (less than 200 cumulative patents per province) and the ratio takes the value of 1 or close to 1. This means that for most provinces, the spillover effect from patenting activity is negligible. Third, a size effect is observed. The ratio increases significantly after the threshold of approximately 200 cumulative patents per province. Owing to the small number of observations in this range, a spurious 'waving' effect is observed starting from around 700 patents. Figure 3 examines the effect of the volume of scientific publications at the province level. Once again, we observe a positive effect, up to the peak value of 1.5, for the provinces of Milano and Roma (not shown in the figure). However, in the positive-sloped region, a few provinces show a peak value approximately 1.05-1.1, which is lower than that observed for patents. There seems to be a threshold of approximately 5,000 cumulative publications, given that below this value, provinces are located in a flat region where Q^z_m is close to 1 (no impact of knowledge). Interestingly, most Italian provinces are located in this region of no impact of knowledge. In the interval beyond 15,000 cumulative publications, we can find both large university cities (Roma, Milano, Napoli, Torino, etc.) but also medium-sized cities (Padova, Pavia, Pisa and Trieste) with strong university and research activities. Note that after 10,000 publications, some spurious "waving" effects appear due to the small number of observations in this range.

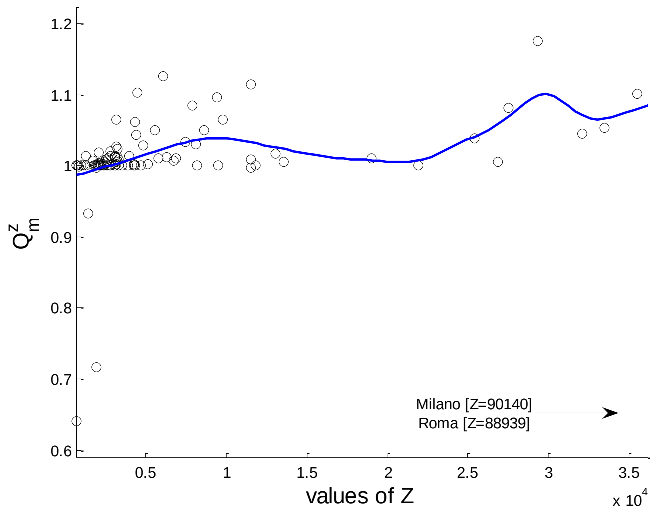

Figure 3. Impact of size of total publication activities on production efficiency of Italian provinces.
Inputs: X1 = Number of employees (ULA IND), X2 = Infrastructural stock (IP), X3 = Share of private capital stock (KPRIV), Outputs: Y = Added value of manufacturing industries (VA IND), External factors: Z = Publication size (PUB TOT).

The examination of the separate effects of patents and publications indicates the existence of a positive but small impact, which is subject to threshold effects. It is important to emphasize that these effects would not be captured by a traditional regression approach. Given that most units lie in the flat region, conventional regression-based measures would fail to find any effect. In reality, the distribution of individual points follows several differentiated patterns, that are locally valid.

Let us investigate the joint impact of the overall volume of patents and publications. This is possible in a three dimensional plot in which the two external factors are represented on the horizontal plane according to their values and the value of the Q^z_m ratios are shown on the vertical axis (now the ratios are obtained by dividing the conditional measure of efficiency -in which the external factors are patents and publications- with the unconditional measure). Figure 4 shows several interesting findings. First, when publications and patents are considered separately, they show that the maximum value (approximately 1.5) is reached only by the outlier value (Milano) and the rest of the distribution lies in the 1.05-1.2 region. However, when the external factors work jointly, they create a region on top of the hyperplane, where the overall ratio is approximately 1.4. This suggests a strong complementarity effect between the knowledge generated in the public research system and the technological knowledge incorporated in the inventive activity in companies. This complementarity effect is stronger for publications: for a province to be located in the top region, the number of publications have to be large (Z_2 beyond 5,000). Second, once again, the shape of the hyperplane suggests that a certain threshold is applicable. In fact the value of Q^z_m ratios drop sharply when the size of the actual publication and patent activities in the provinces are considerably lower than the absolute values (sizes) of both these activities.

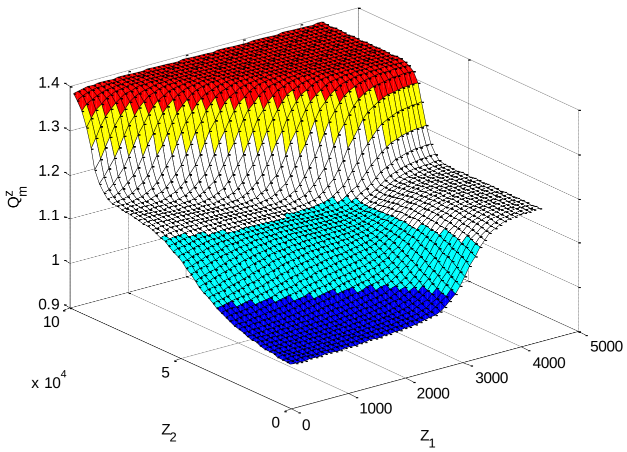

Figure 4. Combined effect of the size of publications and patenting activities on the productivity performance of Italian provinces. Surface of Q^z_m on Patent size (Z_1) and Publication size (Z_2).
Inputs: X1 = Number of employees (ULA IND), X2 = Infrastructural stock (IP), X3 = Share of private capital stock (KPRIV), Outputs: Y = Added value of manufacturing industries (VA IND), External factors: Z_1 = Patent size (PAT TOT), Z_2 = Publication size (PUB TOT).

As shown by Daraio and Simar (2007), the conditional technique also permits the investigation of the effect of each of the external factor when the other is fixed at a certain level. For this purpose, it may be useful to define the fixed values of the external factors in terms of quartiles.

The top panel of Figure 5 shows the variations in the Q^z_m ratios when the external factor Z_1 (PAT TOT) is permitted to vary in its interval for each quartile of the distribution of the external factor Z_2 (PUB TOT). This figure shows that the impact of the variability of patents on efficiency does not vary significantly according to the level of publications (the three lines are close to each other in the space). Confirming the findings from previous figures, the top panel of Figure 5 shows that a jump in the 92 Q^z_m ratios is obtained only when the number of patents per province is very large, that is, a cumulate value of approximately 2,000, which implies that very few provinces benefit from the external factors. The bottom panel of Figure 5 reveals very different results, which is quite interesting. If we permit the number of publications to vary along the horizontal axis, there is a positive but small effect on the efficiency of production when there are only a few patents (first quartile of patents, shown as the almost flat, dashed line at the bottom of the figure). Interestingly, if there are many patents, then the overall impact of publications is very strong and the ratios jump from 1.2 to 1.4.

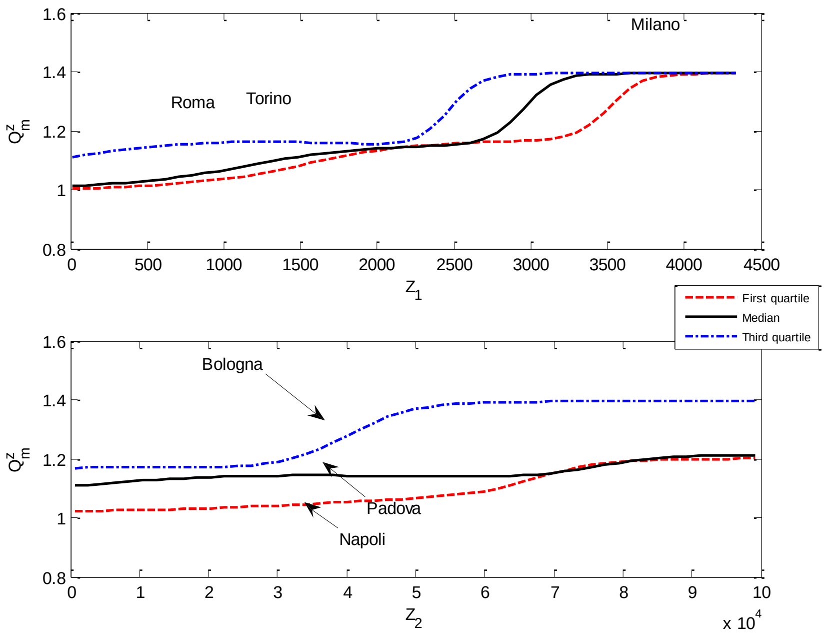

Figure 5. Combined effect of publications and patenting activities on the productivity performance of Italian provinces. Interaction effects.
Inputs: X1 = Number of employees (ULA IND), X2 = Infrastructural stock (IP), X3 = Share of private capital stock (KPRIV), Outputs: Y = Added value of manufacturing industries (VA IND), External factors: Z_1 = Patent size (PAT TOT), Z_2 = Publication size (PUB TOT). Top panel: Smoothed nonparametric regression of Q^z_m on Z_1 for Z_2's quartiles. Bottom panel: Smoothed nonparametric regression of Q^z_m on Z_2 for Z_1's quartiles. Dashed line (--): First quartile; solid line (-): Median; dashdot line (-.): Third quartile.

This joint analysis not only confirms the importance of complementarity but also defines the direction of complementarity more precisely: The effect of an increase in the volume of patents in a province is unaffected by the volume of publications (large or small) in that province. However, considerable scientific activity, represented by publications, in a province has a significant effect provided there is considerable technological activity, as represented by patents, in the same province. We believe that this result confirms the role of absorptive capacity at the territorial level. If the local economy and society do not have sufficient accumulation of human capital, organizational capital and entrepreneurship, the local impact of scientific activity may be negligible.

The previous analysis has shown that the volume (in absolute terms) of public and private knowledge production in a given territory positively influences the technical efficiency of the industrial system located in the same territory.

Now, let us address a different question: Is a positive spillover effect visible when we consider the intensity of knowledge production, that is, the relationship between volume and underlying population, instead of the absolute volume of knowledge production? This provides a rough measure of the relative importance of knowledge production over the general social and economic activities of a territory.[16] In terms of population and value added, the difference between size and intensity effects is particularly important in the case of small provinces where scientific and technological activity is concentrated. Is the magnitude of the knowledge spillovers of such provinces the same as that produced by large cities? For the sake of brevity, we have only presented the main findings and have omitted the figures.[17]. We find an overall positive effect of publication and patent intensity; however, this effect is smaller than the

[16] In future studies, we will introduce other intensity measures, using GDP or industrial value added.
[17] All the detailed results are available from the authors on request.

one observed for the volume of knowledge spillovers. The two intensity effects are complementary.[18] This means that provinces with limited knowledge production but strong intensity (e.g. some medium-sized research-oriented provinces, such as Parma, Siena and Padova) can exploit knowledge spillovers. However, as also previously observed for the volume of publications and patents, the majority of Italian provinces do not show any spillover effects.

6. Discussion of results and conclusions

We investigated the magnitude and distribution of knowledge spillovers on the basis of the overall volumes and intensities of patenting and publication activities. The introduction of conditional efficiency analysis offered a powerful tool to examine the spillover effects without including knowledge as a separate input, given that knowledge is neither an input nor an output, but may influence the production process. We found strong (positive) size effects and moderately positive intensity effects. In both cases, patenting and publications are strategic complements, but the effect of volumes is stronger than that of intensity. Provinces with maximum volumes of both patents and publications exhibited the strongest spillover effect. Alternatively, medium-sized provinces with high knowledge intensities also showed knowledge spillovers, but with a smaller magnitude. Therefore, the new technique enables us to identify and quantify several important dimensions of spillovers, which are discussed below in light of the most recent literature.

First, spillover effects disappear at low levels of scientific and technological activity. Most Italian provinces do not experience any knowledge spillover effects. This is a striking result and confirms the recent findings in the literature. Second, large metropolitan areas, which experience intense publication and patenting activities that exceed a give threshold, benefit from the largest spillovers. This confirms the importance of the recent debate on cities and metropolitan areas as centers of innovation. This debate considers various factors, such as diversity economies (Jacobs), mobility in urban labour markets,

[18] This finding also holds for publications in engineering and technical fields (figure not shown), the profiles of which almost completely overlap with the general type of publications.

division of labour and attractiveness of the quality of life. These areas are the only candidates for real agglomeration effects. Agglomeration requires both size and intensity effects. This finding offers a means for understanding the process of geographic concentration of innovative activities observed in Europe. To be attractive for public research and industrial R&D, a territory must exhibit *both* large absolute volumes and high intensity of knowledge activity. The size effect constitutes a large talent pool in the labour market and promotes the division of innovative labor. The intensity effect ensures that the social and economic systems are conducive to innovation because the administrative and political systems, interest groups and cultural forces will be influenced by the relative strength of research activities. Third, territories that lack a volume effect may continue to benefit from knowledge spillovers, but on a smaller scale. This effect is unlikely to generate sustainable agglomeration and attractiveness. Provinces with high research intensity benefit from small to moderate spillovers to industry; however, this effect is conditional on a minimum level of patent activity. Provinces with strong industrial bases are those that benefit more from the abstract and general knowledge produced at universities. This is confirmed by *specialization* effects; the spillovers are mainly generated by scientific activity in engineering. This is usually associated with large and/or research-oriented engineering faculties, which have a positive effect on the quality of graduates in local labor markets.

Interestingly, and consistently with Ghinamo (2012), the most recent literature has somewhat shifted the attention from the question of whether spillovers exist and what is their magnitude to the question of why spillover effects seem to have highly selective effects. In other words, now there is significant interest in explaining why the observed impact of spillovers is absent or negligible in some regions and/or some sectors, while it is significant in others. We summarize these contributions by highlighting the following three explanatory mechanisms: (a) allocation of talent and cost of commercialization of knowledge, (b) absorptive capacity and (c) institutional context. For the sake of simplicity, one may relate these explanations to the emphasis placed on (a) the source of knowledge, (b) the recipients or (c) the process and context of knowledge transformation.

The first line of explanation emphasizes the fact that the knowledge produced in research does not have immediate economic value, but needs to be processed or transformed to make it usable. Owing to the intrinsic nature of knowledge and the imperfections of the markets for technology, this transformation usually requires intensive cooperation from the producers. This calls for an analysis of the decisions of knowledge producers, such as academic researchers.[19] The second line of explanation emphasizes that the impact of spillovers also depends on the attributes of the recipient economic system. This is particularly important for spillovers that are not based on innovative entrepreneurship but on the absorption of knowledge by incumbent firms. Regions characterized by incumbent firms with low technology and/or traditional tertiary activities may find it frustrating to see negligible spillover effects from public investment into R&D.[20] Third, the magnitude of spillover effects may be greatly reduced by frictions in the transformation process, rather than by the attributes or decisions of either the producers or recipients of the knowledge. For example, the knowledge spillover theory of entrepreneurship (Carlsson et al., 2009) posits that innovative entrepreneurship is generated by the ability to exploit those opportunities generated by new knowledge that have not been exploited by incumbents. Only a fraction of the knowledge created generates opportunities and such knowledge is termed economic knowledge. Therefore, new and innovative firms not only benefit from an increase in knowledge creation but also

[19] Lacetera (2009) shows that researchers may find the cost of commercialization of research so high that the expected returns are not large enough to compensate for the foregone benefits accruing from reputation in pure science. Michelacci (2003) finds that the impact of R&D investment on growth follows an inverted U-shape, because the allocation of highly qualified human resources between research and entrepreneurship must be balanced and over-investment in R&D may reduce its impact. Some factors that may hinder the impact of public sector research include the low efficiency of firms generated by research spinoff and the lack of entrepreneurial capabilities (Yasar and Morrison Paul 2012). Moreover, commercial opportunities from research are higher in academic fields, such as Engineering (Landry et al. 2007; Bonaccorsi et al. 2013), probably owing to lower costs of commercialization.

[20] Wennberg et al. (2011) argue that the most important spillover from university knowledge is the indirect one, that is university graduates first being employed at large companies and then founding their own companies. This finding sheds light on a possible explanation for lack of spillovers in laggard regions. Both entrepreneurship and large advanced companies are missing in these regions. Furthermore, in low-technology sectors, the absorptive capacity may be insufficient. Medda et al. (2005) indicate that investment in R&D activity conducted with universities does not produce a positive rate of return for firms, and Bonaccorsi et al. (2012) show that the engagement of universities in commercial activities is lower in laggard regions.

from the creation of institutions that generate a higher proportion of economically relevant knowledge (Acemoglu et al. 2004).[21]

The analysis conducted in this paper paves the way for numerous future developments. First, we could extend the geographic scope of the analysis to the European level (NUTS 2 or NUTS 3). Second, an extension of the model to tertiary activities would be an interesting development (Kay et al. 2007). Third, the conditional efficiency analysis[22] could be combined to other spatial dependence models that introduce measures of geographic proximity, with definitions of 'neighbor knowledge spillovers' based on dimensions other than the distance-based approach used in this paper, as external factors.[23] After these extensions are tested, an interesting area of research would be to include robust efficiency estimates in input-output models of the economy, allowing for a direct estimate of spillovers. This would be significant contribution to the existing literature.

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[21] This has led to the concept of knowledge filter (Acs et al. 2004), according to which the magnitude of spillovers not only depends on the source of knowledge but also on the overall institutional context. Caragliu and Nijkamp (2012) argue that the level of spillover is a function of the accumulation of cognitive capital in the region, so that the regions that have lower endowments for historical reasons cannot appropriate the knowledge produced by the public sector locally.

[22] Including its recent developments; see Badin et al. (2012a,b).

[23] We thank an anonymous referee for suggesting us this extension.

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Appendix: descriptive statistics and territorial maps

Table 2 Descriptive statistics on inputs and output

	Range	Minimum	Maximum	Mean	Std. Deviation
ULA IND	509	5	514	54	67
IP	598	36	634	100	83
DPM	156	27	184	96	32
K PUB	66301	1639	67940	10219	10025
K PRIV	106026	1380	107406	9735	13465
K PUB1	63907	1859	65766	10204	9517
K PRIV1	98119	1555	99675	9717	12693
VA IND	32052	190	32242	2692	3940

Table 3 Descriptive statistics on external factors

	Range	Minimum	Maximum	Mean	Std. Deviation
PAT TOT	3927	14	3941	218	453
PAT INT	1301	22	1323	275	261
PAT TOT AVE	803	3	806	46	93
PAT INT AVE	270	4	274	58	55
PUB TOT	89486	654	90140	8384	14465
PUB INT	70904	787	71691	10150	12826
PUB TOT AVE	10879	77	10956	1003	1717
PUB INT AVE	8720	96	8816	1221	1513
PUB TEC TOT	3143	19	3163	276	489
PUB TEC INT	2665	20	2685	313	440
PUB TEC AVE	286	2	288	25	44
PUB TEC INT AVE	243	2	245	29	40
COMP MAN	2.381	0.041	2.422	0.853	0.464
COMP TOT	0.528	0.005	0.533	0.198	0.130
APE TOT	1.255	0.020	1.274	0.373	0.231

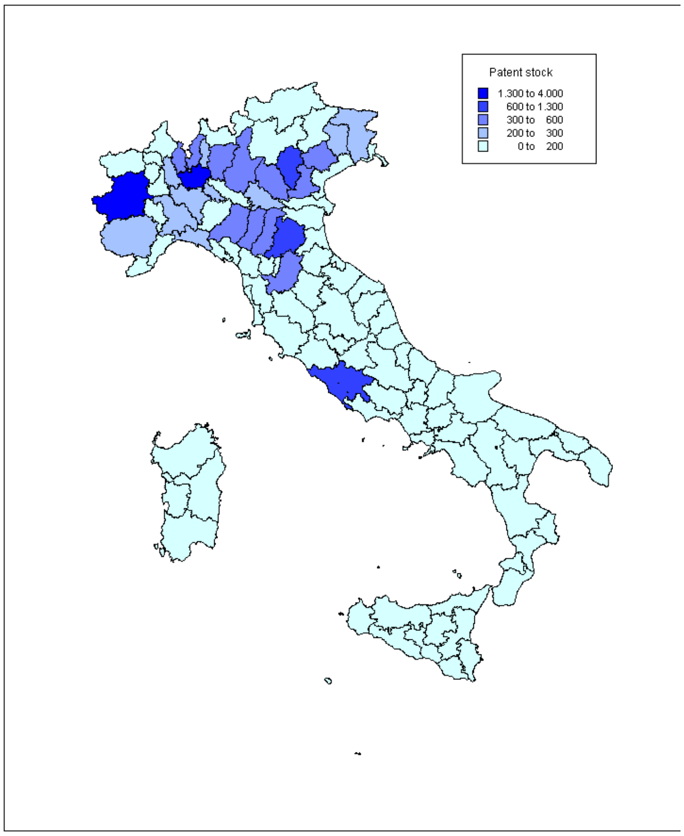

Figure 6. Territorial distribution of patent stock (PAT TOT, 1999-2003).

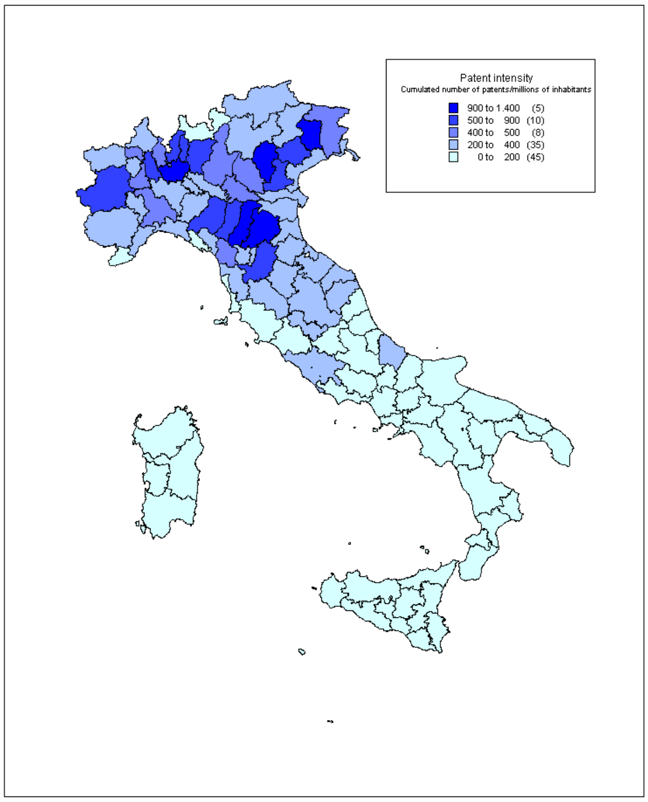

Figure 7. Territorial distribution of patent intensity (PAT INT, 1999-2003).

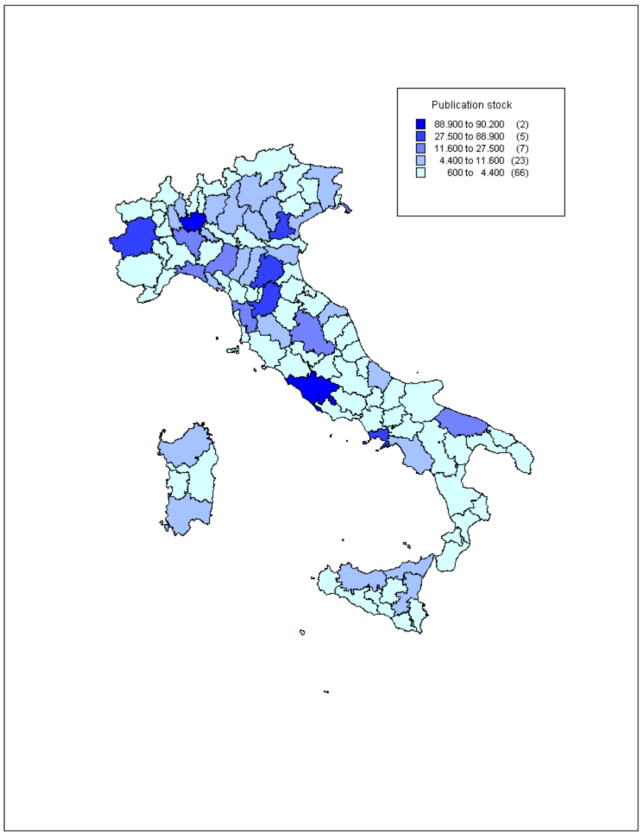

Figure 8. Territorial distribution of publication stock (PUB TOT, 1990-2000).

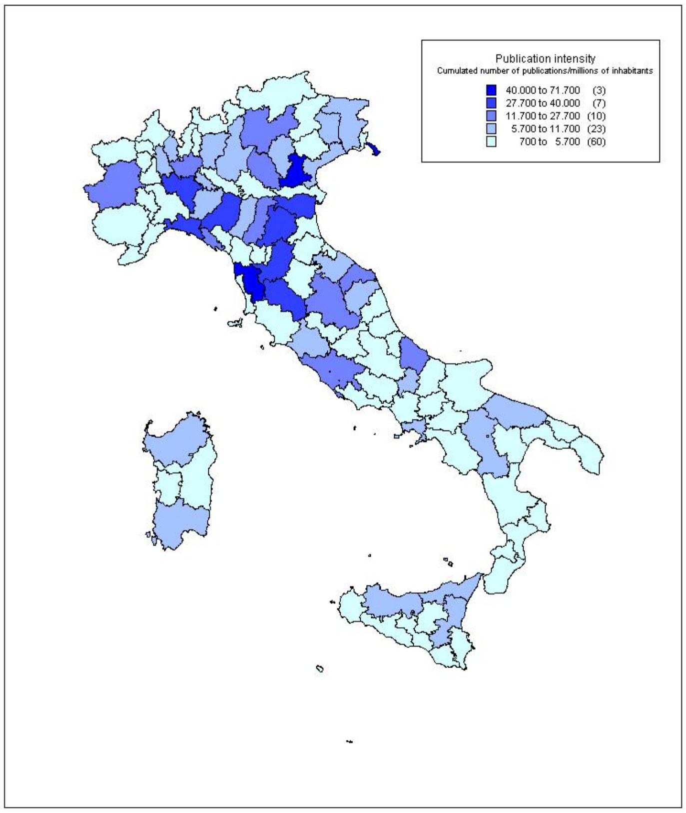

Figure 9. Territorial distribution of publication intensity (PUB INT, 1990-2000).

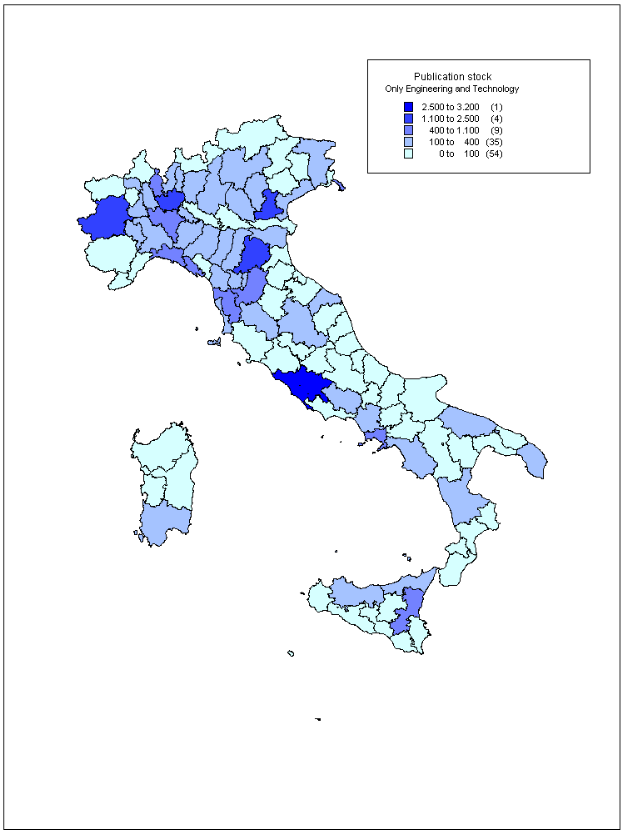

Figure 10. Territorial distribution of publication stock in Engineering and Technology (PUB TECH TOT, 1990-2000).

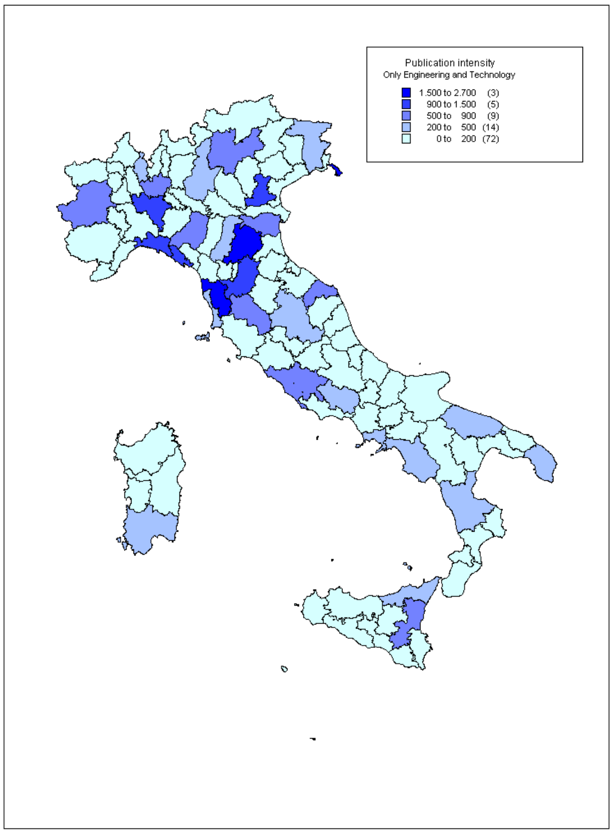

Figure 11. Territorial distribution of publication intensity in Engineering and Technology (PUB TECH INT, 1990-2000).