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EVALUATING THREE PROPOSALS FOR TESTING INDEPENDENCE IN NON LINEAR SPATIAL PROCESSES

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Abstract

Spatial econometric studies have usually employed linear regression frameworks when modelling relationships between geo-referenced units. Nevertheless, as Kovach (1960) stated, life can be (and used to be) non linear. This fact explains the growing interest of the profession in developing new models for dealing with non linearities. As a natural complement, new families of tests have also become necessary, particularly those better suited to a non linear world. This paper evaluates the behaviour of the main type of tests employed when checking for spatial independence assumptions in the presence of non linearities: parametric, nonparametric and semiparametric. To reach this goal we select three representative proposals from each family of tests. First, we study one of the most well known parametric tests, the I-Moran test. Secondly, we select the nonparametric proposal of Brett and Pinkse (1997), the BP test. Finally, we analyse the behaviour of a semiparametric test which has been applied to epidemiology studies but still not generalised to spatial econometrics literature, namely the Kulldorff test or Ku test (Kulldorff et al., 2009). In order to establish a comparison among these proposals, we generate different nonlinear spatial structures throughout Monte Carlo simulations and conduct an empirical exercise on the matter. Results of both sections indicate that, under nonlinear spatial structures, the classical I-Moran test usually fails, but semiparametric and nonparametric proposals perform much better, showing greater power in all cases. Results recommend updating spatial testing proposals in the presence of non linearities, allowing for corresponding robustness gains in the estimation procedure.

Key words: Non linear spatial processes, spatial independence tests, Monte Carlo simulations, R&D.

JEL classification: C-14, C-63, O-32, R-12.

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1. Introduction

Literature on spatial econometrics, which builds on the importance of including spatial dimension when explaining real world phenomena, has been largely confined to linear models (Anselin and Bera, 1998). In fact, spatial modelling of the type of linear regressions with spatial interdependence, taking the form of a linear additive association of observations on neighbours, still dominates literature (Anselin, 2010; Su and Jin, 2010). Nevertheless, as earlier noted by Kovach (1960), life can be (and used to be) non linear. Therefore, careful modelling of relationships in space requires progressive introductions of econometric models employing non linear specifications. This explains the recent increase of attention to this issue in spatial econometrics literature.[1]

Such a new research direction is generally related to the shortcomings faced by conventional equilibrium models when explaining reality, given that "ignoring the potential non linear relationship in spatial dependence models often results in inconsistent estimations of the parameters of interest and misleading conclusions" (Su and Jin, 2010, p. 18). It is also true that the most recent developments have actually been possible because of the increasing availability of new software and sets of micro-data, allowing for empirical testing exercises (de Graaff, Florax and Nijkamp, 2001). To this extent, the present boost of non linear methods for spatial analysis opens new grounds for spatial econometric models, improving our understanding of socio-economic systems. In certain ways, it also reminds us of the journey travelled by traditional econometrics some years ago, for example in time series models.[2]

Original efforts to introduce non linear interdependences in spatial econometrics took the form of introducing non linear distance decay functions (Dubin, 1988), as well as allowing for flexible functional specifications, useful for dealing with certain forms of non linearities in the models (Yang et al., 2006; Pace et al., 2004; Baltagi and Li, 2001; van Gastel and Paelinck, 1995). Most of these papers introduce a parametric transformation (e.g., Box-Cox one) on the response variable and/or on the regressors. Recent approaches include the use of transition processes defined as gradual regime-switching structures in the form of smooth autoregressive models (STAR). The STAR framework allows the parameters of the model to take on different values across regimes in a smooth transitional process, with spatial correlation being taken into account through the use of a weight matrix suited to identifying the topology of the entire spatial system (Pede, Florax and Holt, 2008). The contributions of Mur et al (2009) and

[1]See, for example, the monography that the *Journal of Econometrics* has recently devoted to the topic (*JoE*, Vol. 157 (2010), Elsevier).

[2]See the monography of the *Journal of Econometrics*, Vol. 157, particularly the contribution of Su and Jin, 2010; see also Pede, Florax and Holt, 2008; Yatchew, 1998.

Lopez et al (2009) follow the same line of reasoning, but introducing instability in the spatial dependency mechanisms.

As techniques advance, academic staff are increasingly exploring nonparametric and semiparametric methods in order to identify the presence of spatial structures in the presence of non linearities (de Graaff, Florax and Nijkamp, 2001; Yatchew, 1998). Their main advantage is concerned with the fact that data is allowed to speak for itself in order to determine the functional form linking variables in the model, without having to previously specify a parametric model, which constitutes a pivotal issue in spatial econometrics literature (Lu, 2009). In this context, the present paper pursues to compare the power of the three salient proposals employed in literature when checking for the spatial independence assumption: parametric, nonparametric and semiparametric proposals. To reach this goal we select three representative specifications of every family of tests. First, we analyse one of the most well known parametric tests, the I-Moran test (Moran, 1948), which is widely employed in the first stages of many exploratory and spatial econometrics studies. Second, we select the nonparametric proposal of Brett and Pinkse (1997), the BP test. In comparison with the Moran Index this contrast is little in literature, probably due to the lack of usable software for calculations. Finally, we analyse the behaviour of a semiparametric test which has been applied to epidemiology literature but still not generalised to spatial econometrics literature, namely the Kulldorff test or Ku test (Kulldorff et al., 2009). This contrast belongs to the family of scan windows contrasts and although it is usually employed with the aim of identifying cluster regions of different behaviour, it can also be used as a general test to contrast the hypothesis of independency. The test for normal models has been incorporated into the freely available SaTScan software (http://www.satscan.org).

To establish a comparison among these proposals for identifying spatial dependence patterns, we run simulations of linear and non linear spatial processes through Monte Carlo methods. After that, we develop an empirical exercise where evaluate the spatial effect in a production function with internal R&D in two Spanish regions (Madrid and Barcelona). Anticipating some of our findings, in the Monte Carlo exercise, we observe that under non linear spatial structures the semiparametric and nonparametric tests show much more power than the classical I-Moran test usually employed in literature. Moreover, the I-Moran test fails to capture the presence of spatial dependence for non linear models, with the corresponding miscomputation of the parameter estimates. Finally, in the case of empirical application, we found that the typical linear spatial structure (spatial error model) is not enough to capture all spatial effect in the model.

After this introduction, the remainder of the paper is organised as follows: Section 2 presents three tests to be compared, including some comments about its computation.

In Section 3, Monte Carlo simulations are carried out in order to compare the power and main characteristics of the three families of tests. Section 4 includes the empirical exercise of the paper, where testing the power of the three families of tests is completed. Finally, section 5 gives the conclusion.

2. Three proposals for testing independence in non linear spatial processes

This section introduces the previously mentioned spatial dependence tests, indicating the main advantages and disadvantages of their use.

The Parametric Moran's test (Moran, 1948)

Moran's I test specification is an extension to Pearsons product moment correlation coefficient to a univariate series (Cliff and Ord, 1981). In this sense, Moran's I tests for a variable x measures if the values of this variable, at different locations (x_i and x_j with $i, j = 1, 2, \ldots, n$ and $i \neq j$), are associated. Formally, Moran´s I test follows the expression (1) which is asymptotically distributed as a normal:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} (x_i - \overline{x}) w_{ij} (x_j - \overline{x})}{\sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{1}$$

where $\overline{x}$ is the sample mean for the variable x, w_{ij} is the (i, j)-element of the known Weight Matrix (W) which quantifies the different intensities among spatial locations in function of their proximity. Finally, S_0 is the sum of all W elements and n is the number of observations.

$$S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \tag{2}$$

Moran's I is not, strictly, a test of independence but a no correlation test between the values of a variable in the different locations and its spatial surroundings. Its good properties in comparison with alternative spatial dependence tests (Florax and de Graaff, 2004) have extended its application to spatial econometrics literature. Despite its good qualities, the Moran's I test has some limitations which should be taken into account when we are testing spatial correlation characteristics. Among them, Moran's I test requires that the weight matrix (W) is specified in function of the dependence relationship assumed under the alternative hypothesis (Cliff and Ord, 1981). Besides that, the Moran test could fail to detect spatial dependence under nonlinearities (López et al. 2010).

Non-parametric spatial dependence test: τ *of Brett and Pinkse (Brett and Pinkse, 1997)*

This is a nonparametric test which is built, taking into consideration the properties of the characteristic functions. Specifically, it is based on the property that if two variables (in our case, X and his spatial lag WX) are independent, the joint characteristic function must factorize into the product of their marginal characteristic functions. To compute the test, a f practitioner-chosen density function with infinite support is considered with $h(x)=\int e^{iux} f(u)du$ its Fourier transform. Let $\{Y_t\}$ and $\{Z_t\}$ be independent copies of the process $\{X_t\}$ and let X_t^N be the average of proximate observations of X_t. We also need to define $h_{ts}=h(X_t-X_s)$, $h_{ts}^{NN}=h(X_t^N-X_s^N)$ and, $\eta_{n1}=n^{-2}\sum_{s,t} h_{ts}h_{ts}^{NN}$, $\eta_{n2}=n^{-3}\sum_{s,t,u} h_{ts}h_{tu}^{NN}$ $\eta_{n3}=n^{-4}\sum_{s,t,u,v} h_{ts}h_{uv}^{NN}$, with n the number of observations. Let

$$\eta_n=(\eta_{n1}-\eta_{n2})^2(\eta_{n2}-\eta_{n3})^2 \tag{3}$$

and

$$\upsilon_n=(\gamma_n-\mu_n^2)^2 n^{-1}\sum_t n_t^{-1}(I(n_t>0)+\sum_s n_s^{-1}(I(s\in N_t)I(t\in N_s)) \tag{4}$$

where $\mu_n=n^{-2}\sum_{t,s} h_{ts}$, $\gamma_n=n^{-3}\sum_{t,s,u} h_{ts}h_{tu}$, N_t the set of proximate observations of point t and n_t, that is, the cardinal of set N_t.

Then, under the null of independence, the Brett and Pinkse statistic

$$\tau=\frac{n\eta_n}{2\upsilon_n} \tag{5}$$

is asymptotically χ_1^2 distributed.

As in the Moran I test, the BP test considers, under the null hypothesis, some knowledge about the spatial dependence structure. Among the different advantages of the BP test is that it behaves well with different sizes even in the case of reduced sample sizes. On the negative side, the BP test could fail when the analysed process is non-stationary, also being sensitive to the scaling of the observations. Additionally, the BP has infra-size problems if the analysed variable does not follow a normal distribution. The Brett and Pinske test needs some information about the spatial dependence structure to be computed. In this sense, at least the neighbourhood connections are required. Once, they are defined, the BP test is quite powerful and its power does not vary even with reduced size samples (Pinkse, 1998). This test is good to detect non linear spatial dependence structures. A limitation of the BP test, is that it requires stationarity because in other cases we could over-reject the null hypothesis.

Semiparametric spatial dependence Kulldorff test (Kulldorff et al., 2009)

The Kulldorff Test is a classic tool in the field of epidemology (Kulldorff and Nagarwalla, 1995). It has regularly been used to identify high incidence clusters of rare sicknesses, mainly cancer. It has been developed under null hypothesis that are supposedly carried out under a discrete type process. The latest version of the contrast in this line of work is a statistic carried out under normal observation hypothesis. This version allows its application to variables usually employed in economics and regional science, in this way generalising its use to new fields of research.

Basically, the test identifies regional clusters with a different behaviour to others. To contrast this hypothesis, central windows of different size and shape are put into each region (circular, elliptical or flexible) comparing the mean value of the observations inside the window with that which is observed outside it. The window moves across the entire map changing the size and shape to identify the maximum differential between the values inside and outside the window. Once the window where the maximum differential is identified, it is evaluated by checking if the difference is significant.

The Kulldorff test is a scan statistic in which the null hypothesis is that all the observations are independent and the variable come from some considered distribution. Under the alternative hypothesis, there is one cluster location where the observations have either a larger or a smaller mean than outside that cluster.

In this paper we present the circular version of the statistic but it can very easily be extended to non-circular windows. The circular spatial scan statistic is defined through a huge number of overlapping circles. For each circle, z , a log likelihood ratio $LLR(z)$ is calculated, and the test statistic is defined as the maximum LLR over all circles. The scanning window will depend on the application, but it is typical to define the window as all circles centred on an observation and with a radius varying continuously from zero up to some upper limit. Circles with only one observation are ignored. Let $n_z = \sum_{s \in z} n_s$ be the number of observations in circle z , and let $x_z = \sum_{s \in z} x_s$ be the sum of the observed values in circle z .

Under the null hypothesis, the maximum likelihood estimates of the mean and variance are $\mu = \frac{1}{n}\sum_i x_i$ and $\sigma^2 = \frac{\sum_i \left(x_i - \mu\right)^2}{n}$ respectively. The likelihood under the null hypothesis is then

$$L_0 = \prod_i \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x_i-\mu)^2}{2\sigma^2}} \qquad (6)$$

and the log likelihood is

$$\ln L_0 = -N\ln(\sqrt{2\pi}) - N\ln(\sigma) - \sum_i \frac{(x_i-\mu)^2}{2\sigma^2} \qquad (7)$$

Under the alternative hypothesis, we first calculate the maximum likelihood estimators that are specific to each circle z, which is $\mu_z = x_z / n_z$ for the mean inside the circle and $\lambda_z = (X - x_z)/(n - n_z)$ for the mean outside the circle. The maximum likelihood estimate for the common variance is

$$\sigma_z^2 = \frac{1}{n}\left(\sum_{i\in z} x_i^2 - 2x_z\mu_z + n_z\mu_z^2 + \sum_{i\notin z} x_i^2 - 2(X - x_z)\lambda_z + (n - n_z)\lambda_z^2\right) \qquad (8)$$

The log likelihood for the circle z is

$$\ln L(z) = -n\ln(\sqrt{2\pi}) - n\ln(\sqrt{\sigma_z^2}) - n/2 \qquad (9)$$

As the statistic test we use the maximum likelihood ratio

$$\max_z (L_z / L_0) \qquad (10)$$

or more conveniently, but equally, the maximum log likelihood ratio

$$Ku = \max_z(\ln L_z - \ln L_0) = \max_z\left(n\ln(\sigma) + \sum_i -\frac{(x_i-\mu)^2}{2\sigma^2} - n/2 + n\ln(\sqrt{\sigma_z^2})\right) \qquad (11)$$

Only the last term depends on z, so from this formula it can be seen that the most likely cluster selected is the one that minimizes the variance under the alternative hypothesis, which is intuitive. The significance of this statistic is obtained through re-testing and checking.

The Ku test scans the surface, looking for the shape and size which maximises the difference, while the normal independency contrasts introduce in the null hypothesis a close structure that should be specified previously. In this way, the most important difference in comparison with the I-Moran and BP tests, is that Ku test does not need the spatial dependence structure information from the weight matrix. On the negative side, Kulldorff test assumes the null hypothesis of iid, following a normal distribution with the same mean value. This is a restrictive assumption. Therefore, the rejection of the null hypothesis could be motivated by the real existence of spatial dependence structure or by the existence of atypical observations with different average values. To discriminate between these results further analysis is required, for example, the study of the outliers.

2. The finite sample behaviour of spatial dependence tests under non linear processes

In this section we analyse the finite sample behaviour of different spatial dependence tests under a non linear framework. To reach this purpose: (1) we generate different spatial processes throughout alternative mechanisms to the classical linear spatial dependence structures to include a non linear behaviour and (2) examine the power of the proposed spatial in this scenario.

In order to generate non linear spatial processes, we consider that there are $i = 1, \ldots, n$ observations spatially distributed in irregular lattices which centroids have coordinates (x_i, y_i) generated by a bivariant normal $NMV(0, I_2)$ where I_2 is the identity matrix 2x2. Despite the fact that the use of regular lattice is a very widespread practice, this is not a real situation in the analysis of economic data when the studied data is referenced by regions or cities. Due to this, there is an extensive amount of researchers who highlight the need of using non regular lattices (Robinson 2010, Faber et al. 2009). We also use the four (closer) nearest neighbours row standardised weight matrix (W_{4nn}) in our study and three sample sizes ($n = 49, 100, 225$).

However the MI and BP statistics have an asymptotic distribution and their significance could be determined throughout the distribution they converge into. Nevertheless, in a non linear framework, it is more consistent for a comparative analysis, to evaluate the significance through the method of re-sampling. In some cases, the concepts of non linearity and non normality could be interrelated (Lu, 2009). Therefore, the existence of nonlinearities could generate the lack of normality. Because of this, in our study, we use the bootstrap technique considering 999 iterations. For the MI and BP tests, we evaluate the null hypothesis applying the four order (W_{4nn}) weight matrix independently of the weight matrix W used to generate the data. To carry out the computing of the Ku test, it is not necessary to have information about the W weight matrix, only the shape of the window. It is considered to be irregular and based on the closer neighbours. The p-value for this statistic is obtained through Monte Carlo hypothesis testing (Dwass 1957), by comparing the rank of the maximum likelihood from the real data set with the maximum likelihoods from the random data sets. If this rank is r, then the p-value = r/(1 + # simulations).

Linear processes

As a previous step in our analysis, Table 1 shows the results corresponding to the size and power of the spatial dependence tests in one of the more frequent linear cases: the SAR structure.

$$DGP_0 : Y = (I - \rho W)^{-1} e \quad \text{with } e \approx N(0,1) \qquad (12)$$

Table 1: Size and power with DGP_0 at 95%

ρ	$n=49$ IM	BP	Ku	$n=100$ IM	BP	Ku	$n=225$ IM	BP	Ku
0.00	0.049	0.058	0.047	0.042	0.039	0.050	0.049	0.046	0.052
0.10	0.078	0.064	0.100	0.139	0.075	0.105	0.224	0.087	0.121
0.20	0.224	0.136	0.175	0.331	0.178	0.195	0.592	0.286	0.250
0.30	0.379	0.240	0.247	0.604	0.393	0.344	0.883	0.613	0.467
0.40	0.580	0.413	0.365	0.830	0.637	0.534	0.987	0.917	0.679
0.50	0.755	0.612	0.548	0.948	0.881	0.719	1.000	0.994	0.874
0.60	0.928	0.854	0.761	0.991	0.971	0.881	1.000	1.000	0.976
0.70	0.967	0.928	0.842	1.000	0.999	0.961	1.000	1.000	0.997
0.80	0.985	0.967	0.917	1.000	1.000	0.997	1.000	1.000	0.999
0.90	0.998	0.997	0.988	1.000	1.000	1.000	1.000	1.000	1.000
0.98	1.000	0.999	0.990	1.000	1.000	1.000	1.000	1.000	1.000

The size of the three tests does not indicate any problem with ρ values closer to the nominal level of 5%. With regard to the power, as was expected, the MI is the test which presents the best results. The power of the three tests improves when the value of the parameter (ρ) and/or the size of the lattice (n) increases.

Non linear processes

In this section, throughout Monte Carlo simulations, we undertake different experiments which introduce nonlinearities in the spatial dependence structure. To present our results, we classify the different designed DGP to include the non linear behaviour attending to three criteria: (i) inadequate specification of the weight matrix (W) (ii) parametric instability of spatial effects and (iii) transformation of the linear processes.

(i) Inadequate specification of the weight matrix (W)

The weight matrix (W) defined to evaluate the existence of spatial dependence in a process plays a fundamental role in the majority of the spatial dependence tests. In this sense, the specification of this matrix (W) used to be included in the null hypothesis (Pinkse, 2004). One of the most used specifications for the weight matrix (W) is the binary matrix. This matrix does not consider different degrees of intensity in the interrelations among the observations. Only in the case when W is row standardised is there a weighting effect generated by the number of neighbours. Our first approximation to the non linearity is to consider processes where the spatial dependence intensity changes in function of the distance. With the aim of introducing this characteristic, we consider DGP obtained from weight matrixes which introduce different number of neighbours with different weights among them, while the null hypothesis of independence is contrasted applying the matrix W_{4nn}.

The first DGP that we propose in this framework is the following:

$$DGP_1 : Y = (I - \rho W)^{-1} e \quad \text{with} \quad e \approx N(0,1) \text{ and } W = \left\{ w_{ij} = 1/d_{ij} \right\} \qquad (13)$$

Table 2a shows the values of the power of the three tests when the processes are generated according to DGP_1

A second case, in which the non linearity of the spatial interaction is related to an incorrect selection of the weight matrix W is generated when the matrix W has a huge level of connectivity. Therefore, our second DGP proposal is:

$$DGP_2 : Y = (I - \rho W)^{-1} e$$
$$\text{with } e \approx N(0,1) \text{ and } W = \left\{ w_{ij} = 1 \ if \ d_{ij} < Me(d_{ij}) \ and \ 0 \ otherwise \right\} \qquad (14)$$

where *Me* is the median.

In this case, the number of neighbours is different for each spatial unit and, therefore, the intensity of each region with the others is different. The results about the power of the spatial dependence tests when we use W_{4nn} to contrast the null hypothesis appear in Table 2b.

The third and last approximation to this case (i) is based on the inclusion of spatial dependence only in a reduced number of observations leaving the others without spatial dependence effects. To develop this proposal, we select any observation (k) and it is interconnected with its ten near neighbours $NN(k,10)$.

$$DGP_3 : Y = (I - \rho W)^{-1} e \quad \text{with} \quad e \approx N(0,1) \text{ and}$$
$$w_{ij} = \begin{cases} 1 \ \text{if} \quad i,j \in NN(k,10) \\ 0 \qquad \text{in other case} \end{cases} \qquad (15)$$

The results about the power of the tests appear in the Table 2c.

In the three non linear cases (Table 2abc), the power of the tests is lower than that obtained in the linear case (Table 1) although the decrease in the power is more noticeable for the MI and BP tests. The loss of power is explained by the generated mistake to contrast the null hypothesis because the given information is wrong due to the weight matrix used in the DGP (W) which is different to the weight matrix applied to evaluate the contrast (W_{4nn}).

Table 2: Nonlinear process under misspecification of W matrix

Table 2a: DGP_1

	$n=49$			$n=100$			$n=225$		
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.057	0.066	0.070	0.073	0.055	0.073	0.055	0.061	0.088
0.50	0.122	0.087	0.138	0.147	0.091	0.141	0.167	0.079	0.148
0.70	0.222	0.131	0.225	0.183	0.120	0.175	0.189	0.116	0.168
0.98	0.384	0.264	0.368	0.363	0.219	0.307	0.422	0.220	0.404

Table 2b: PGD_2

	$n=49$			$n=100$			$n=225$		
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.053	0.073	0.077	0.051	0.046	0.071	0.045	0.055	0.078
0.50	0.135	0.116	0.161	0.103	0.075	0.135	0.070	0.051	0.102
0.70	0.210	0.154	0.265	0.139	0.114	0.178	0.106	0.086	0.157
0.98	0.415	0.343	0.454	0.335	0.277	0.273	0.213	0.103	0.214

Table 2c: PGD_3

	$n=49$			$n=100$			$n=225$		
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.064	0.062	0.073	0.043	0.061	0.057	0.050	0.051	0.067
0.50	0.126	0.093	0.145	0.077	0.068	0.135	0.071	0.071	0.130
0.70	0.170	0.109	0.271	0.215	0.203	0.336	0.175	0.191	0.287
0.98	0.922	0.908	0.936	0.925	0.922	0.945	0.937	0.947	0.950

(ii) Parametric instability in the spatial dependence

An alternative way of introducing non linear spatial interaction structures is to suppose that the intensity of the interaction is different among spatial units. Following Mur et al. (2009), we account for DGP:

$$Y = (I - \rho HW)^{-1} e \quad with \quad e = N(0, \sigma^2 I) \quad and \quad H = diag(h_i; i = 1,...n) \tag{15}$$

Different specifications for the H matrix generate different spatial dependence structures. In our case, we consider some situations in which the non parametric and semi-parametric tests exceed the power of the MI test.

Our proposal consists of introducing spatial dependence in an two-step way, in such a way that the spatial dependence level is a function of some initial conditions. So, we associate the value of the ρ parameter to the value of the variable in each location throughout a two-step process,

- In the first step, a process without spatial structure is generated $e \approx N(0,1)$.

- In the second step, according to the expression (15) a spatial dependence structure is generated following the cases that we expose here

Case (i) $$h_i = \begin{cases} \rho & if \quad e_i \geq Q_3 \\ 0 & \text{in other case} \end{cases}$$

Case (ii) $$h_i = \begin{cases} \rho & if \quad e_i \geq Me \\ -\rho & if \quad e_i < Me \\ 0 & \text{in other case} \end{cases}$$

Case (iii) $$h_i = \begin{cases} \rho & if \quad e_i \in (Q_1, Q_3) \\ \text{-}\rho & \text{in other case} \end{cases}$$

Case (iv) $$h_i = 2\left|e_i^3\right| / \max_i \left|e_i^3\right|$$

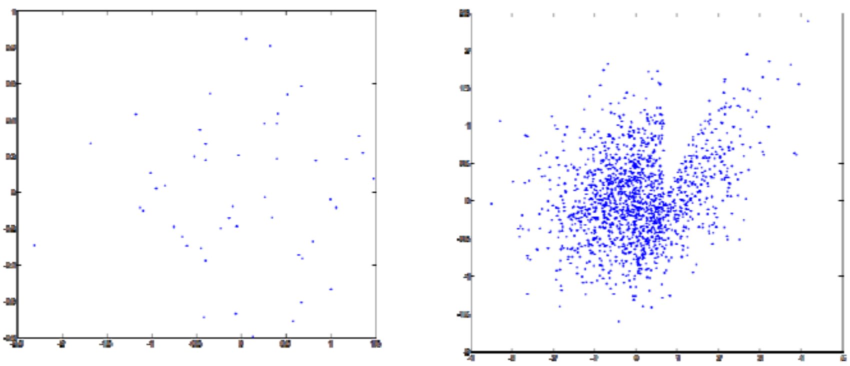
Case (v) $$h_i = \sin(\frac{\pi}{4} e_i)$$

Where e_i is the first-step process value and Q_k is the k-quartile of the observations obtained from the first step. Me is the e median.

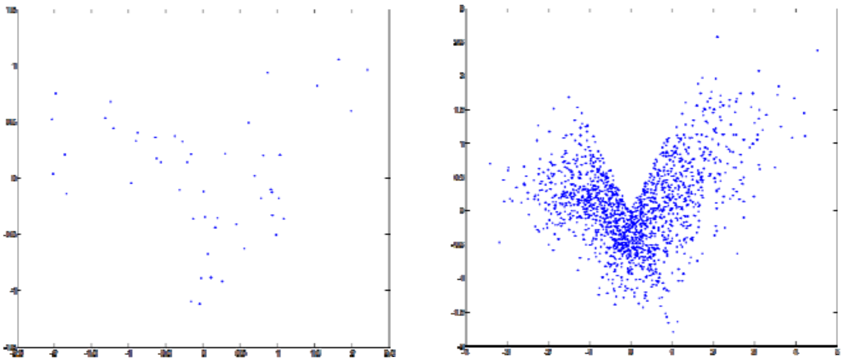
Figure 1 shows the scatter-plot $(Y, W_{4nn}Y)$ of a process generated for each of these cases for two sample sizes $n = 49$ and $n = 1600$. The spatial interaction structure is clearly non linear as we can see when the sample is large and there is a strong spatial dependence structure ($\rho = 0.8$). In the case of small size samples, there are hardly any spatial dependence symptoms despite maintaining the values of the parameter ρ.

Figure 1: Scatterplot $(Y, W_{4nn}Y)$ in GDP$_5$ with $\rho = 0.8$

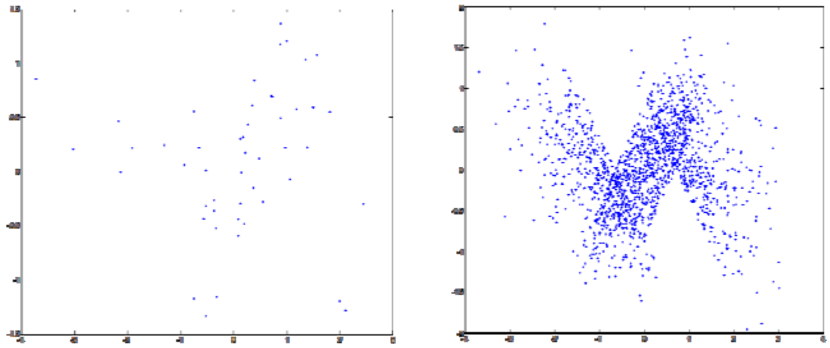
Matrix H	$n = 49$	$n = 1600$
$h_i = \begin{cases} \rho & if \quad e_i \geq Q_3 \\ 0 & \text{in other case} \end{cases}$		



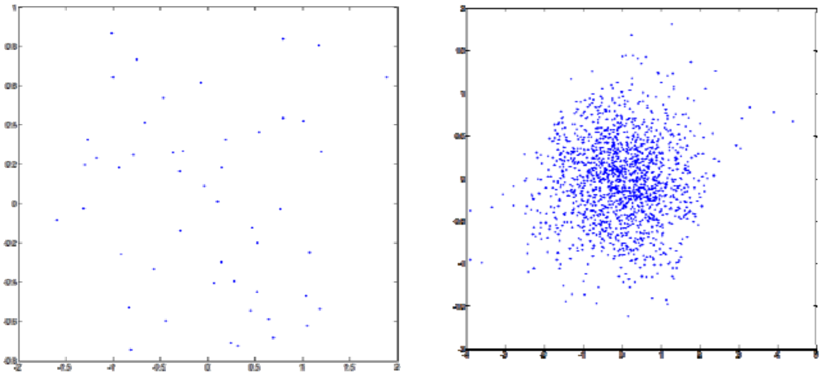
$$h_i = \begin{cases} \rho & if \quad e_i \geq Me \\ -\rho & if \quad e_i < Me \\ 0 & \text{in other case} \end{cases}$$



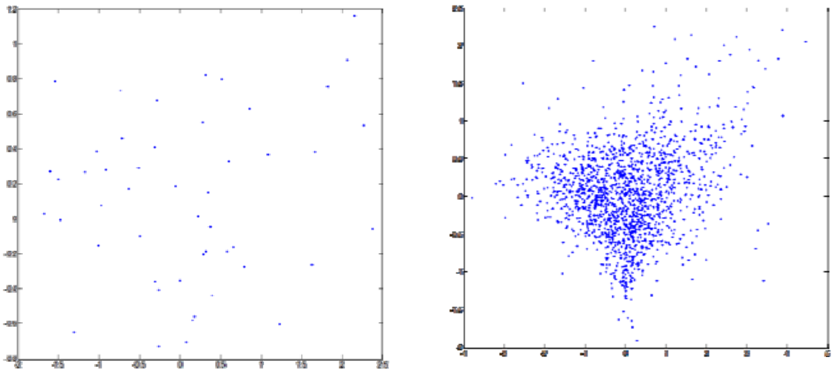
$$h_i = \begin{cases} \rho & if \quad e_i \in (Q_1, Q_3) \\ -\rho & \text{in other case} \end{cases}$$



$$h_i = 2\left|e_i^3\right| \Big/ \max_i \left|e_i^3\right|$$



$$h_i = \sin\left(\frac{\pi}{4} e_i\right)$$



The matrix by which the spatial dependence is included and contrasted is the same W_{4nn} weight matrix. Table 3 presents the results corresponding to the power of the spatial dependence tests in this case.

Table 3: Nonlinear process under instability spatial dependence. Discrete case.

Table 3a: $h_i = \begin{cases} \rho & if \quad e_i \geq Q_3 \\ 0 & \text{in other case} \end{cases}$

	$n=49$			$n=100$			$n=225$		
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.050	0.066	0.085	0.088	0.060	0.125	0.093	0.083	0.124
0.50	0.124	0.115	0.177	0.179	0.157	0.240	0.339	0.250	0.372
0.70	0.187	0.146	0.230	0.313	0.242	0.342	0.557	0.465	0.571
0.98	0.280	0.253	0.308	0.523	0.453	0.529	0.814	0.704	0.762

Table 3b: $h_{ii} = \begin{cases} \rho & \text{if } e_i > Me \\ -\rho & \text{if } e_i < Me \\ 0 \text{ in other case} \end{cases}$

	$n=49$			$n=100$			$n=225$		
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.049	0.090	0.088	0.053	0.110	0.136	0.045	0.149	0.145
0.50	0.089	0.337	0.239	0.115	0.549	0.305	0.154	0.860	0.503
0.70	0.128	0.519	0.319	0.212	0.852	0.501	0.310	0.991	0.754
0.98	0.221	0.752	0.456	0.370	0.973	0.713	0.630	0.999	0.911

Table 3c: $h_i = \begin{cases} \rho & if \quad e_i \in (Q_1, Q_3) \\ -\rho & \text{in other case} \end{cases}$

	$n=49$			$n=100$			$n=225$		
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.041	0.079	0.051	0.042	0.074	0.054	0.035	0.086	0.036
0.50	0.042	0.181	0.063	0.046	0.340	0.032	0.036	0.638	0.014
0.70	0.062	0.344	0.062	0.050	0.691	0.039	0.030	0.967	0.022
0.98	0.110	0.643	0.100	0.091	0.936	0.093	0.150	1.000	0.149

Table 3d: $h_i = 2\left|e_i^3\right| / \max_i \left|e_i^3\right|$

	$n=49$			$n=100$			$n=225$		
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.078	0.075	0.081	0.063	0.062	0.081	0.06	0.064	0.097
0.50	0.107	0.068	0.124	0.102	0.074	0.142	0.094	0.089	0.171
0.70	0.132	0.067	0.161	0.172	0.099	0.193	0.186	0.118	0.228
0.98	0.233	0.139	0.252	0.231	0.114	0.217	0.294	0.168	0.299

Table 3e: $h_i = \sin(\frac{\pi}{4} e_i)$

	$n=49$			$n=100$			$n=225$		
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.039	0.078	0.078	0.044	0.067	0.108	0.033	0.079	0.109
0.50	0.061	0.150	0.156	0.064	0.181	0.196	0.087	0.306	0.312
0.70	0.079	0.207	0.197	0.102	0.319	0.282	0.141	0.561	0.468
0.98	0.122	0.344	0.262	0.181	0.575	0.450	0.265	0.824	0.636

In all cases, the power of the MI test is lower than the values obtained in Table 1 and the non parametric ***BP*** and semiparametric ***Ku*** tests show better results. The selection of the matrix H functional form is determinant to locate in a better position the ***BP*** test than the ***Ku*** test.

(iii) Process transformations:

The transformation of a linear process is another alternative to introduce non linear spatial dependence structures. Following López et al. (2010), we explore two possible transformations of a SAR process:

(i) $Y = \exp\{-(I-\rho W)^{-1} e\}^3$

(ii) $Y = 1/\{(I-\rho W)^{-1} e\}^{1/3}$

Table 4 shows the power results for the three spatial dependence tests. While the MI test only presents high power values for large sample sizes with high spatial dependence values, the non parametric and semi-parametric tests give better results for more reduced sample sizes and moderate spatial dependence.

Table 4: Nonlinear process. Process transformations.

Table 4a: $Y = \exp\{-(I-\rho W)^{-1} e\}^3$

		$n=49$			$n=100$			$n=225$	
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.070	0.140	0.117	0.072	0.140	0.133	0.053	0.175	0.154
0.50	0.095	0.388	0.206	0.099	0.595	0.254	0.095	0.843	0.344
0.70	0.111	0.709	0.356	0.097	0.946	0.488	0.102	0.999	0.726
0.98	0.678	0.919	0.865	0.916	0.993	0.986	0.976	0.999	1.000

Table 4b: $Y = 1/\{(I-\rho W)^{-1} e\}^{1/3}$

		$n=49$			$n=100$			$n=225$	
ρ	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***	***IM***	***BP***	***Ku***
0.20	0.083	0.086	0.085	0.084	0.096	0.078	0.130	0.157	0.080
0.50	0.262	0.325	0.184	0.309	0.484	0.185	0.531	0.778	0.145
0.70	0.457	0.622	0.364	0.668	0.893	0.388	0.928	0.999	0.337
0.98	0.882	0.957	0.879	0.963	0.999	0.910	0.999	1.000	0.937

4. Empirical exercise: Production function with internal R&D

This section develops an empirical application where the spatial dependence tests are applied in an economic-theory-of-production scenario. Specifically, we consider the output of a firm, as a function of their traditional production factors (capital and labour) and we include the internal R&D effort as an additional input to explain the production values of each firm i (Tseng, 2008). Expression (16) shows this relationship:

$$Y = f(K, L, RD, i) \qquad (16)$$

where Y is the output measure of a firm and the inputs are physical capital (K), labour (L) and internal R&D (RD). We also consider that the production function is different for each firm i.

The usual way to model expression (16) is by considering a log form transform of the Cobb-Douglas specification,

$$\ln Y_i = a + \alpha \ln K_i + \beta \ln L_i + \lambda \ln RD_i + e_i \qquad (17)$$

where a is the constant term, the coefficients α, β and λ represent the output elasticity with respect to the capital, labour and internal R&D, respectively. Finally e_i is the error term.

In order to avoid biased estimations generated by possible heterogeneity into the sample, we include a break of our dataset by the firm´s size. Expression (18) shows the corresponding new specification of the model:

$$\begin{aligned} \ln Y_i = a + \alpha \ln K_i + \alpha' \ln(S_i K_i) + \beta \ln L_i + \beta' \ln(S_i L_i) + \\ + \lambda \ln RD_i + \lambda' \ln(S_i RD_i) + e_i \end{aligned} \qquad (18)$$

with S_i being a dummy variable which takes the value one for the big size[3] firms and zero otherwise.

4.1 Data and variables

All data comes from the Community Innovation Survey (CIS) for Spain computed by the Statistical Spanish Institute (INE). This is a survey which collects information on more than 40,000 Spanish companies, providing information on the structure of their innovation efforts and investments (R&D). Such a database is employed in most Spanish studies on innovation processes of companies, so we decided to use it in our empirical exercise, giving the traditional non linearity spatial features characterizing innovation processes (Autant-Bernard *et al*, 2007). Because CIS database does not collect information on the volume of capital stock in a firm, we get additional information from the SABI database (Sistema de Análisis de Balances Ibéricos). Merging both data sets together has also allowed us to obtain the companies' geographical coordinates which provide the necessary spatial dimension to the model.

To run our empirical application we have selected those manufacturing firms which have answered the CIS questionnaire from the years 2004 and 2006 (around 6,169 companies). Our study is focused on the manufacturing sector because the firms belonging to that sector have a higher probability of developing R&D activities, and therefore appearing interesting for our empirical exercise. Moreover, this type of firm

[3] Following the classification of the European Commission, we consider a firm with more than 250 employees as a big size (BS) company. A Small and Medium Enterprise (SME) is that employing up to 250 workers.

tends to be distributed in spatial clusters, so it seems more likely to find spatial dependence structures in the associated indicators of these industrial firms (see, i.e., Arbussa and Coenders, 2007; Harris and Li, 2008).

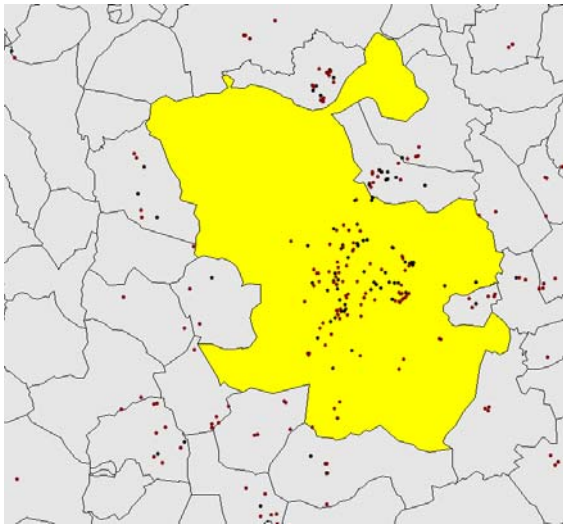
Additionally, and with the aim of making our results more informative, we estimate the model (18) for two regional groups of firms: those located in the municipality of Madrid and those in Barcelona (levels NUTS III, according to Eurostat nomenclature). Our final data set is then integer by one subset of 805 firms (142 with over 250 employees or BS companies) located in Barcelona and another subset with 330 firms (112 with over 250 employees-BS) being in Madrid, both with data over the period 2004-2006. Figure 2 shows the spatial distribution of these two sets of firms for both defined municipalities.

The variables required to estimate equation (18) are: (1) the input variable (PRODUCTION), which is measured as the total sales of each company. (2) Input variables: (a) CAPITAL (K) which is computed as the stock of net fixed assets of the firm and LABOUR (L) which is measured by the declared employee's number by company. All three variables are taken from the CIS database. We also include as an additional input our variable of interest, that is, the internal R&D ($RD_{i,t}$) expenditure of the firm. To employ this variable as a stock variable we apply the perpetual inventory method, something usual in this type of model (Tseng, 2008):

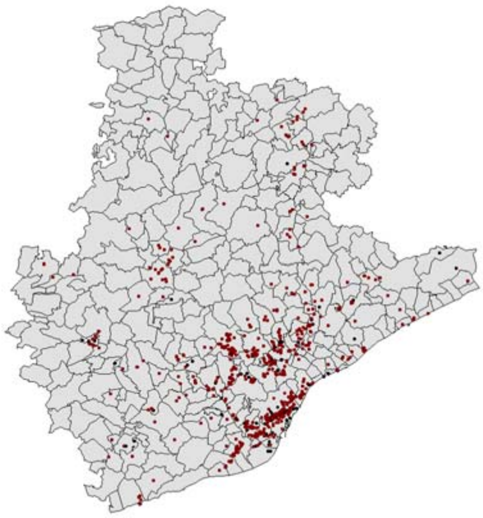
$$RD_{i,t} = RDE_{i,t} + (1-0,15)^2 RDE_{i,t-2} \tag{19}$$

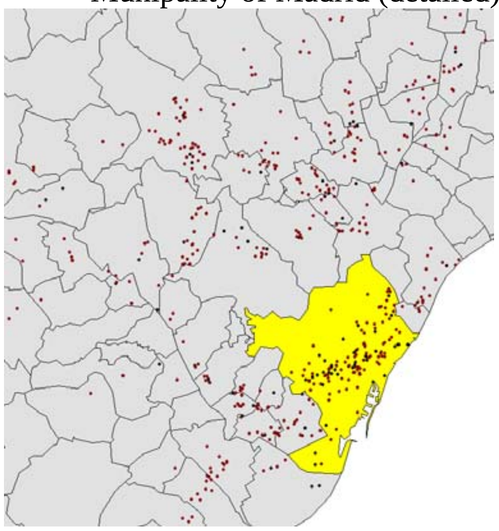
where $RDE_{i,t}$ represents the corresponding R&D expenditure of the firm i in period *t*. Expression (18) assumes that R&D expenditure affects the final R&D output ($RD_{i,t}$) with some delay, accounting for an annual depreciation rate of 15 per cent. Expression (19) has been approached using several specifications depending on the authors' preferences. In our case, we apply the one used most often, following the example of Hall (1997).

Figure 2: Firms' Spatial distribution in Madrid and Barcelona



Madrid | Munipality of Madrid (detailed)





Barcelona | Municipality of Barcelona (detailed)

Note: Red dots represent firms with less than 250 employees while black dots those with more than 250 employees

4.2 Results

We start estimating the model without space by Ordinary Least Square (OLS), then testing different hypothesis on the presence of spatial dependence in the residuals. Estimation results for the model are included in Table 6.

Regarding the OLS estimation, both the estimated coefficients are in line with literature. In general terms, for both Madrid and Barcelona, production output is determined by the capital stock, with major intensity in the SME establishments, and by employment. The contribution of employment to output, particularly in the case of Barcelona, does not seem to show differences between BS and SME, although employment is still an important element of the production function. In the case of Madrid the capital stock seems to be relatively less important for stimulating output growth for BS than for SME, while for labour the correlation seems to be the reverse, now showing major effects of labour on production for BS than for SME. Explanations for such differences include the role of Madrid as the “capital” of the country (Turner and Turner, 2011), and its major capacity for attracting BS, and more elaborate arguments linked to the debate about the rising importance of human capital and the descending relevance of traditional physical capital in (increasingly weightless and globalised) production processes (Leamer, 2007). Finally, the impact of expenditure in R&D activities does not seem to play a significant role for SME, but shows a very interesting role for BS in both locations, with a bigger coefficient and significance in the case of Madrid.

All the results appear to be congruent with previous findings in literature, showing an important role of R&D activities on the production side of that companies that are able to invest major amounts of resources in such activities (normally the BS companies). The smaller significance of this variable for SME is surely explained by the particularities of our sample, where the segment of small companies just accounts for 16 per cent of total expenditure in R&D in the case of Barcelona, and 10 per cent in that of Madrid, so total investments in R&D are practically linked to the segment of BS. In terms of the size of the estimated coefficients of the model, for both cities, all of them appear in line with previous findings in literature (see. i.e., Tseng, 2008).

Regarding the spatial diagnostic measures for both local estimations (Barcelona and Madrid) we find that the three employed tests (IM, BP and Ku) detect the presence of spatial dependence structures in the residuals of the OLS regressions. In order to compute the MI and the BP tests, we build a contiguity weight matrix (W) based on the four nearest neighbours criteria. According to test results the next step in our research is to estimate the model (18) by including a spatial dependence structure. In order to identify the adequate structure to be applied, we compute the Lagrange Multiplier (LM) tests. For both estimations, the RS-LE test appears as non significant, therefore, following Hendry’s methodology (Florax et al., 2006) we conclude that the spatial structure is better specified as a Spatial Error Model (SEM). Therefore, we re-run the estimation of the model (18) but now including a SEM structure. Results of this estimation are also included in Table 6. As we can see, for both samples, the spatial coefficient (ρ) appears positive and significant, showing the presence of a spatial dependence effect in our model (18).

Another important result is related to the appropriateness of spatial dependence tests to be applied in a non linear case as this is: IM, BP or Ku. Once we have modelled the spatial dependence structure, throughout a SEM specification, the MI test indicates that there are no traces of spatial dependence structures in the residuals of the SEM model (see Table 6), while the nonparametric (BP) and semiparametric (Ku) tests still continue pointing to the presence of such spatial effects, both rejecting the null of non space in the residuals with a high degree of significance. This result is similar for both geographical subsets of Madrid and Barcelona. Following further spatial tests conducted in our empirical exercise, such as complementary local spatial dependence measures, we observe that the failure of MI test would be explained by the existence of a non linear spatial process in the model specification of our production function. In this sense, the SEM specification allows us to capture some part of the spatial dependence structure (in a linear structure) present in the model, but it does not drop out the spatial structure in data completely, now distributed in a non linear pattern. Under this situation, the MI test is not as useful as the BP or the Ku test to detect the existence of an additional spatial effect in the residuals. This result highlights the need of applying new spatial dependence test, semiparametric or nonparametric ones, if we have to deal with non linear specification of economic models with spatial effects.

Table 6: Models Cobb-Douglas of productivity for Madrid and Barcelona

	MADRID				BARCELONA			
	OLS		SEM		OLS		SEM	
	Coeff.	*t-ratio*	*Coeff.*	*t-ratio*	*Coeff.*	*t-ratio*	*Coeff.*	*t-ratio*
a	3.273*	6.931	3.303*	7.040	2.941*	11.074	2.892*	10.895
α	0.698*	16.654	0.695*	16.796	0.756*	32.569	0.757*	32.859
α'	-0.135*	-2.991	-0.147*	-3.304	-0.065**	-1.773	-0.067**	-1.848
β	0.421*	6.926	0.426*	7.083	0.315*	10.130	0.315*	10.252
β'	0.103	1.054	0.120	1.239	0.029	0.306	0.042	0.456
λ	-0.005	-0.166	-0.005	-0.177	-0.013**	-0.777	-0.011	-0.652
λ'	0.115*	2.581	0.121*	2.774	0.062	1.951	0.058*	1.951
ρ			0.160*	2.275			0.169**	3.438
R^2-adj	0.937				0.933			
Log-Lik	-252.72		-247.39		-450.63		-436.99	

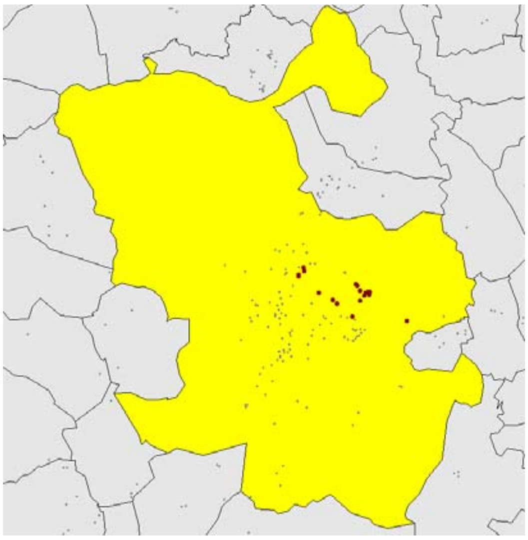
SPATIAL DIAGNOSTIC MEASURES

	Statistic	*p-value*	*Statistic*	*p-value*	*Statistic*	*p-value*	*Statistic*	*p-value*
IM	3.311	0.012	0.930	0.529	5.483	0.000	1.771	0.516
BP	8.635	0.002	2.968	0.035	33.894	0.000	11.972	0.000
Ku	14.855	0.004	10.701	0.040	15.344	0.040	11.345	0.022
LM-EL	10.217	0.001			29.274	0.000		
RS-EL	7.883	0.005			27.993	0.000		
LM-LE	3.528	0.060			1.457	0.227		
RS-LE	1.195	0.274			0.176	0.675		
LRCOM			6.224	0.514			5.211	0.735

* p-value<0.05; ** p-value< 0.10; LM-EL and LM-LE: Lagrange Multiplier tests for residual autocorrelation and omission of a spatial lag of the endogenous variable in the model. Respectively, robust to local specification errors in the null hypothesis (Anselin et al. 1996) RS-LE and RS-EL: Lagrange Multiplier tests for residual autocorrelation and omission of a spatial lag of the endogenous variable in SEM and SLM models, respectively (Anselin and Bera 1998). LRCOM: Likelihood Ratio test of common factors (Burridge. 1981). Log-lik: estimated log-likelihood.

Finally, it is possible to delve into the analysis of the spatial structure appearing in the residuals by means of the Ku test, which allows us to identify the existence of spatial clusters of firms. In this way, in the estimations for Madrid, the Ku test shows the existence of a set of 27 companies located in the North of Madrid responsible for such remaining spatial dependence pattern detected by Ku and BP tests. This subset of firms also presents an error average value of 0.50 in comparison with a global average value of 0.00 in the test results, showing that they are responsible for the remaining spatial structure in the estimated SEM model, that the MI test have not been able to capture. Figure 3 shows the specific location of these companies in the North of the municipality of Madrid. According to this result, our hypothesis is that the nonparametric tests are able to detect instability in the spatial dependence structure of the estimation output of the SEM model that we have not been able to observe if applying a simple spatial dependence parameter in the specification of the model.

Figure 3: Spatial Cluster of firms in Madrid



In the case of the estimation for Barcelona´s companies, results are not as clear as those of Madrid. For this last subset of firms, we just get two contiguity firms with residual average values significantly superior to zero (1.39). Moreover, we would like to point out that, according to this last analysis, the lack of linearity in our spatial model equation (18) could be provoked by the existence of outliers with spatial interactions effects of different intensities among firms (Mur and Lauridsen 2007).

5. Conclusions

Spatial econometrics studies have usually employed the linear regression framework when modelling socio-economic relationships in space, but recently we have assisted in a growing interest of the profession in developing new models for dealing with nonlinearities. Improving our understanding of how phenomena occur in a world clearly driven by non linear processes is the basis of that new academic focus. As a natural complement, new families of tests also become necessary, particularly those better enabled for a non linear world. In this paper we have evaluated the behaviour of the main type of tests employed when checking for the spatial independence assumption in the presence of nonlinearities: parametric, nonparametric and semiparametric. To reach this goal we have selected three representative proposals of each family of tests: the parametric I-Moran test, the nonparametric proposal of Brett and Pinkse (1997), namely the BP test, and a semiparametric test applied on epidemiology studies, the Kulldorff test or Ku test (Kulldorff et al., 2009).

In order to establish a comparison among these proposals, first we have generated different nonlinear spatial structures throughout Monte Carlo simulations, and second we have conducted an empirical exercise studying how R&D expenditures affect the production side of firms for two samples of manufacturing companies located in Madrid and Barcelona. Monte Carlo simulations have shown that the parametric MI test used to fail when the process under study adopted a non linear specification. This result emerges for nearly every simulated process. The ***Ku*** and ***BP*** tests have clearly shown greater power under this situation. Regarding the empirical exercise, we have found that in addition to the traditional production factors (capital, labour and R&D), including the spatial dimension in the production model plays a fundamental role in such location models. That result is in accordance with, for example, the New Economic Geography Theory, where introducing the role of geography appears to improve our understanding of economic facts dramatically. Usually our approach lies in the broader field of Spatial Econometrics literature. In this context, we find that usual linear structures applied in economic modelling exercises do not allow for accounting of spatial interaction effects among economic agents, individuals or firms, and also it is shown that it is necessary to take into account additional elements which could be generating non linear spatial dependence patterns. Among the different factors which could produce these behaviours are, the parametric instability in the spatial dependence which could be a key factor, as we have explored in our final exercise of the paper. In this context, nonparametric tools appear to be powerful tools in capturing and identifying such spatial structures present in data.

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