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Clusters of firms in space and time[1]

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Abstract: The use of the *K*-functions (Ripley, 1977) has become recently popular in the analysis of the spatial pattern of firms. It was first introduced in the economic literature by Arbia and Espa (1996) and then popularized by Marcon and Puech (2003), Quah and Simpson (2003), Duranton and Overman (2005) and Arbia *et al*. (2008). In particular in Arbia *et al*. (2008) we used Ripley's *K*-functions as instruments to study the inter-sectoral co-agglomeration pattern of firms in a single moment of time. All this researches have followed a static approach, disregarding the time dimension. Temporal dynamics, on the other hand, play a crucial role in understanding the economic and social phenomena, particularly when referring to the analysis of the individual choices leading to the observed clusters of economic activities. With respect to the contributions previously appeared in the literature, this paper uncovers the process of firm demography by studying the dynamics of localization through space-time *K*-functions. The empirical part of the paper will focus on the study of the long run localization of firms in the area of Rome (Italy), by concentrating on the *ICT* sector data collected by the Italian Industrial Union in the period 1920-2005.

Keywords: Agglomeration, Non-parametric measures; Space-time *K*-functions, Spatial clusters, Spatial econometrics.

JEL classification codes: *C21 · D92 · L60 · O18 · R12*

1. Introduction: The spatial-temporal analysis of clusters of firms

There is no question about the fact that the process of localization of firms in space is essentially a dynamic phenomenon. At the hearth of the observed spatial patterns of clustering or inhibition of firms, we always find considerations related to time, dynamics, lagged dependence and evolution. As a matter of fact we cannot study phenomena like firm demography, birth-death processes and growth in space by disregarding the time dimension. Yet in the literature the study of the clustering of firms in space and time have stubbornly followed two separated histories. On one side there is a long tradition of a substantial number techniques available for modelling clustering of firms in time based on purely time-series methods and on the analysis of business cycles (Hamilton, 1994). These techniques may assist in the identification of situations of time-concentration where we observe a higher number of new firms in some particular period due to cyclical movements or trends. On the other side research on spatial clustering of economic activities has only a more recent history and it is originated by a reinterpretation of Marshall's insights on 19th-century industrial localization operated by some authors in the nineties (e.g. Krugman, 1991; Fujita *et al*., 1999). Following these seminal works the empirical analysis of spatial clusters has developed along two distinct lines of

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research. The first was an attempt to examine directly the underlying economic mechanism, using the spatial dimension only as a source of data (see e.g. Ciccone and Hall, 1996; Jaffee *et al.* , 1993; Rauch, 1993; Henderson, 2003). The basic methodology here is that of a panel data or pure spatial regressions that employs observable covariates related to space (Arbia, 2006; Baltagi, 2008). The second line of researches attempts to characterize the spatial distribution of economic activities by observing the joint behaviour of the different units distributed across space (Devereux *et al.*, 2004; Duranton and Overman, 2005; Ellison and Glaeser, 1997; Ioannides and Overman, 2004). The reference methodology under this respect is that of the spatial point pattern analysis (Diggle, 2003). In particular in this field the use of the *K*-functions (Ripley, 1977) has become recently popular. First introduced in the economic literature by Arbia and Espa (1996) was then popularized by Marcon and Puech (2003), Quah and Simpson (2003), Duranton and Overman (2005) and Arbia *et al.* (2008). In particular Arbia *et al.* (2008) proposed the use of Ripley's *K*-functions as an instrument to study the inter-sectoral co-agglomeration pattern of firms in a single moment of time.

The analysis of clusters in space and time, thus, have followed so far two different roads and two separated methodologies with no interactions among them. Time series methods have generally disregarded the spatial dimension while spatial clustering models have been essentially static and they analysed just the outcome of the dynamic adjustments as it is observed in one single moment of time. This approach is obviously partial and doomed to leave without explanations a number of different empirical cases that may occur in practice. In fact new firms settlements may display no spatial concentration if we look separately at each moment of time and yet they may present a remarkable agglomeration if we look at the overall resulting spatial distribution after a certain time period. With respect to the contributions previously appeared in the literature, this paper attempts to unify the two approaches and to uncover the process of firm demography in a more comprehensive way by tackling it, both under a spatial and a under a temporal point of view, within a unified framework. This framework is provided by the theory of space-time *K*-functions.

In the epidemiological context, Diggle *et al.* (1995) have proposed an extension of the spatial univariate *K*-function (Ripley 1976 and 1977) to allow for the detection of space-time interactions in what was termed a *time-labelled spatial point pattern*. Our purpose is to introduce this statistical framework in the context of economic geography to study the interactions between the spatial and temporal distributions of firms. Specifically, we intend to test empirically the presence of space-time clustering of firms. Once the significance of space-time clustering phenomenon is assessed by using the space-time *K*-function approach, we will be in the position to test the presence of hypothetical spatial configurations like, e.g., leader-follower patterns or the presence of spatial segregation between 'old' and 'young' industries.

The structure of the paper is the following. In Section 2 we will introduce the methodological framework and we will present the theory of the space-time *K*-functions. To help the interpretation of the subsequent empirical analysis, in this section we will also describe some stylized spatial distributions of firms that may occur in empirical cases and the corresponding behaviour of the *K*-functions diagnostics. Section 3 will be devoted to the empirical part of the paper by first introducing the working dataset based on the spatial distribution of *Information Technology and Communication* (*ICT*) firms in the area of Rome (Italy) collected by the Industrial Union in the period 1920-2005. It will also contain the empirical application of the models presented in Section 2 based on this dataset. Section 4 contains the discussion of the results and the analysis of their economic implications. Finally Section 5 contains some concluding remarks and directions for future developments in this field.

2. The statistical methodological framework

2.1 Space-time K-function analysis

Economic events, such as the establishment of new firms, may occur at different points in space and time. As a consequence, in order to study the geographic concentration of industries, we should control for the temporal dynamics that characterize the localization processes. Accordingly, we need to explore the possibility that the spatial and temporal phenomena, producing the observed pattern of firms at a given moment of time, interact to provide space-time clustering. This requirement can be performed referring to a statistical test about the independence between the spatial distribution and the temporal distribution of firms. In the case of dependence, the geographic pattern of firms is characterized by the presence of space-time interaction meaning that such a pattern cannot be explained only by static factors, but we should also consider the dynamic evolution of the spatial concentration phenomenon.

Univariate spatial *K*-functions (proposed by Ripley 1976 and 1977) have been already used in the economic literature to detect the geographical concentration of industries (see e.g., Arbia and Espa 1996; Marcon and Puech 2003; Quah and Simpson 2003). They can be exploited in a dynamic context by analysing separately the spatial and the time clustering pattern. However a more comprehensive approach refers to the analysis of both dimensions simultaneously thus paying attention also to the space-time interactions. In this paper we will consider a dynamic extension of the univariate *K*-functions proposed and fully described in Diggle *et al.* (1995). In what follows we will present a brief account of the theory of space-time *K*-functions. The symbolism and definitions are in accordance with those used in Arbia *et al.* (2008) to which the reader is referred for the simple, purely spatial, *K*-function.

Generally speaking, the technique involves the comparison between the observed spatial-temporal point pattern and a theoretical pattern that has the same temporal and spatial properties as the original data, but no space-time interaction (Diggle *et al.*, 1995; French *et al*., 2005). In this context an auxiliary information is associated to every observed spatial point in the form of the time of occurrence. Under the assumption of stationarity and isotropy (Diggle, 2003; Arbia, 2006), we can build the space-time *K*-function:

$$\lambda_{DT} K(d,t) = E\{\text{\# of points falling at a distance and a time respectively } \leq d \text{ and } t \text{ from an arbitrary point}\}$$

(French *et al.* 2005), with $E\{\cdot\}$ indicating the expectation operator and the parameter λ_{DT} representing the spatial and temporal joint intensity of the point process, i.e. the number of points per unitary area and per unit time. If the processes working in time and space are independent (that is if there is no space-time interaction) the functional $K(d,t)$ should be equal to the product of the spatial and temporal *K*-functions $K_D(d)K_T(t)$ (Diggle *et al*., 1995), where $K_D(d)$ and $K_T(t)$, are defined, respectively, as follows:

$$\lambda_D K_D(d) = E\{\text{\# of points falling at a spatial distance} \leq d \text{ from an arbitrary point}\}$$

and

$$\lambda_T K_T(t) = E\{\text{\# of points falling at a time interval} \leq t \text{ from an arbitrary point}\}.$$

In the previous expressions λ_D represents the spatial intensity, that is the number of points per unitary area. In a similar fashion λ_T denotes the temporal intensity, i.e. the number of points per unit time. The meaning of a univariate spatial *K*-function ($K_D(d)$) is well known (see Ripley, 1977 and Arbia *et al.*, 2008 for economic interpretation). They suggest visually if the firms tend to concentrate significantly in some portions of the study area rather than in others. Purely temporal *K*-function ($K_T(t)$) are not treated in the statistical literature and help in identifying if in the observed time series a significantly higher number of firms is concentrated in some periods rather than in others.

In the case of no space-time interaction, we might theoretically expect that $K(d,t) = K_D(d)K_T(t)$ (Diggle *et al.*, 1995; Gatrell *et al.*, 1996). The product functional $K_D(d)K_T(t)$, in fact, represents the expected *K*-function under the hypothesis of absence of space-time interaction and can be used as a reference for comparison with the observed space-time *K*-function, $K(d,t)$.

Turning now to the estimation aspects, considering a univariate 'time marked' point map, we can define the estimators of the three component processes (i.e. $K(d,t)$, $K_D(d)$ and $K_T(t)$) by close analogy to those suggested in the unmarked univariate case (Ripley, 1977; Diggle, 2003).

To start with, let us consider the space-time *K*-function that is, as we mentioned above, the expected number of points within a spatial distance *d* and a time interval *t* of an arbitrary point, scaled by the expected number of points per unitary area and per unit time. Diggle *et al.* (1995) have shown that a proper edge-corrected estimate of $K(d,t)$ from an observed 'time marked' point pattern with *n* observations can be the following:

$$\hat{K}(d,t) = \frac{AT}{n^2} \sum_i \sum_{j \neq i} \frac{I_d(d_{ij}) I_t(t_{ij})}{w_{ij} v_{ij}}$$

where *A* is the total surface of the area and *T* is the whole observed span of time. In addition the terms d_{ij} and t_{ij} represent, respectively, the spatial distance and the time interval between the *i*th and *j*th observed points. Finally $I_d(d_{ij})$ and $I_t(t_{ij})$ represent indicator functions assuming the value 1 if $d_{ij} \leq d$ and $t_{ij} \leq t$, respectively, and 0 otherwise.

Due to the presence of spatial and temporal edge effects (which might potentially distort the estimates close to the boundary of the area *A* and to the time limits of *T*) the adjustment factors w_{ij} and v_{ij} are introduced. The weight function w_{ij} expresses the proportion of the circumference of a circle centred on point *i*, passing through the point *j*, which lies within *A* (Boots and Getis, 1988). By analogy, the factor v_{ij} refers to whether a time segment centred on *i*, of length t_{ij}, lies entirely within the observed total duration time, between 0 and *T* (Diggle, 2003; Diggle *et al.*, 1995; Gatrell *et al.*, 1996).

Referring to the same statistical framework, the edge-corrected estimators of the spatial and temporal *K*-functions, $K_D(d)$ and $K_T(t)$ are defined, respectively, as:

$$\hat{K}_D(d) = \frac{A}{n^2} \sum_i \sum_{j \neq i} \frac{I_d(d_{ij})}{w_{ij}}$$

(Boots and Getis, 1988; Diggle, 2003) and:

$$\hat{K}_T(t) = \frac{T}{n^2} \sum_i \sum_{j \neq i} \frac{I_t(t_{ij})}{v_{ij}}$$

(Diggle *et al.*, 1995; Bailey and Gatrell, 1995). As already said, when there is no space-time interaction we have that $K(d,t) = K_D(d)K_T(t)$. As a consequence one possible exploratory tool for the independence between the processes operating in time and space is the functional:

$$\hat{D}(d,t) = \hat{K}(d,t) - \hat{K}_D(d)\hat{K}_T(t) \qquad (1)$$

(Gatrell *et al*., 1996). This functional is proportional to the increased numbers of points within spatial distance d and time interval t with respect to a process which possesses the same temporal and spatial characteristics, but no space-time interaction. As a consequence, the presence of space-time interaction might be revealed in the appearance of peaks on the 3-dimensional surface of $\hat{D}(d,t)$ plotted against the spatial distance and the time sequence.

Diggle *et al.* (1995) and French *et al.* (2005) have proposed a transformation of (1) which allows for the possibility of working with relative quantities rather than absolute numbers. This is defined as:

$$\hat{D}_0(d,t) = \hat{D}(d,t) / \{\hat{K}_D(d)\hat{K}_T(t)\} \tag{2}$$

Expression (2) is proportional to the relative increase in points within spatial distance d and time interval t with respect to a process with the same temporal and spatial characteristics, but no space-time interaction. Similarly to $\hat{D}$, the functional $\hat{D}_0$ can be plotted in a 3-dimensional graph versus d and t to help the visualization and the detection of interdependence between the spatial and temporal processes.

2.2 Some stylized space-time distributions

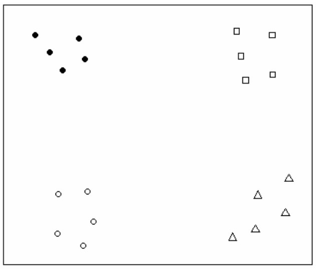
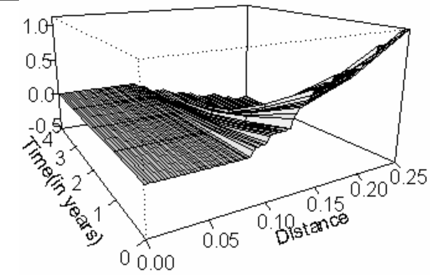
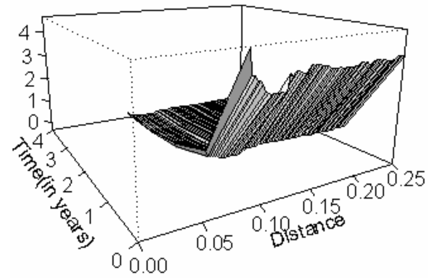
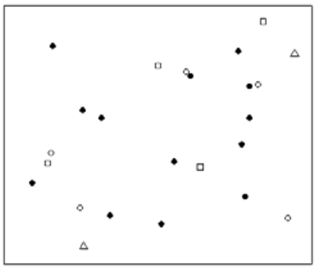
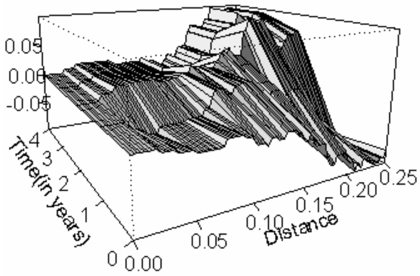
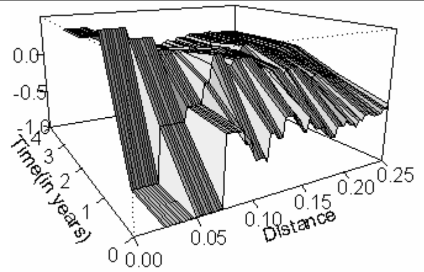
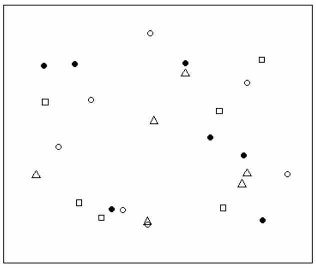
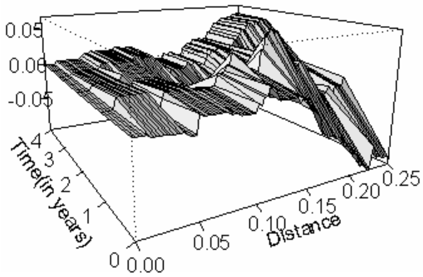
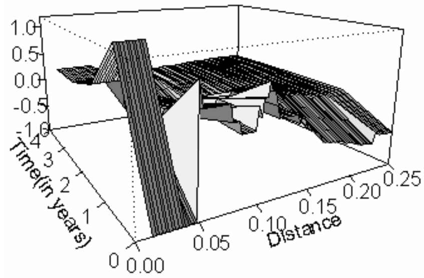
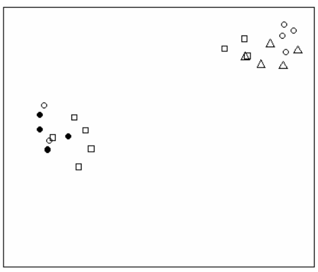
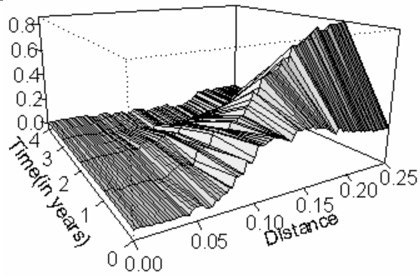
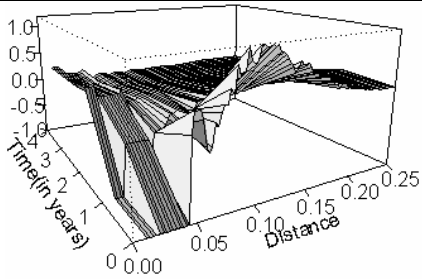
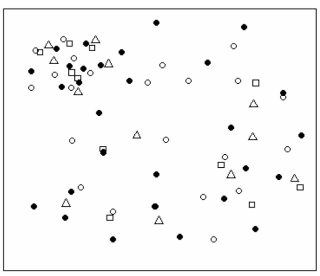
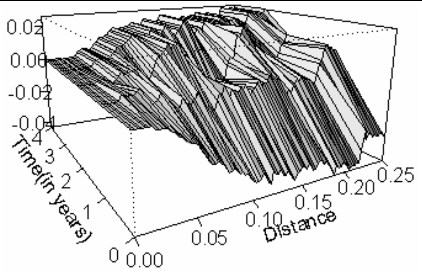
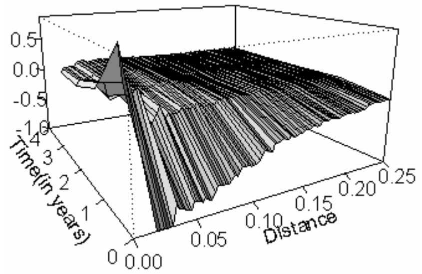
Before moving to presenting the important aspects related to the inferential evaluation of space-time interaction, in this section it is useful to present some stylized situations that may occur in empirical cases when observing the spatial distribution of firms. The exam of these extreme, paradigmatical, situations and the analysis of the corresponding behaviour of the K functionals, will help the interpretation of the functionals $\hat{D}(d,t)$ and $\hat{D}_0(d,t)$ in the empirical situations that will be analysed in Section 3.

Figure 1 reports some theoretical spatial distributions of firms and the corresponding diagnostic plots. These could be used as benchmark to be compared with in the empirical situations that may occur in practical instances. Of course these are but a few examples and certainly they do not exhaust all the cases that may be found in practice. The distributions reported in column a) of the figure are stylized simplified arrangements used to clarify five extreme situations. The graphs reported in columns b) and c), in contrast are obtained with simulations based on a larger number of points.

Notice that time dynamics in these examples is partially masked by the fact that we do not consider the death of firms, but only the process of new firm creation.

Case i) refers to the instance of clustering in space with no clustering in time and no space-time interaction. The map appears with a strong visual impression of clustering in each time period, but the number of newly born firms is constant over time (see the different time symbols in the maps), thus displaying no time concentration. The situation is represented by a flat $\hat{D}_0(d,t)$ function in the time direction and a peak at distance 0.06 in space. Case ii) refers to the opposite situation where we do have clustering in time, but no clustering in space and no interaction. In this case the visual impression is that of spatial randomness both in each time period taken individually and as a whole, but the number of firms in some periods is significantly higher than in others with, in particular, a strong concentration of new firms in the first time period. This situation is revealed in the graph c) with a peak of the $\hat{D}_0(d,t)$ function in time at lag 2 and an (almost) flat function on the spatial axis. Case iii) refers to the case of no space, no time clustering and, as a result, no interaction and has an appearance of no clustering in space with new firms that are created randomly in the different time periods. The $\hat{D}_0(d,t)$ function here is flat in both the space and time direction.

Figure 1: Some theoretical spatial arrangements of firms in space and time (column a) and the corresponding $\hat{D}(d,t)$ (column b)) and $\hat{D}_0(d,t)$ plots (column c)).

a) Spatial distribution	b) $\hat{D}(d,t)$ function	c) $\hat{D}_0(d,t)$ function
 Case i) *p*-value Test Montecarlo: 0.443		
 Case ii) *p* -value Test Montecarlo: 0.104		
 Case iii) *p* -value Test Montecarlo: 0.477		
 Case iv) *p* -value Test Montecarlo: 0.001		
 Case v) *p* -value Test Montecarlo: 0.401		

NOTES: Case i: Spatial clustering, no time clustering, no space-time interaction
Case ii**:** No spatial clustering, time clustering, no space-time interaction
Case iii**:** No spatial clustering, No time clustering, no space-time interaction.
Case iv**:** Spatial and time clustering and space-time interaction.
Case v: Spatial and time clustering, no space-time interaction.

Legend

Symbol	Year
●	1
□	2
○	3
△	4

For the meaning of the *p*-value Monte Carlo test see the discussion in Section 2.3. *p*-values larger than 0.05 refer to non significant space-time interaction.

Case iv) considers the instance where points are clustered both in time and space with an interaction between the two dimensions. Graph a) presents points that are highly agglomerated in space if observed in each individual time period and also if we look at all points jointly disregarding the different time markers. In this graph it is also evident a strong time concentration with a higher number of new firms created in the second time period. Finally Case v) considers the situation where points are clustered both in time and space, but there is no interaction between the two dimensions. Observing each year individually produces a visual impression of clustering, however looking at the whole map without distinguishing between the different time periods the visual impression is that of randomness. There is also a considerably high degree of time concentration with a higher number of new firms created in the first time period. This situation was generated artificially considering the product of the two marginals *K*-functions in space and time separately.

Obviously any substantive conclusions on the prevailing spatial and time pattern cannot be based merely on the visual inspection of the graphs and they need a more grounded validation based on inferential tools. These tools will be introduced in the following section.

2.3 Inference

In the present section we will introduce an inferential framework in order to formally assess the significance of the empirically observed values of $\hat{D}(d,t)$. However, since the exact distribution of the functional *D,* is unknown, its variance cannot be evaluated theoretically and no exact statistical testing procedure can be adopted. To overcome this aspect Diggle *et al.* (1995) suggested to obtain a significance test by exploiting a Monte Carlo approach. In the quoted paper the authors suggested to perform *m* simulations, where at each step the *n* geographical points are marked at random with the observed *n* time 'markers'. Having thus obtained *m* simulated spatial-temporal point patterns, we can thus compute *m* different estimates of $\hat{D}(d,t)$. We will refer to these estimates with symbol $\hat{D}_i(d,t)$, $i=1,\dots,m$. The observed variance of these *m* estimates, say $\hat{V}(d,t)$, can be reasonably used as an estimator of the variance of $\hat{D}(d,t)$ (Gatrell *et al.*, 1996). Having made these definitions, we can now introduce the set of "standardized residuals" as

$$\hat{R}(d,t)=\hat{D}(d,t)\Big/\sqrt{\hat{V}(d,t)}. \tag{3}$$

It is better to clarify that the term "standardized residual" is the one used in the literature, as suggested by Diggle *et al.* (1995), and refers to the ratios between the observed values of $\hat{D}(d,t)$ and its estimated standard deviation, Equation (3). However it has nothing to do with the meaning assigned to this term in regression analysis. In practice, it represents the excess number of points of $\hat{K}(d,t)$ with respect to $\hat{K}_D(d)\hat{K}_T(t)$, and it is a measure of space-time interaction. In the absence of any space-time interaction, these residuals have zero expectation and a variance equal to one. Therefore, an appropriate inferential method to test if the spatial and temporal processes are independent on one another consists in plotting the graph associated with Expression (3) against $K_D(d)K_T(t)$. If there is no space-time interaction then approximately 95% of the values of $\hat{R}(d,t)$ would lie within two standard errors (French *et al.*, 2005). The interpretation of the $\hat{R}(d,t)$ plot is not always straightforward. In fact it could be masked by the fact that the residuals could be strongly dependent. In addition to this test, an further overall Monte Carlo testing procedure of space-time clustering have been suggested. It consists in taking the actual observed sum of the functionals $\hat{D}(d,t)$ over all *d* and *t* and make a comparison with the empirical distribution of the *m* analogous sums of $\hat{D}_i(d,t)$ over all *d* and *t*, with $i=1,\dots,m$. A particularly high value of the observed sum among the values of this 'artificial' distribution would constitute an evidence of overall space-time interaction. For example, as Gatrell *et al.* (1996) pointed out, if the observed sum is ranked above 95 out 100 simulated values, then the probability that the observed space-time interaction occurred by chance is less than 5 per cent.

3. The use of space-time *K*-functions in the analysis of the long run dynamics of firms: the case of *ICT* industries in Rome (Italy) 1920-2005

3.1 Data description

The empirical part of this paper focuses on a set of micro data on the firms of the *ICT* sector in the area of Rome. This dataset has been collected over a fairly long period ranging from 1920 to 2005 by the Industrial Union of Rome. The datasets reports the full address and the year of establishment of the 169 industries currently operating in the area thus disregarding those that were born in the period considered, but that did not survive until the present year. The *ICT* industries are further classified into two groups: *Electronic and communication* (*C*) and *Information Technology* (*IT*). In our database there are 66 firms belonging to the first group and 103 belonging to the second group. Table 1 reports the time evolution of the sector in the 85 years considered in terms of the number of firms born in each decade. It is evident the slow development of the sector until the early eighties and the more pronounced increase in the birth of new companies in the eighties and in the nineties. The dynamic is very similar for the *Electronic and Communication* and the *Information Technology* sectors.

Table 1: Frequency distribution of the number of firms by year of establishment

	Number of firms		
Years of establishment	(1) Electronic and Communication	(2) Information Technology	(3) *ICT* = (1) + (2)
1920-1960	5	0	5
1961-1970	5	1	6
1971-1980	4	10	14
1981-1990	15	30	45
1991-2000	29	37	66
2001-2005	8	25	33
Total	66	103	169

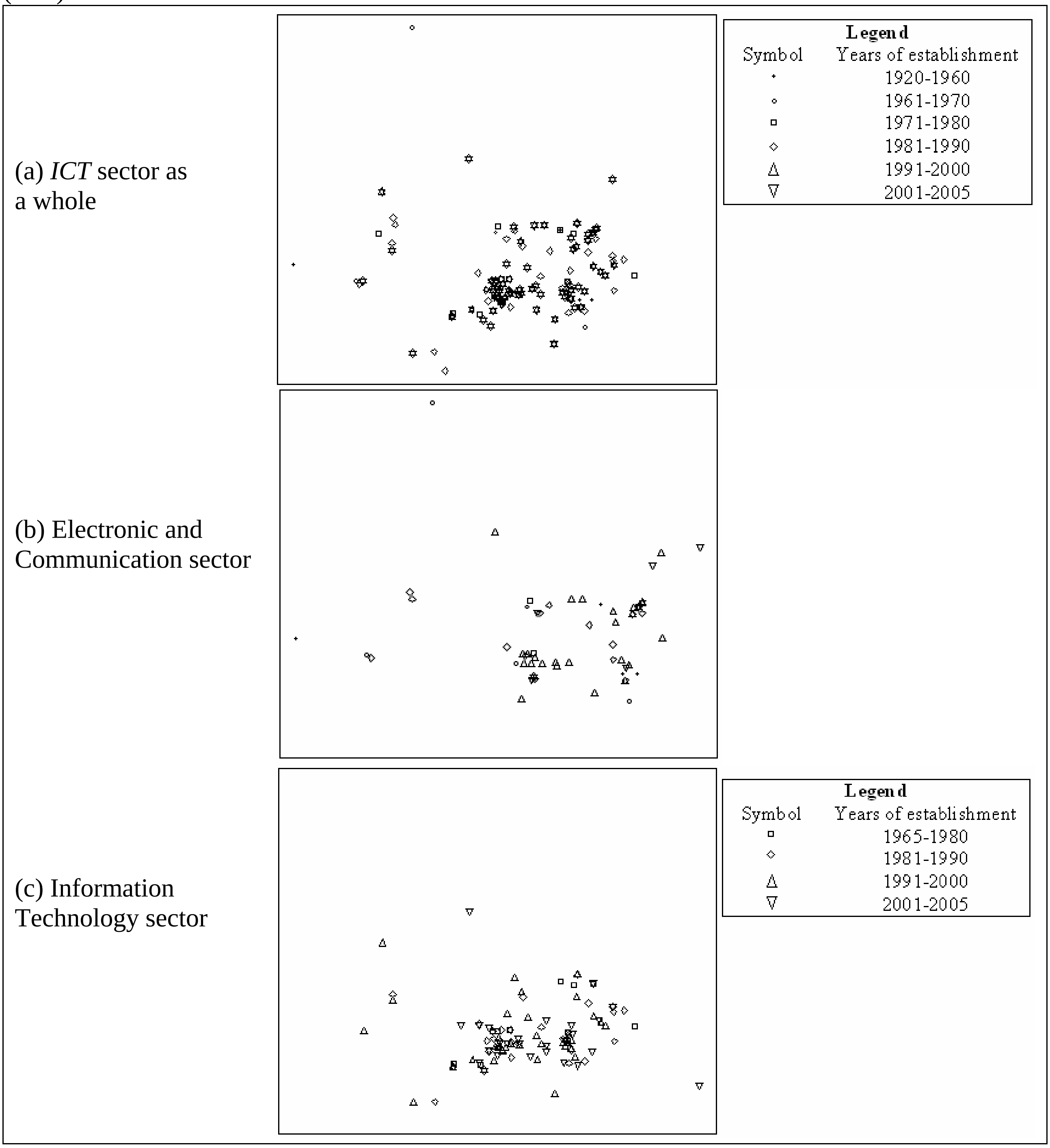
The spatial distribution of the 169 firms of the *ICT* sector is reported in Figure 2, which also provides an idea of the dynamics by marking with different symbols firms born in the different decades. Data are available at the finest level of time and spatial resolution, having in hand the full address and the exact date of registration of them, and it is only for the purpose of illustration that they have been temporally grouped into decades in Table 1 and Figure 2.

Figure 2 (a) reports the spatial distribution of the whole *ICT* sector. It is clear from a first visual inspection of the graph that data display a marked tendency to cluster by concentrating in some specific portions of space, namely the South of the area and particularly in the central part of it. Different graphical symbols are used to illustrate the temporal dynamics. However in Figure 2 (a) the number of points is too large to identify any definite time pattern so that it cannot be easily identified on purely visual considerations and requires further and more sophisticated analysis. The tendency to cluster is rather different in the two groups. By looking at the different graphical symbols, in the case of Figure 2 (b), due to the limited number of points that are reported (66), we can also notice a certain tendency of firms to locate in space nearby industries existing in previous time periods thus revealing evidence of space-time interaction.

This preliminary descriptive analysis clearly indicates that the observed pattern is characterized by a distinctive spatially and temporally localized process, but with different features in the two groups of firms that need further investigation.

The visual inspection adds further scope to the space-time analysis in that it emphasizes the interest to test whether the spatial and temporal distributions are dependent and if there is any space-time interaction. This aim will be accomplished by the next section.

Figure 2: Spatial location and time evolution of the Location of 66 firms of *ICT* sector in Rome (Italy), 1920-2005. Source: Our computations on the data provided by the Industrial Union of Rome (UIR).



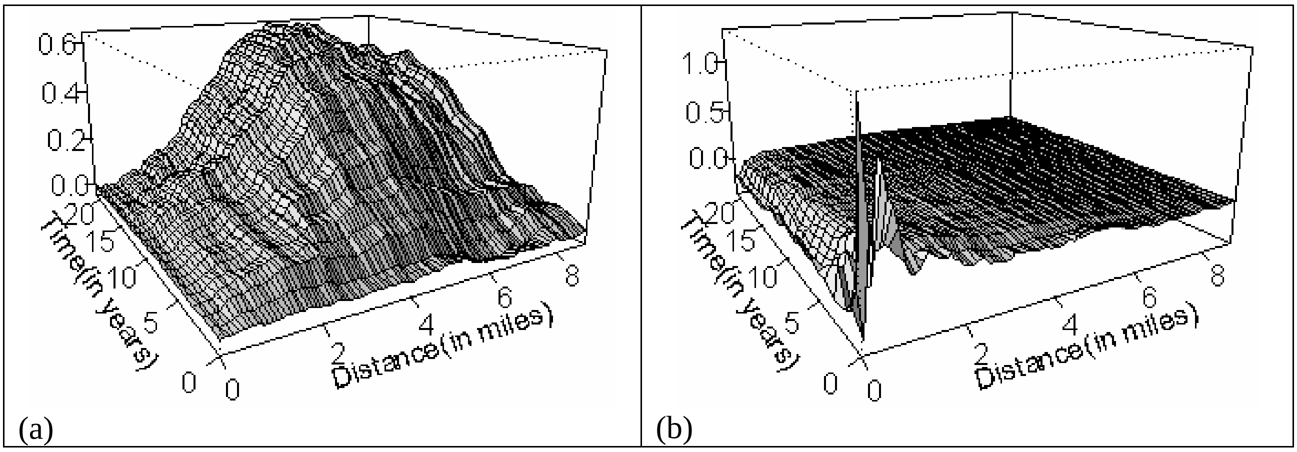
3.2 Analysis of the K-functions

3.2.1 Analysing the distribution of the ICT sector

Figure 3 reports the plot of the space-time *K*-functions[4] computed for the 169 firms of the whole *ICT* sector, as a function of both space and time. In particular, Figure 3 (a) reports the absolute functional $\hat{D}(d,t)$ where the spatial distance ranges between 0 and 9 miles (9 being one forth of the maximum possible distance in the graph) while the temporal lag ranges between 0 and 21 (21 being one fourth of the time span that is 85 years). This limitation is due to the corrections that are needed in order to minimize the distortions induced by border effects (see Haase, 1995; Goreaud and Péllissier, 1999; Arbia *et al.* , 2008).

The exam of Figure 3 (a) clearly suggests the presence of space-time clustering, but the extent of such phenomenon is not noticeable because of the range of computed values of $\hat{D}(d,t)$ is too narrow. In order to investigate more formally this space-time effect of interdependence, we also computed the relative functionals. Figure 3 (b) reports the plot of $\hat{D}_0(d,t)$ (see Equation (2)). From the graph it is evident a peak at the short spatial distances (around the zero) and at a temporal interval of one and a second peak at distance of approximately 1 mile and a time lag of 5 years. This shows that the underlying concentration phenomenon tends to drive clusters with a small spatial magnitude (circles with radius of 1 mile) and where the firms are temporally correlated in terms of year of establishment.

Figure 3: 3-dimensional plot of the (a) $\hat{D}(d,t)$ function and (b) $\hat{D}_0(d,t)$ function for the *ICT* sector as a whole.

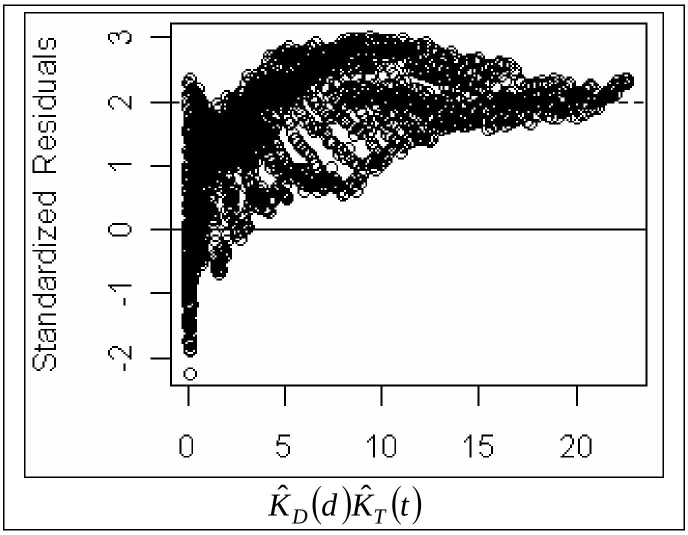


To evaluate this result more formally under an inferential point of view, a set of 999 simulations was performed, permuting at random the time 'markers' attached to every point, thus allowing us to plot the standardized residuals against the product of the separate spatial and temporal *K*-functions (Figure 4). As we have mentioned in Section 2, in the case of no space-time interaction the standardized residuals are expected to have zero mean and unitary variance.

In the empirical case examined, we can clearly see that a relatively large number of estimated residuals lays above 2 standard errors (corresponding to 34.5% of cases), providing support to the hypothesis of interaction between the spatial and temporal component processes. However, because of the, potentially strong, interdependence amongst the estimates $\hat{R}(d,t)$ for different values of *d* and *t*, this diagnostic plot cannot be considered particularly robust.

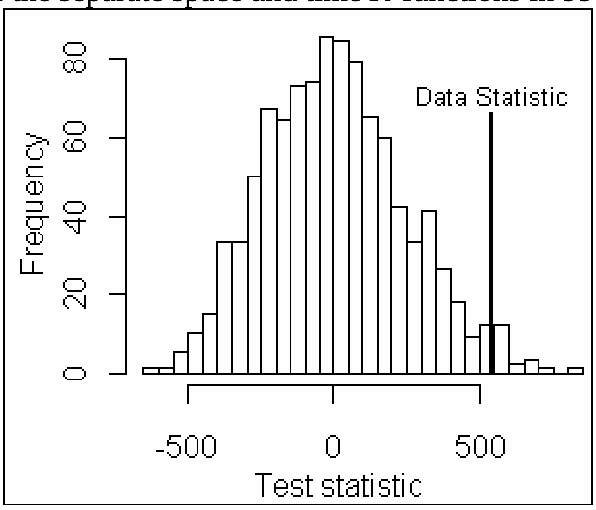
[4] All the computation of the *K*-functions and the related analysis were implemented using the SPLANCS library (Rowlingson and Diggle, 1993) available in the R software.

Figure 4: Plot of the estimated standardized residuals of $\hat{R}(d,t)$ against $\hat{K}_D(d)\hat{K}_T(t)$ for the *ICT* sector.



For this reason, in order to test the statistical significance of the results reported in Figure 4, a Monte Carlo test of space-time clustering was performed. Figure 5 displays the frequency distribution of the sum of the differences between the space-time *K*-function and the product of the separate space and time *K*-functions as they occurred in the 999 simulations. The sum of such differences in the observed dataset ranked 998 out of 1000. Therefore, the empirical *p*-value of the test is 0.002, thus providing formal evidence for the space-time clustering situation described by the plot of $\hat{D}_0(d,t)$. In other words, in the Rome area, the firms belonging to the *ICT* sector tend to agglomerate at a relatively small geographic distance and, moreover, the clusters are constituted by firms that were established with a strong dynamic component.

Figure 5: Empirical frequency distribution of the sum of the differences between the space-time *K*-function and the product of the separate space and time *K*-functions in 999 simulations. *ICT* sector.

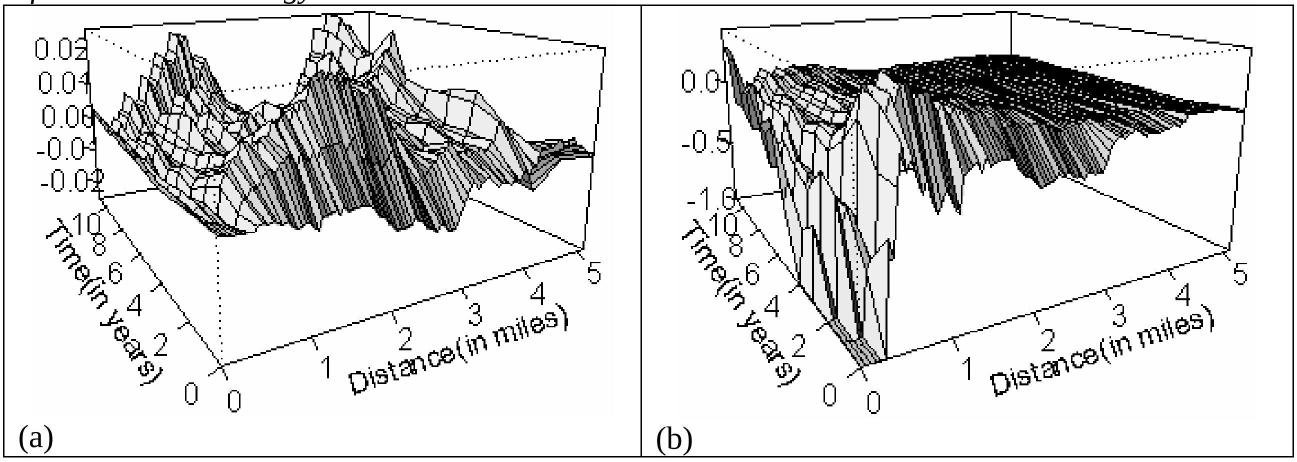


3.2.2 Disaggregated analysis of the two groups "Information Technology" and "Electronic and Communication"

As already said the *ICT* sector is constituted by two groups, namely *Information Technology* and *Electronic and Communication*. In this section we wish to analyse the concentration pattern and its dynamics of the two groups separately.

To start with Figure 6 reports the plot of the absolute and relative D functionals for the group of firms belonging to the *Information Technology* group of industries.

Figure 6: 3-dimensional plot of the (a) $\hat{D}(d,t)$ function and (b) $\hat{D}_0(d,t)$ function for the *Information Technology* sector.



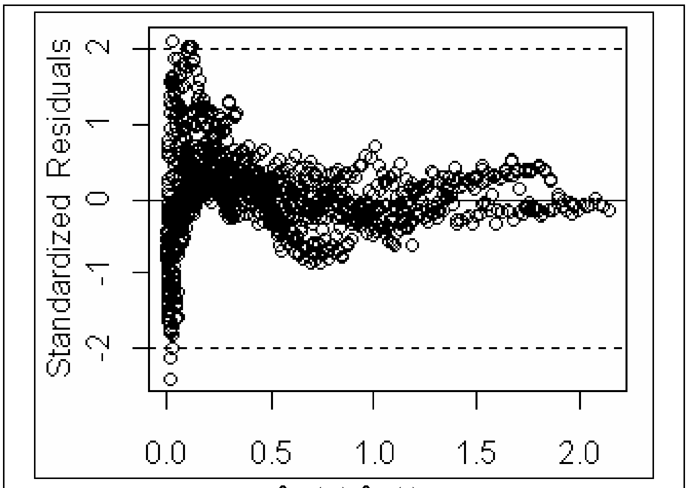
The visual features of this graph are rather different from those observed for the *ICT* sector as a whole (see Figure 3). In fact, the $\hat{D}_0(d,t)$ functional displays a rather less marked spatial clustering and a negative time one (graph below the zero line in the time direction). More specifically Figure 6 (a) displays the plot of $\hat{D}(d,t)$ where, in order to manage the edge effects, the spatial distance and the temporal lag range, respectively, between 0 and 5 miles and 0 and 11 years. Although the graph evidences some peaks in the surface of the functional, their magnitude is small. Indeed, the higher positive peak reaches a value of 0.025 and analogously the lower negative extremity is –0.025. As a consequence, this does not support the hypothesis of significant space-time interaction.

On the other hand, the plot of the relative functional $\hat{D}_0(d,t)$ (Figure 6 (b)) might suggest the presence of a weak space-time segregation phenomenon (downside peaks) within a short spatial distance and a temporal lag of approximately 4 years. These characteristics, in turn, are evidences of a tendency to locate in space and time further away from the existing firms. However, as already done before, these visual considerations need to be supported by a more formal statistical testing procedure. In order to obtain this, we start by looking at Figure 7 that reports the plot of the estimated standardized residuals of $\hat{R}(d,t)$ against $\hat{K}_D(d)\hat{K}_T(t)$ for the *Information technology* group.

Figure 7 shows that most of the residuals (99.5% of points) lay within the ± 2 standard deviations. Thus the diagnostic test of residuals shows that the observed tendency to segregation is not substantive. Therefore the space-time segregation phenomenon, observed when commenting on Figure 6, is not substantial and it is only apparent.

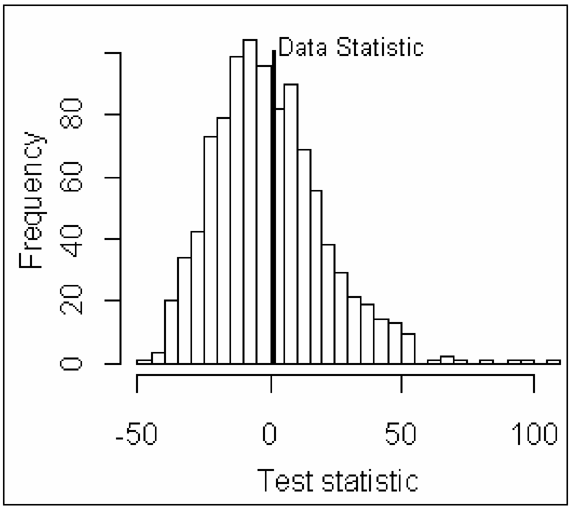
This conclusion is corroborated by the Monte Carlo test for space-time interaction. To run a formal Monte Carlo test of randomness, Figure 8 reports, as before, the sum of the differences between the space-time *K*-function and the product of the separate space and time *K*-functions as they occurred in the 999 simulations. This sum in the observed dataset ranked 576 out of 1000. Therefore, the empirical *p*-value of the test is 0.424, thus providing formal evidence for the space-time randomness in the plot of $\hat{D}_0(d,t)$ and supporting the fact that the weak negative interaction between the spatial and temporal component processes is occurred by chance and is not driven by a systematic underlying phenomenon. As a consequence, even if in the Rome area the *ICT* industries as a whole tend to be clustered both in space and time, those belonging to the *Information* *technology* group present spatial agglomeration in each time period, but no significant interaction between space and time. This behaviour is similar to the stylized fact presented in Figure 1 case v).

Figure 7: Plot of the estimated standardized residuals of $\hat{R}(d,t)$ against $\hat{K}_D(d)\hat{K}_T(t)$ for the *Information Technology* group.



$\hat{K}_D(d)\hat{K}_T(t)$

Figure 8: Empirical frequency distribution of the sum of the differences between the space-time *K*-function and the product of the separate space and time *K*-functions in 999 simulations. *Information technology* group.



Let us now move to comment on similar graphics and test for the *Electronic and Communication* group. Figure 9 reports the plot of the space-time *K*-functions computed for the 66 *Electronic and Communication* industries observed in the area of Rome. Again, as in Figure 3, we find evidences of a space-time clustering at short distances with a peak around zero distance and at a temporal interval of 1. The *Electronic and Communication* firms therefore, display a similar pattern to that observed for the *ICT* industries considered as a whole.

Figure 10 reports the standardized residuals originated by 999 random permutations of the industrial sites plotted against the product of the separate spatial and temporal *K*-functions. A high share of the residuals (46.5%) lays above the 2 standard deviations line supporting the hypothesis of dependence between the spatial and temporal component processes and the significance of the considerations made on the previous graph.

Finally Figure 11 displays the frequency distribution of the sum of the differences between the space-time *K*-function and the product of the separate space and time *K*-functions in the 999 simulations. The sum of such differences in the observed dataset ranked 993 out of 1000 leading to an empirical *p*-value of 0.007, and hence providing a probabilistic significance to the previously observed space-time clustering pattern.

Figure 9: 3-dimensional plot of the (a) $\hat{D}(d,t)$ function and (b) $\hat{D}_0(d,t)$ function for the *Electronic and Communication* group.

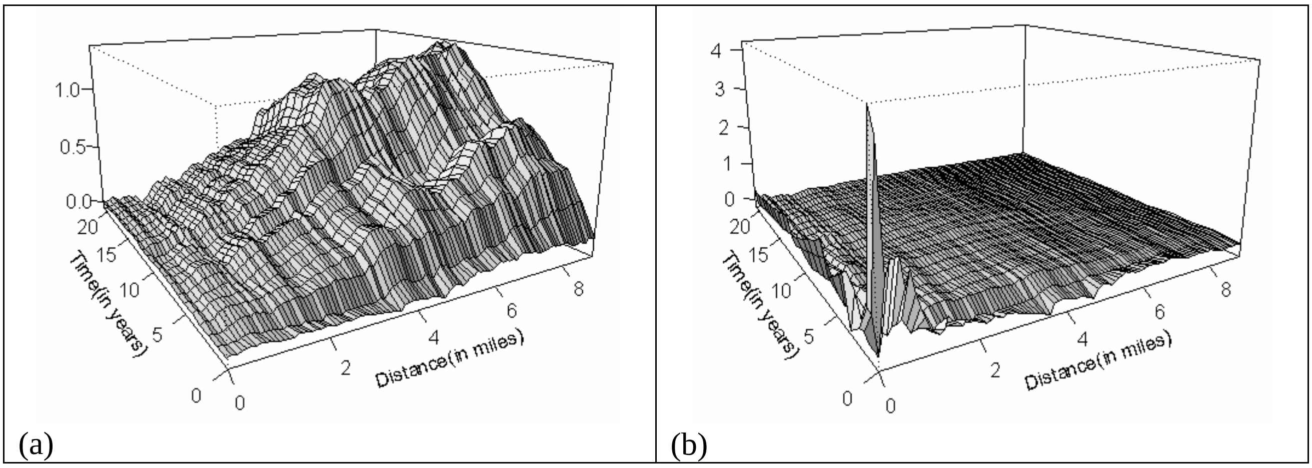
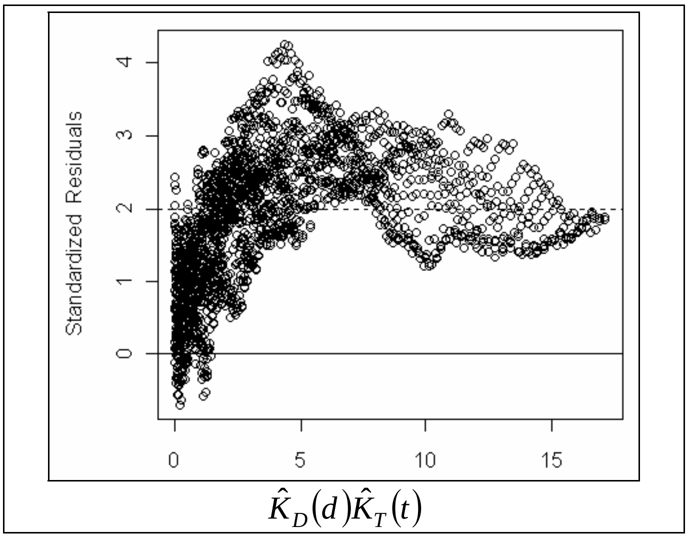


Figure 10: Standardized residual plots of $\hat{R}(d,t)$ against $\hat{K}_D(d)\hat{K}_T(t)$ for the *Electronic and Communication* sector.

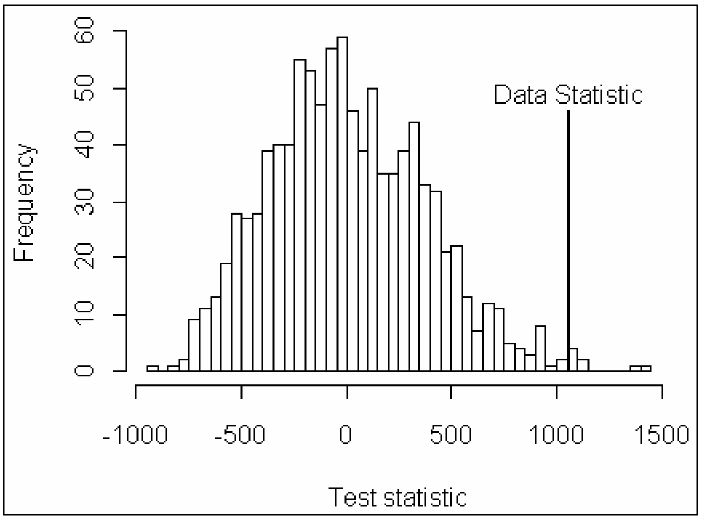


Summing up, the *Information technology* and the *Electronic and Communication* groups have a different spatial behaviour. *The Information technology* industries tend to locate in space with no remarkable space-time interaction. Conversely the *Electronic and Communication* companies tend to display a marked agglomeration pattern both in space (at small distances) and time. This dynamic effect is so strong that it is the one that dominates if we look at the *ICT* sector as a whole.

4. Discussion and analysis of the economic implications

The previous empirical findings clearly display a different spatial pattern in the distribution of firms belonging to the *Information technology* and those belonging to the *Electronic and Communication* groups within the *ICT* sector. The observed clusterized process for the sector as a whole is mainly due to the very strong agglomeration pattern displayed by the industries belonging to the *Electronic* *and Communication* group, while the *Information technology* companies do not display any significant tendency to space-time interaction in the formation of clusters. As a matter of fact the industries belonging to the *ICT* sector are quite heterogeneous and they display different managerial and organization behaviour. In fact, the industries belonging to the *Information technology* group located in our study area are mainly branches of medium-large multinational companies (the name are not reported here for privacy reasons). These enterprises have in mind a network that is global rather than local. Thus, in their locational choices they mainly tend to be present in the big metropolitan areas (basically Rome and Milan in Italy), rather than distribute in the entire territory. This global network manifests itself mainly in the form of the *global city* described by Sassen (1994), that is more with the aspect of a production process than as a place in the conventional meaning: a process in which geography plays a very limited role and where the production and the consumption centres are interlinked on the basis of information flows and no more on the basis of physical flows between the geographical space. The advent of a new, high-tech, manufacturing industry assisted by computers and microelectronics, led to a new logic in the localization processes. Historically the *Information technology* industries were those that started this new form of spatial location based on information. Such a location pattern is characterised by the technological and managerial ability to split the production process into different places and to integrate them subsequently through telematic links (Castells, 1996). The irregular spatial distribution of activities that is thus produced was already observed empirically by, e.g., Gordon (1994) who also noticed how the new distribution (which is determined more by information than by geography) produced also, as a by-product, a new spatial division of labour, characterized by *variable geometries* and by reciprocal links between industries that are located within spatial agglomerations (those that are termed *innovation milieu*; see Camagni, 1991; Castells, 1996).

Figure 11: Empirical frequency distribution of the sum of the differences between the space-time *K*-function and the product of the separate space and time *K*-functions in 999 simulations. *Electronics and Communication* group.



With these premises one may think that in the *ICT* market the only driving force is what Cairncross termed the *death of distance* (see Cairncross, 2001) that is the phenomenon of a space-time compression generated by the possibility of communicating in real time with any point in the world as if everything took place in just one single, dimensionless, point (see also Quah, 1993). However the realization of a production process of this kind requires a direct and physical interaction among entrepreneurs, managers and specialized workers that are in charge of integrating competences that are very different on one another.

This behaviour could be at the basis of the observed space-time clustering pattern in the Rome area for the *Electronic and Communication* industries and for the *ICT* firms as a whole despite the distribution with no space time interaction observed for the *Information technology* group.

In other words the *ICT* industries, rather than totally eliminating the relevance of space in their location decisions, increase the need for a spatial concentration of some activities that contribute to the dispersion of other activities and are in support of the integration among them (Sassen, 1994).

5. Conclusions and research priorities

In this paper we have introduced in the economic literature a set of tools, proposed in the spatial statistical literature, to analyse simultaneously the spatial arrangements of firms, their temporal trends and the interactions between the spatial and temporal components of growth. These tools are based on the family of *K*-functions and fall within the realm of the so-called *marked point pattern analysis.* They were introduced, in an epidemiological context, in the seminal work of Diggle *et al*. (1995) and, to our best knowledge, it is the first time that they are used in the regional sciences.

In the empirical part of this paper we have shown that the space-time *K*-function explorative tools are appropriate instruments to uncover the process of firm demography, both under a spatial and a temporal point of view thus being able to treat trends and cycles in time and spatial agglomeration phenomena within the same methodological framework. In particular we have applied the proposed methodology to the analysis of the space-time distribution of the *ICT* firms in the area of Rome in the time period between 1920 and 2005.

In this respect we obtained the following substantial findings:

- *ICT* firms considered as a whole tend to display a marked tendency to agglomerate in space and, furthermore, the process of firm creation in time presents a significant space-time interaction. New firms thus tend to be created in the neighbourhood of the existing one.
- A very similar and significant pattern is detected for the subgroup constituted by only the *Electronic and Communication* industries.
- In contrast, the subgroup constituted by only the *Information Technology* firms presents a distinctive feature with respect to the whole *ICT* sector. While presenting a (less marked) tendency to agglomerate in space likewise the *Electronic and Communication* and *ICT* industries, they do not display any significant space-time interaction. The process of firm creation in time thus follows a dynamic that is independent from the spatial location of existing firms.

While presenting the theoretical and the empirical results, in this paper we aimed at making it clear the usefulness of the proposed methodology. Once the presence of a specific space-time interaction phenomenon has been detected, the researcher is in the position to model specific hypotheses concerning the geographical and dynamical configurations of economic activities. Under this respect there are many possible questions that can be addressed using the proposed methodology that we plan to tackle in some future studies. We review some of them here below while describing the limitations of the examples reported in the present work and, in this way, delineating the future agenda in the field.

A first advance with respect to the work presented here is represented by the extension of the analysis to the inter-type *K*-function approach proposed by Lotwick and Silverman (1982) and applied in an economic context by Arbia *et al.* (2008). This tool enables us to detect more into depth the complex space-time processes that may occur in practice. For instance, by categorizing the point process in terms of year of establishment, we could test whether phenomena of geographic segregation or aggregation between ‘old’ and ‘young’ firms occur, hence indicating the presence of specific leader-follower patterns. In addition we could test the co-agglomeration dynamics between different sectors.

The space-time *K*-functions used in the present context are built under the basic assumption of stationarity and isotropy of the underlying generating process (Diggle 2003; Arbia 2006). In other words, the geography of firms is considered substantially observed on a homogeneous space. This in turn implies that we do not consider the possible presence of physical or administrative limits that could introduce strong constraints in the locational choices of firms. As a consequence, one of our future research priorities will consist in removing this assumption that is often violated in an economic context. We argue that possible methods to disentangle spatial heterogeneity and spatial aggregation phenomena could be based on the integration of inhomogeneous *K*-functions (Baddeley *et al*., 2000) in a space-time perspective. A second possible approach to tackle the problem of heterogeneity could consist in removing the potential heterogeneous sub-areas from the initial study area, thus obtaining a homogenous map. However this solution is not entirely satisfactory because it introduces extra complexity by leading the researcher to analyse irregular polygonal surfaces rather than rectangular areas as it happened for instance in the present context. As a consequence the analysis should also include methods for correcting edge effects when computing space-time *K*-function in study areas of complex shape (see Goreaud and Pélissier, 1999).

A further limitation of the present study consists of the fact that, for a correct analysis of firm demography, we should consider not only the process of birth of new firms, but also the process of growth of the existing ones and the space-time dynamics of the firms that cease their activity in the span of period considered (see e.g. Arbia *et al*., 2009). Under this respect in the present context we did not take into account the aspects of firm growth and we totally neglected in our analysis the firm dimension (as measured, e.g., by the number of employees or the value added). However, when studying the pattern of industrial agglomeration, the firm dimension is of paramount importance in that a pattern of increased agglomeration of firms can be equally due to a higher number of firms concentrating in the same area or, alternatively, to the firms expanding their dimension. In contrast, in the present context we considered each economic activity in space as a dimensionless point so that what we have detected here was the mere geographic concentration of firms and not the more general concept of industrial agglomeration suggested, e.g., by Duranton and Overman (2005). An important step forward in the analysis of firm clustering in space and time will be constituted by removing this strong limitation and by considering marked point patterns where the marks refer not only to different time periods (as it is done in the present context), but also to different firm dimensions. A final point refers to the consideration of the death of the existing firms, an aspect that was also left aside in the present paper. While a correct approach to firm demography should consider jointly the process of firm creation and that of firms ceasing their activity, under the methodological point of view this adds extra complexity in that the spatial pattern and the interaction between space and time, should be evaluated separately in each time period and not as the resulting process at a given moment of time as we did here when analysing the empirical data on the *ICT* firm distribution in Rome. Methodological tools should be developed in future researches to overcome this further limitation.

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