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Abstract

This paper introduces a new measure to approach the accessibility of places in the frame of the digital economy. Information and Communication Technologies (ICTs) and the Internet are not equally spread around places and this heterogeneity affects spatial configuration. Despite the wide societal changes due to ICTs and the extensive interest in accessibility studies, these two themes have not yet come together in order to study the digital accessibility (DA) of places. Adopting an infrastructural perspective and a potential accessibility framework, a DA measure – embedding different types of impedance distance functions – is calculated for cities in Europe. Spatial Interaction Model and Complex Network Analysis are employed to calibrate and validate the DA results. The outcome of this approach is a new urban hierarchy which reveals a core-periphery pattern in Europe owing to digital accessibility.

Keywords: digital accessibility, Internet geography, potential accessibility, impedance functions

1. Introduction

This paper introduces a new concept for the accessibility of places in the frame of the *digital economy* based on a conventional potential accessibility measure. Starting in the late 1940s, scholars studied the way individuals and aggregates of individuals respond to the constraints of cost, time, and effort to access places, individuals, and other spatially-distributed opportunities (Couclelis & Getis, 2000; Couclelis, 2000). A common component of the various different accessibility concepts is the easiness to reach opportunities: while Hansen (1959) defines accessibility as the potential of opportunities for interaction, Morris et al. (1979) approach accessibility as the ease with which activities can be reached from a certain location; in a more general way, Couclelis (2000) reinforces the concept of accessibility as the geographic definition of opportunity, while Reggiani et al. (2011a, 2011b) link it with spatial structure effects and notions such as network connectivity.

Regardless of the substantial literature on accessibility, research on accessibility has not yet incorporated questions related to the rapid increase in information and communication technologies (ICTs). Exceptions include the rather conceptual, but also empirical, proposals found in the volume edited by Janelle and Hodge (1998) and the graph oriented approach by Wheeler and O'Kelly (1999). The novelty of this paper is the amalgamation of *opportunities* for virtual interaction and the *cost* to reach the opportunities in the digital economy. ICTs have impacted heavily on the spatial configuration, and led Castells (1996) to develop his ideas about this new spatial organization identified as the *space of flows*. ICTs affect spatial configuration as a result of their friction reducing character, and their ability to reduce the cost of distance (Cohen et al., 2002; Cohen-Blankshtain & Nijkamp, 2004).

This lack of interest is not surprising, as it reflects the rather limited attention ICTs attract from the wider field of economic geography and spatial economics because of their technical and intangible nature. Indeed, both economic and urban geography usually deal with tangible objects, contrary to the elusive and complex technical nature of telecommunications, and specifically the Internet (Bakis, 1981; Hepworth, 1989; Kellerman, 1993). After all, telecommunications infrastructure only becomes visible when it stops working (Star, 1999). In addition, the lack of – freely accessible – relevant secondary data has also discouraged researchers in entering this research field.

However, there is scope for the above-mentioned disciplines to include research questions regarding the geographic effects of new technologies, and, consequently, the accessibility of places from a *digital* perspective: ICTs, in general, and the Internet, more specifically as the broader telecommunications platform, are not a unique system evenly scattered regardless of core or periphery (Gorman & Malecki, 2000). Geographic location affects the Internet connectivity and the speed at which data can be transmitted and received, because of the uneven spatial allocation of the Internet's physical infrastructure across space (Malecki & Moriset, 2008). This might not be visible from the end-user point of view, but, at an aggregated meso – metropolitan and regional – level, the allocation of the Internet infrastructure, such as vast and redundant international and local Internet links and peering locations, can affect the location advantage. The concentration of digital infrastructure in specific locations may influence the economic development of these areas, as it will provide better access to the digital economy, affecting the competitiveness at the micro- and the macro- level: through efficiency and effectiveness effects, Internet infrastructure can result in cost reduction and revenue increase for corporations; and through connectivity effects and the endowment of location factors it can impact the accessibility and the attractiveness of territories (Camagni & Capello, 2005). Put simply, the Internet infrastructure can both result in attracting new firms (Cornford & Gillespie, 1993) in a city which can exploit such infrastructure (financial firms, back-office activities, creative industries) and increase the productivity of existing firms. Additionally, such infrastructure might also result in higher quality digital services for end-users.

Our conceptual and empirical proposal of a digital accessibility (DA) measure builds upon the well-established parallel between transportation and ICT networks. On a first level, both perform infrastructural roles: the Internet transports the valuable weightless goods of the digital economy in the same way transportation networks transport the industrial goods (O'Kelly & Grubesic, 2002;

Moss & Townsend, 2000). Similarly, while transportation infrastructure reduces the transaction costs on trade in goods, telecommunications infrastructure lowers the transaction costs of trading information and ideas (Cieślik & Kaniewska, 2004). However, the importance of knowledge creation needs to be highlighted here, which is related with personal interaction. The latter can be subdivided in two components: the conversation and the handshake, with the former being the metaphor for simultaneous real-time interactive visual and oral messages, and the latter representing the physical co-presence. ICTs can lower the cost of the conversation component (Leamer & Storper, 2001), but also facilitate physical spatial interaction. This discussion is reflected in the different types of relation between transport and ICTs identified in the literature (Salomon, 1986; Banister & Stead, 2004; Mokhtarian, 1990, 2002; Cho & Mokhtarian, 2007): substitution (reduction, elimination), complementarity (stimulation, generation), modification (change time, mode, destination, etc.), and neutrality (no impact of one medium on the other).

At a more technical level, both ICTs and transportation share topological similarities, as both are usually rolled out as spatial networks (e.g. Gorman & Malecki, 2002; O'Kelly & Grubesic, 2002; Wheeler & O'Kelly, 1999). Both consist of nodes and edges, and both of them can be analyzed using network techniques (Malecki & Gorman, 2001). Table 1 presents this analogy: the backbone links, which are the highest tier networks of the Internet physical infrastructure symbolize the motorways; the Internet Exchange Points (IXP) and Points of Presence (POP), which are the points where different networks exchange data – a process known as peering – and final users gain access to the global network, represent the transport nodes (interchanges and access nodes); the Metropolitan Access Network (MAN) and the local loops symbolize the intra-city roads; and the Internet Protocol (IP) addresses denote the numerous final destinations in the cities – the Internet real estate according to Dodge and Shiode (2000).

Table 1: The parallel between the Internet physical infrastructure and the road infrastructure

Importance at:	**Internet infrastructure**		**Road infrastructure**
Inter-city level	Backbone networks	↔	Motorways
	IXP / private peering points	↔	Interchanges
	POP	↔	Access nodes
Intra-city level	MAN / local loops	↔	Intra-city road networks
	IP addresses	↔	Premises

The above supports Couclelis and Getis's (2000) findings that recent technological and societal developments require the re-conceptualization of the notion of accessibility at all scales, as ICTs have radically changed and expanded the scope for notions such interaction and accessibility (Janelle & Hodge, 2000). More specifically, Dodge argues about the need to expand the notion of accessibility in order to include notions of information accessibility. Overall, ICTs have affected the three essential elements of accessibility (Dijst, 2004, p. 27): “the reference location from which access to destinations is determined; the set and attractiveness of opportunities; and travel impedance”. From an empirical standpoint, it can be said that, while basic Internet access is available almost everywhere nowadays, the capacity of the installed infrastructure varies dramatically across different cities and regions, thus affecting the aggregated opportunities in these areas to participate and benefit from the digital economy. Given the above, the aim of this paper is to develop a city-level potential DA indicator based on the installed digital infrastructure. In other words, we will conceive here an analogy to transport network accessibility and potential opportunities, and estimate a compound value which takes into account the capacity of the digital infrastructure, as well as the cost of virtual communications.

The paper is structured as follows: next, Section 2 presents the conceptual and methodological framework and the relevant data; Section 3 illustrates the different DA measures. Then in Section 4 complex network analysis is employed to validate the results of the DA followed by the discussion of the results in Section 5. The paper ends in Section 6 with some concluding remarks and ideas for further research.

2. Conceptual and methodological framework and relevant data

The starting point of the DA measure lies in Hansen’s (1959) seminal work, and, on the basis of this, we define DA as the *potential for virtual interactions*, which have the form of digital communications. At a generic level, the rich theoretical foundations and universal properties of the potential accessibility measures are well established in the literature (Reggiani, 1998). The basic formula for calculating DA has the form:

$$, \qquad (1)$$

The DA_i is the digital accessibility interpreted as the aggregated potential opportunities for virtual interaction in the city *i*, while CP_j (cyberplace, following Batty’s (1997) distinction between cyberplace and cyberspace) denotes the capacity of the installed digital infrastructure in city *j*. In more detail, *CP* indicates the total installed capacity for international intercity IP communications ($CP_i = \Sigma_j CP_j$). This type of digital infrastructure is responsible for the Internet’s global character, as it connects remote destinations (Malecki, 2004). The installed capacity due to such networks in a city reflects the potential of the city to attract, generate, or route IP data flows. While the first two urban Internet functions (generation/attraction) are rather straightforward and share strong commonalities with traditional transport networks, the third (routing) is a characteristic of the Internet function. In a nutshell, a high capacity of installed infrastructure for international intercity IP communications reflects to a certain extent the localized demand for such communications – both attracting and generating communications. In addition, and because of the importance of routing in IP communications, the installed capacity at city level also reflects the nodal role that a city performs for IP data-flows routing at a global scale.

The data for the *CP* is derived from Telegeography (2009). Telegeography is a private consultancy firm, and nowadays is the only provider of such data at the global scale, and most of the related research in the emerging field of Internet Geography utilises this data source (for a review, see Tranos & Gillespie, 2011). In order to obtain such data and verify the results, Telegeography (2009) has integrated confidential surveys and interviews, network discovery tools, and public and private information sources. For the needs of the empirical research, the utilised data reflects the capacity (bandwidth) of the international intercity Internet backbone links for Europe for the years 2005 and 2008 (Telegeography, 2009). To give an example, the capacity of the Internet backbone links between London and Paris were included in the analysis, but links between London and Manchester were excluded. Based on this data-set and after applying network analysis techniques (see Tranos, 2011), the accumulated capacity at the city level was calculated. For analytical reasons, both the links and the accumulated capacity were aggregated at the NUTS3 [Nomenclature of Territorial Units for Statistics (Eurostat, 2011)] regional level.

What is less straightforward is the role of the impedance function in virtual interactions, denoted here as $f(d_{ij})$ and defined below (expressions (2)-(4)). It is common in transport-related accessibility studies that physical distance represents the cost for spatial interactions. The emerging question is: How can we transfer this basic element of Newtonian physics to the digital world? In order to answer this question, the Internet function should be further analysed. One of the main characteristics of the Internet is that its users consider it as a black box, something which is usually associated with other older urban infrastructure networks, such as water, sewerage, etc. (Graham & Marvin, 2001). In reality, the Internet is a complex dynamic system: it is complex due to the numerous interconnected networks which form what we experience as a global system, and it is dynamic because of the constant and rapid change of the structure of the interconnected networks. Because the Internet's function is based on IP data-packet routing through various nodal points, these indirect routes which enable the global IP communication are not fixed but change constantly in order to reflect the most efficient route over the network (UN, 2006). And, because of the private character of the Internet infrastructure, the interconnection – known as peering – of different networks which is necessary in order to achieve global reach (Malecki & Gorman, 2001) involves some cost. Indeed, Pastor-Satorras and Vespignani (2004) propose the physical distance (d_{ij}) as a proxy for the cost of the Internet communication. Therefore, they highlight (2004, p. 99) that the "connection cost increases with distance and eventually imposes a preference for a nearby, medium-sized hub, instead of the largest one that could be located far away in geographical distance". In addition, the first Internet topology generator, which was produced by Waxman (1988), and was extensively used for protocol testing, incorporated the negative impact of physical distance between any two nodes (Pastor-Satorras & Vespignani, 2004). On the basis of the above, we would expect that physical distance would have a negative effect on the digital accessibility of a place.

Further to this, the nature of the impedance function will also be explored. Drawing upon discussion in the relevant literature (Taylor, 1979; Olsson, 1980; for a synopsis see Reggiani et al., 2011a), three different non-linear forms will be tested: negative exponential; negative power; and negative log-linear:

; (2)

; (3)

, (4)

where d_{ij} is the physical distance and b_1, b_2 and b_3 are the distance-sensitivity parameters.

The negative exponential (2) form is the more widely used in the literature and better fits homogeneous interactions (Fotheringham & O'Kelly, 1989; Wilson, 1967). However, there has been a long debate in the literature on the adoption of an exponential or a power form from as far back as the 1970s and 1980s, with recent discussions in De Vries et al. (2009) and Reggiani et al. (2011a). Contrary to the above function, the power form better represents accessibility for long-distance patterns due to its long tail (Reggiani et al., 2011b), and, in general, more heterogeneous interactions (Fotheringham & O'Kelly, 1989). Furthermore, the power form supplies scale-independent parameter estimates. Because of these attributes, the power form (3) better reflects spatial disparities such as those observed as a result of large agglomeration effects (Wilson, 1967). In addition to these two forms, the log-normal form (4) is also tested here, because of its attribute as a bridge between the above two distributions (Parr & Susuki, 1973). The common characteristic of the three forms is the existence of the *distance-sensitivity* parameters (b_1-b_3), which can be useful for observing the aggregate behaviour of Internet backbone providers (IBPs), who design and control the topology and the capacity of this digital infrastructure. Put simply, IBPs decide how much capacity should be installed between any two cities in order to meet the overall network routing plan, but also the expected demand for city-to-city IP communications (Tranos & Gillespie, 2009).

The aim here is to understand the way distance affects the digital accessibility of places. These forms will be tested against data representing both the demand and the supply side of city-to-city virtual interactions and the necessary digital infrastructure. The latter, as well as the estimation of the relevant distance-sensitivity coefficients (b_1-b_3), will be materialized using a spatial interaction model (SIM). SIMs have been extensively used as an essential tool in analysing and predicting spatial flow patterns. SIMs' long history has a starting point in Newtonian physics and gravity models and carries on until entropy theory (Wilson, 1970) and, the utility maximization approach (for a review, see Reggiani, 2004). In this case, following Patuelli et al. (2007), a simple unconstrained SIM will be utilized as a first approximation of the DA, which will have the following form:

, (5)

where CP_i and CP_j denote the overall capacity in cities i and j, and CP_{ij} presents the installed capacity between cities i and j. It should be noted here that the overall installed capacity at the city level is the summation of the capacity of *all* the links terminating there, and not only the summation of the intra-European links (i.e. Internet backbone links with non-European cities are also included). In order to estimate (5) the logged version is used here:

—— . (6)

If $f(d_{ij})$ represents an exponential function, the above equation is rewritten as follows:

—— . (7)

On the contrary, if $f(d_{ij})$ represents a power function, the SIM will be written as:

—— . (8)

Finally, if $f(d_{ij})$ represents a log-normal function, the SIM will be written as:

$$\frac{\quad}{\quad} \tag{9}$$

Equations (7), (8) and (9) will be estimated using ordinary least squares (OLS). The analysis involves two repeated cross-sections for the years 2005 and 2008. This will enable us to observe the dynamics of the DA across the European cities. The results are presented in Table 2, where *N* represents the number of observations. In addition, the form of the impedance function for the years 2005 and 2008 can also be observed in the relevant scatter plots in the Appendix. For better visualization, a second set of scatter plots is also presented (see Figure A1 in the Appendix), the main difference being the removal of a few obvious outliers. The latter are also included in Table 2, and are denoted with a decreased number of observations (*N*).

Table 2: OLS results for $f(d_{ij})$ estimation using SIM

Year	$f(d_{ij})$	b	R^2	t	N
2005	Exponential (b_1)	-0.002	0.292	-8.86***	192
		-0.002	0.280	-8.48***	187
	Power (b_2)	-1.915	0.402	-11.31***	192
		-1.653	0.321	-9.36***	187
	Log-normal (b_3)	-0.150	0.393	-11.08***	192
		-0.127	0.325	-9.43***	187
2008	Exponential (b_1)	-0.002	0.267	-8.68***	209
		-0.002	0.264	-8.50***	204
	Power (b_2)	-1,523	0.277	-8.92***	209
		-1,376	0.238	-7.94***	204
	Log-normal (b_3)	-0.123	0.284	-9.08***	209
		-0.110	0.252	-8.24***	204

* significant at 10%; ** significant at 5%; *** significant at 1%

The outcome of the above analysis is that no obvious function better explains the impact of distance on the capacity of the digital infrastructure. The power function scores the highest R^2 for 2005 and the log-normal the highest R^2 for 2008. However, the differences in the explanatory power of the different forms are marginal. The latter, in combination with the lack of previous knowledge on the digital accessibility of cities, lead us to calculate in the first instance the DA for all the three different impedance functions. At a later stage (Section 4) a topological measure will be also utilized in order to better understand the nature of the digital network, and choose the most relevant impedance function. The results and the relevant discussion are presented in the next sections.

In order to further validate the calibration process, the simple unconstrained SIM is also tested against another *CP* variable. The data for this variable have been derived from the DIMES research project and have been gathered using traceroutes[1] measures (DIMES, 2010). It contains the (captured) IP links between any two cities on a weekly basis. The data have been aggregated here yearly, and at the level of NUTS3 regions. A major difference exists between the two variables. While the former represents point-to-point Internet backbone links, the latter refers to IP physical links in general. Due to this structural difference between the two datasets, we will not expect a high R^2. Nevertheless, significant negative b-coefficients can verify the above calibration process. The results, which are presented in the Appendix (Table A1), indicate a very low R^2 due to the above structural difference ($R^2 \leq 0.02$), but still significant negative coefficients. The latter verifies to a certain extent the results of the first calibration, which will be used for the calculation of the accessibility indicator.

Before presenting the three different DA indicators, another methodological choice needs to be clarified. It is common in potential accessibility studies to incorporate the potential for internal interactions with respect to the spatial units. Although different approaches exist in the literature, a common point is that the exclusion of internal accessibility can lead to counterintuitive outcomes with high scores for smaller regions which are near to large ones, and low scores for the large regions themselves (for a discussion, see Bruinsma & Rietveld, 1998). Here we include in the analysis a notion of internal digital accessibility. A frequent problem, which has also occurred in our case, is the lack of internal data. In order to overcome this difficulty, we replace the diagonal elements (*i,i*) of the d_{ij} matrix with an approximation of the *diameter* of each region. We define the latter as the diameter of a circle, the circumference of which is equal to the perimeter of the polygon of each NUTS3 region. The underlying assumption is that each region is able to utilize the installed capacity denoted above as the *CP*. Of course, it would have been of great help here to have solid information about the internal *CP* capacity, but because this data does not exist at such an aggregated level, the total *CP* capacity is used instead.

3. Different Digital Accessibility measures

Applying the methodology described in the previous section, the DA is calculated based on equation (1), using the three different impedance functions (2-4), and the b_s are estimated using (7-9). The derived rankings based on the results for the different DA measures for the 20 most accessible cities are presented in Table 3[2] for the two time periods.

The first observation is that accessibility measures based on power and log-normal functions are almost identical (Pearson correlation = 0.98), and measures based on exponential and power functions are the most different, but still highly correlated (0.7). Indeed, the cluster of the four most accessible cities of London, Paris, Frankfurt and Amsterdam, the ‘golden diamond’ of the Internet infrastructure in Europe (Tranos, 2011), is formed here according to the power and log-normal

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[1] Traceroutes are specific programs, which map the route that a data packet travels through the different nodes in order to reach its final destination (Dodge & Kitchin, 2000).

[2] The overall table of the DA is provided in the Appendix (Table A2).

function, but this is not the case for the exponential-function-based DA, according to which Geneva is the fourth most accessible city in the *CP*, displacing Amsterdam in the fifth place. The DA of cities from the periphery of Europe such as Bucharest, Budapest, Oslo, Warsaw, Copenhagen and Dublin, but also more central ones, such as Berlin, Dusseldorf and particularly Brussels is underestimated using the exponential function. On the contrary, core European cities such as Geneva, Turin and also less central ones such as Barcelona and Venice appeared to be overestimated using the exponential function.

Table 3: Different DA measures, ranking

	2005			2008		
	Exp.	**Power**	**Log-norm.**	**Exp.**	**Power**	**Log-norm.**
London	*1*	*2*	*1*	*1*	*2*	*1*
Paris	*2*	*1*	*2*	*3*	*1*	*2*
Frankfurt	*3*	*3*	*3*	*2*	*3*	*3*
Amsterdam	*4*	*6*	*4*	*5*	*4*	*4*
Düsseldorf	*16*	*9*	*10*	*19*	*5*	*5*
Copenhagen	*5*	*4*	*5*	*22*	*6*	*6*
Milan	*8*	*15*	*11*	*6*	*9*	*7*
Vienna	*11*	*8*	*8*	*17*	*8*	*8*
Brussels	*10*	*5*	*6*	*24*	*7*	*9*
Hamburg	*7*	*10*	*9*	*20*	*10*	*10*
Geneva	*12*	*7*	*7*	*4*	*11*	*11*
Prague	*17*	*13*	*14*	*18*	*12*	*12*
Nuremberg	*60*	*45*	*51*	*10*	*17*	*13*
Stockholm	*6*	*23*	*18*	*12*	*20*	*14*
Oslo	*15*	*14*	*13*	*32*	*13*	*15*
Monaco	*56*	*56*	*57*	*7*	*26*	*16*
Warsaw	*14*	*12*	*12*	*33*	*14*	*17*
Madrid	*9*	*22*	*16*	*15*	*23*	*18*
Zürich	*13*	*18*	*15*	*21*	*19*	*19*
Marseilles	*31*	*36*	*35*	*8*	*28*	*20*
Budapest	*20*	*17*	*17*	*39*	*15*	*21*
Turin	*62*	*61*	*62*	*9*	*30*	*22*
Brno	*33*	*39*	*37*	*23*	*29*	*23*
Lisbon	*25*	*26*	*27*	*25*	*24*	*24*
Dublin	*19*	*20*	*19*	*36*	*22*	*25*

Overall, we observe two different spatial patterns. Regarding the DA measures based on the exponential form, an almost centre-weighted pattern is apparent. Indeed, with the exemptions of Zurich and Brussels, the DA declines as we move away from Europe's pentagon[3]. However, this is not the case with the power and the log-normal functions because they appear to be less location-

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[3] The area enclosed by a pentagon with its corners being the cities of London, Hamburg, Munich, Milan and Paris, often used to be denoted s the 'core' area of Europe.

sensitive, as they better reflect accessibility patterns where longer distances are involved. And this appears to be the case for the DA, which is based on the heterogeneous Internet infrastructure.

It becomes apparent from the above that the DA is heavily based on the topology of the infrastructural network, as topology is 'hidden' in the impedance function. The next section sheds light on the topological attributes of the IBN, and this exercise will enable us to make an informed choice for the most appropriate impedance function.

4. Complex network analysis perspective

In order to further understand the topology of the digital infrastructure, which is a vital element of the proposed approach of the DA, we adopt here concepts and methods from the complex network analysis (CNA) field. In particular, we are aiming to explore connectivity patterns in the topological configuration and compare them with the spatial economic structure revealed by the DA analysis. To provide a brief introduction, the ideas which underpin the next section derive from the *new science of networks* (Barabási, 2002; Buchanan, 2002; Watts, 2003, 2004), an analytical field which has expanded rapidly over the last 10-15 years, the main focus of which is the large-scale real-world networks and their universal, structural, and statistical properties (Newman, 2003).

While the starting point of CNA lies in statistical physics, strong parallels exist between CNA and regional science and spatial economics, as the latter traditionally have a strong interest in networks and interregional systems (Cornell University, 2010). Reggiani (2009) explores this link in detail. Among other things, she highlights that while spatial economic analysis focuses on spatial structure, network analysis focuses on topological structure, and, while the former emphasizes on the economic meaning of functional forms, the latter stresses the connectivity patterns of functional forms. Drawing upon this conceptual parallel, CNA will be used here in order to validate the DA results, and to choose the most appropriate impedance function, highlighting the connectivity patterns of the digital infrastructure.

In more detail, network degree centrality and the related degree distribution are utilized here. The former is a connectivity measure and, in this case, can be defined as the accumulated capacity at the city level. Such a measure reflects the topology of the network. However, it needs to be highlighted here that the adopted approach of degree centrality incorporates the capacity of the links, and does not focus only on the *bare* topology, which excludes the capacity of the links from the analysis and focuses only on the number of links, a practice which is quite common in studies with a starting point in statistical physics. The advantage of our approach is that the critical information about the capacity of links, which is vital for the Internet function, is not excluded from the analysis.

The second CNA tool introduced here is the nodes' degree distribution. This simple statistical instrument is part of the core of complex network analytics, and reveals valuable information about the topology of the network by comparing the degree distributions of the links of the empirical networks with those of well-established theoretical models. The main distinction lies between what are known as the *small world* (SW) and the *scale free* (SF) networks: while the former are characterized by an exponential degree distribution, the latter follow power laws[4]. Both these types of networks are characterized by short average distances[5] and high clustering coefficients[6], but their main difference is the heterogeneity of the nodes, as SF networks are characterized by the existence of a very few super connected hubs and a vast majority of less-connected vertices (Barabási & Albert, 1999), while the structure of SW networks resembles highly-connected clusters of nodes, which gain global connectivity via a few links, which span the entire network, linking distant clusters (Watts & Strogatz, 1998)[7].

The first step is to analyse the degree distribution in order to explore the heterogeneous nature of IBN. Following Newman (2005), the estimation of the degree distribution curve is based on the cumulative degree distribution derived from an inverse rank-plot graph and OLS (Faloutsos et al., 1999; Gorman & Kulkarni, 2004; Patuelli et al., 2007; Schintler et al., 2004; Tranos, 2011; Reggiani et al., 2011b). The plots can be found in the Appendix (Figure A2) and the results of OLS are presented in Table 4.

Table 4: Degree distribution fit

	Exponential		**Power**	
	R^2	**Coef.**	***R^2***	**Coef.**
2005	0.80	5.00E-06	0.84	-0.33
2008	0.74	2.00E-06	0.78	0.30

Apparently, no clear fit can be identified for the degree distribution of the IBN. While a higher R^2 can be observed for power functions for both years, the difference is marginal with the exponential fit. This ambiguity is not surprising as it confirms the previous results of the SIM calibration (Table 2), where again no clear structure was identified. In addition, this indistinctness of IBN to follow a power function indicates the absence of an extreme hub and spoke structure. Drawing on previous research (Tranos, 2011), it can be added here that the exclusion of the edge's weights from the analysis, would have resulted in even more homogenous connectivity patterns.

The next step is to compare the DA ranking with the degree centrality. Although these measures are different, both of them are based on the IBN topology. After performing the relevant correlation

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[4] Random Networks (RN) are also a unique strand of networks in the literature, and are characterized by Poisson degree distribution. They are not included in our analysis as IBN are characterized by short network distances and high clustering coefficients (Tranos, 2011), characteristics which are not compatible with RN.

[5] In the network analysis jargon, distance does not refer to Euclidean distance, but to the number of nodes that separate any two nodes. And because usually there is more than one different way to connect any two given nodes (also known as a *walks*), the focus is usually on the shortest walk, known as the *geodesic distance* (Nooy et al., 2005).

[6] The clustering coefficient of node *i* is the ratio between the number of edges E_i that exist among its nearest neighbours (nodes which are directly connected with node *i*) and the maximum number of these edges, where k_i is the number of nodes in clique *i*: $C_i = 2E_i / k_i(k_i - 1)$ (Latora & Marchiori, 2001).

[7] For a review of the new science of networks from a spatial economics perspective the reader can refer to Reggiani and Vinciguerra (2007) and for an application of CNA on the IBN to Tranos (2011).

tests, it becomes apparent (see Table 5) that, on average for the two time periods, the DA based on log-normal impedance function better fits the degree centrality distribution.

Table 5: Correlation between DA and degree centrality

	2005	2008	Average 2005-2008
Exp.	**0.98**	0.78	0.88
Log-norm	0.92	**0.93**	**0.92**
Power	0.86	0.87	0.86

On the basis of the above results, but also because no clear fit was indentified for the degree distribution, the log-normal impedance function will be used for the DA, and the results are discussed in the next section.

5. Discussion

As mentioned above, the core of the most accessible cities in terms of virtual interaction remains unchanged over time, and this is also confirmed by the degree centrality measures (see Table A2). However, quite intensive urban dynamics are observed over time. Cities such as Nuremberg, Marseille, Turin, Brno, Venice, and Berlin managed to dramatically improve their relative position in the overall digital accessibility ranking during only the 4-year study period. On the contrary, cities such as Munich, Basel, Stuttgart, Athens and Helsinki went down up to 14 places in the relative ranking over time. The above changes echo the urban dynamics reflected in the digital infrastructural network and the derived DA. The network changes over time, as the IBN providers rearrange their networks in trying to meet the changing demand for such infrastructure. This explains why the least accessible cities in 2008 were not connected to any IBN in 2005, and, more importantly, why the city of Turin, which was at the bottom of urban hierarchy in 2005, climbed to the 22nd position in 2008.

Furthermore, regional digital hubs can be identified. Moving away from Europe’s core, we can identify the dominant role that Copenhagen performs in northern Europe, and also the supporting roles of Stockholm and Oslo. These three cities, but mainly the Danish capital, are the most accessible cities in this part of Europe, and apparently perform hub roles for this region. Similarly, in Eastern and South-Eastern Europe, Vienna appears to perform the most central role followed by Prague and Warsaw, and more distantly by Bucharest and Bratislava. Interestingly enough, the maturity of Vienna’s role in the overall system can be demonstrated, as the Austrian capital has maintained its position over time. Interestingly enough, the south of Europe appears to be less accessible in the digital economy framework. Indeed, Monaco, Madrid and Marseilles are the most accessible cities from the south of Europe, although none of them is one of the 15 most accessible cities for both time-periods, indicating the disadvantaged character of this region.

Another interesting point is the dominance of the German cities. From the 72 cities present in our analysis, which includes the European cities served by at least one international Internet backbone connection, 10 cities are German. And even more importantly, 3 German cities are found in the 10 most digitally-accessible cities. Apparently, this reflects the polycentric structure of the German national urban system. Interestingly enough, Germany is followed by Poland and Italy in terms of participation in the IBN, two countries which are also characterized by polycentric urban systems (OECD, 2011; Meijers, 2008). The latter indicates the metropolitan character of this infrastructure (Rutherford et al., 2004) and the cherry-picking pattern of the IB connectivity and the derived DA (Graham & Marvin, 1996).

In general, the DA pattern reveals an alternative urban hierarchy incorporating the cost and the opportunities for virtual interaction. This new hierarchy, while still employing physical distance as a proxy for the cost of virtual interactions, results in a European geography, the core of which remains similar to that revealed by other more traditional accessibility measures, but new roles, and consequently higher rankings, are revealed for second-tier cities in the frame of the digital economy.

6. Conclusions

This paper aims to conceptually and empirically introduce the new concept of DA. Regardless of the extensive interest in accessibility issues and the immense societal changes that ICT penetration has generated, and although there is a strong parallel between transportation and telecommunications networks, accessibility studies have largely ignored the transforming impact of ICTs on space because of their complex, technical and intangible nature. Here, we have attempted to create a methodological framework where the opportunities and cost for virtual interactions could be defined on a spatial basis. While for the former a *CP* measure was adopted – the accumulated international IP backbone capacity – physical distance proved to be a good proxy for the cost of virtual interactions. Conceptually, a potential accessibility framework was utilized and a SIM was employed in order to calibrate the model. In addition, drawing on the similarities between CNA and spatial economics, the basic tools from the former were employed in order to validate the DA results.

The results of our analysis indicate a consistent 'golden diamond' of DA in Europe spanned by London, Paris, Amsterdam and Frankfurt. Outside this new – digital – core, cities have the opportunity to perform new hub roles for their peripheries and gain a higher position in the European urban hierarchy. In addition, new peripheral areas within the frame of the digital economy were highlighted, such as the south of Europe. What is more, the strong urban character of the digital infrastructure and the derived potential accessibility has also emerged, as the new urban hierarchy to a certain extent reflects the structures of national urban systems.

Conceptually, the main innovation of this paper is the utilization of digital measures in a spatial context in order to understand the spatial effects of the digital infrastructure. Regardless of what the average Internet user experiences, spatial heterogeneity is inherent in the digital infrastructure, and this may affect the spatial configuration. In addition, a traditional geographical notion such as physical distance proved to be able to reflect virtual interaction costs just like physical interactions.

Apart from the methodological advances, the results of this paper could be used to inform urban and regional policy. Because of the complex nature of ICTs, urban and regional planners have neglected the impact of the digital revolution in their plans. Nonetheless, cities can take advantage of the digital infrastructure, climb the global urban hierarchy, and benefit from their new roles in the digital economy. As noted elsewhere (Tranos, 2010), the digital infrastructure, and, consequently, the derived DA appears to have a significant positive impact on regional economic development. Planners need to be informed about such mechanisms and address them in their long-term plans.

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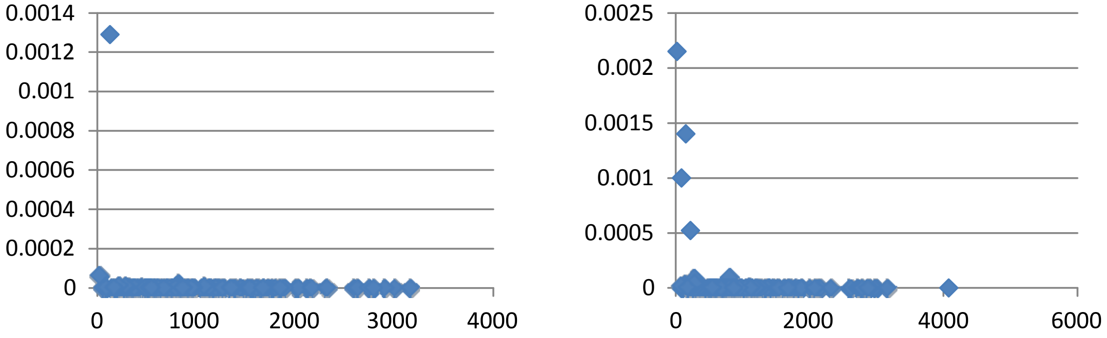
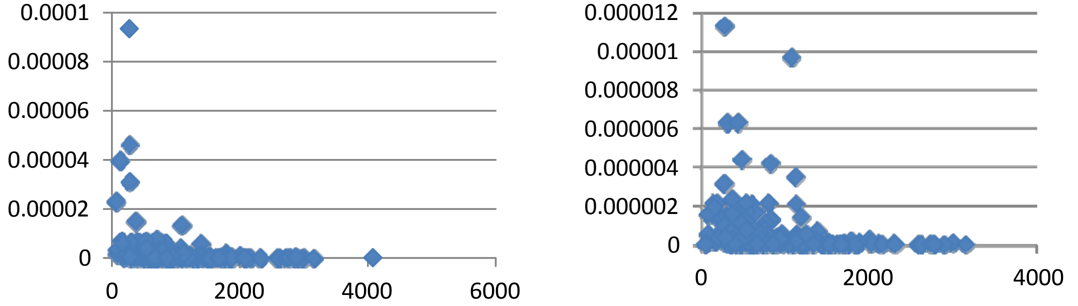
Appendix – Statistical data and results

Figure A1: Plots of the impedance functions, 2005 and 2008: y-axis = , x axis =



2005, all observations (N = 192)

2008, all observations (N = 209)



2005, after the removal of some outliers (N = 187)

2008, after the removal of some outliers (N = 204)

Figure A2: IBN cumulative degree distribution function (y axis: ranking; x axis: degree)

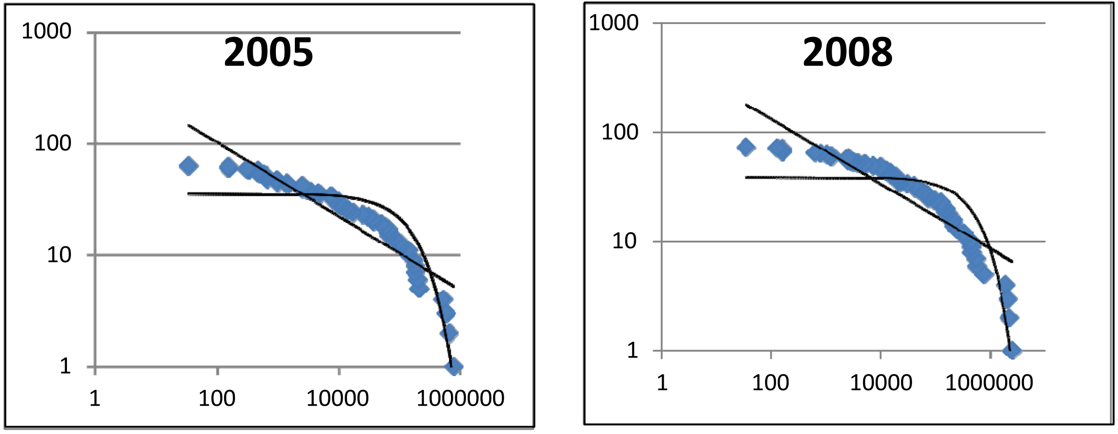


Table A1: OLS results for *f(d$_{ij}$)* estimation using SIM and IP data flows

f(d$_{ij}$)	**exponential (*b$_1$*)**	**power (*b$_2$*)**	**log-normal (*b$_3$*)**
b	-0.0004	-0.640	-0.005
R^2	0.013	0.020	0.019
T	-4.170***	-5.260***	-5.120***
N	1322	1322	1322

Table A2: DA measures and degree centrality

	2005								**2008**							
	exp.		**power**		**log-norm.**		**degree**		**exp.**		**power**		**log-norm.**		**degree**	
London	100.0	*1*	79.5	*2*	100.0	*1*	*100.0*	*1*	100.0	*1*	76.5	*2*	100.0	*1*	*100*	*1*
Paris	61.7	*2*	100.0	*1*	84.0	*2*	*84.5*	*2*	74.4	*3*	100.0	*1*	95.5	*2*	*82.49*	*2*
Frankfurt	46.9	*3*	33.1	*3*	44.4	*3*	*74.8*	*3*	75.0	*2*	46.2	*3*	63.8	*3*	*87.51*	*3*
Amsterdam	44.8	*4*	9.2	*6*	22.3	*4*	*66.2*	*4*	61.7	*5*	14.7	*4*	32.1	*4*	*74.85*	*4*
Copenhagen	17.1	*5*	14.4	*4*	17.5	*5*	*26.0*	*6*	11.3	*22*	9.0	*6*	11.5	*6*	*14.01*	*6*
Brussels	10.7	*10*	11.1	*5*	12.1	*6*	*18.1*	*10*	10.3	*24*	8.4	*7*	9.9	*9*	*13.05*	*10*
Geneva	9.4	*12*	7.1	*7*	9.2	*7*	*13.3*	*12*	65.6	*4*	2.9	*11*	7.1	*11*	*3.784*	*12*
Vienna	10.5	*11*	4.7	*8*	8.0	*8*	*18.1*	*11*	17.5	*17*	6.1	*8*	10.3	*8*	*18.34*	*11*
Hamburg	13.6	*7*	3.2	*10*	7.3	*9*	*23.3*	*7*	12.2	*20*	3.5	*10*	7.2	*10*	*18.03*	*7*
Düsseldorf	4.9	*16*	3.8	*9*	4.9	*10*	*8.4*	*17*	12.7	*19*	9.1	*5*	12.1	*5*	*17.42*	*17*
Milan	12.7	*8*	1.4	*15*	4.4	*11*	*21.9*	*9*	58.2	*6*	3.5	*9*	10.3	*7*	*21.77*	*9*
Warsaw	5.9	*14*	2.0	*12*	3.9	*12*	*10.3*	*14*	5.0	*33*	2.0	*14*	3.5	*17*	*7.377*	*14*

Oslo	5.4	*15*	1.7	*14*	3.4	*13*	*8.7*	*15*	5.7	*32*	2.1	*13*	3.9	*15*	*8.563*	*15*
Prague	4.9	*17*	1.8	*13*	3.4	*14*	*8.5*	*16*	12.8	*18*	2.5	*12*	4.8	*12*	*8.35*	*16*
Zürich	7.1	*13*	0.9	*18*	2.7	*15*	*12.6*	*13*	11.7	*21*	1.2	*19*	3.3	*19*	*9.549*	*13*
Madrid	12.5	*9*	0.4	*22*	2.0	*16*	*23.1*	*8*	18.1	*15*	1.0	*23*	3.5	*18*	*22.36*	*8*
Budapest	2.9	*20*	1.1	*17*	2.0	*17*	*4.9*	*20*	4.2	*39*	1.7	*15*	3.1	*21*	*5.995*	*20*
Stockholm	13.7	*6*	0.4	*23*	1.9	*18*	*27.3*	*5*	20.3	*12*	1.2	*20*	4.2	*14*	*30.17*	*5*
Dublin	3.8	*19*	0.7	*20*	1.8	*19*	*6.4*	*19*	4.3	*36*	1.0	*22*	2.3	*25*	*5.27*	*19*
Basel	0.6	*35*	2.6	*11*	1.1	*20*	*1.0*	*34*	4.3	*37*	1.7	*16*	1.2	*34*	*0.785*	*34*
Munich	1.3	*24*	0.8	*19*	1.1	*21*	*2.2*	*24*	2.9	*45*	1.0	*21*	1.6	*31*	*2.494*	*24*
Bristol	0.8	*28*	1.1	*16*	1.0	*22*	*1.3*	*29*	0.6	*59*	0.3	*35*	0.4	*51*	*0.392*	*29*
Athens	2.6	*21*	0.2	*28*	0.7	*23*	*4.0*	*22*	3.5	*41*	0.3	*38*	1.0	*37*	*2.825*	*22*
Stuttgart	0.6	*32*	0.5	*21*	0.7	*24*	*1.1*	*31*	1.1	*55*	0.9	*25*	1.1	*36*	*1.627*	*31*
Bratislava	1.8	*23*	0.2	*27*	0.6	*25*	*3.2*	*23*	7.4	*30*	0.6	*31*	1.8	*30*	*5.974*	*23*
Helsinki	3.8	*18*	0.1	*29*	0.5	*26*	*7.4*	*18*	4.2	*38*	0.2	*43*	0.9	*38*	*6.443*	*18*
Lisbon	1.1	*25*	0.2	*26*	0.5	*27*	*1.8*	*25*	9.6	*25*	0.9	*24*	2.3	*24*	*4.963*	*25*
Riga	0.6	*34*	0.3	*24*	0.5	*28*	*1.0*	*33*	0.9	*57*	0.3	*39*	0.5	*47*	*0.852*	*33*
Barcelona	2.3	*22*	0.1	*31*	0.4	*29*	*4.7*	*21*	20.0	*13*	0.6	*32*	2.1	*26*	*8.3*	*21*
Bucharest	0.4	*38*	0.3	*25*	0.4	*30*	*0.6*	*36*	2.7	*47*	1.3	*18*	1.8	*29*	*2.357*	*36*
Hannover	1.0	*26*	0.1	*30*	0.3	*31*	*0.3*	*42*	0.8	*58*	0.1	*57*	0.2	*57*	*0.049*	*42*
Ljubljana	0.9	*27*	0.1	*32*	0.3	*32*	*1.7*	*26*	18.9	*14*	0.3	*36*	1.3	*32*	*0.792*	*26*
Palermo	0.7	*30*	0.0	*35*	0.1	*33*	*0.1*	*56*	4.4	*35*	0.2	*44*	0.8	*40*	*0.738*	*52*
Rotterdam	0.4	*37*	0.0	*33*	0.1	*34*	*0.3*	*39*	3.1	*43*	0.3	*40*	0.8	*39*	*1.968*	*39*
Marseilles	0.7	*31*	0.0	*36*	0.1	*35*	*1.3*	*30*	42.9	*8*	0.8	*28*	3.2	*20*	*2.954*	*30*
Tallinn	0.7	*29*	0.0	*37*	0.1	*36*	*1.4*	*27*	1.7	*48*	0.1	*51*	0.4	*48*	*2.955*	*27*
Brno	0.6	*33*	0.0	*39*	0.1	*37*	*1.3*	*28*	10.3	*23*	0.7	*29*	2.4	*23*	*0.001*	*28*
Hilden	0.1	*44*	0.0	*34*	0.1	*38*	*0.2*	*44*	0.6	*60*	0.0	*60*	0.1	*60*	*0.11*	*44*
Lausanne	0.2	*40*	0.0	*40*	0.1	*39*	*0.4*	*38*	17.8	*16*	0.3	*41*	1.2	*35*	*0.434*	*38*
Luxembourg	0.2	*41*	0.0	*41*	0.1	*40*	*0.4*	*37*	3.0	*44*	0.1	*55*	0.3	*54*	*0.518*	*37*
Vilnius	0.5	*36*	0.0	*44*	0.1	*41*	*1.0*	*32*	0.4	*62*	0.0	*65*	0.1	*63*	*0.723*	*32*
Venice	0.2	*42*	0.0	*43*	0.1	*42*	*0.3*	*40*	28.8	*11*	0.4	*34*	1.9	*27*	*0.098*	*40*
Sofia	0.1	*45*	0.0	*42*	0.0	*43*	*0.2*	*43*	1.3	*54*	0.2	*47*	0.4	*49*	*0.885*	*43*
Kolding	0.3	*39*	0.0	*48*	0.0	*44*	*0.6*	*35*	0.3	*63*	0.0	*66*	0.1	*64*	*0.628*	*35*
Rome	0.2	*43*	0.0	*47*	0.0	*45*	*0.3*	*41*	4.5	*34*	0.1	*54*	0.3	*52*	*0.098*	*41*
Msida	0.0	*58*	0.0	*38*	0.0	*46*	*0.0*	*58*	1.0	*56*	0.1	*52*	0.2	*56*	*0.147*	*54*
Berlin	0.0	*50*	0.0	*46*	0.0	*47*	*0.1*	*50*	3.2	*42*	0.8	*27*	1.8	*28*	*4.876*	*47*
Bielsko-Biala	0.1	*46*	0.0	*49*	0.0	*48*	*0.1*	*45*								
Skopje	0.0	*51*	0.0	*50*	0.0	*49*	*0.1*	*49*	1.3	*52*	0.1	*56*	0.2	*55*	*0.283*	*46*
Klagenfurt	0.0	*49*	0.0	*51*	0.0	*50*	*0.1*	*48*								
Nuremberg	0.0	*60*	0.0	*45*	0.0	*51*	*0.0*	*60*	40.5	*10*	1.3	*17*	4.7	*13*	*0.589*	*56*
Ostrava	0.1	*47*	0.0	*53*	0.0	*52*	*0.1*	*46*								
Maribor	0.0	*54*	0.0	*52*	0.0	*53*	*0.1*	*54*	9.4	*26*	0.3	*37*	1.3	*33*	*0.049*	*50*
Timisoara	0.1	*48*	0.0	*55*	0.0	*54*	*0.1*	*47*	0.1	*71*	0.0	*70*	0.0	*70*	*0.006*	*45*
Thessaloniki	0.0	*55*	0.0	*54*	0.0	*55*	*0.1*	*57*	3.7	*40*	0.1	*53*	0.4	*50*	*0.123*	*53*
Nicosia	0.0	*53*	0.0	*58*	0.0	*56*	*0.1*	*53*	0.1	*69*	0.0	*63*	0.1	*62*	*0.005*	*49*
Monaco	0.0	*56*	0.0	*56*	0.0	*57*	*0.1*	*55*	46.8	*7*	0.8	*26*	3.6	*16*	*0.196*	*51*
Nice	0.0	*59*	0.0	*57*	0.0	*58*	*0.0*	*59*	9.0	*27*	0.2	*48*	0.6	*44*	*0.59*	*55*

Malmö	0.0	*52*	0.0	*59*	0.0	*59*	*0.1*	*51*	1.3	*53*	0.1	*58*	0.2	*58*	*1.65*	*48*
Gyor	0.0	*61*	0.0	*60*	0.0	*60*	*0.0*	*62*	0.1	*70*	0.0	*71*	0.0	*71*	*0.006*	*58*
Gothenburg	0.0	*57*	0.0	*62*	0.0	*61*	*0.1*	*52*								
Turin	0.0	*62*	0.0	*61*	0.0	*62*	*0.0*	*61*	42.2	*9*	0.6	*30*	2.8	*22*	*0.006*	*57*
Oradea									8.5	*28*	0.2	*45*	0.7	*42*	*0.006*	*61*
Porto									7.5	*29*	0.2	*46*	0.7	*43*	*0.041*	*62*
Bilbao									6.8	*31*	0.1	*49*	0.6	*46*	*0.394*	*63*
Cluj									2.7	*46*	0.0	*61*	0.2	*59*	*0.196*	*66*
Antwerp									1.7	*49*	0.3	*42*	0.6	*45*	*1.577*	*60*
Manchester									1.6	*50*	0.1	*50*	0.3	*53*	*0.492*	*64*
Dresden									1.4	*51*	0.5	*33*	0.7	*41*	*1.183*	*59*
Eindhoven									0.6	*61*	0.0	*68*	0.0	*66*	*0.039*	*70*
Wroclaw									0.3	*64*	0.0	*59*	0.1	*61*	*0.098*	*65*
Kraków									0.3	*65*	0.0	*67*	0.0	*69*	*0.025*	*69*
Turku									0.2	*66*	0.0	*69*	0.0	*68*	*0.394*	*71*
Katowice									0.2	*67*	0.0	*62*	0.1	*65*	*0.098*	*67*
Poznan									0.2	*68*	0.0	*64*	0.0	*67*	*0.049*	*68*
Szeged									0.0	*72*	0.0	*72*	0.0	*72*	*0.031*	*72*