Urban Studies
1–18, 2011

Street Centrality and the Location of Economic Activities in Barcelona

Sergio Porta, Vito Latora, Fahui Wang, Salvador Rueda, Emanuele Strano, Salvatore Scellato, Allessio Cardillo, Eugenio Belli, Francisco Càrdenas, Berta Cormenzana and Laura Latora

[Paper first received, January 2011; in final form, April 2011]

Abstract

The paper examines the geography of three street centrality indices and their correlations with various types of economic activities in Barcelona, Spain. The focus is on what type of street centrality (closeness, betweenness and straightness) is more closely associated with which type of economic activity (primary and secondary). Centralities are calculated purely on the street network by applying a multiple centrality assessment model and using a kernel density estimation method on both street centralities and economic activities to correlate them. Results indicate that street centralities are correlated with the location of economic activities and that the correlations are higher with secondary than primary activities. The research suggests that, in urban planning, central urban arterials should be conceived as the the cores, not borders, of neighbourhoods.

Sergio Porta and **Emanuele Strano** are in the Urban Design Unit, Department of Architecture, University of Strathclyde, 131 Rottenrow, Glasgow, G4 0NG, UK. E-mail: sergio.porta@strath.ac.uk and emanuele.strano@gmail.com.

Vito Latora and **Alessio Cardillo** are in the labouratory for Complex Systems, University of Catania, Catania, Italy. E-mail: latora@ct.infn.it and alessio.cardillo@ct.infn.it.

Fahui Wang *(corresponding author)* is in the Department of Geography and Anthropology, Louisiana State University, 227 Howe-Russell, Baton Rouge, Louisiana, 70803, US. E-mail: fwang@lsu.edu.

Salvatore Scellato is in the Computer labouratory, University of Cambridge, William Gates Building, Thomson Avenue, Cambridge, UK. E-mail: ss824@cam.ac.uk.

Eugenio Belli is with Deicke Richards Architects, 58 Baxter Street, PO Box 507, Fortitude Valley, Brisbane, Queensland 4006, Australia. E-mail: eugeniobelli@gmail.com.

Salvador Rueda, Francisco Càrdenas, Berta Cormenzana and **Laura Latora** are in the Urban Ecology Agency of Barcelona, Barcelona, Spain. E-mail: rueda@bcnecologia.net, cardenas@bcnecologia.net, bertacormenzana@bcnecologia.net and laura.latora@libero.it.

0042-0980 Print/1360-063X Online
© 2011 Urban Studies Journal Limited
DOI: 10.1177/0042098011422570

1. Urban Location and Centrality

Urban researchers and planners have long been interested in understanding how economic activities are distributed in urban regions, what forces influence their spatial pattern and how urban structure and functions are mutually dependent. Urban land use intensities, in terms of land price and economic activity densities, vary significantly within an urban region. The classic urban economic (monocentric) model (Muth, 1969; Mills, 1972) simply emphasises the access (i.e. distance) to the only centre at the central business district (CBD). Others recognise that cities have become increasingly polycentric and that urban dwellers value access to all or some of the centres (for example, Heikkila *et al.*, 1989) or access to the major centre (CBD) and the nearest minor centre (a lower-level sub-centre) (Wang, 2000). More recently, the dispersed model argues that cities have become increasingly edgeless and central-city downtown has lost its primacy to suburbia in most major office markets in the US since 1980 (for example, Lang, 2003). Basically, the relationship between land uses and mobility is conceptualised in the regional space with emphasis on the role of centres or magnets, classically interpreted with the gravity model and its derivates (Wilson, 2000).

However, when it comes to the neighbourhood scale, the local configuration of the street network also appears to be relevant. A substantial amount of research in space syntax analysis has been devoted to establishing the correlation between street centrality and economic or social dynamics (Hillier and Hanson, 1984; Hillier, 1996; van Nes, 2005). In particular, non-residential economic and service activities at this scale have been found to be positively correlated with most central streets by following the 'natural movement' of people. Natural movement is

> the proportion of movement … that is determined by the structure of the urban grid itself rather than by the presence of specific attractors or magnets (Hillier *et al.*, 1993, p. 32).

It is a product of both the architecture of the street network at the macro scale and the level of 'constitutedness'—i.e. the extent to which the interface between private and public spaces exchanges at the micro scale. This macro–micro combination is regarded as the sign of a traditional self-organised way of building cities since ancient times (Lopez and van Nes, 2008). 'Live activities', defined as retail, markets, catering and entertainment, and other activities which benefit unusually from movement, located on the ground floor of buildings, have been found to correlate equally well with global connectors and local main streets (for example, Hillier, 1999; Hillier *et al.*, 2010). However, little if any distinction is made among different levels of activities.

In this case study, we focus on the central area of Barcelona instead of the much wider metropolitan area to examine the interdependence between street network and economic activities at a fine resolution. By using a multiple centrality assessment model (MCA), derived by complex network analysis, we measure centrality as a pure function of the street network (Porta *et al.*, 2006a). Recent studies (Porta *et al.*, 2009; Battaglia *et al.*, 2010; Wang *et al.*, 2011) used similar methods, but analysed only specific sectors of activities or general land use intensity. The dataset of Barcelona with detailed breakdowns of all economic activities permits the inquiry into the following question: do local *secondary* activities need lower or different centrality than global *primary* activities? The kernel density estimation (KDE) method is applied to both street centralities and activities so that the correlations between them can be examined. By the KDE, this research also explores whether the *density* of street centrality interprets realistically the effect of distance from streets, and what contribution the sheer street density makes in determining the density of street *centrality*.

2. The Case of Barcelona and its Relevance in Planning

>Barcelona, with a population of 1.7 millions, is the capital of Catalunya in north-east Spain. The history of the city has shaped its current street layout, a unique case for urban studies. Since the mid 1800s, the city has experienced a steady growth by absorbing former separate municipalities surrounding the inner core (Figure 1). A vast extension, the Eixample, first planned by Ildefons Cerdà in 1859 with a rigid grid-iron structure of streets and blocks, was subsequently constructed all around the ancient medieval core (Ciutat Viella). The Cerdà Plan holds a prominent position in the history of urban planning. It is regarded as anticipation of a scientific approach to city planning for its analytical consideration of basic needs of hygiene, access to green space and sunlight, and modern infrastructure and mass mobility, far from aesthetic principles of simple beautification. The plan made a conscious effort to integrate a consistent hierarchical relationship between services and communities at various scales into the physical structure of the new city (de Aberasturi, 1984). The grid-iron street structure was laid out in an urban hierarchy built of octagonal blocks: 25 blocks would constitute a quarter serviced by a social centre, a church and all local shops; 4 quarters (100 blocks) a neighbourhood serviced by a market; 2 neighbourhoods (8 quarters) a district serviced by an urban park; 2 districts (16 quarters) a sector

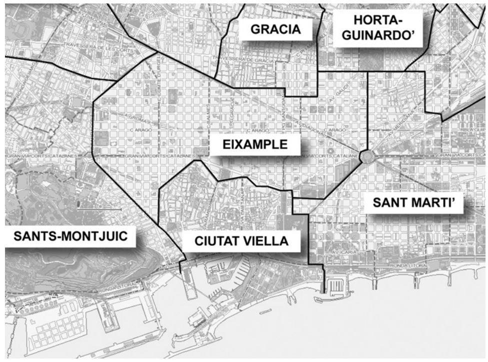

Figure 1. Districts in Barcelona's contemporary plan.

serviced by an external hospital. The need for diagonal movement in the grid would be reduced to a minimum and limited to reaching major urban functions.

The development of city planning as a discipline has been deeply informed by the idea that services and shops of different levels should be consistently located in places of a corresponding level of 'importance' or 'prominence'. It is evidenced by the definition of the most influential 'neighbourhood unit' (Perry, 1927; Ben-Joseph, 2005), the Radburn Layout (Stein and Wright, 1928), the New Towns movement (Osborn *et al.*, 1963) and the most recent debate on the New Urbanism and place making (Frey, 1999; Calthorpe and Fulton, 2001; Duany *et al.*, 2003; Farr, 2008). According to this principle, major urban roads should be attractors for global urban functions, while local services that constitute neighbourhood cores could be accommodated along secondary 'calmed' streets. Against this tradition, arguments have been raised in favour of internalising major roads within the neighbourhood cores on the basis that movement is fundamental for the survival of global and local economic activities, with mutual benefits for both. Such a shift has a deep impact on how policies for urban regeneration are conceived. Neighbourhood, reframed as a fundamental social and cultural entity, is therefore neither necessarily nor permanently coincident with geographical boundaries (Montgomery, 2003; Mehaffy *et al.*, 2010).

The street structure conceived by the Cerdà Plan about 150 years ago is still visible, while its envisaged functional complement never took place. The inner structure of the blocks, building density, interwoven network of green and open spaces, and especially the gravitation of hierarchical public functions and the spatially fixed structure of communities have been reconfigured on the ground. The Eixample is by far the most densely populated commerce and service space in the city, home to the largest number of new knowledge-based activities (Rueda, 2009). The form of a multinodal distribution of urban functional centres in the Eixample has kept the overall density substantially high even at the regional scale (Catalan *et al.*, 2008), although signs of a more dispersed pattern appear to emerge (Garcia-López, 2010).

In summary, Barcelona offers a unique opportunity to investigate how a rigidly planned street structure has influenced the spatial configuration of shops and services that has run its own course not conceived by the original planner. Bear in mind that this spatial organisation has emerged in one urban core of exceptionally high density in a regional space characterised by a multinodal concentration of functions.

3. Methodology: Multiple Centrality Assessment (MCA) and Kernel Density Estimation (KDE)

The multiple centrality assessment (MCA) model was recently introduced for quantifying the centrality of links in spatial networks, including those of urban streets (Porta *et al.*, 2006a, 2006b). The MCA represents streets as a network, following a tradition started by Euler (1736) with seminal work on the Konigsberg bridge and then widely used to model the structure of transport systems (Garrison and Marble, 1962; Kansky, 1963). The advancement of physics in studying complex systems of a spatial nature (Boccaletti *et al.*, 2006) and the availability of extensive geographical datasets have led to a wealth of studies on the 'architecture' of street networks in cities (Masucci *et al.*, 2009; Jiang, 2007; Jiang and Claramunt, 2004; Carvalho and Penn, 2004; Lämmer *et al.*, 2006). Among many applications of network science, 'structural sociology' developed several centrality indices to examine the non-spatial nature of social networks (Freeman, 1977, 1979; Wasserman and Faust, 1994). The MCA model builds on these works by applying the measures in the spatial case of streets and intersections (Crucitti *et al.*, 2006). This approach expands the interpretation of location as 'being close to' by conventional economic geography, defined either in terms of simple metric distance or transport cost (Meyer and Miller, 2000; Goulias, 2002). As illustrated later, the MCA also measures centrality in terms of 'being between' and 'being straight to'.

The MCA model shares some common ground with space syntax including its latest development, which defines the axial lines of streets, naturally continuous paths or named streets (Jiang and Liu, 2007). Potential and pitfalls of the conventional space syntax have been discussed in the literature (Steadman, 2004). Differences and advantages of the MCA have also been highlighted in Porta *et al.* (2006a). In short, the MCA uses a primal graph approach that represents streets as links and intersections as nodes, and computes distance between nodes metrically along the network rather than just topologically in terms of the number of turns like in space syntax.

This is conducive to higher reliability of network representation, lower analytical costs and stronger realism of outputs. Recently, the MCA has been extended to density of centrality in space by deploying the KDE (Porta *et al.*, 2009). Therefore, the MCA represents the forefront of a growing wave of interest in applying GIS to network analysis (Batty, 2005, 2008).

Let us assume that an urban network is constituted by N nodes and K edges, where nodes are street intersections and edges are streets. The network is described by a matrix L whose element l_{ij} equals the length of the edge connecting nodes i and j, or 0 if there is no edge. Another matrix D is derived whose element d_{ij} equals the shortest path between i and j; therefore, the shortest path is the only variable that the MCA model takes into account for evaluating the centrality of a street. The MCA model is composed of three major indices: closeness centrality (C^C), betweenness centrality (C^B) and straightness centrality (C^S). C^C may be interpreted as proximity and captures the notion of accessibility of a place. C^C measures how close a node is all others along the shortest paths, C^C is defined as

$$C_i^C = \frac{N-1}{\sum_{j=1, j \neq i}^{N} d_{ij}} \quad (1)$$

C^B captures a special property for a place in a city that does not act as origin or destination, but as a pass-through space. C^B measures the extent to which a node is traversed by a larger number of the shortest paths connecting every pair of nodes in the study area, such as

$$C_i^B = \frac{1}{(N-1)(N-2)} \sum_{j=1;k=1;j \neq k \neq i}^{N} \frac{n_{jk}(i)}{n_{jk}} \quad (2)$$

where, n_{jk} is the number of shortest paths between nodes j and k, while $n_{jk}(i)$ is the number of such shortest paths that traverse node i.

C^S measures the extent to which a place can be reached directly, on a straight line, from all other places in a city. C^S was originally proposed by Vragovìc *et al.* (2005) as a normalisation procedure in non-spatial graphs, but we have deployed it in spatial cases to capture qualities inherent in navigation. C^S is based on the idea that efficiency in communication between nodes increases when there is less deviation of the shortest path from the virtual straight line between them, a quality that makes it prominent in terms of 'legibility' and 'presence' (Conroy-Dalton, 2003). C^S is defined as

$$C_i^s = \frac{1}{N-1} \sum_{j=1;j \neq i}^{N} \frac{d_{ij}^{Eucl}}{d_{ij}} \quad (3)$$

where, d_{ij}^{Eucl} is the Euclidean distance between nodes i and j.

MCA calculates centrality globally and locally. The global indices in every node were calculated with respect to all other nodes in the system, while the local index is calculated just to those within distance d measured along the network.

The street network with centrality values and the distribution of economic activities are two distinct spatial features. For examining their spatial relationship, transforming both into one unit of analysis, a KDE is performed on both street centrality and economic activities. The KDE reflects the nature of spatial navigation—i.e. that getting through space does cost and that the cost declines with distance. The KDE values access to all events (opportunities) by cumulating proximity to them. The KDE uses the density within a range or window of each cell to represent the value at the centre of the window. Within the window, the KDE weighs nearby objects more than far ones based on a kernel function, calculating distance in a Euclidean way—i.e. not along the network (Silverman, 1986; Bailey and Gatrell, 1995; Fotheringham *et al.*, 2000). By doing so, KDE generates a density of events (discrete points) as a continuous field (for example, raster). Applying KDE to the two datasets of streets weighted by centrality values and economic activities yields two raster datasets with the same resolution and thus permits the analysis of relationship between them.

4. Data Sources and Preparation

The street network of Barcelona is made of 6452 nodes and 11 222 edges. For centrality values (Table 1), we calculated three indices of street centralities: C^C_{glob}, C^B_{glob} and C^S_{glob} and one local centrality, local closeness C^C_d with a catchment radius of $d = 800$ metres, 1600 metres and 2400 metres.

The economic database included 166 311 business entities, representing all activities located on all building floors in 2002. The geo-referenced database of activities, provided by the Agencia de Ecología Urbana de Barcelona, contains tax information of economic activities, a list of public services, a list of associations, etc. All entries were classified by the research team with reference to the National Classification of Economic Activities (NACE), established by the European Union. The data were also expanded to include specialised activities in the city. All economic activities have been grouped into seven general categories. Three general categories (2, 4 and 0) do not have any sub-categories, while the other four general categories (1, 3, 5 and 6) are further divided into 17 sub-categories (Table 1). For example, the general category of 'retail commerce' is split into two sub-categories: those related to motor vehicles and those not so related.

The great detail of the Barcelona database also enabled us to create a further classification differentiating between primary and secondary activities. In her seminal work on complex urban neighbourhoods in American cities, Jacobs (1961, pp. 161–162) introduced the definitions: primary activities are "those which, in themselves, bring people to a specific place because they are anchorages", including manufactures and nodal activities at the metropolitan and regional levels; and secondary activities are "enterprises that grow in response to the presence of primary uses, to serve the people the primary uses draw". The work was further elaborated and expanded by others (Comedia, 1991; Montgomery, 1998, 2003). Secondary activities are therefore local in scale and service in type. While depending economically on the primary, the secondary activities are fundamental for the long-term economical success of cities and are deeply interlinked with the complex environmental, social and cultural well-being of neighbourhoods in their ordinary daily life. This approach has had a deep impact on how modern policies for urban regeneration are conceived and contributed to a shift towards a more complex notion of quarters and urban communities.

It is this distinction of activity orders that we assumed in this research with a focus on neighbourhood dynamics at the interface between space, behaviours and the local economy. After discussion at length with the Agencia de Ecología Urbana of Barcelona, we tabulated the categories and sub-categories of economic activities in the Barcelona dataset to a primary or a secondary order on a case-by-case interpretation of their nature. Primary activities are characterised by a larger-than-local market or catchment area; they are typically highly

Table 1. Economic activities and their correlation with street centralities

Rank	*Type*	*General category*	*Sub-category*	*Number of points*	*Activity*	*Correlations R with density of street centrality (NXX)*							
						C^B_{glob}	C^C_{glob}	C^S_{glob}	C^C_{1600}	$C^B_{glob}+S_{glob}$	$C^B_{glob}+C_{glob}$	$C^B_{glob}+C_{1600}$	$C^B_{glob}+C_{glob}+S_{glob}$
1	SEC	1	—	39,685	Retail commerce	0.550	0.709	0.615	0.599	0.653	0.691	0.654	0.686
2	SEC	1	2	*36,310*	Retail except motor vehicles, fix domestic and personal devices	0.525	0.691	0.597	0.587	0.631	0.669	0.635	0.666
3	SEC	3	10	*6,492*	Other services to people	0.517	0.682	0.554	0.527	0.608	0.662	0.605	0.651
4	SEC	2	—	12,758	Hotel, B&B, hostel, restaurant, pub, café	0.479	0.680	0.565	0.567	0.589	0.642	0.599	0.637
5	PRIM/SEC	3	—	44,253	IT tech, services to business and people, R&D	0.621	0.601	0.435	0.381	0.576	0.654	0.654	0.595
6	PRIM/SEC	5	—	12,348	PA, services of education, health and social assistance	0.524	0.611	0.449	0.321	0.543	0.579	0.488	0.581
7	PRIM/SEC	6	—	14,883	Associational, recreational and sport activities	0.467	0.620	0.488	0.427	0.536	0.620	0.547	0.580
8	SEC	5	2	*4,655*	Education	0.522	0.600	0.430	0.393	0.535	0.614	0.530	0.572
9	PRIM	3	9	*17,189*	Other service activities	0.590	0.568	0.386	0.329	0.536	0.622	0.526	0.559
10	SEC	6	2	*9,162*	Recreational, cultural and sport activities	0.427	0.580	0.445	0.444	0.491	0.556	0.500	0.536
11	PRIM	5	3	*4,727*	Health and social assistance	0.491	0.566	0.382	0.339	0.494	0.580	0.487	0.534
12	PRIM	6	1	*5,721*	Associational activities	0.429	0.564	0.451	0.456	0.496	0.547	0.509	0.533
13	PRIM	4	—	12,723	Gross commerce	0.535	0.540	0.372	0.488	0.499	0.599	0.547	0.524
14	PRIM	0	—	29,661	Other activities (not related to public)	0.398	0.515	0.515	0.480	0.516	0.501	0.500	0.523
15	PRIM	3	1	*2,961*	Activities related to transport and travel	0.506	0.518	0.381	0.355	0.490	0.553	0.492	0.510
16	PRIM	3	2	*4,598*	Financial intermediation, exept insurance	0.543	0.500	0.332	0.272	0.492	0.564	0.480	0.505

(continued)

Table 1. (Continued)

Rank	Type	General category	Sub-category	Number of points	Activity	*Correlations R with density of street centrality (NXX)*							
						C^{B}_{glob}	C^{C}_{glob}	C^{S}_{glob}	C^{C}_{1600}	$C^{B}_{glob}{}^{+S}_{glob}$	$C^{B}_{glob}{}^{+C}_{glob}$	$C^{B}_{glob}{}^{+C}_{1600}$	$C^{B}_{glob}{}^{+C}_{glob}{}^{+S}_{glob}$
17	PRIM	3	6	*1,110*	Rental of machines, domestic and personal devices	0.458	0.495	0.387	0.244	0.475	0.520	0.467	0.493
18	PRIM	1	1	*3,375*	Sell, fix and maintenance motor vehicles and fuel	0.424	0.488	0.424	0.367	0.475	0.497	0.453	0.489
19	PRIM	3	5	*10,343*	Real estate	0.533	0.474	0.304	0.244	0.464	0.541	0.451	0.477
20	PRIM	3	4	*563*	Activities related to financial intermediation	0.443	0.366	0.205	0.144	0.378	0.443	0.364	0.382
21	PRIM	3	3	*657*	Insurance	0.426	0.318	0.175	0.101	0.353	0.407	0.332	0.349
22	PRIM	5	1	*2,966*	Public Administration	0.282	0.370	0.287	0.306	0.321	0.360	0.339	0.348
23	PRIM	3	7	*138*	IT activities	0.228	0.154	0.110	0.079	0.200	0.212	0.194	0.187
24	PRIM	3	8	*202*	R&D	0.168	0.077	–0.014	–0.041	0.096	0.133	0.090	0.090

skilled, larger or more specialised economic activities such as wholesale, industry and those not related to the public or not mainly serving the end-users; and their location choice is more likely to be driven by a formal top–down decision-making process. Secondary activities are characterised by a local market or catchment area and they are typically retail and services that respond to the ordinary needs of a general public on a daily or regular basis. Due to the local nature of their market, customers of the secondary activities are less dependent on automobiles and more driven by a large number of self-organised decisions that are less affected by authorities or formal planning processes. Therefore, secondary activities express the kind of economic milieu that sustains and embodies the sense of a vibrant and walkable local community at the scale of the neighbourhood, regarded in much of current city planning as the building-block of a sustainable city (Newman and Kenworthy, 1999).

In the implementation of KDE, we set the cell's sise at 10 metres × 10 metres and followed the outer metropolitan ring roads of Barcelona to define the boundary. This resulted in a raster framework of 1 571 093 cells. We adopted a bandwidth $h = 300$ metres (unless stated otherwise), which approximates the typical sise of neighbourhoods in urban design literature (Perry, 1927). After preparation of the data, the KDE was performed on centralities and on economic activities to derive their densities. Only cells with density value >0 are used in the correlation analysis. The number of raster cells for each KDE varied from 688 482 for activity no. 3 (IT, services to business and people, research and development activities, with 44 253 entities) to 219 970 for activity no. 73 (Public Administration activities, with just 202 entities).

The various raster layers resulting from the KDE of each centrality index were then combined to construct four composite indices: $C^B_{glob} \; ^{+C}_{glob} \; ^{+S}_{glob}$; $C^B_{glob} \; ^{+S}_{glob}$; $C^B_{glob} \; ^{+C}_{glob}$ and $C^B_{glob} \; ^{+C}_{1600}$. These composite centrality indices were drawn from a recent work on 'town centredness' (Thurstain-Goodwin and Unwin, 2000), which experimented with the idea that a business might value not just one type of centrality, but a combination of centrality types.

5. Geography of Street Centrality in Barcelona

Figure 2 shows geographies of C^B_{glob}, C^C_{glob} and C^S_{glob} with distinctive patterns. C^B_{glob} (Figure 2a) reveals that 'corridors' of highly central paths along the main roads constitute the backbone of the urban fabric in Barcelona. It highlights several of the most popular spaces along major arterials such as the Av. Diagonal, the Gran Via de les Corts Catalanes, the outer route Carrer de Badal/Gran Via de Carles III/Ronda del General Mitre/Tr. de Dalt/Av. de l'Estatut de Catalunya/C. del Mas Casanovas, or the inner route Av. de Josep Taradellas/Tr. de Gracia/C. de Pi i Margall, as well as narrower spaces like the ring around the old city centre, C. de Ribes/C. del Comerc/C. Ample/Av. del Parallel. Somehow surprisingly, the historical centre is portrayed as a 'hole' surrounded by the aforementioned ring with weaker connections with the regular Cerda addition to the north-west, limited to Via Laietana and Ronda de Sant Antoni. Even the Paseo de Gracia does not emerge prominently. The C^C_{glob} map (Figure 2b), however, shows a very different concentric pattern, part of which may be attributed to the 'edge effect' (i.e. the artificial emergence of an urban core in the centre due to the definition of a study area). The C^S_{glob} map (Figure 2c) offers another different geography, which highlights the configurational consistency of

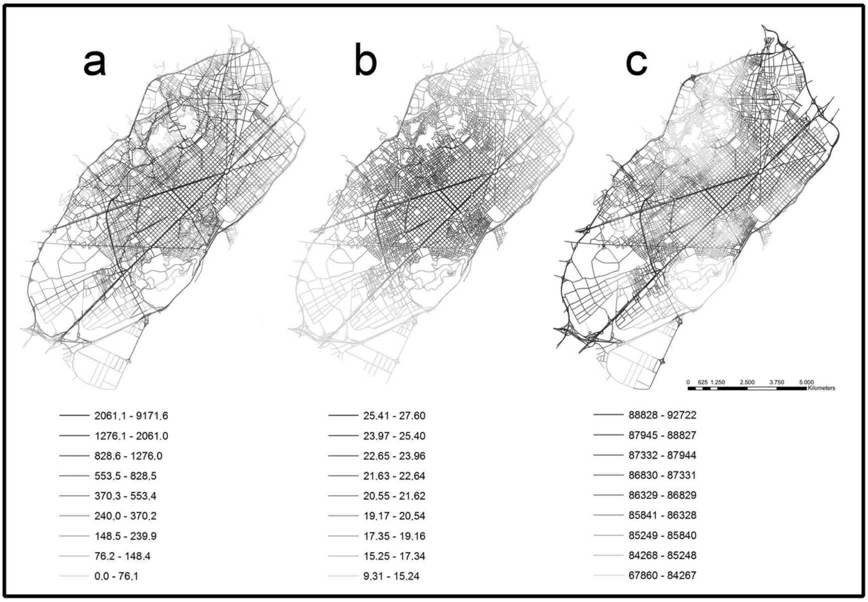

Figure 2. Global street centrality in the urban core: a. betweenness, C^{B}_{glob}; b. closeness C^{C}_{glob}; c. straightness C^{S}_{glob}.

Cerda's layout in creating a whole new centre at the metropolitan level around the new focus of Placa de les Glories Catalanes.

Figure 3 shows the corresponding KDE results. The spatial smoothing effect from the KDE helps to outline spatial patterns more clearly. Compared with C^{B}_{glob} (Figure 2a), the density of C^{B}_{glob} (Figure 3a) shows that the ring around the old city centre appears neater and more continuous. Moreover, the 'main gate' to the centre around Placa Catalunya clearly emerges along with the three internal links Via Laietana, Ronda de Sant Antoni and Ronda de Sant Pere. Moreover, a continuous central route emerges to link the Cathedral to Av. Diagonal and all the way through Placa Catalunya and Paseo de Gracia, the commercial backbone of the whole central city. Differences between C^{C}_{glob} (Figure 2b) and its density (Figure 3b) are even more striking. The whole old historical centre on the east side stands out. The homogeneous dark circle at the centre of Figure 2b is shown to be nicely structured in Figure 3b as a clear hierarchy of spaces around the Paseo de Gracia and the Gran Via de les Corts Catalanes. A whole new central spot appears towards the south-west and a new central corridor emerges along the outer high-speed roads. Differences between C^{S}_{glob} (Figure 2c) and its density (Figure 3c) are most significant. Figure 2c shows the whole north-eastern part of Cerdà Eixaimple around Placa de les Glories Catalanes as central, while Figure 3c highlights once again the old city centre, the south-west district around C. de la Creu Coberta in addition to Placa de les Glories Catalanes and the major axis converging directly on it.

Comparing Figures 2 and 3 on the geographies of street centralities and their corresponding densities calculated through KDE, we notice two important features. First, the highly diverse patterns of the three centrality indices in Figure 2 are reduced to substantially similar patterns in Figure 3. This is clearly an effect of the sheer concentration of

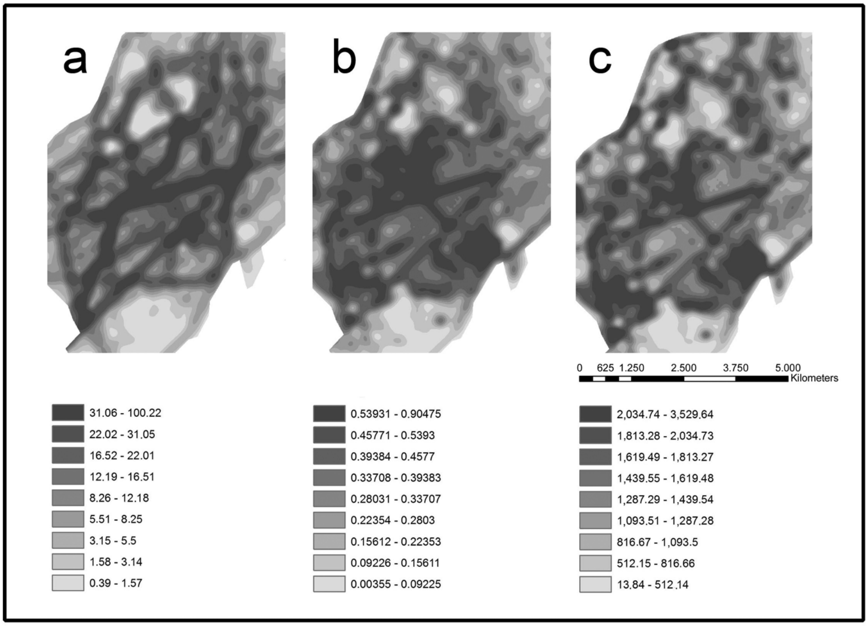

Figure 3. Density (h = 300 metres) of street centrality: a. betweenness C^B_{glob}; b. closeness C^C_{glob}; c. straightness C^S_{glob}.

streets captured by KDE and it echoes our univocal experience of urban space: we navigate in spaces that merge different ways of being central in a holistic whole. It is the presence of streets that ensures coherence to these otherwise diverging dimensions. Secondly, densities of centrality by KDE increase substantially at intersections. This also reflects our typical experience of urban spaces where corners and crossings are widely recognised in prominence.

Figure 4 shows maps of *local* closeness centrality C^C_d at three different distances. The C^C_{1600} map (Figure 4b) expresses the radius of an urban district—i.e. the catchment area of 20-minute walk or 10-minute bike. More than C^C_{800} (Figure 4a) and C^C_{2400} (Figure 4c), the C^C_{1600} geography turns out to capture the existence of historically determined sub-cores in formerly autonomous municipalities all around the Ciutat Vella. We then choose this index to inform the correlation with economic activities illustrated in section 7. Based on Figure 4b, the old city, like a heart, has been split into two distinct 'ventricles' separated by the low-centrality space of the Rambla. This pattern can be explained by the historical evolution of the city's fabric. The medieval city in fact originated around the Cathedral in the denser right 'ventricle' (the north-eastern part of the 'heart') and ran along the footprint of the ancient city walls. Rambla used to be a separating rather than a unifying factor in the city structure, which has left its mark permanently on today's street layout.

6. Statistical Distributions of Densities of Centrality and Activities

Similar to the density of street centrality, the KDE is also used to define the density of economic activities. As examples, Figure 5a

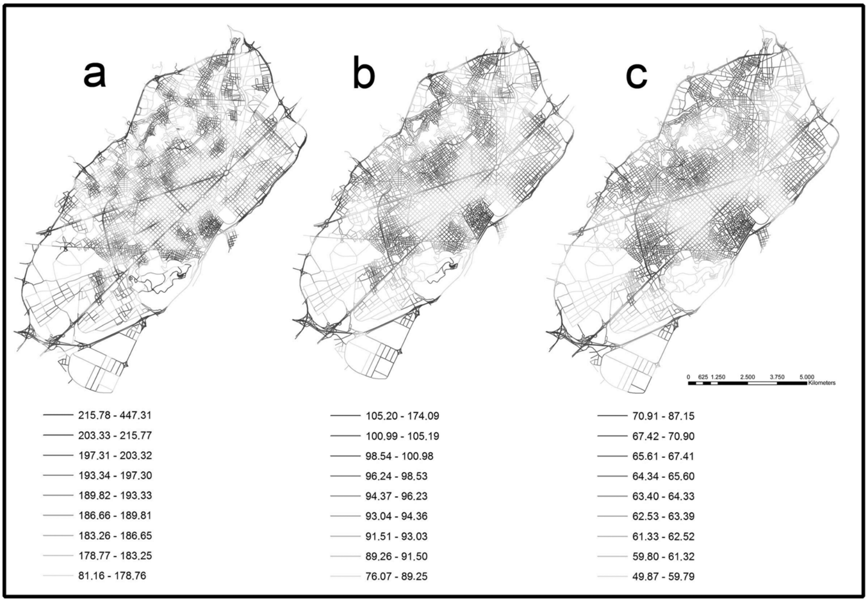

Figure 4. Local closeness C_d^C: a. d = 800 metres; b. d = 1600 metres; c. d = 2400 metres.

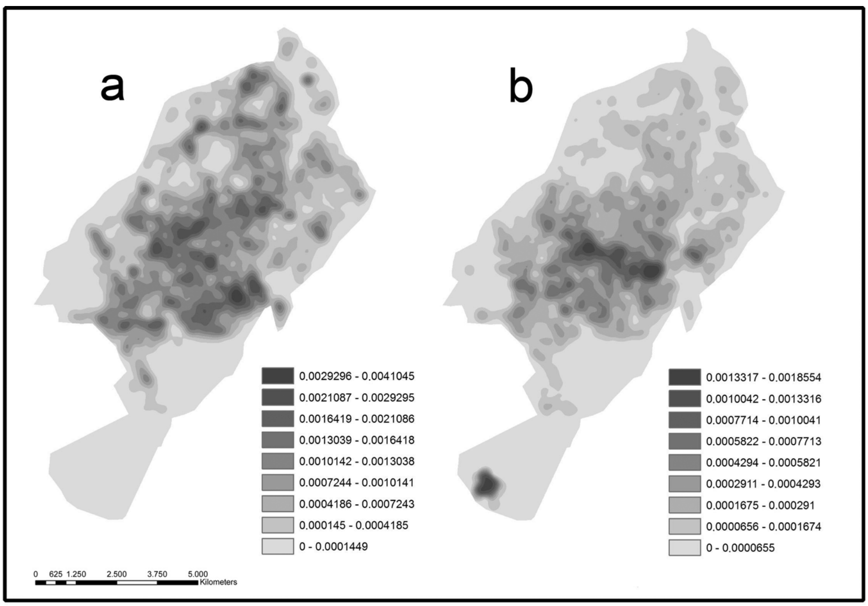

Figure 5. Density (h = 300 metres) of economic activities: a. retail commerce; b. gross commerce.

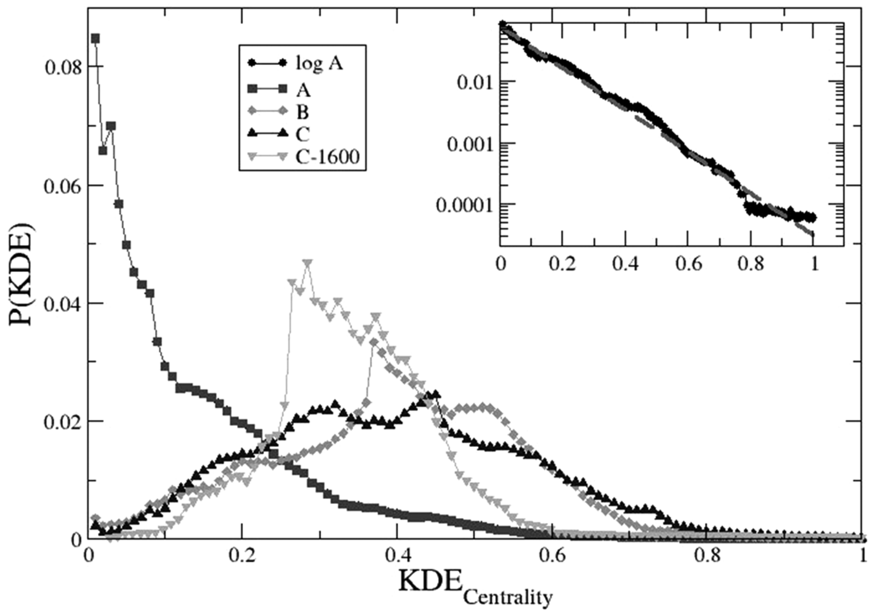

Figure 6. Probability distribution of street centrality densities: A for C^B_{glob}; B for C^S_{glob}; C for C^C_{glob}; C-1600 for C^C_{1600}.

shows the density of retail commerce and Figure 5b shows the density of gross commerce. The spatial patterns are in general consistent with those of the density of street centrality shown in Figure 3.

It is worthwhile to examine the statistical properties of the probability distributions of both street centrality and economic activity densities. The whole range of values can be viewed as a probability density function p(x), where a random chosen cell in the city has a KDE value x of street centrality (or activities) and a corresponding frequency p(x). Street centrality distributions (Figure 6) show that $C^B_{glob}$and other indices exhibit very different patterns. The distribution of C^B_{glob} fits an exponential law (shown in the upper-right inset), and the other two are more likely to fit a Gaussian function. This means that C^B_{glob} seems to exhibit a particular scale, but closeness and straightness are symmetrically distributed around a mean value.

For economic activities (Figure 7), a cumulative probability function P(x), instead of the probability density function p(x), is used to define the probability that a randomly chosen activity has a KDE value greater than x. A cumulative distribution is smoother than its corresponding density function and thus allows a finer estimation of the fitting function's parameters. Each cumulative distribution can be accurately fitted by an exponential function with its unique slope. Again, different economic activities show similar behaviour. This means that different activities spread differently on the city surface, but the intrinsic stochastic process that rules their spreading is always the same. For example, comparing hotels/bar/cafés and gross commerce, it can be seen that their densities decrease with a simlar slope.

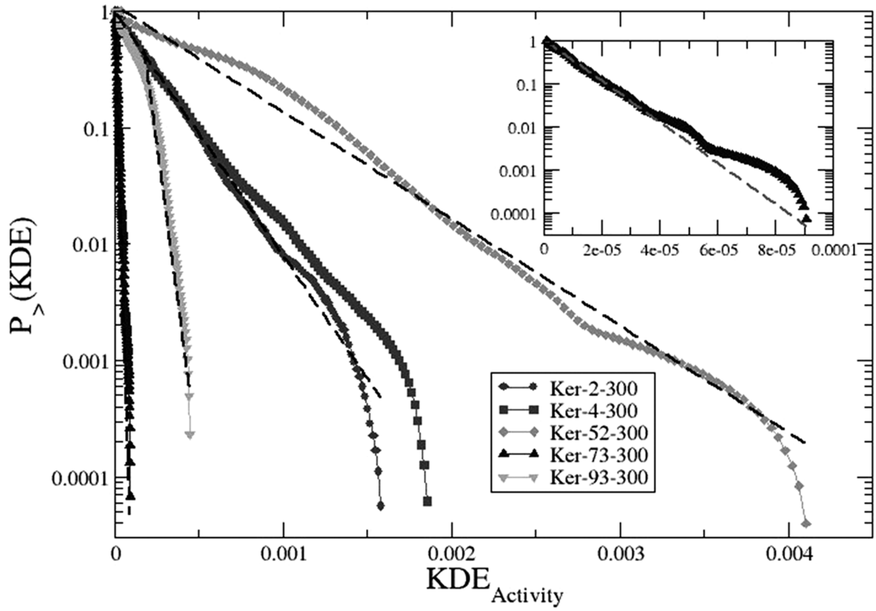

Figure 7. Cumulative probability distribution of densities of selected economic activities: Ker-2 = Hotel, B&B, hostel, restaurant, pub, café; Ker-4 = gross commerce; Ker-52 = retail, except fix motor vehicle and domestic devices; Ker-73 = research and development; Ker-93 = other services to people.

7. Correlations between Economic Activities and Street Centrality

This section examines the correlations between the densities of centrality and economic activities. Table 1 shows all possible correlations between densities of activities (7 general categories plus 17 sub-categories, for a total of 24 categories) and street centrality (4 simple and 4 composite indices). Correlation coefficients between economic activities and the complete composite index of street centrality $(C^{B}_{glob} + C^{C}_{glob} + C^{S}_{glob})$ range from $R = 0.52$ (‘other activities’) to $R = 0.69$ (‘retail commerce’) with an average R=0.59. Among the three simple global centrality indices, C^{C}_{glob} generally commands the highest correlation with economic activities with an average $R = 0.61$; C^{B}_{glob} comes second with an average $R = 0.51$; and C^{S}_{glob} has the lowest average $R = 0.49$. That is to say, economic activities considered altogether exhibit the highest correlation with street centrality as “being close”—i.e. how the street is spatially close to all others through the road network. Among the 192 R values, 190 are positive and 92 are even higher than 0.50. Given the large sample sises (average number = 568 000 cells), these correlations are considered significant.

Figure 8 ranks the correlations between the four simple street centrality indices (C^{B}_{glob}, C^{C}_{glob}, C^{S}_{glob}, C^{C}_{1600}) and the 20 detailed categories of economic activities (all the 17 sub-categories plus the 3 general categories that do not have any sub-categories). Do primary activities correlate with street centrality differently from secondary activities? Based on Table 1, the following observations can be made.

First, ‘retail commerce’ and ‘hotels, restaurants and cafes’ have the two highest correlations with the composite street centrality

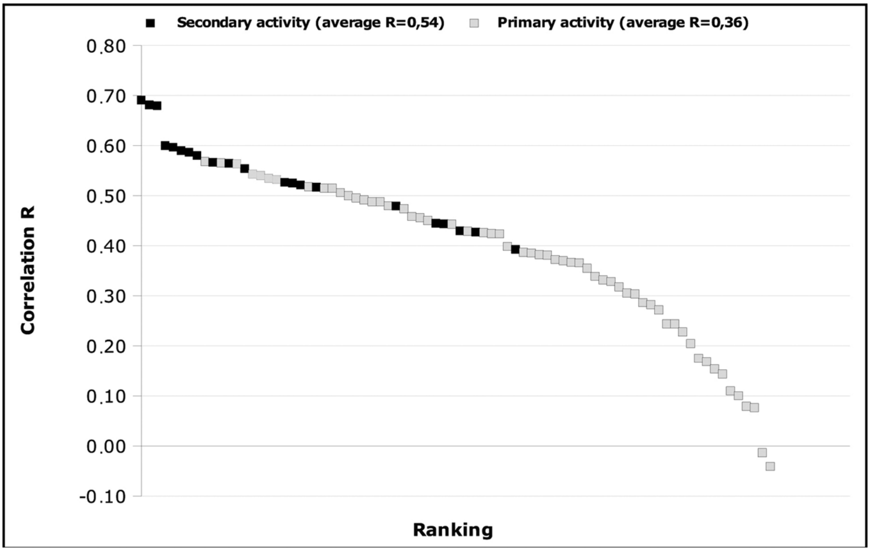

Figure 8. Correlations between street centrality indices and economic activities.

index $C^B{}_{glob} + C^C{}_{glob} + C^S{}_{glob}$. 'Gross commerce' and 'other activities not related to the public' (i.e. all industries, agriculture, farming and fishery) have the two lowest scores. This pattern is consistent across all centrality indices with only one exception in $C^B{}_{glob}$ (i.e. its correlation with 'retail commerce' is second to its correlation with 'IT services to business and people').

Secondly, activities of 'IT services to business and people' are ranked in third in terms of correlation with the composite $C^B{}_{glob} + C^C{}_{glob} + C^S{}_{glob}$ centrality index. However, such activities are sub-divided into 10 sub-categories. Nine of the sub-categories are primary and show relatively low correlations with street centrality (average R = 0.39). Only one sub-category—namely, 'other services to people', accounting for less than 15 per cent of all its 44 253 events—is secondary with $R = 0.60$.

Thirdly, among activities in the 'PA, services of education, health and social assistance' general category, 'PA, public administration' is primary and has by far the lowest correlation with street centrality. On the other side, the sub-category 'education' is secondary, but has the highest correlation with street centrality, which is attributable to its ordinary nature and dedication to generic end-users.

Finally, in Figure 8, secondary activities (Black squares) are clearly ranked higher than primary ones (light grey squares). The former have an average correlation $R = 0.54$ whereas the latter have an average $R = 0.36$. A t-test indicates that the difference is statistically significant at 0.001.

8. Conclusions

This research examines the geography of street centrality in a large European city, Barcelona, by a MCA model. The KDE method is used to measure the proximity of every place to streets and to various types of economic activities. The two sets of densities are then analysed to see whether correlations exist and whether primary or secondary economic activities are more correlated with specific types of street centrality. Do lower-order economic activities favour proximity to lower orders of central streets, and vice versa? Additional questions are raised from the KDE analysis. Does the geography of centrality density capture dynamics in urban space that would otherwise be concealed in a traditional network analysis? Does the sheer concentration of streets play a role in the correlation with economic activities?

The findings suggest that secondary economic activities show rather a higher correlation with street centrality than primary ones. Moreover, the correlation of secondary activities is generally higher with global indices of street centrality than with local indices. This counters the conventional principle in urban planning that emphasises a correspondence between the hierarchy of centres and that of economic activities located in those centres. That principle was first conceived by Ildefons Cerdà in his plan for the extension of Barcelona in the mid 19th century and, since then, has permeated the history of urban planning with major consequences for the design of neighbourhoods and cities in the 20th century. This research suggests a different approach to the relationship between neighbourhood and streets. If secondary services essential to the life of neighbourhoods mainly benefit from their proximity to urban streets that are *globally* central (for example, major thoroughfares), such urban arterials must be conceived as cores, not as borders, of neighbourhoods (Mehaffy *et al*., 2010).

This confirms the findings suggested by the direct analysis of urban spatial configurations undertaken in space syntax, and makes them more specific. Retail categories that are strictly linked with the movement of economy do preferentially locate on the most central streets, with little distinction between global and local centrality. Secondary activities, in short, even more than primary, need all the centrality they can get. This is easy to understand: primary activities are attractive enough—mainly because of their *function*—to draw people as final destinations, while secondary activities live solely on passers-by, therefore on their *location*.

The KDE analysis also reveals the centrality patterns that are not captured by the network analysis alone. Density of centrality naturally increases towards intersections because of the sheer convergence of streets in one space. In addition, the density patterns of various centralities are much more consistent than those of network centralities. That captures places experienced by us every day in cities: we are not impacted by closeness, betweenness and straightness separately, but altogether in a synthetic way. Therefore, *density in cities matters a lot*, in many senses.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Acknowledgements

Comments from three anonymous reviewers helped the authors to improve and prepare the final version.

References

Aberasturi, A. de (1984) Per una lettura di Cerdà. Introduzione alla teoria generale dell'urbanizzazione, in: I. Cerdà and A. de Aberasturi (Eds) *Teoria generale dell'urbanizzazione*, pp. 9–63. Milan: Jaka Book.

Bailey, T. and Gatrell, T. (1995) *Interactive Spatial Data Analysis*. Edimburgh: Addison-Wesley Publishers.

Battaglia, F., Borruso, G. and Porceddu, A. (2010) Real estate values, urban centrality, economic activities: a GIS analysis on the city of Swindon (UK), in: ICCSA 2010 (International Conference on Computational Science and Applications), pp. 1–16.

Batty, M. (2005) Network geography: relations, interactions, scaling and spatial processes, in: P. Fisher and D. Unwin (Eds) *Re-presenting GIS*, pp. 149–170. London: Wiley.

Batty, M. (2008) Whither network science?, *Environment and Planning B*, 35(4), pp. 569–571.

Ben-Joseph, E. (2005) *The Code of the City: Standards and the Hidden Language of Place Making*. Boston, MA: MIT Press.

Boccaletti, S., Latora, V. and Moreno, Y. *et al.* (2006) Complex networks: structure and dynamics, *Physical Reports*, 424, pp. 175–308.

Calthorpe, P. and Fulton, W. (2001) *The Regional City: Planning for the End of Sprawl*. Washington, DC: Island Press.

Carvalho, R. and Penn, A. (2004) Scaling and universality in the micro-structure of urban space, *Physica A*, 332, pp. 539–547.

Catalan, B., Sauri, D. and Serra, P. (2008) Urban sprawl in the Mediterranean? Patterns of growth and change in the Barcelona metropolitan region 1993–2000, *Landscape and Urban Planning*, 85, pp. 174–184.

Comedia (1991) *Out of hours: a study of economic, social and cultural life in twelve town centres in the UK*. Comedia, London.

Conroy-Dalton, R. (2003) The secret is to follow your nose: route path selection and angularity, *Environment and Behavior*, 35, pp. 107–131.

Crucitti, P., Latora, V. and Porta, S. (2006) Centrality measures in spatial networks of urban streets, *Physical Review E, Journal of the American Physical Society*, 73(3), article no. 036125.

Duany, A., Plater-Zyberk, E. and Alminana, R. (2003) *New Civic Art : Elements of Town Planning*. New York: Rizzoli.

Euler, L. (1736) Solutio problematis ad geometriam situs pertinentis, *Commentarii Academiae Scientiarium Imperialis Petropolitanae*, 8, pp. 128–140

Farr, D. (2008) *Sustainable Urbanism: Urban Design with Nature*. Hoboken, NJ: John Wiley and Sons.

Fotheringham, A. S., Brunsdon, C. and Charlton, M. (2000) *Quantitative Geography: Perspectives on Spatial Data Analysis*. London: Sage.

Freeman, L. (1977) A set of measures of centrality based on betweenness, *Sociometry*, 40, pp. 35–41.

Freeman, L. (1979) Centrality in social networks: conceptual clarification, *Social Networks*, 1, pp. 215–239.

Frey, H. (1999) *Designing the City: Towards a More Sustainable Urban Form*. London: Taylor & Francis.

Garcia-López, M.-À. (2010) Population suburbanization in Barcelona, 1991–2005: is its spatial structure changing?, *Journal of Housing Economics*, 19, pp. 119–132.

Garrison, W. and Marble, D. (1962) *The structure of transportation networks*. The Transportation Center, Northwestern University. Chicago, IL.

Goulias, K. (Ed.) (2002) *Transportation Systems Planning: Methods and Applications*. Boca Raton, FL: CRC Press.

Heikkila, E. P., Gordon, P. and Kim, J. *et al.* (1989) What happened to the CBD–distance gradient? Land values in a polycentric city, *Environment and Planning A*, 21, pp. 221–232.

Hillier, B. (1996) *Space is the Machine: A Configurational Theory of Architecture*. Cambridge: Cambridge University Press.

Hillier, B. (1999) Centrality as a process: accounting for attraction inequalities in deformed grids, *Urban Design International*, 4, pp. 107–127.

Hillier, B. and Hanson, J. (1984) *The Social Logic of Space*. Cambridge: Cambridge University Press.

Hillier, B., Turner, A., Yang, T. and Park, H. (2010) Metric and topo-geometric properties of urban street networks: some convergences, divergences and new results, *Journal of Space Syntax Studies*, 2, pp. 258–279.

Hillier, B., Penn, A. and Hanson, J. *et al.* (1993) Natural movement: or, configuration and attraction in urban pedestrian movement, *Environment and Planning B*, 20, pp. 29–66.

Jacobs, J. (1961) *The Death and Life of Great American Cities*. New York: Random House.

Jiang, B. (2007) A topological pattern of urban street networks: universality and peculiarity, *Physica A*, 384, pp. 647–655.

Jiang, B. and Claramunt, C. (2004) A structural approach to the model generalization of an urban street network, *GeoInformatica*, 8, pp. 157–171.

Jiang, B. and Liu, C. (2009) Street-based topological representations and analyses for predicting traffic flow in GIS, *International Journal* *of Geographical Information Science*, 23, pp. 1119–1137.

Kansky, K. (1963) *Structure of Transportation Networks*. Chicago, IL: University of Chicago Press.

Lämmer, S., Gehlsen, B. and Helbing, D. (2006) Scaling laws in the spatial structure of urban road networks, *Physica A*, 363, pp. 89–95.

Lang, R. E. (2003) *The Edgeless City: Exploring the Elusive Metropolis*. Washington, DC: The Brookings Institution Press.

Lopez, M. and Nes, van A. (2008) Measuring spatial visibility, adjacency, permeability and degrees of street life in excavated towns. Paper presented at the Centre for the Study of Architecture in the Arab Region (CSAAR) Conference, Amman.

Masucci, P., Smith, D., Crooks, A. and Batty, M. (2009) Random planar graphs and the London street network, *European Physical Journal B*, 71, pp. 259–271.

Mehaffy, M., Porta, S., Rofè, Y. and Salingaros, N. (2010) Urban nuclei and the geometry of streets: the 'emergent neighbourhoods' model, *Urban Design International*, 15, pp. 22–46.

Meyer, M. and Miller, E. (2000) *Urban Transportation Planning*. Columbus, OH: McGraw-Hill.

Mills, E. S. (1972) *Studies in the Structure of the Urban Economy*. Baltimore, MD: Johns Hopkins University Press.

Montgomery, J. R. (1998) Making a city: urbanity, vitality and urban design, *Journal of Urban Design*, 3, pp. 93–116.

Montgomery, J. R. (2003) Cultural quarters as mechanisms for urban regeneration. Part 1: conceptualising cultural quarters, *Planning, Practice & Research*, 18, pp. 293–306.

Muth, R. (1969) *Cities and Housing*. Chicago, IL: University of Chicago Press.

Nes, A. van (2005) Spatial conditions for a typology of shopping areas, in: Proceedings of the 3rd International Space Syntax Symposium, Atlanta.

Newman, P. and Kenworthy, J. (1999) *Sustainability and Cities: Overcoming Automobile Dependence*. Washington, DC: Island Press.

Osborn, F., Mumford, L. and Whittick, A. (1963) *The New Towns: The Answer to Megalopolis*. New York: McGraw-Hill.

Perry, C. A. (1927) The neighborhood unit, in: *Monograph One, The Regional Plan of New York and Its Environs*, New York Regional Plan Association.

Porta, S., Crucitti, P. and Latora, V. (2006a) The network analysis of urban streets: a primal approach, *Environment and Planning B*, 33, pp. 705–725.

Porta, S., Crucitti, P. and Latora, V. (2006b) The network analysis of urban streets: a dual approach, *Physica A*, 369, pp. 853–866.

Porta, S., Latora, V. and Wang, F. *et al.* (2009) Street centrality and densities of retail and services in Bologna, Italy, *Environment and Planning B*, 36, pp. 450–465.

Rueda, S. (2009) *Sustainable urban expansions: the legacy of the Cerdà plan* (http://www.barcelonametropolis.cat/en/page.asp?id=23&ui=292&prevNode=33&tagId=166; accessed 31 March 2011).

Silverman, B. W. (1986) *Density Estimation for Statistics and Data Analysis*. London: Chapman and Hall.

Steadman, P. (2004) Developments in space syntax, *Environment and Planning B*, 31, pp. 483–486.

Stein, C. and Wright, H. (1928) Radburn, NJ, a town of modern plan, *Architecture*, 57(3), pp. 135–136.

Thurstain-Goodwin, M. and Unwin, D. (2000) Defining and delimiting the central areas of towns for statistical modelling using continuous surface representations, *Transactions in GIS*, 4, pp. 305–317.

Vragovìc, I., Louis, E. and Diaz-Guilera, A. (2005) Efficiency of informational transfers in regular and complex networks, *Physical Review E*, 71, article no. 36122.

Wang, F. (2000) Modeling commuting patterns in Chicago in a GIS environment: a job accessibility perspective, *Professional Geographer*, 52, pp. 120–133.

Wang, F., Antipova, A. and Porta, S. (2011) Street centrality and land use intensity in Baton Rouge, Louisiana, *Journal of Transport Geography*, 19, pp. 285–293.

Wasserman, S. and Faust, K. (1994) *Social Networks Analysis*. Cambridge: Cambridge University Press.

Wilson, G. (2000) Complex Spatial Systems: The Modelling Foundations of Urban and Regional Analysis. Upper Saddle River, NJ: Prentice Hall.