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Revealing centrality in the spatial structure of cities from human activity patterns

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Abstract

Identifying changes in the spatial structure of cities is a prerequisite for the development and validation of adequate planning strategies. Nevertheless, current methods of measurement are becoming ever more challenged by the highly diverse and intertwined ways of how people actually make use of urban space. Here, we propose a new quantitative measure for the centrality of locations, taking into account not only the numbers of people attracted to different locations, but also the diversity of the activities they are engaged in. This 'centrality index' allows for the identification of functional urban centres and for a systematic tracking of their relative importance over time, thus contributing to our understanding of polycentricity. We demonstrate the proposed index using travel survey data in Singapore for different years between 1997 and 2012. It is shown

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that, on the one hand, the city-state has been developing rapidly towards a polycentric urban form that compares rather closely with the official urban development plan. On the other hand, however, the downtown core has strongly gained in its importance, and this can be partly attributed to the recent extension of the public transit system.

Keywords
polycentricity, travel survey data, spatial convolution, urban centrality, urban functions, urban spatial structure

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Introduction

Over the last century and a half, new transport and information technologies have enabled many cities to spread out from their historic cores, sprawling at much lower population densities then anything possible hitherto, and thus growing into vast metropolitan areas (Buliung, 2011). In tandem with these developments, the socioeconomic functions of traditional central business districts (CBDs) have been increasingly evolved into a multitude of dispersed and interacting hubs of employment, business and leisure (Anas et al., 1998). Understanding these new 'polycentric' forms of urban organisation is crucial for the development of adequate planning strategies, since spatial structure exerts such a strong influence on people's daily life, economic growth, social equity and sustainable urban development (Anas et al., 1998; Horton and Reynolds, 1971; Rodrigue et al., 2009). It is therefore hardly surprising that during recent years the quantitative characterisation of urban structure has gained much attention in many scientific fields, ranging from urban geography and regional science to urban economics, social physics and spatial planning (Burger and Meijers, 2012; Kloosterman and Lambregts, 2001; Meijers, 2008).

Measuring urban spatial structure

Generally, it is agreed that the two most important aspects of the (polycentric) urban spatial structure are (1) its morphological dimension, which denotes the size and spatial distribution of intra-urban centres, and (2) its functional dimension, which additionally addresses the linkages between different centres such as the daily flows of commuting or the strength of business and social network connections (Burger and Meijers, 2012; Green, 2007; Vasanen, 2012). Though high correlation exists between these two aspects, in some cases, the functional changes are not necessarily the result of morphological changes (Burger and Meijers, 2012).

A wide range of analytical methods has been proposed to measure morphological or functional aspects. Greene (1980), for instance, identifies centres using a set of reference thresholds that are derived from local knowledge. The method proposed by McDonald (1987) examines the spatial distribution of density functions and considers local peaks as possible sub-centres. A parametric method has been proposed using a regression model based on density and distance (McDonald and Prather, 1994), and non-parametric methods have been introduced thereafter based on smoothed density functions (McMillen, 2001; Redfearn, 2007). Weighted methods of combining retail density and measures of diversity have been used by Thurstain-Goodwin and Unwin (2000) to define town centres as hotspots of retail, commercial and public services for all England and Wales. Drawbacks of these approaches are the arbitrariness of the chosen population or job density thresholds and the sensitivity of the identified centres to the spatial scale of the analysis (Anas et al., 1998). There are other widely applied methods based on accessibility measures. One with quite wide popularity is called space syntax, and is based on morphological aspects of urban spatial structure. The method extracts and quantifies the relative nearness of streets based on how they are related through their topology (Hillier, 1996) but tends to ignore that centres are composed of activities other than those indirectly associated with the accessibilities of individual streets. Recent work has highlighted the importance of considering the connectivity between centres (Vasanen, 2012). This functional aspect of urban spatial structure has been suggested as playing a key role in the overall performance of an urban system (Burger and Meijers, 2012). Exemplary approaches for measuring functional interdependencies include spatial interaction models to predict the interactions between spatial units based on their size and distance (De Goei et al., 2010; van Oort et al., 2010), the use of network properties to measure connectivity based on people flows (Thiemann et al., 2010), or the concept of connectivity fields to quantify the connection of each centre to the rest of the urban system (Vasanen, 2012). A review of many of these measures is given by Batty (2013). Together, polycentricity is usually associated with the number of co-existing centres in one urban region (Kloosterman and Lambregts, 2001; Parr, 2004) and measured with the distributions of the relative importance of those centres (Burger and Meijers, 2012; Kloosterman and Lambregts, 2001; Meijers, 2008). Thus, a polycentric development can be studied as a spatial process where urban functions diffuse from major centres to sub-centres (Hall, 2009; Hall and Pain, 2006; Kloosterman and Musterd, 2001). Understanding this spatial process is particularly important, providing the basis for adequate urban planning policies (Champion, 2001; Lambregts, 2006; Riguelle et al., 2007).

Human activity data for measuring the use of urban space

As indicated above, most empirical studies of urban structure have focused on single attributes such as population or employment density as proxies to measure morphological aspects (Hall and Pain, 2006; Riguelle et al., 2007), and commuting or shopping trips for the functional aspect (Burger and Meijers, 2012). In contrast, the multiplex nature of spatial interactions that combine, for example, trips for commuting, shopping or leisure, has rarely been studied systematically (Burger et al., 2013). More importantly, these approaches are not able to measure the increasingly intertwined use of urban space: people working at home instead of at the office, students studying in coffee-shops instead of in university libraries, and so on (Harrison et al., 2003).

The recent availability of rich and often large-scale data on human activity now provides unprecedented possibilities to fill this gap and, more generally, to gain new insights in the actual use of urban space. Examples are the identification of urban functions from smart card and related survey data (Ordóñez Medina and Erath, 2013), assessing the function of different regions in a city using floating car and point of interest data (Yuan et al., 2012), or inferring land uses by combining mobile phone records with zoning regulations (Toole et al., 2012). At a larger scale, smart card data of individual person movements in the London subway has been analysed to identify the polycentric structure and organisation of the city (Roth et al., 2011). Together, these examples demonstrate a clear trend towards directly measuring the real usage and heterogeneous functions of urban space, resulting in a better understanding of the urban dynamics.

On these premises, this paper proposes a new approach to adequately measure the polycentric spatial structure of cities. The method is able to capture the functional diversity of places as reflected in different human activities for work, leisure, residence and so on. The clustering of these activities and how they are linked in urban space gives rise to a more comprehensive definition of functional urban centres that reflect the actual usage of places. More specifically, we propose a simple centrality index that can be applied to different kinds of human activity data. It is demonstrated how this centrality index can be deployed to identify urban centres and to eventually track changes in the overall spatial structure of cities over time. Note that the centrality index is not primarily designed to directly compare locations from different cities in absolute terms; but rather to track changes in the spatial structure and to compare cities in terms of the speed of such changes. In this study, detailed travel survey data is used which contains direct information on human activities, but the proposed method is equally applicable to other types of urban data from which locational activities can be derived.

Measuring the centrality of locations

The theoretical basis: Applied central place theory

Central place theory (CPT) emerged in the 19th century in France as part of early location theory (Reynaud, 1841; Robic, 1982) but it was formally introduced by Christaller (1933) in empirical terms and theoretically by Lösch (1944, 1954). This constitutes the starting point of our proposed method. CPT was originally developed to explain the size and number of towns and cities, together with their distribution in space as a result of economic competition and optimisation principles. The theory is focused on the inter-urban scale, and is based on the formal idea of a hierarchy of centres that are perfectly nested but overlapping within one other (Berry and Garrison, 1958). Centres in this hierarchy are differentiated by their *size* in terms of population and their *order* in terms of the range of functions that they provide. Accordingly, higher-order centres provide more specialised functions (goods and services) and thus are characterised by a larger trade area or hinterland from which they draw population. This nestedness implies that higher-order centres embrace all the functions of lower order centres plus an additional set of functions that differentiates them from lower order centres, and in this sense, the diversity of centres increases with their increasing size.

All this implies that diversity is a key component of centrality. Empirical studies have shown that such a nested hierarchy is indeed present in real urban systems (Berry and Garrison, 1958) with such structures being entirely consistent with spatial interaction models. Translating these basic considerations into the context of urban activity and movement data, the two fundamental aspects that determine the importance, or *centrality*, of a location within a given city are (1) the number of people attracted to different centres, reflecting their size, and (2) the diversity of their activities, reflecting their order. Functional intra-urban centres can then be identified as spatial clusters of locations with a high centrality as for example shown by Roth et al. (2011) and Thurstain-Goodwin and Unwin (2000).

Diversity and density as a basis for centrality

Half a century ago, the notion that cities become more diverse as they grow in size and in the populations served by their hinterlands was hard to measure formally because of limits on data. Berry (personal communication, 2014) recalls that although it could be clearly observed that the functions of smaller cities were subsumed into larger ones, there was little data on the frequency of visits to cities and thus it was not possible to measure the extent to which lower order goods were purchased more frequently than higher order. That large cities were more diverse than smaller ones in terms of the opportunities they offered for work and social activities was argued much more qualititively, for example by Jacobs (1961) whose mantle has been taken up more recently by Glaeser (2011). Since then there has been a veritable explosion in the literature characterising diversity (although much less on its measurement) and there are now explicit attempts to measure size–diversity relationships in works as diverse as that of Hidalgo and Hausmann (2009) on the economic performance of countries, of the Santa Fe group on the allometry of urban size (Bettencourt et al., 2007; Schläpfer et al., 2014), and of the service functions of world cities by the Globalization and World Cities (GaWC) group (Taylor et al., 2002).

Density has been more widely used as a measure of centrality largely because most cities grow from their historic core which is the functional centre for exchange of goods – in contemporary terms, the so-called central business district (CBD) – where residential and employment densities are highest. In fact, residential densities tend to be lower in the actual core as employment tends to displace residential land uses but in general, urban economic theory suggests that the cost of space in terms of rent and consequently densities for all land uses rises inexorably as one get closer to the CBD. Notwithstanding the sorts of variations that distort such regular monocentric patterns, the notion that the demand for space is highest at the most central points of the cities is key to the way land uses are organised according to the trade-off between the ability to pay and the cost of transport as encapsulated in the so-called bid rent hypothesis (Alonso, 1964). What is clear now is that different kinds of density associated with different land uses characterise different kinds of centrality and thus one needs to be careful about the choice of density type.

Merging density and diversity into a composite measure of centrality has been attempted before. Batty et al. (2004) measure diversity as the amount of activity or land use of each type located in each place, but normalised so that it is expressed as a density with respect to its distribution over the whole space. They then measure this as a difference from the region-wide average. The measure is actually constructed to pick up the degree of multifunctionality of each place but it is also used as a measure of centrality. What this measure does not do is compare the array of activity or land use types with other measures of concentration such as the number of persons visiting each place which is related to how those activities are used – for work, residence, leisure and so on. What we need to develop is such a measure and, in the next section, we will build on these ideas to show how one such measure can be constructed so that it identifies the degree of centrality of any place as a convolution of density and diversity.

A centrality index

The method proposed here quantifies the centrality of a given location by combining the number of people attracted to locations and the range of their activities that they engage in at these locations into a single value called the *Centrality Index* (CI). Moreover, it provides a smoothed density function that detects spatial clusters of locations with high centrality (CI) values. These clusters can be understood as functional centres that shape the overall spatial structure of a city. The calculation of the CI-values consists of the following three steps:

Step 1: Density and diversity. We first define density and diversity before we combine them. Density statistics measure how concentrated human activities are in one spatial unit, while diversity measures how mixed the different kinds of activities are (Cervero and Kockelman, 1997; Mitchell Hess et al., 2001). For our purposes, we define density here as the number of distinct people attracted to a given unit area (x, y), normalised by the total number of people visits in the overall $m * n$ unit space S during a time unit which is implicit. Then:

$$D(x,y) = \frac{N(x,y)}{\sum_{i=1}^{m}\sum_{j=1}^{n} N(i,j)}, \quad \text{with} \sum_{i=1}^{m}\sum_{j=1}^{n} D(i,j) = 1 \tag{1}$$

where $N(x, y)$ is the number of people visiting unit area (x, y) during a pre-determined time unit (e.g. one day). We will define these numbers below when we introduce the application.

Diversity is measured by an entropy which here is a quantitative index that describes the amount of disorder in activities, as originating from information theory (Shannon, 1948). It has long been adopted to measure the degree of complexity and order in many different types of spatial distribution, particularly in ecology but relevant here is their application to the organisation of land use arrangement (Cervero and Kockelman, 1997; Kockelman, 1997). Diversity $E(x, y)$ measures the mixing of activity types in a unit area (x, y) formulated as:

$$E(x,y) = -K\sum_{j=1}^{J} P_j(x,y) Ln P_j(x,y) \quad \text{with} \sum_{j=1}^{J} P_j(x,y) = 1 \tag{2}$$

where $P_j(x, y)$ is the proportion of those travelling to engage in activities in cell (x, y) for the activity type j during a given period of time. The constant K is defined from the maximum entropy $Ln(J)$ as $K = 1/Ln(J)$ where J is the total number of activity types. From the definitions in equations (1) and (2), it is clear that the density and diversity measures are normalised over the range from 0 to 1 such that $0 \leq D(x, y) \leq 1$, and $0 \leq E(x, y) \leq 1$.

Step 2: Ranking density and diversity. Density and diversity are two quantities with different dimensions and physical meanings. To integrate them into a single function, we first convert them from absolute values to an ordering that we refer to as a ranking. The simplest way is to set the rank of the largest density (or entropy) to 1, and then the ranks of all other areas are scaled so that the comparative scale between each of them and the highest ranked area reflects an inverse ordering. Another possibility is provided from the perspective of probability theory. We assume that the area with highest density (or entropy) value implies a maximum probability of being a higher-order centre, and we thus set its probability to 1. The probabilities of the other locations are defined across the related scales. A formal definition is given as follows. In a two-dimensional $m * n$ space S, we denote the density function as $D_{xy} = D(x, y)$, with $x = 1, 2, ..., m$, $y = 1, 2, ..., n$, and D_{xy} as being the density of cell (x, y) in S. For each cell, there is a

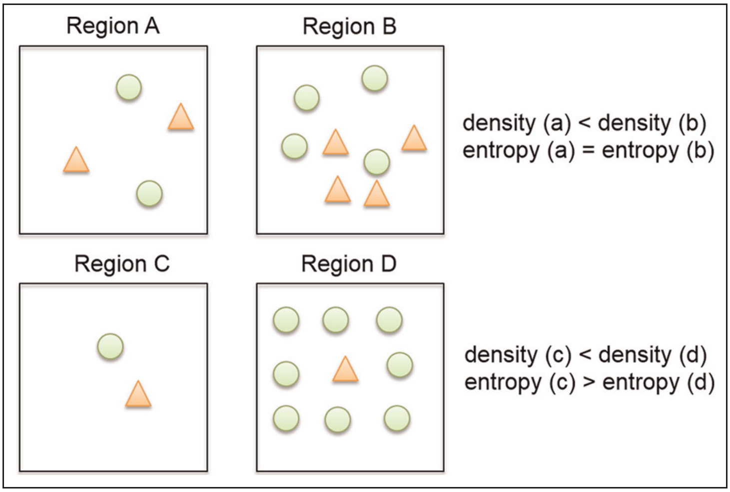

Figure 1. Possible differences between the density and diversity of activities in a given location. Circles and triangles represent two different types of activities.

function $R_D(x,y) = f(x,y,D_{xy})$ that denotes the probability of a cell to be a city centre i.e. the point of greatest centrality based on its density only. Thus, we define the density ranking function as:

$$R_D(x,y) = f(x,y,D_{xy}) = \frac{D_{xy}}{\max\limits_{xy} D_{xy}} \quad (3)$$

Similarly, $R_E(x,y) = f(x,y,E_{xy})$ is a probability density function related to the diversity $E_{xy} = E(x,y)$ at cell (x,y). We define the probability density function of diversity as:

$$R_E(x,y) = f(x,y,E_{xy}) = \frac{E_{xy}}{\max\limits_{xy} E_{xy}} \quad (4)$$

Step 3: Computing centrality by convolution-based smoothing. Density and diversity are two complementary indices referring to the spatial distribution of activities. None of them can fully represent central areas individually, especially in the context of modern cities where mono-functional areas exist alongside multi-functional ones (Batty et al., 2004). For instance, a residential district might have very high density but a limited number of activity types, which should be differentiated for multi-functional centres. Moreover, as shown in Figure 1 (top), there could be two areas having the same level of diversity but with very different densities. Figure 1 (bottom) shows that there could be some non-central areas with a high diversity of activity types yet with only a small number of people who interact (visit) the areas in question. The proposed centrality index considers both locational characteristics by integrating them into a single value. To that end, we define the centrality index $C(x,y)$ as the probability of a grid cell (x,y) being a centre, derived by combining the density of person interactions and the diversity of their activities through a spatial convolution function.

$$C(x,y) = R_D(x,y) * R_E(x,y) \quad (5)$$

Convolution is a fundamental concept in signal processing and analysis (Young et al., 1998). Generally, given two time-dependent functions $f_1(t)$ and $f_2(t)$, their convolution is calculated as $\int_{-\infty}^{+\infty} f_1(\tau)f_2(t-\tau)d\tau$ and often being denoted as $f(t) = f_1(t) * f_2(t)$. A spatial convolution follows directly and can be written as:

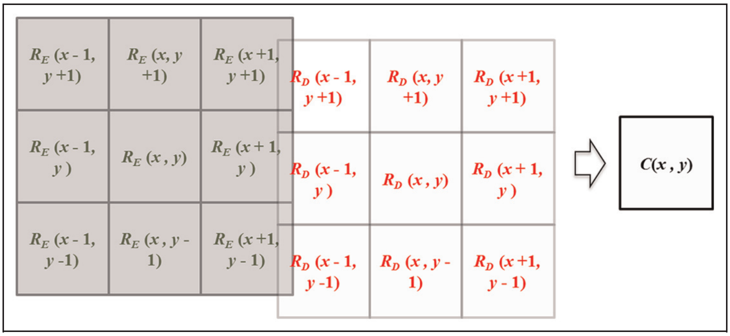

Figure 2. Spatial convolution with contiguity edges and corners.

$$f(x,y) * g(x,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(\tau_1,\tau_2)g(x-\tau_1,y-\tau_2)d\tau_1\tau_2 \tag{6}$$

where the function $f(\tau_1,\tau_2)$ is convoluted with a comparable filter $g(\tau_1,\tau_2)$ that is applied over the limits of the two-dimensional space. Equation (6) can be translated into a discrete 2D spatial convolution which 'adds' the variables $R_D(x,y)$ and $R_E(x,y)$ either of which can be considered as the filter as the convolution operator is symmetric.

In Figure 2, we illustrate the mechanism as a moving window which introduces a smoothing (or sharpening) of the joint convolution of the density and the diversity where the symmetry is visually obvious. At each cell (x,y) in the output function, we place two 3*3 windows, each of which covers 9 cells for $R_D(x,y)$ and $R_E(x,y)$ individually, and the discrete form is thus defined as:

$$C(x,y) = \sum_{\tau_1=-1}^{\tau_1=+1}\sum_{\tau_2=-1}^{\tau_2=+1} R_D(x,y) * R_E(x-\tau_1,y-\tau_2) \tag{7}$$

$C(x,y)$ is therefore the sum of the nine multiplications and the results of the convolution operation are twofold: (1) two dimensions are reduced to a single index, which is then used to delineate urban centres by a customised ranking and (2) areas with opposed density and diversity values are 'filtered out'. On a casual level, it is easy to see that conjoint high values of density and diversity are less likely than high values of either and in this sense, the centrality index is sharpened while adjacent values tend to smooth the overall function. There are strong links here to kernel density estimation as used for the simpler index by Batty et al. (2004) and of course to many smoothing techniques that are central to image processing and time-series analysis.

Measuring centrality in the evolving spatial structure of Singapore

Urban planning in Singapore

Singapore is a city-state in Southeast Asia with an area of 710 km^2. Its population including non-residents was approximately 5.4 million in 2013, 4.6 million in 2007, 4.2 million in 2004, and 3.7 million in 1997 according to national statistics.[1] Hence, the total population today has grown by about 30% compared with its population a decade ago. During the last 50 years as an independent city-state, Singapore has experienced rapid urban development and transformed itself from a declining trading post to a world city in the global economy (Huat, 2011).

From the 19th to the mid-20th century, Singapore's physical growth was rather haphazard and largely unregulated. It was only in the mid-1950s that the city-state began to implement its first concept plan with far-reaching impacts on its urban spatial structure. In particular, the revised concept plan[2] of 1991 emphasised sustainable economic growth and proposed the idea of decentralisation. It has been one of the most influential plans that shaped the structure of Singapore. The CBD was planned to be surrounded by several regional centres, sub-regional centres and fringe centres, as illustrated in Figure 3(a), with the urban plan attempting to bring jobs closer to the homes and to relieve congestion in the old central areas. As such, the plan provided a focus of transforming the city into a polycentric structure of higher and lower order centres.

The 1991 plan was implemented through a comprehensive set of planning instruments (Huat, 2011). For instance, new public transportation infrastructures such as the 'Massive Rapid Transit' (MRT) have been built to better link regional centres and to greatly shorten travel times. New residential towns along the MRT lines (e.g. Yishun or Punggol) were built, significantly increasing the population density in those areas. Industrial zones became self-contained satellite towns and became better accessible by new road systems. Moreover, several new commercial and entertainment areas were constructed outside the traditional CBD, for instance in Jurong East or Woodlands.

Data processing

Extensive travel survey data, the so-called Household Interview Travel Survey (HITS), is used to generate the measures for our empirical demonstration. The survey is conducted by the Singapore Land Transport Authority (LTA) every 4–5 years to provide transport planners and policy-makers with insights into different forms of travel behaviour. About 1% of all households in Singapore are surveyed, with household members answering detailed questions about their trip-making activities. The sampled locations for the year 2008 are shown in Figure 3(b). The HITS data provide comprehensive information about age, occupation, travel purpose, travel destination and travelling time for all those in the household who engage in travel (see Cheong and Toh, 2010).

To compare the urban spatial structure at different years, we use the HITS data for 1997, 2004, 2008 and 2012 and these contain 48,881, 51,000, 76,923 and 75,646 records after initial data processing. The data vary in terms of the way they are classified by activity types for each year, as we show in Table 1, and thus to get a unified base classification for the different years, an aggregation was conducted resulting in a total of nine aggregated activity categories. The total number of trips for each aggregated activity is given in Table 2. With these available data sets, we first show the relationships between diversity, density and resulting centrality indices. Subsequently, we examine changes in the spatial structure over the different years and compare them with the official urban plan.

Density, diversity and centrality

The values of density, diversity and centrality for the year 2008 are shown in Figure 4. As indicated, there are some locations with highly opposed density and diversity patterns. An example is the area around Jurong West, which is mostly occupied by residential blocks and some schools. Consequently,

Table 1. Aggregation of the different HITS activity categories for each year.

Aggregated categories	Original HITS categories for each year			
	1997	2004	2008	2012
1	Going home	Go home	Return home	Household activities (household chores, personal care, rest)
2	Going to school	Go to school	Education	Education
3	Going to workplace	Go to workplace	Go to work	Working for paid employment
4	Part of work	Part of work (travelling on business)	Work-related business	Work-related trip Work-related (meetings, sales etc.)
5	Shopping	Shopping	Shopping	Shopping
6	Eating	Eating	Meal/eating break	Dining, refreshment
7	Social	Social	Social visit/gathering/ religion	Religious related matters Entertainment – social
8	Recreation	Recreation	Recreation Entertainment Sports/exercise	Recreation
9	Others	For some other reason	Others	Others
	Serve passenger	Serve passenger (e.g.: pick up/drop off passenger)	To drop off/pick-up someone	Pick up drop off professional driver
	Personal business	Personal business (e.g.: visit doctor, bank)	Personal errand/task (pay bill/banking)	Other personal business
			Medical/dental (self) To accompany someone	Medical visit (self) Accompanying someone

Jurong West is characterised by high density values but low diversity values, resulting in relatively low CI-values after the spatial convolution. More examples are provided in Figure 5, showing the association between density and diversity for each grid cell. Though the linear correlation between the two dimensions is very high ($r \geq 0.5$, see Table 3), there are some clear exceptions from this general trend. For instance, the selected grid cells in Figure 5 correspond to areas in the northeast of Singapore (the Hougang area) which has comparatively high density but a lower diversity of human activities. Similar to the case of Jurong West, residential buildings dominate the land-use in that area, so that the spatial convolution reduces the CI-values into lower level bins as shown in the histograms in Figure 5. Note that the development path in this area is also characterised by an increase of the centrality values between 1997 and 2004, followed by a decrease between 2004 and 2008, as we will show below in Figure 6. Changes in these activity patterns can be attributed to a continuous development of new neighbourhoods in the area in the 1990s, but the opening of a rapid transit line in the 2000s led to a reduction of external visitors, thus reducing the areas centrality. It is worth noting that in order to assess the influence of the smoothing operation

Table 2. Number of trips broken down into the aggregated categories for each year.

Categories	Year			
	1997	2004	2008	2012
1	21,100	23,543	34,314	35,429
2	3177	7498	9757	8650
3	8407	10,425	18,310	18,293
4	1166	736	1453	1546
5	3511	2372	2239	3226
6	2966	830	1634	1988
7	1768	1115	2108	517
8	1212	267	767	490
9	5574	4123	6341	5507
Valid records in total	48,881	50,909	76,923	75,646
Original records in total	52,801	60,917	88,601	85,880

(equation (7)), we additionally calculated centrality values without applying this filter. We found that the resulting values reveal qualitatively similar trends to those reported above.

Singapore's polycentric urban transformation

The statistical and spatial distributions of centres are compared for the different years from three perspectives: (1) in terms of the overall value of centrality which reflects on how Singapore has developed in general, (2) in terms of the balance of the spatial distribution, that is, where and how are the locations of high centrality located, and (3) in terms of 'anomalous' developments, that is, any local developments which fly against the general trends. A histogram indicating the number of locations with a given CI-value is given in Figure 7 while the corresponding geographical mapping is provided in Figure 6. A comparison of further attributes of Singapore's spatial structure is given in Table 3.

(1) The overall value of centrality. During the observation period of this study the average centrality has increased substantially (see Table 3), suggesting that people engage in more diverse activities that require trips to more diverse locations. A possible reason behind this trend could be the fast economic development that created many new commercial, entertainment and social activity places. This change can also be captured from the geographical distributions shown in Figure 6, suggesting that areas with medium centrality values ($0.1 < CI < 0.3$) have become more dispersed.

At the same time, changes during different periods of the development can be observed. The number of grid cells with high CI-values ($CI > 0.3$) has substantially increased as Figure 7 and Table 3 reveal, indicating a significant increase in the number of central hubs between 1997 and 2004. The histogram in Figure 7 also shows evidence of a high heterogeneity in the locations with respect to their centrality. Simply put, most locations are visited by just a few people and for similar reasons, that is many places have a lesser number of functions and fewer interactions while a few central 'hubs' attract a huge part of Singapore's population undertaking many different activities for many different reasons.

(2) Balance of the distribution. To characterise the spatial distribution of urban activity

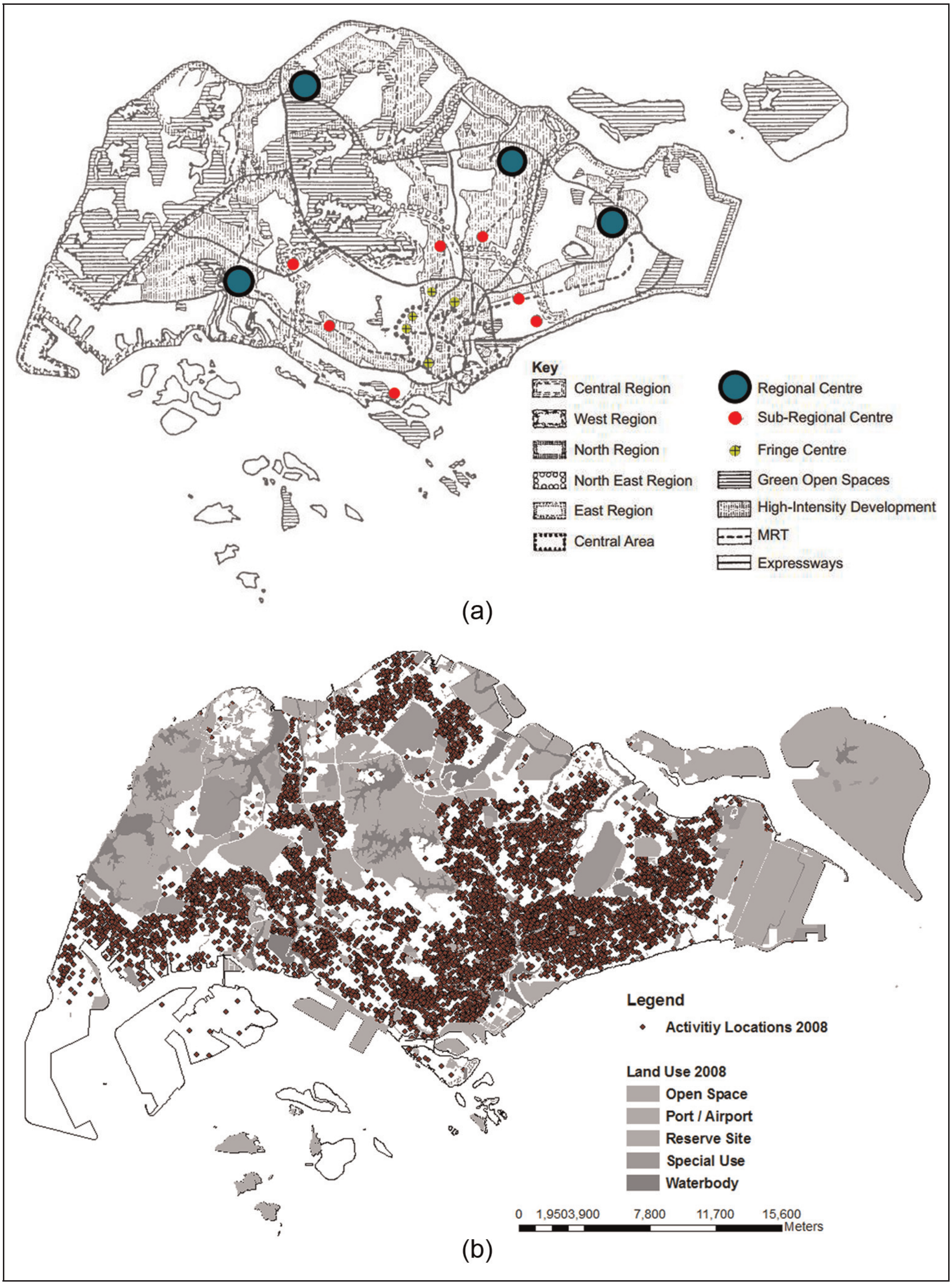

Figure 3. The case study area. (a) The concept plan of 1991 redrawn from an image created by Field (1999). (b) The survey data: activity locations are arrival locations of trips in HITS 2008. Note: The areas which barely have any activity locations are mainly open space, port, reserve sites, special use areas, and water bodies according to the 2008 Master Plan.

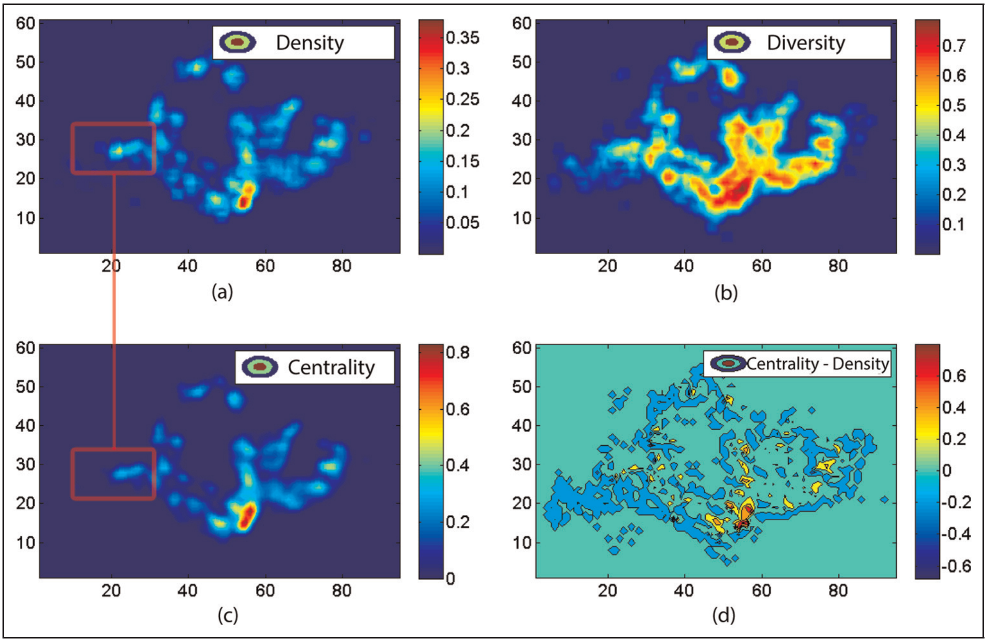

Figure 4. (a) Density of urban activities in 2008. (b) Diversity of urban activities in 2008. (c) Centrality values in 2008. (d) Differences between centrality and density to assess the functionality of convolution. The axes represent the geographical coordinate system of Singapore. The rectangles in (a) and (c) highlight the area of Jurong West.

centres we first delineate clusters of adjacent cells that have the same minimum centrality value. As indicated in Table 3, the number of these clusters also increased during the period between 1997 and 2012. Inspecting the geographic mapping in Figure 6, we can see quite clearly how the location and clustering of high CI cells has changed between 1997 and 2012. For instance, the three regions Jurong (in the west), Tampines (in the east), Woodlands (in the north) and Tao Payoh (in the middle) have gradually grown into intra-urban centres with similarly high centrality values, which correspond well to Singapore's official concept plan as shown in Figure 3. Comparing the centrality map in 2004 with 2008 shows that the CI-values in the Hougang area have decreased, while those of the centres in the western part of Singapore have slightly increased. The result generated from Singapore's latest travel survey data shows an even more balanced distribution where even the relative centrality value in downtown core area has decreased. This suggests a development trend towards more evenly distributed centres in the entire space of the city-state. The standard deviations of both density and diversity increased in 2004 and decreased in 2008 and 2012, which indicates that the distribution of activity is volatile over the period influenced by the fast development in Singapore. For instance, the western region of Singapore – the Jurong East area – was mainly occupied by industry, and the blueprint to transform the Jurong Lake district into unique lakeside destinations for business and leisure has been implemented only in recent years.

However, our study also reveals other emerging sub-centres from the results of the

Table 3. Attributes describing the spatial structure of Singapore.

Attributes	Year			
	1997	2004	2008	2102
Avg. centrality	0.025	0.040	0.047	0.049
Max. centrality	0.5435	0.7083	0.8378	0.700
Standard deviation centrality	0.057	0.091	0.096	0.097
Moran I index	0.74	0.75	0.78	0.76
Max. density	0.0185	0.0085	0.0091	0.0031
Standard deviation density	0.0008	0.0007	0.0006	0.0004
Moran I index	0.73	0.76	0.76	0.78
Avg. diversity	0.29	0.21	0.28	0.09
Max. diversity	2.03	2.13	1.97	1.91
Standard deviation diversity	0.52	0.42	0.48	0.29
Moran I index	0.86	0.84	0.86	0.89
Density & diversity correlation coefficients	0.57	0.69	0.63	0.69
Number of grid cells with centrality $>$ 0.3	23	94	104	125
Number of centres $>$ 0.3	5	10	10	14
Number of grid cells with centrality $>$ 0.7	0	1	6	0
Number of centres $>$ 0.7	0	1	1	0
Avg. travel distance (m)(point to point distance)	6679	6025.	7198	NA
Avg. in vehicle time (walking excluded)	NA	20.52	21.28	NA
Avg. travel distance for working (m)	NA	8233	9143	NA
Avg. travel distance for shopping (m)	NA	4790	6044	NA
Avg. travel distance to school (m)	NA	3697	4933	NA
Avg. travel distance for eating (m)	NA	3829	5135	NA

2008 analysis, such as the ones in Yishun and Bedok have higher relative CI-values than one would anticipate from the official plans. To some extent, this may show evidence of bottom-up and thus hard-to-predict changes that are intrinsic to shaping urban spatial structure going well beyond classic top-down planning.

(3) Anomalous developments. To further quantify the spatial clustering of locations with high CI-values, we have calculated the global spatial autocorrelation using Moran's I index (Moran, 1950). As reported in Table 3, this value increases throughout the analysis years, suggesting first that there is a strong spatial clustering of high centrality areas and second, an increasing difference of centrality between distinct areas. This second point is in line with an increasing standard deviation of the overall centrality values (see Table 3). Thereby the numbers of cells that form the highest centrality indices in the southern part of Singapore (the traditional CBD area) have been increasing (see Figure 6). The CBD has been growing (notwithstanding a decrease in the centrality values of some locations between 2008 and 2012), since the development of this area has had high priorities in early 21st century urban plans that have promoted its economic development. Retail and entertainment centres are agglomerated and closely linked to form a big commercial belt, expanding the highly popular shopping area around Orchard Road. In addition, this growth is influenced by the recent development of the public transit system. The transit system was built to substantially shorten the travel time from almost all over the island to the CBD, which, in turn, may foster increased travel distances.

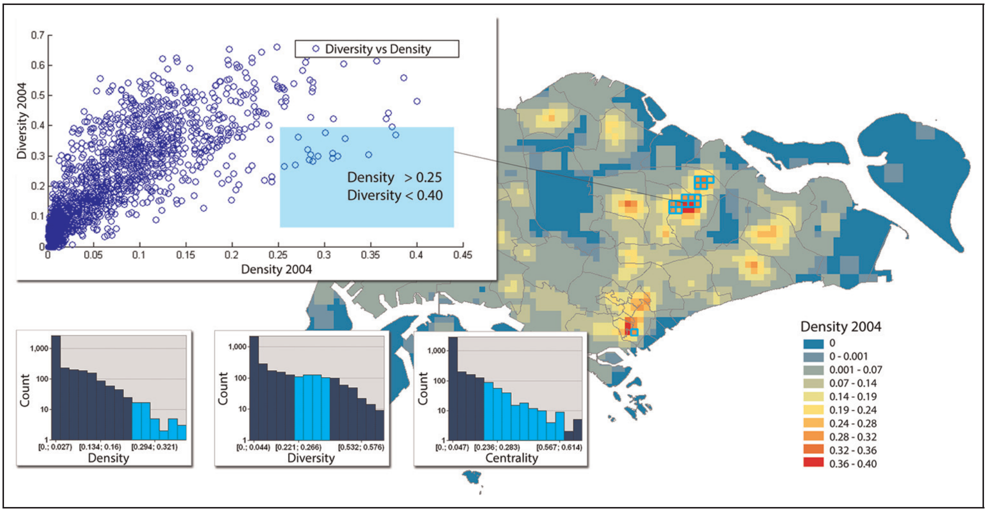

Figure 5. Density, diversity and centrality patterns. The density and diversity values are shown for the year 2004 (top left). We selected a number of cells with high density but low diversity values, mostly corresponding to areas in the northeast of Singapore (which we show in the map to the right). The histograms of density, diversity and centrality values of all areas are also given (bottom left). We highlighted the bins to which the selected values belong.

The growing importance of the CBD is consistent with a recent study of Zhong et al. (2014) and can be seen as a contra-development against the general trend towards a more polycentric urban structure through the decentralisation of activities in Singapore. The increase in the average travel distance and only small changes in the average travel time further support this outcome (see Table 3).

Conclusions

Quantitative measures for the spatial structure of cities have the potential to greatly contribute to a better understanding and management of the processes that determine urban evolution and transformation. By rethinking recent debates about polycentricity and motivated by the growing availability of human activity data, this paper has proposed a new measure of locational centrality. In contrast to existing measures that focus on either the density or diversity of human activities, this simple quantitative index integrates both aspects of centrality. Centres can thus be identified as spatial clusters of locations with high centrality, allowing us to assess how the spatial distribution of centres evolves over different years and tracing various processes of urban transformation. Taking Singapore as a case study area, we made use of extensive longitudinal travel survey data to demonstrate the effectiveness of the proposed measurement method, revealing a clear urban transformation towards polycentricity. Together our quantitative approach can be used as a starting point for more explicitly interpreting and representing urban change, being crucial for data-informed urban planning applications.

Further research is needed to advance the current method and to fully explore potential applications. First, the proposed indices are not limited to travel survey data, as they can be derived from other human mobility data with a higher spatiotemporal resolution, such as mobile phone records or smart

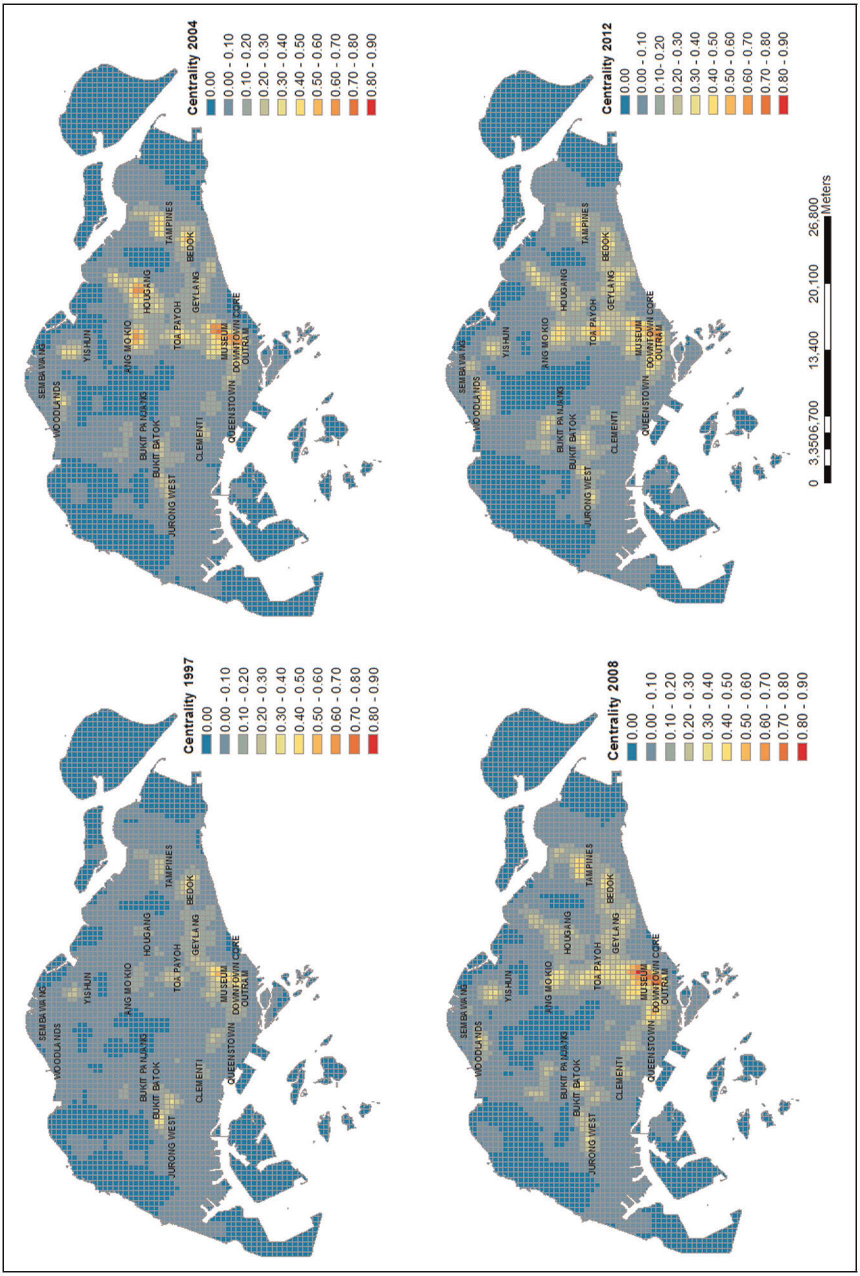

Figure 6. Centrality maps generated from the HITS travel survey for the years 1997, 2004, 2008 and 2012.

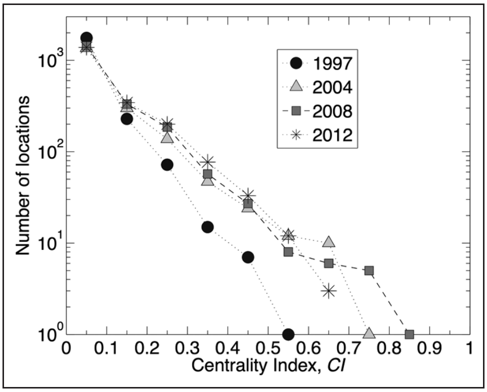

Figure 7. The number of locations with a given CI-value for the studied years.

card transit data. The growing availability of such data may overcome possible limitations caused by the scarcity or different nature of the data. Furthermore, the density and diversity functions we proposed are rather simple and can be replaced by more comprehensive ones that include, for instance, multi-purpose trips. Beyond these two basic functions, other dimensions, for instance, economic factors could also be added to the convolution. Finally, incorporating local expert knowledge into our proposed framework may help to achieve a better monitoring and explanation of the spatial structure of urban phenomena.

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Notes

1. Singapore National Statistics http://www.singstat.gov.sg/ (accessed 26 May 2014).
2. Singapore Concept Plan https://www.ura.gov.sg/uol/concept-plan.aspx?p1 = View-Concept-Plan&p2 = Concept-Plan1991 (accessed 26 May 2014).

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