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Defining Functional Polycentricity From a Geographical Perspective

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Despite the prevalence of polycentricity as a normative strategy in planning documents, a lengthy and inconclusive debate regarding its definition in academic research persists. The aim of this article is to eliminate the conceptual confusion surrounding functional polycentricity from a geographical perspective. By classifying different approaches to polycentricity, we outline the properties that characterize all forms of functional polycentricity. Accordingly, we redefine functional polycentricity and propose a corresponding framework with which to measure it. The commuting and leisure functional polycentricity of Atlanta is used as an example to illustrate the application of this framework.

Introduction

Polycentricity has been regarded as a strategy or vision in many spatial planning documents produced in Europe, Asia, and North America (CEC 1999; Sorensen 2001; RTK 2004; ESPON 2005; Dewar and Epstein 2007; Yue, Liu, and Fan 2010; Lee and Shin 2012; Li and Wu 2012; Liu and Wang 2016; Liu, Derudder, and Wang 2017). Officials and planners have high expectations that polycentricity leads to sustainable and balanced territorial development and improves economic competitiveness and social cohesion (Davoudi 2003; Meijers, Waterhout, and Zonneveld 2007; Veneri 2013). As a normative notion, polycentricity is not new to the fields of urban and regional development. In fact, an early reference can be traced back to Mumford (1938), who makes an appeal to “break up the functionless, overgrown urban masses of the past” and establish a new type of poly-nucleated city that comprises “a cluster of communities, adequately spaced and bounded” (cited in Green 2007). Some similar principles can be found even earlier, as in Howard’s (1898) scheme for the social city (Adolphson 2009) for example.

Despite the prevalence of polycentricity as a normative strategy in planning documents, a lengthy and inconclusive debate regarding its definition in academic research persists (Markusen 1999; Van Meeteren et al. 2016). Such conceptual fuzziness helps polycentricity gain universal political popularity (Davoudi 2003). However, to address a broader scope of related issues, such

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as the economic influence of polycentricity, we still need a clarified definition and suitable measurements as premises (Hanssens et al. 2014). In the words of Parr (2004), we can treat a concept as a hypothesis to be tested only after it has been sufficiently scrutinized both theoretically and empirically within a definitive framework. Therefore, this article generally aims to offer a new proposal to conceptualize and measure polycentricity. The following review provides a brief introduction on how polycentricity has evolved into an inconclusive concept.

The work of Geddes (1915: 25) marks the beginning of the study of the analytical aspect of polycentricity. He coined a new word, *conurbations*, to describe the emerging spatial entity constituted by the coalescence of several industrial towns and cities in the United Kingdom. Fawcett also adopts this term in his serial works but with the added conceptual restriction that coalesced towns and cities should not be separated from one another by rural land (Fawcett 1922, 1932). Both Geddes' and Fawcett's discussions focus on the inter-urban scale and are based on empirical findings obtained from British city regions, especially Greater London. London also inspired the first discovery of polycentricity at the intra-urban scale. Taking metropolitan London and Chicago as their two examples, Harris and Ullman (1945) propose two types of multi-nuclei cities. Metropolitan London was formed from pre-existing centers, while Chicago's centers developed because of migration and specialization. However, the use of polycentric models to describe urban structures did not gain any real currency until the 1960s (Kloosterman and Mustered 2001; Davoudi 2003), when the explanatory power of monocentric models (Wingo 1961; Alonso 1964; Muth 1969) was challenged by the evolving spatial structures of cities with multiple centers in advanced economies, thus leading to calls for new models (Berry and Kim 1993; Kloosterman and Musterd 2001). The ensuing decades thus witnessed the rise of modified polycentric models (Odland 1978; Ogawa and Fujita 1980; Papageorgiou 1990; cited in Clark 2000: 142–143). Marked by the term "megalopolis," coined by Gottmann (1957), the scale at which polycentricity is explored has even expanded to the inter-regional level (Davoudi 2003).

Clearly, the notion of polycentricity in urban research and planning was originally intertwined with scalable perspectives. However, scale is not the only issue around which the debate on polycentricity has revolved; measurement also serves as a key differentiator. In this respect, a foundational, and perhaps the most cited, framework for defining polycentricity was developed by European Spatial Planning Observation Network (ESPON 2005), which distinguishes between two complementary structural aspects of polycentricity, namely, morphology and relation. This distinction has been widely accepted in follow-up research, although relational polycentricity is usually rephrased as functional polycentricity (Green 2007; Adolphson 2009; Vasanen 2012). A related question is whether a polycentric urban area should exhibit both types of polycentricity (Green 2007; Meijers 2008; Burger and Meijers 2012). This question is echoed by some recent comparative research (Burger and Meijers 2012; Vasanen 2012; Liu, Derudder, and Wu 2016).

When measuring polycentricity, another important issue is the entity under consideration. Polycentricity may refer to the spatial clustering of many different phenomena (Vasanen 2012), and outcomes may differ depending on the entity that is investigated (Adolphson 2009), which "enables the user to 'create' the outcome as his or her desire" (Dieleman and Faludi 1998; Lambregts 2009: 16).

While research on polycentricity thus far is not limited, polycentricity remains a highly versatile, "fuzzy" and inconclusive concept (Markusen 1999; Van Meeteren et al. 2016). However, due to the extensive volume of related research, scholars have achieved substantial progress in clarifying polycentricity. The continual and widespread calls to eliminate the Babel-like conceptual confusion surrounding polycentricity (Van Meeteren et al. 2016) have increased our awareness of the aforementioned two distinctions of scale and measurement in defining this essential concept. Some comparative attempts have also been carried out to bridge the gaps between different conceptual divisions (Van der Laan 1998; Green 2007; Burger and Meijers 2012; Vasanen 2012; Liu, Derudder, and Wu 2016; Liu, Derudder, and Wang 2017). However, a recent meta-study on this topic (Van Meeteren et al. 2016) provides some new insights.

Through a scientometric analysis of more than 9,000 research studies containing more than 20,000 citations, Van Meeteren et al. (2016) find no clear division between morphology and functionality. Furthermore, influential studies on polycentricity are almost all based on the term's functional connotations. Therefore, the authors conclude that the difference between morphology and functionality may be insufficiently significant to act as a key criterion for categorizing polycentricity. According to Hall and Pain (2006: 209), the unbalanced pattern between these two aspects may result from our incomplete understanding of what functional polycentricity actually is.

Van Meeteren et al.'s (2016) findings indicate that using scale to categorize the literature on polycentricity may also be misleading. They find that the influential literature on intra-urban polycentricity is all based on studies of United States metropolitan areas, while the literature on inter-urban polycentricity is almost exclusively based on case studies of northwestern Europe. Thus, Van Meeteren et al. suggest that distinguishing among different geographic contexts rather than different scales may be more appropriate, precisely echoing the classification of Champion (2001) regarding evolutionary approaches to polycentricity, who distinguishes between regions that are polycentric due to regional integration and cities that are polycentric due to urban decentralization. By focusing on the evolutionary modes of polycentric regions/cities, this perspective provides a possibility of introducing different empirical observations into a developmental continuum of polycentricity (Lambregts 2009: 168), which can then serve as a stepping stone towards a unified definition of polycentricity.

In summary, considering that discussions and debates on functional polycentricity carry substantially more weight than morphological arguments in current research, our attempt to redefine polycentricity will mainly focus on the functional aspect. More importantly, distinction between different evolutionary modes has greater explanatory power than that based on scales and is also a promising basis for proposing a unified definition of polycentricity. Nevertheless, the scientometric analysis mentioned above indicates that such attempts are lacking. This article is an exploratory attempt to fulfill this task.

To this end, we review previous discussions on functional polycentricity from a geographical perspective and reclassify the concept according to how it is approached. We attempt to identify the key properties that characterize all routes and distinguish functional polycentricity from other similar concepts. Taking these considerations together, we propose a concise but precise definition of functional polycentricity and a framework with which to measure it. Finally, we use Atlanta as a case study to demonstrate the applicability of this framework.

Towards a definition of functional polycentricity

An intuitive strategy to define a compound concept such as functional polycentricity is to examine its parts separately. Then, how to define the functional dimension of functional polycentricity? We begin with a brief review on this aspect.

Decentralization compared with coalescence

The focus on the functional aspect of polycentricity may have two different academic origins, analogous to the two evolutionary routes of polycentricity. The first origin can be traced to decentralized metropolitan areas, especially those in the United States, such as Los Angeles, Chicago, the San Francisco Bay area and Greater Washington, D.C. After WWII, advances in transportation and infrastructure enabled increasing numbers of people to move centrifugally from crowded city centers to more desirable areas outside of the city center (Riguelle, Thomas, and Verhetsel 2007). Consequently, in the 1970s, subcenters emerged and began to characterize these areas, weakening the explanatory power of the dominant monocentric model of urban structures and leading to new models with reformulated multi-centered density gradients and trend surfaces (Gordon, Richardson, and Wong 1986; Giuliano and Small 1991; Berry and Kim 1993; Clark 2000: 142–143). Initially, the identification of these subcenters was mainly mixed with estimations of patterns of commuting flows (Cervero and Wu 1997; Vasanen 2012). Soon, the same process of decentralization was also discovered for commercial activities (Fishman 1990). Because of the growing availability of relevant data, contemporary researchers have broadened the scope of the activities that they investigated to include the recreation, education, and even the overall trips of residents (Roth et al. 2011; Zhong et al. 2015). Here, functionality refers to the choices that urban areas provide to residents as they engage in certain activities, and functional polycentricity reflects the degree to which residents have multiple options.

The second and more complicated route can be observed in the regions created by the coalescence of originally separate cities or towns. This perspective was first introduced by Peter Hall's (1966[1984]) seminal book, *The World Cities*. In this book, Hall notes that in addition to the "highly centralized giant city," a type of polycentric metropolis exists that can be functionally equivalent to the former highly centralized city (Van Meeteren et al. 2016). He describes this metropolis as a set of regions that each consist of a number of smaller, specialized, closely related centers and appreciates this type of metropolis as an ideal urban form for the mid-twentieth century (cited in Lambregts 2009: 3). The Rhine-Ruhr in Germany, the Randstad in Netherlands and the Flemish Diamond in Belgium are the most cited examples (Priemus 1994; Albrechts 1998; Kloosterman and Lambregts 2001; Hall and Pain 2006; Lambregts 2009; Van Oort, Burger, and Raspe 2010). Unlike historically centralized countries such as the United Kingdom and France, the regions mentioned above were traditionally marked by decentralized political systems and thus experienced dispersed urbanization incipiently (Hall 1982: 90; Dieleman and Faludi 1998). Since 1945, when all of Western Europe began to experience rapid population growth, this balanced pattern created the historical background for the constituent cities' topographical coalescence. In addition, facilitated by advances in communication and transportation, the subsequent decades witnessed increasingly overlapping commuter sheds in these regions (Dieleman and Faludi 1998).

Hall's comparison of large monocentric metropolises and polycentric cities is underpinned not only by polycentric cities' topographical fusion but also by the functional cooperation that characterizes these regions (Hall 1982: 54–55, 75–77). For example, in the Randstad, The Hague serves as the administrative center, Rotterdam distinguishes itself as a port city with related heavy industries and wholesale businesses, and Amsterdam functions as the cultural, financial and retail center. Discovery of the peculiarity of cases such as the Randstad later triggered the proposal of the concept of polycentric/polynuclear/polynucleated urban regions (the PUR concept). The PUR concept is an analytical approach to denoting these regions and also serves as a normative response to the challenges caused by giant world cities in the global economy (Bailey and Turok 2001; Ipenburg and Lambregts 2001; Kloosterman and Lambregts 2001; Kloosterman and Musterd 2001; Parr 2004; Van Oort, Burger, and Raspe 2010). The definition of PURs also remains subject to debate, nevertheless, regarding functionality, a consensus has been reached on the constituents of a PUR, namely, the functional interdependence among the involved cities/towns. This definition is usually phrased as "well connected" (Bailey and Turok 2001), "functionally interrelated" (Burger, Van Der Knaap, and Wall 2014), "functional interconnection" (CEC 1999) or "functional complementarity" (Ipenburg and Lambregts 2001). Thus, PURs can be further divided into two types depending on their functional configurations (Kloosterman and Musterd 2001). Heterogeneous PURs are exemplified by the Randstad, while homogeneous PURs can be historically exemplified by the Rhine-Ruhr area, where all cities were once supported by coal-related industries. Although Kloosterman and Musterd argue that this classification may be exclusive to unified (inter-urban) polycentric areas, it echoes Harris and Ullman (1945), who propose a similar distinction for individual cities, as cited above. The observation of the functional interdependence of polycentric areas also challenges the central place model and promotes the concept of "network cities" (Batten 1995; Castell 1996 [2010]; Van Oort, Burger, and Raspe 2010; Vasanen 2012), whose rationale rests purely on the economic relations among constituent cities, such as advanced producer service linkages (Hoyler, Kloosterman, and Sokol 2008; Hanssens et al. 2014). The concepts of both PURs and network cities emphasize the specialized functions that each constituent city can provide, and this emphasis essentially represents a second type of coalescence in which physical fusion is no longer necessary but functional interdependence matters.

In the review thus far, we have outlined a threefold route leading to functional polycentricity. By drawing on previous classifications (Champion 2001; Parr 2004), we list some comparative attributes of the three types in Table 1.

Topography compared with topology

Returning to the question stated at the beginning of this section, we can now conclude that the functional aspect of polycentricity has two connotations. On the one hand, functionality refers to the capacity (space, facilities, etc.) provided by urban areas to local and neighboring agents (residents, firms, etc.) for certain activities. On the other hand, functionality also represents cities' specialized functions (or comparative advantages, from a competitive perspective) when they are increasingly incorporated into a highly connected economic network.

At first glance, this twofold connotation resides in the differences among the activities used to assess polycentricity. However, from a geometrical perspective, such differences can be further expressed by a distinction between topography and topology, two spatial forms of those activities. In topographical space, activities can always be aggregated into fields with continuous distributions (Haggett 1965; Van Meeteren, Neal, and Derudder 2016). In most cases, this is the form that we use to map activities such as commuting and shopping. In contrast, activities in topological space are usually described in networks/discrete graphs through "nodalization" (Van Meeteren, Neal, and Derudder 2016), which corresponds to the form that we use to depict many "trans-spatial" relationships, such as advanced producer-service linkages.

Returning to Table 1, the classification of each coalescence can also be derived from this distinction. Accordingly, Coalescence I and Coalescence II can be rephrased as topographical coalescence and topological coalescence, respectively. This distinction reflects the type of space where functional polycentricity can exist.

Taking this distinction as a second dimension, together with the distinction between decentralization and coalescence, we can deduce a quartering framework to conceptualize functional

Table 1. Comparison of Three Types of Functional Polycentricity

		Coalescence	
Spatial process	Decentralization	Coalescence I	Coalescence II
Historical Exemplary areas	Chicago, USA Los Angeles, USA San Francisco, USA Greater Washington, D.C., USA	The Rhine-Ruhr, Germany The Randstad, the Netherlands The Flemish Diamond, Belgium The Kansai, Japan	
Challenges	Congestion; High commuting cost	Regional disparities; Disadvantaged economic competitiveness	
Adjusted model	From a monocentric city to a multicentric city/PUR		From the central place theory to network cities/PUR
Typical Functionality	Commuting and shopping		Advanced producer-service linkages

polycentricity; this framework includes topographical decentralization, topological decentralization, topographical coalescence and topological coalescence. Compared with the empirical classification shown in Table 1, topological decentralization is added to exhaust the theoretical possibilities.

Centrality compared with polycentrality

The question then becomes what properties are shared among the four evolutionary prototypes of functional polycentricity?

As stated earlier, when discussing the distinction between topography and topology, the connotation can refer to the space where polycentricity is measured. However, the differences between spatial types do not necessarily indicate total heterogeneity between corresponding spatial activities. Indeed, only one form of activity is strictly used to assess functional polycentricity, namely, the flows.

The unanimous employment of flow data to assess the functional aspect of polycentricity, or urban structures at a more general level, is deeply embedded in the terminology of the "space of flows." In his seminal book, *The Information Age: Economy, Society and Culture (Vol. I: The Rise of the Network Society)*, Castells (1996 [2010]: 442) coins this term to denote a new spatial logic. According to this logic, with the advent of the Information and Knowledge Era, flow processes have come to dominate our social practices, and physical contiguity is no longer necessary for interaction. This logic has been correspondingly accompanied by an academic paradigm shift in urban science, from the conventional methodology founded on cities' own attributes to a flow-data-based network paradigm (Liu, Derudder, and Wu 2016). In the research on polycentricity, the notion of the "space of flows", together with Sassen's (1991) emphasis on advanced producer services in globalization and Taylor's (2004) "world city network", later led to an influential project called POLYNET (Hall and Pain 2006; Hoyler, Kloosterman, and Sokol 2008). However, the existence of the "space of flows" does not indicate that no flows exist in the "space of place." This paradigm shift can also be identified in subsequent research on urban topographical structures (Roth et al. 2011; Zhong et al. 2015). Additionally, an independent academic discourse begins using commuting trips to explore urban structures, as cited above (Cervero and Wu 1997; Van der Lann 1998; Vasanen 2012).

The ubiquitous use of flows to explore functional polycentricity both topographically and topologically clearly indicates that some degree of isomorphism exists between these two perspectives. In fact, when we use flows to explore urban structures, these flows are seldom expressed as their entire forms but rather as directed sequences of crucial locational nodes. When a functional aspect is added, flows boil down to directed functional practices with one end indicating providers' locations and the other end indicating users' locations. Therefore, for a certain function, flows embody the spatial relationship between an urban area's centers and hinterlands; that is, the spatial pattern of centrality. Previously, Burger and Meijers (2012) drew a useful distinction between nodality and centrality. According to their analysis, centrality reflects a center's ability to provide goods, services and jobs to non-local inhabitants. This definition captures the same aspect of flows because it crystallizes the relationship between centers and hinterlands. Note that in regard to topological cases, which are usually in the form of nodal graphs, regarding all nodes as centers is misleading because the functional flows between them suggest that a center-hinterland relationship exists. Thus, in these cases, we should similarly provide a distinction between center nodes and hinterland nodes.

Indeed, the distinction between topography and topology is not as much an empirical generalization as a methodological taxonomy. As stated above, topographical space helps stretch the continuous distribution ("field") of entities, while topological space is suited to situations where connectedness plays a crucial role (Van Meeteren, Neal, and Derudder 2016). Therefore, the choice of spatial type that we use depends more on our intentional focus rather than the implications that associated activities actually entail. In other words, different spatial types or geometries provide us with different languages to describe different properties of the same object (Van Meeteren and Bassens 2016; Van Meeteren, Neal, and Derudder 2016), and the center-hinterland relationship is the "same object" here.

In sum, we argue that the isomorphism between topography and topology lies in both concepts being analyzable within a center-hinterland discourse. Thus, in seeking a unified definition of functional polycentricity, what remains to be established is to eliminate the distinction of spatial process (decentralization compared with coalescence) under the same discourse remains to be established.

In fact, discussions of the center-hinterland relationship are not implicit at the very beginning of research on polycentricity, either from a decentralization perspective or a coalescence perspective. The discovery of the polycentric pattern in decentralized United States metropolises was initially based on the observation of new centers that emerged on suburban peripheries. These new centers took over part of the original centers' hinterlands, especially in terms of commuting (Giuliano and Small 1991; Cervero and Wu 1997; Lee 2007). Similarly, typical coalesced regions in north-western Europe are also characterized by overlapping commuting hinterlands that surround centers, as noted above (Dieleman and Faludi 1998; Clark 2000: 145). Concerning the cases with functional complementarities/divisions among coalesced cities, overlapping hinterlands are also regarded as an essential feature of polycentric areas (Ipenburg and Lambregts 2001: 81; ESPON 2005: 4). These observations that reveal overlapping hinterland features suggest different approaches to polycentricity and may be a promising stepping stone toward a unified definition.

A definition of functional polycentricity

Although the feature of overlapping hinterlands is crucial, it is far from adequate to distinguish polycentricity. For that task, we need additional refined statements.

In a multicentric system, an overlapping system suggests that the agents (residents or firms) can be served by several centers with either homogeneous or heterogeneous functions. This reflects the exact emphases of previous scholars in the adjectives they use to restrict the connotation of functional polycentricity, such as "well-connected," "functionally interrelated," "functional interconnection," and "functional complementarity." Accordingly, we can use the term "integrated" to indicate this aspect of polycentricity. Another widely accepted essential property featuring functional polycentricity lies in the balanced pattern among the involved entities. In previous research, this property is usually phrased as "with no one center dominant" (Bailey and Turok 2001), "without a clear hierarchical ranking" (Davoudi 2003), "a certain balance in the centrality of constituent centers" (Hanssens et al. 2014), "equally important" (Burger, Van Der Knaap, and Wall 2014; Liu, Derudder, and Wu 2016), "a relatively even distribution of importance" (Liu and Wang 2016) and so on.

Both properties distinguish functional polycentricity from other similar concepts. Integration draws a dividing line between functionally polycentric systems and systems comprising isolated entities that may still show a certain degree of morphological polycentricity; balance renders them distinctive from hierarchical urban systems. The pattern of overlapping hinterlands can then be used to underpin a unified method to measure these two properties simultaneously. Specifically, totally overlapping hinterlands among centers are equal to both an integrated and a balanced pattern, thus constituting a functional polycentric area.

Therefore, we can define functional polycentricity as a cluster of balanced and integrated centers with totally overlapping hinterlands. Certainly, this is a theoretical situation that may never appear in reality. Actual patterns are more likely to form a continuum that includes all possible patterns of the center-hinterland relationship. This continuum begins with a situation in which everywhere is isolated from everywhere and ends with a contrary situation in which everywhere is hinterland/center to everywhere. Interestingly, both situations can be described as acentric regions. Other situations at least contain monocentricity, multicentricity, and polycentricity. Multicentricity refers to an intermediate pattern where centers have been functionally connected through overlapping hinterlands but are still insufficiently integrated or balanced and thus do not present a polycentric pattern.

A process of polycentralization begins with the isolated acentric pattern, advances through the three stages of monocentricity, multicentricity, and polycentricity, and reaches the integrated acentric pattern. This process can be observed in both topographical and topological space and can be driven by either decentralization or coalescence. Accordingly, we can list four evolutionary routes to functional polycentricity, as shown in Table 2.

Measurement

The question then becomes, how do we measure this pattern?

Suppose that a set of entities (e.g., cities) $\{I_1, I_2, \ldots, I_n\}$ comprise a center set $\{C_1, C_2, \ldots, C_n\}$ and a corresponding hinterland set $\{H_1, H_2, \ldots, H_n\}$. H_i is the hinterland of C_i. Thus, for I_i and I_j, when H_i and H_j are closer, I_i and I_j are more balanced with each other.

To measure the degree of integration, we have H_{ij} denote the overlapping part between H_i and H_j. Then, we further have

$$O_{ij} = \frac{H_{ij}}{H_i} \tag{1}$$

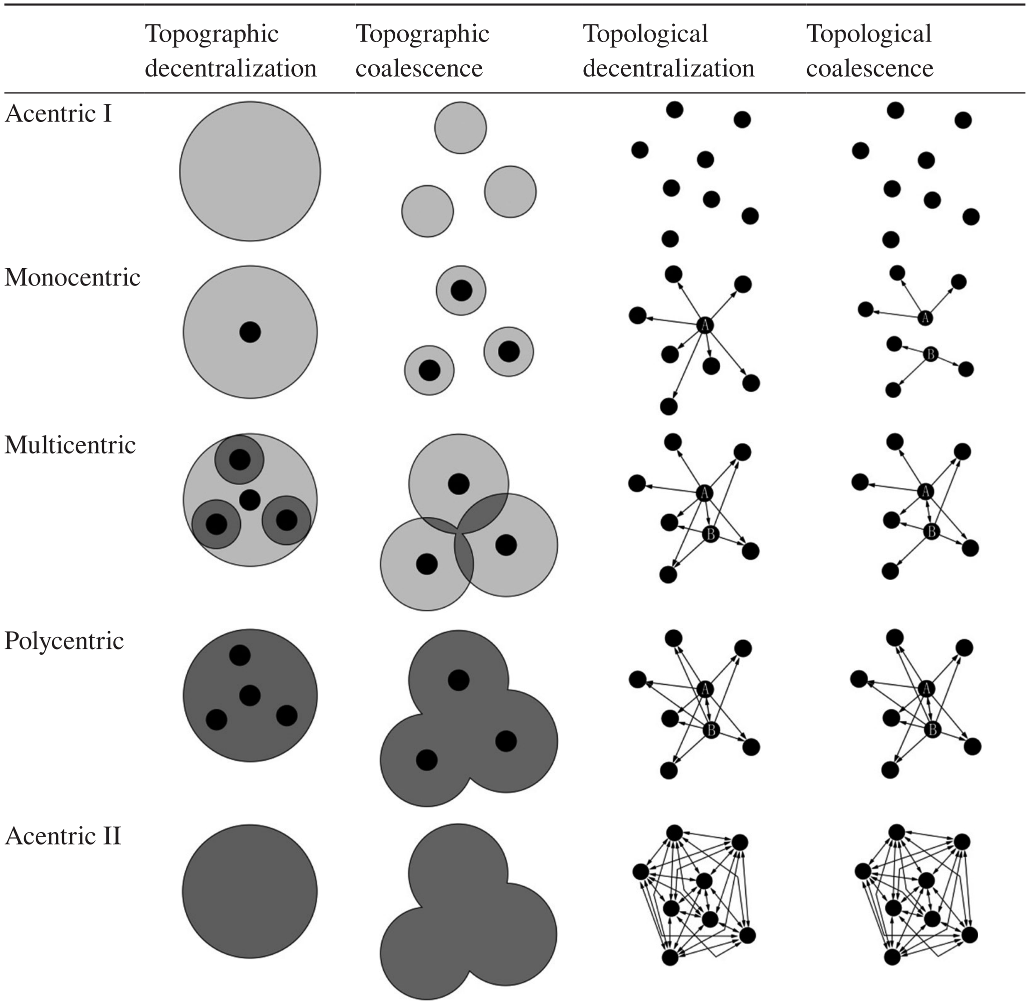
$$O_{ji} = \frac{H_{ij}}{H_j} \tag{2}$$

where O_{ij} and O_{ji} denote the proportion of H_i's overlap with H_j and the proportion of H_j's overlap with H_i, respectively. When either O_{ij} or O_{ji} is equal to 100%, one entity becomes totally integrated into the other entity; that is, even the one-sided approximation to 1 in the pairing elements is sufficient to determine that the involved entities have formed an integrated system. Therefore, when the maximum of O_{ij} and O_{ji} is closer to 100%, I_i and I_j are more integrated.

When $O_{ij} = O_{ji} = 100\%$, which indicates that $H_{ij} = H_i = H_j$, that I_i and I_j can be deduced to constitute a functional polycentric system since their hinterlands are totally balanced and integrated.

The case above indicates a two-center situation, while for a system I with more than two centers, we can obtain an overlapping hinterland matrix $\boldsymbol{O}$ as

Table 2. Polycentralization by Four Different Routes



● center/node; ▭ exclusive hinterland; ▬ overlapping hinterland; ⟶ center-hinterland relationship; ⟷ mutually center-hinterland relationship.

$$\begin{bmatrix} 1 & O_{12} & \cdots & O_{1n} \\ O_{21} & 1 & \cdots & O_{2n} \\ \vdots & \ddots & \ddots & \vdots \\ O_{n1} & O_{n2} & \cdots & 1 \end{bmatrix}$$

where n is the number of entities (or centers), and O_{xy} denotes the proportion of H_x's overlap with H_y. Clearly, we have $0 \leq O_{xy} \leq 1$, $O_{kk} = 1, k = 1, 2, \ldots, n$. This matrix is also suitable for depicting a system with heterogeneously functional centers. In this case, H_i and H_j denote the hinterland concerning the two different functions that are provided by C_i and C_j, respectively.

Similar to the two-center case, for a functional polycentric system I, its ideal overlapping hinterland matrix $\boldsymbol{E}$ is an $n \times n$ unit matrix.

$$\begin{bmatrix} 1 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 1 \end{bmatrix}_{n \times n}$$

If we can measure the similarity between matrices $\boldsymbol{O}$ and $\boldsymbol{E}$, we can measure the degree to which system I can be considered functionally polycentric. Here, we use the standardized distance to measure this similarity, which is also the index of the polycentricity, as

$$P_{\text{general}} = 1 - \frac{\sqrt{\sum_{x=1}^{n} \sum_{y=1, y \neq x}^{n} \left(O_{xy} - 1\right)^2} - 0}{\sqrt{n^2 - n} - 0} \tag{3}$$

where $\sqrt{n^2 - n}$ and 0 are the theoretical maximum and minimum of the Euclidean distance between $\boldsymbol{O}$ and $\boldsymbol{E}$, respectively. This calculation yields a value of 1 for a completely polycentric system and 0 for a system of totally isolated entities. However, P_{general} is a general index that is less capable of reflecting the compound nature of functional polycentricity, which is formed from balance and integration.

To approach such a compound index, we can first measure the degree of balance of system I by calculating the geometric mean of the ratio of the smaller hinterland to the larger hinterland for each pair of centers. Formally,

$$P_{\text{balance}} = \sqrt[\frac{n(n-1)}{2}]{\prod_{x=1}^{n} \prod_{y=x+1}^{n} \frac{\min\left(H_x, H_y\right)}{\max\left(H_x, H_y\right)}} \tag{4}$$

where $n\,(n-1)\,/2$ is the number of pairs of centers. The theoretical maximum is equal to 1 when $H_x = H_y$ for all x and y, suggesting a totally balanced pattern.

Similar to the two-center situation expounded above, integration can be measured by calculating the standardized distance between 1 and the larger value in each pair of transposed elements in $\boldsymbol{O}$. Formally,

$$P_{\text{integration}} = 1 - \frac{\sqrt{\sum_{x=1}^{n} \sum_{y=x+1}^{n} \left[\max\left(O_{xy}, O_{yx}\right) - 1\right]^2}}{\sqrt{\frac{n(n-1)}{2}}} \tag{5}$$

where $\sqrt{(}n\,(n-1)\,/2$ is the maximum of the sum of distances, and the minimum is equal to 0 when $\max\left(O_{xy}, O_{yx}\right) = 1$ for all x and y.

When P_{balance} or $P_{\text{integration}}$ is closer to 1, system I is more balanced or integrated. Thus, by multiplying these two parts, we can identify a compound index for measuring functional polycentricity:

$$P_{\text{compound}} = P_{\text{balance}} \times P_{\text{integration}} \tag{6}$$

Case study: Commuting and leisure functional polycentricity in Atlanta

Study area and data

We take Atlanta as the study area. According to previous literature, this region is a typically polycentric or at least multicentric metropolitan area (Cutsinger and Galster 2006; Griffith and Wong 2007; Hajrasouliha and Hamidi 2017). We use data from the Household and Activity Travel Survey conducted by the Atlanta Regional Commission and the Georgia Department of Transportation in 2011. This survey covers a study area with 20 counties of the Atlanta Regional Commission (the ARC region). Based on an investigation of 10,278 households within the study area, this survey records a total of 119,488 trips of these households and their members during assigned 24-hour periods.[1]

Functional trips can then be identified according to their purposes. In this article, we measure both the commuting functional polycentricity and leisure functional polycentricity of Atlanta. Commuting trips are defined as trips whose primary or secondary purpose concerns work-related activities, while leisure trips are defined as those whose primary or secondary purpose concerns shopping, dining, recreation, or attending major sporting events. The origin and destination of each trip are coded using the traffic analysis zone (TAZ). These TAZs constitute the analytic units, based on which we can further identify the centers of the ARC region.

There are two reasons why leisure function is also involved in this article. Firstly, previous research on the spatial structure of Atlanta is mostly focused on its population distribution or employment distribution. However, a polycentric city with regard to one function may be monocentric with regard to another. This causes us to question whether Atlanta, a universally acknowledged polycentric, or at least multi-centric, urban region with regard to employment, may also feature a similar pattern with regard to other urban functions such as entertainment and leisure. Besides, entertainment and leisure themselves have been very important reasons for people to make a journey now (Kloosterman and Musterd 2001). For example, of the total 119,488 recorded trips in Atlanta, 17,959 ones are leisure trips, exceeding commuting trips by 33%. This trend reflects the functional diversification of urban centers (Zhong et al. 2015), which cannot be reflected by commuting/employment alone (Veneri 2013).

Identifying centers

Two opposing methodologies exist for identifying urban centers. One approach is top-down, indicating that the centers are usually predetermined and identifying them depends heavily on prior knowledge. The other method is based on bottom-up approaches, through which centers are usually algorithmically detected from the microdata of human activities. Comparatively, the bottom-up method provides a more comprehensive and substantial means of understanding urban structures (Davoudi 2008; Vasanen 2012). Therefore, in this article, we follow the bottom-up methodology.

Bottom-up methods can be further classified into two types: parametric methods, such as threshold/cut-off-based measures, and nonparametric methods, such as locally weighted regression (LWR) and exploratory spatial data analysis (ESDA) (Veneri 2013; Li and Liu 2018). These two types of methods have their respective advantages and disadvatnages. The former embodies a principle of consistency and is easy to employ but has a problem of arbitrariness, while the latter requires little local knowledge; however, each has some specific methodological problems. For example, LWR is associated with several statistical problems, including cases with extreme coefficients, poor fitting local models, and multicollinearity, which are difficult to solve when the sample size is large (Hajrasouliha and Hamidi 2017).

Considering that the ARC region consists of approximately 2,000 TAZs, we think that ESDA, local Moran's I for instance, is a more reasonable choice for this article. This spatial autocorrelation index has been widely used in spatial research to identify centers or hotspots (Riguelle, Thomas, and Verhetsel 2007; Vasanen 2012; Han and Shu 2017; Arribas-Bel and Tranos 2018).

Certainly, Local Moran' I is also not flawless. As it determines local non-randomness in the data, this indicator will also detect rather weak spatial clusters (Vasanen 2012). Therefore, a two-step method would be more preferable. First, Local Moran's I is employed to detect candidate centers. Then, a threshold can be applied to exclude weak candidates. This two-step combination enables us to best exploit the advantages and bypass the disadvantages of the both types of methods.

Employing Local Moran's I requires two predefined parameters, including the significance level and spatial matrix measure. The former is usually set 5%. However, for Local Moran's I, the significance level is actually a pseudo-significance level and a problem of overlapping neighboring elements exists among spatial units in its calculation; therefore, using a lower level such as 1% is more reasonable (Baumont, Ertur, and Le Gallo 2004). For the spatial weight matrix, distance-based measures may lead to methodological problems when the size of spatial units varies significantly (Baumont, Ertur, and Le Gallo 2004). In addition, these measures will also smooth out the value for the neighborhood, which may blur the lines between centers and the remaining areas (Riguelle, Thomas, and Verhetsel 2007). Therefore, in this article, the contiguity-based measure is adopted.

For the measured attribute, centers can be defined as places with high centrality. According to Alderson and Beckfield (2004) and Burger and Meijers (2012), centrality is a place's attractiveness or its ability to provide goods, services, jobs, and opportunities to non-local entities. Thus, for each TAZ, we use the number of incoming flows, namely, flows with their destinations inside this TAZ and origins outside of it, to represent its centrality. Then, neighboring "HH" (high-high) and "HL" (high-low) clusters can be selected as candidate centers. Here, two TAZs are regarded as neighboring units if they belong to each other's two-nearest neighbors. This looser definition is applied to balance the effect of heterogeneous spatial division of TAZs, which causes fragmented patterns in high-density areas.

Finally, a relative threshold is adopted to exclude weak candidate centers. Following Vasanen (2012), weak clusters are defined as sites where the number of incoming flows accounts for no more than 0.5% of the total flows.

Figs. 1 and 2 illustrate the identified commuting centers and leisure centers of the ARC, respectively.

Measuring functional polycentricity

To formally define the hinterland of centers, we have t_{ij} denote the number of leisure trips from TAZ T_i to a center C_j. Thus, for each C_j, we have $H_j = \{T_{j_1}, T_{j_2}, T_{j_3} \dots T_{j_m} | t_{j_n j} \neq 0, n = 1, 2 \dots, m\}$ denote its hinterland. Thus, the overlapping hinterland between C_x and C_y can be formulated as

$$H_{xy} = H_x \cap H_y \tag{7}$$

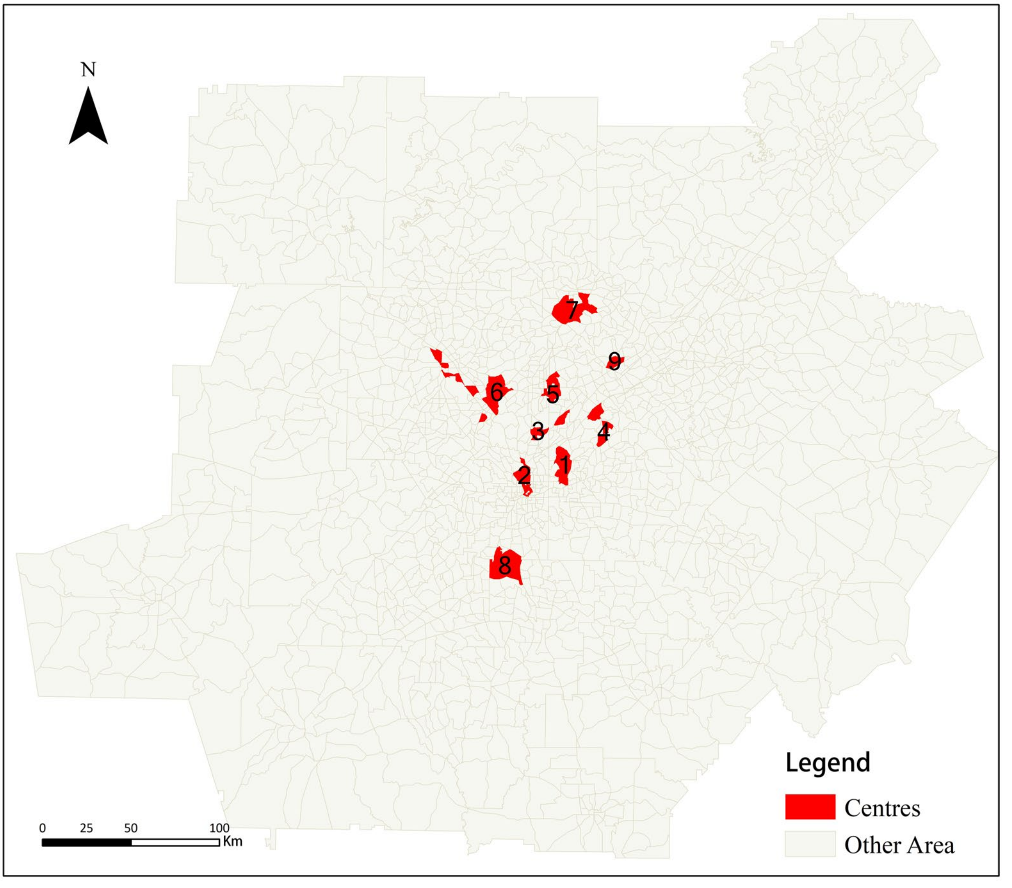


Figure 1. Commuting centers of Atlanta.

$$O_{xy} = \frac{|H_{xy}|}{|H_x|} \tag{8}$$

$$O_{yx} = \frac{|H_{xy}|}{|H_y|} \tag{9}$$

Substituting equations (8) and (9) into equations (3)–(6), we can calculate the degree of functional polycentricity of Atlanta. Tables 3 and 4 illustrate the overlapping hinterlands matrix of detected commuting and leisure centers, respectively.

According to Tables 3 and 4, we can easily calculate the proposed polycentricity indexes for the commuting and leisure functions in Atlanta.

In addition, we have also compared the results obtained from our methods to those from Vasanen's (2012) connectivity field method. Unlike the node-based methods used in most previous research, this method is also based on a center-hinterland discourse with hinterland defined

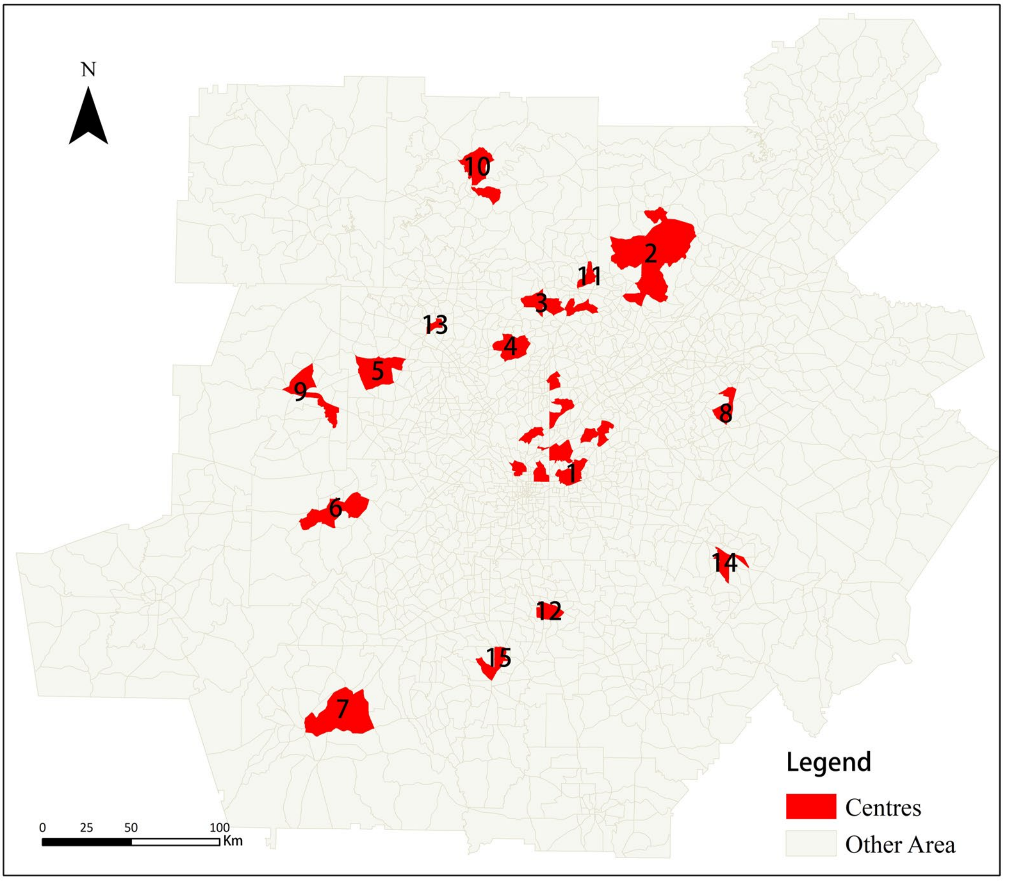


Figure 2. Leisure centers of Atlanta.

as a connectivity field. In this method, functional polycentricity is defined as the average extent to which the connectivity field of each center resembles the potential field, namely, the overall hinterland of all centers. This resemblance is measured by the R^2 statistic of ordinary least regression between these two fields, and functional polycentricity is thus calculated as the average R^2 of all centers.

Table 3. Overlapping Hinterlands Matrix of Commuting Centers

Centers	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	6 (%)	7 (%)	8 (%)	9 (%)
1	100.00	14.60	14.45	17.20	10.41	12.35	6.06	10.74	11.11
2	52.55	100.00	42.20	44.09	37.10	41.56	34.85	34.23	29.63
3	18.25	14.81	100.00	16.13	18.55	15.64	17.42	12.08	13.58
4	11.68	8.32	8.67	100.00	10.86	6.58	6.82	4.70	11.11
5	16.79	16.63	23.70	25.81	100.00	19.34	26.52	10.07	23.46
6	21.90	20.49	21.97	17.20	21.27	100.00	20.45	22.15	22.22
7	5.84	9.33	13.29	9.68	15.84	11.11	100.00	4.03	14.81
8	11.68	10.34	10.40	7.53	6.79	13.58	4.55	100.00	4.94
9	6.57	4.87	6.36	9.68	8.60	7.41	9.09	2.68	100.00

Table 4. Overlapping Hinterlands Matrix of Leisure Centers

Centers	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	6 (%)	7 (%)	8 (%)	9 (%)	10 (%)	11 (%)	12 (%)	13 (%)	14 (%)	15 (%)
1	100	19.7	21.6	22.6	9.3	7.0	6.9	10.4	0.0	5.7	21.1	22.0	14.8	13.6	6.5
2	5.1	100	15.5	3.2	2.3	0.0	0.0	1.5	3.0	2.9	26.3	0.0	3.3	2.3	0.0
3	7.1	19.7	100	14.5	7.0	0.0	3.4	3.0	0.0	11.4	36.8	0.0	4.9	0.0	0.0
4	4.7	2.6	9.3	100	9.3	2.3	0.0	0.0	3.0	11.4	5.3	0.0	13.1	0.0	0.0
5	1.4	1.3	3.1	6.5	100	4.7	0.0	0.0	33.3	0.0	5.3	0.0	19.7	0.0	0.0
6	1.0	0.0	0.0	1.6	4.7	100	0.0	0.0	12.1	0.0	0.0	0.0	0.0	0.0	0.0
7	0.7	0.0	1.0	0.0	0.0	0.0	100	0.0	0.0	0.0	1.8	1.7	0.0	0.0	9.7
8	2.4	1.3	2.1	0.0	0.0	0.0	0.0	100	0.0	0.0	0.0	1.7	0.0	4.5	0.0
9	0.0	1.3	0.0	1.6	25.6	9.3	0.0	0.0	100	2.9	0.0	0.0	4.9	0.0	0.0
10	0.7	1.3	4.1	6.5	0.0	0.0	0.0	0.0	3.0	100	1.8	0.0	0.0	0.0	0.0
11	4.1	19.7	21.6	4.8	7.0	0.0	3.4	0.0	0.0	2.9	100	0.0	3.3	0.0	3.2
12	4.4	0.0	0.0	0.0	0.0	0.0	3.4	1.5	0.0	0.0	0.0	100	0.0	2.3	32.3
13	3.0	2.6	3.1	12.9	27.9	0.0	0.0	0.0	9.1	0.0	3.5	0.0	100	0.0	0.0
14	2.0	1.3	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	1.7	0.0	100	0.0
15	0.7	0.0	0.0	0.0	0.0	0.0	10.3	0.0	0.0	0.0	1.8	16.9	0.0	0.0	100

Table 5 shows the results of all methods.

Compared to their common theoretical maximum, 1, these indices all indicate that it is difficult to regard the ARC region as a functionally polycentric city with respect to either the commuting or leisure aspect.

This finding seems to be contradictory to previous studies such as Griffith and Wong (2007) and Hajrasouliha and Hamidi (2017) who claim that Atlanta is a polycentric area. However, taking a closer look at these studies, such contradiction may result from two causes. The first lies in the difference in the study area. For example, Hajrasouliha and Hamidi's (2017) analysis is actually on Atlanta-Sandy Springs-Marietta, GA MSA, which consists of 28 counties and is much larger than the ARC region studied in this article. More fundamentally, the mainstream conclusion that Atlanta is a polycentric city in previous research is actually drawn primarily from a morphological perspective, especially from the distributions of residence and employment. By contrast, this article is based on a functional perspective considering integration among centers.

Obviously, the low degrees of polycentricity regarding both functions are mainly resulted from the lack of integration, indicating that little similarity exists among these centers' hinterlands. This is exactly what Vasanen's connectivity field method aims to reveal. Thus, Vasanen's method actually only measures integration, yet balance is absent. This is where our measurement has greater comprehensiveness than this method.

Table 5. Degrees of Functional Polycentricity

	$P_{general}$	$P_{compound}$	$P_{balance}$	$P_{integration}$	Connectivity field method
Commuting functional polycentricity	0.1530	0.1085	0.5317	0.2041	0.0144
Leisure functional polycentricity	0.0362	0.0258	0.5439	0.0475	0.0042

Returning to the comparison with previous conclusions, we can find that the hinterlands of centers are not actually so unbalanced as indicated by p_{balance}. p_{balance} is calculated on the comparison of the centrality of centers without considering the interactions among them, which essentially reflects a morphological perspective. Therefore, what is comparable to previous conclusions is actually the indication of p_{balance} alone rather than p_{general} or p_{compound}. In this sense, the conclusion of this article does not contradict previous ones. In summary, as functional polycentricity is a compound concept of balance and integration, it would be more reasonable to regard Atlanta as a functional multicentric area rather than a truly functional polycentric area.

The results above indicate that the ARC region is decentralized regarding both functions of employment and leisure, while the hinterlands of centres are basically separate. Employment and leisure activities are dispersedly concentrated. The life of residents in the ARC region are mainly localized.

Summary and discussion

In this article, we propose a unified definition of functional polycentricity from a geographical perspective. Based on previous work (Champion 2001; Parr 2004; Lambregts 2009), we reclassify the current research and outline two additional distinctions regarding the geographic aspects of polycentricity. One distinction concerns the spatial process of how functional polycentricity forms (decentralization compared with coalescence), while the other distinction concerns the form of the space where functional polycentricity develops (topography compared with topology). Accordingly, we categorize the routes leading to functional polycentricity into four types, namely, topographical decentralization, topological decentralization, topographical coalescence, and topological coalescence. Our efforts then center on discovering the distinguishing property that characterizes all four routes. Considering the unanimous usage of flow data to measure functional polycentricity, which reflects the center-hinterland relationship, we argue that a functional polycentric pattern features overlapping hinterlands among centers. Furthermore, we add two restrictive adjectives from previous discussions to derive a more precise definition: integration and balance. Consequently, we define functional polycentricity as a pattern in which centers share totally overlapping hinterlands with one another. Although this definition is simple, it captures the important features that make (functional) polycentricity distinguishable from other similar concepts such as multicentricity.

According to this definition, we advance two measurement indexes for functional polycentricity, and both of these indexes are grounded in the overlapping hinterland matrix among centers. One index is a general index that compares the measured pattern to an ideal situation, while the other index is a compound index comprising two fundamental indexes that measure the degrees of integration and balance. With a proper transformation of the overlapping hinterland matrix, these indexes also have applications for measuring systems with heterogeneously functional centers or comparing systems with different numbers of centers. The case study of Atlanta indicates that it reflects a more comprehensive connotation of functional polycentricity.

Our definition and measurement of functional polycentricity have some similarities to several previous studies. For instance, Green (2007) also contends that balance (measured by standard deviation) and connection (measured by network density) should be simultaneously considered in the measurement of functional polycentricity. However, in this definition, functional polycentricity is defined only in graphs, namely, the topological space. Moreover, the directions of flows are neglected, which leads to the consequence of taking all the involved nodes (cities) as centers, which lacks empirical rationale. Limtanakool, Dijst, and Schwanen (2007) propose a different flow-focused framework to classify the pattern of urban systems, which also comprises two dimensions, symmetry and structural hierarchy. However, these two dimensions are both used to measure balance. Structural hierarchy reflects the strength balance of flows, while symmetry measures the directional balance.

As the case study implies, polycentricity is based on the identification of centers, and centers can be a derivative concept of centrality. In this respect, our efforts to clarify polycentricity can be considered a connotative expansion of centrality when it concerns multi-center scenarios. Additional future discussions are expected to bridge the gap between these two concepts. Exploratively, it is would be of interest to discuss the relationship between the dimension of integration in this article and the dimension of spatial dispersion emphasized by Pereira et al. (2013) in their definition of urban centrality.

A noteworthy issue regarding the data is the type of flows. Functional activities, which naturally define the center-hinterland relationship, can always be expressed as flows; however, this does not mean that the reverse is true, and not all flows are functional. Actually, flows can be classified into two types according to their functionality (Limtanakool, Dijst, and Schwanen 2007). One type represents directional relationships, such as employer-employee or patron-client relationships. These flows, including commuting or leisure trips, are usually determined by the use of facilities, products or services tied to geographical locations at nodes of arrival. The other represents reciprocal relationships such as friendship. Such flows include journeys undertaken to visit family and friends. We can refer to these two types as functional flows and relational flows, respectively. Only the former can be used to define a center-hinterland relationship because the delimitation of centers and hinterlands must be based on the directions of relationships. In future research, considering whether a distinction also exists between functional polycentricity and relational polycentricity may be interesting.

This article certainly has some limitations that indicate further research possibilities. First, the evolutionary perspective that we use to define functional polycentricity is descriptive rather than explanatory. The absence of an analysis of what leads to this structure may result in our incomplete understanding of the routes of functional polycentricity. Therefore, in future research, it is necessary to refine the proposed categorization by exploring the main driving force that underlies this structure. Second, although both the one-step index P_{general} and the compound index P_{compound} have their own advantages, further discussion of when we should apply each one is necessary. Third, as the number of centers may have different meanings for urban systems with different populations (Louf and Barthelemy 2013), a more general question to answer is whether the polycentricity pattern is comparable among cities of various sizes. At this point, the framework in this article may be more suitable for comparing cities of similar sizes.

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Note

[1]The original data, which provide information on the primary purpose, secondary purpose, origin and destination of each trip, are accessible at https://atlantaregional.org/transportation-mobility/modeling/household-travel-survey/.

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