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Burger, Martijn; van Oort, Frank; Meijers, Evert

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# Examining Spatial Structure Using Gravity Models

**Martijn Burger, Frank van Oort and Evert Meijers**

**Abstract** In this chapter, we discuss the use of gravity models in the study of spatial structure. Using the recent discussion on functional polycentricity as a background, we argue that the gravity model approach has one obvious advantage when examining spatial structure: it can simultaneously assess functional polycentricity and spatial interdependencies within one modelling framework. The chapter concludes with a discussion of methods that can be applied to estimate the gravity model.

## 1 Introduction

Fifty years ago, the French geographer Jean Gottmann (1957, 1961) envisioned the rise of a super-metropolitan region along the northeastern seaboard of the United States, stretching from just north of Boston all the way to Washington DC. Gottmann named this new urban form after the Peloponnesian city Megalopolis, founded by Epaminondas of Thebes as the seat of the Arcadian league in an attempt to form a political counterweight to Sparta. According to Gottmann (1961, p. 4), '*the name applied to* [this area] *should … be new as a place name but old as a symbol of the long tradition of human aspirations and endeavour*'. Indeed, the Greek Megalopolis was planned on an enormous scale; the city was populated through the enforced transfer of inhabitants from 40 local villages and was encompassed by 9 km in circumference of strong walls (Baigant 2004). Although Epaminondas' Megalopolis did not succeed as hoped and gradually faded into oblivion, Gottmann was optimistic about the future of the new Boston–Washington corridor Megalopolis. He felt the

M. Burger (✉) · F. van Oort
Erasmus University Rotterdam, Rotterdam, The Netherlands
e-mail: mburger@ese.eur.nl

F. van Oort
e-mail: vanoort@ese.eur.nl

E. Meijers
Delft University of Technology, Delft, The Netherlands
e-mail: E.J.Meijers@tudelft.nl



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region could function effectively as an interregional polycentric urbanised system that still had many characteristics of a single city. Gottmann (1961, p. 5) argued that:

> We must abandon the idea of the city as a tightly settled and organized unit in which people, activities, and riches are crowded into a very small area clearly separated from its nonurban surroundings. Every city in this region spreads out far and wide around its original nucleus; it grows amidst an irregularly colloidal mixture of rural and suburban landscapes; it melts on broad fronts with other mixtures, of somewhat similar though different texture, belonging to the suburban neighborhoods of other cities.

Gottmann considered the Megalopolis to be the emergent form of spatial organisation, characterised by high average population densities and the flow of high volumes of people, goods, capital and information. Functional relationships between the different parts of the Megalopolis would be of the utmost importance for its ability to function as a single city. The Megalopolis reflected the enlarged scale of urban life and the shift from a single metropolis with a principal centre to an *urban network with multiple centres*. Gottmann also emphasised the importance in the Megalopolis of inter-state cooperation and governance organised on larger geographical scales than the local scale. He claimed local governments would inadequately fulfil the needs of these large cities and their ever-expanding suburbs and sub-centres. The Megalopolis would be characterised by a marriage of urban and rural modes of life, leading to maximum freedom of movement and a perfection of the modern urban lifestyle, one that would remedy the problems of the congested city and the backward village. Visions for the city similar to Gottmann's were also expressed in (earlier) planning concepts such as the Garden City (Howard 1902), Broadacre City (Wright 1935), and the Regional City (Stein 1964).

## 2 Functional Spatial Structure

Gottmann's vision of the Boston–Washington corridor as a polycentric urban network was radical in the 1950s and broke with the conventional conceptualisations of cities as local hierarchical urban systems.[1] This was stressed again by Short (2007), updating much of Gottmann's analysis and referring to the area as a 'liquid city' to stress the fluidity of the city and region at large. Today, super-regions like the Northeastern Seaboard in the United States, the Greater Southeast in the United Kingdom, the Flemish Diamond in Belgium, the Randstad in the Netherlands, and the Rhein-Ruhr and Rhein-Main areas in Germany have gained considerable attention in the academic literature (see e.g. Hoyler et al. 2008; Florida et al. 2008; Burger et al. 2014c). Although it should be acknowledged that Gottmann's original concept was predominantly morphological in nature, he later (in response to critiques) stressed the functional aspects of the various centres in the Megalopolis (Hall 1997). On the one hand, the Megalopolis is a polycentric super-region of cities in close proximity

[1] For an exception at the city-level, see Harris and Ullman (1945) and Alonso (1956).

to each other. On the other hand, without the functional and complementary relationships between places like Boston, New York, Philadelphia and Washington DC it is hard to argue that Megalopolis could be regarded as a truly integrated polycentric region, since it does not function as such. Accordingly, it can be argued that for a super-region to function as a coherent polycentric networked urban entity:

(1) There should not only be a balance in the city size distribution, but also a certain balance in the distribution of functional linkages between places.
(2) There should be a certain extent to which the places within the Megalopolis are functionally linked.

The first condition has been referred to as 'functional polycentricity' (Green, 2007). The second addresses the requirement that there is a significant degree of spatial integration or spatial interdependencies. Hence, (a) spatial structure should not only be addressed by looking at the mere existence of multiple centres within one area, but also by looking at the functional linkages between places within an area and (b) functional polycentricity and spatial interdependencies can be regarded as two defining elements of a polycentric urban super-region (Burger and Meijers 2012).

In analytical work on spatial structure, it is important not to conflate the degree of spatial interdependence with the degree of functional polycentricity: they are different theoretical constructs (Burger and Meijers 2012; Vasanen 2013). There are spatial systems that are strongly networked as well as monocentric, and there are spatial systems that are not networked at all but are polycentric. In fact, previous empirical research has shown that there is no correlation between the degree of functional polycentricity and degree of spatial interdependence, indicating that they should be treated as two distinct aspects of the spatial organisation of regions (Burger et al. 2011; Burger and Meijers 2012).

## *2.1 Functional Polycentricity*

Over the past decades, the urban systems literature has seen a surge in papers that attempt to measure spatial structure along the monocentricity–polycentricity dimension. Accordingly, measuring the degree of a balanced distribution with respect to the importance of centres within a given territory is the focus in these papers. In this literature, it has been debated whether monocentricity–polycentricity refers to only morphological aspects of the urban system or whether it should also incorporate relational aspects between the centres that constitute the urban system in question (Green 2007; Meijers 2008; Burger and Meijers 2012). In other words, should one measure the importance of centres on locational (internal) characteristics or on the basis of flows? This distinction is also represented in Fig. 1. Morphological measures of monocentricity–polycentricity capture the size distribution of the urban centres within a territory, where a more balanced distribution of centre size (usually expressed in terms of population sizes) equates with a polycentric spatial structure

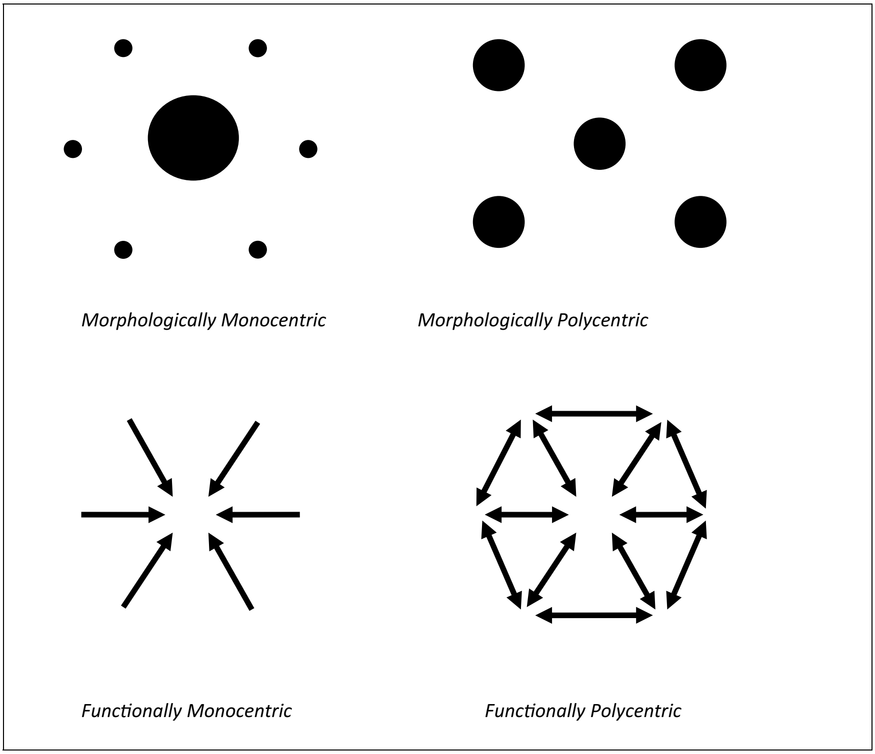


**Fig. 1** Morphological versus functional spatial structures *Source* Burger and Meijers (2012)

(see e.g. Kloosterman and Lambregts 2001; Parr 2004; Meijers and Burger 2010). Functional monocentricity–polycentricity measures, on the contrary, take the functional connections (e.g. commuting, shopping, knowledge collaboration and trade flows) between the settlements into account, and consider a more balanced, multi-directional set of relations to be more polycentric (Green 2007; Burger and Meijers 2012). Within a functional polycentric system, there is a more equal balance in the distribution of inflows, meaning that functional relationships are not only directed at one centre (like in a monocentric urban system), but two-sided (reciprocal) and crisscross (also existing between smaller centres) (Van der Laan 1998; De Goei et al. 2010; Burger et al. 2011; Li and Phelps 2018).

It is important to note that studies that adhere to the functional dimension of monocentricity–polycentricity do not dismiss the morphological approach, but extend it to include also the pattern of functional interaction between the urban centres. The approach generally taken has many similarities with the morphological approach, using—for example—also urban primacy measures and rank-size distributions (based on network data) to assess spatial structure (see, e.g. Van der Laan 1998;

Meijers 2008; Meijers and Burger 2010; Burger et al. 2011; Veneri and Burgalassi 2012).

### *2.2 Spatial Interdependencies*

Functional polycentricity does not so much address the existence or strength of functional relationships between centres within a given territory, but rather the balance in the distribution of these functional relationships. However, another pre-condition for a region like the Megalopolis to exist would be a certain degree of spatial integration or spatial interdependencies. Without functional relationships between the historically and geographically separate parts of a region, it is hard to argue that the places within a territory function as a region. Methods to measure the degree of spatial interdependencies include network density (Green 2007), connectivity fields (Vasanen 2013), geographical scope of functional relations (Burger et al. 2013) and the gravity model (De Goei et al. 2010; Van Oort et al. 2010; Hanssens et al. 2014; Coombes and Champion 2016).

## 3 Gravity Models and Spatial Structure

The gravity model approach has one obvious advantage when examining spatial structure: it can simultaneously assess functional polycentricity and spatial interdependencies within one modelling framework. Using the gravity modelling framework, one can employ Newton's law of universal gravitation to gauge the interaction between spatial units. These interactions can be any kind of functional relationships between places within a region, ranging from commuting and shopping flows to business trade and investment flows. The model holds that the gravitational force between two spatial units is directly proportional to the product of the mass of the interacting spatial units and inversely proportional to the physical distance between them. Traditionally, the gravity model can be expressed by

$$I_{ij} = K \frac{M_i^{\beta_1} M_j^{\beta_2}}{d_{ij}^{\beta_3}},$$

where $I_{ij}$ is the interaction intensity, e.g. the number of people travelling between places $i$ and $j$, K a proportionality constant, $M_i$ the size of place $i$, $M_j$ the size of place $j$, $d_{ij}$ the physical distance between the two places, β1 the potential to generate flows, β2 the potential to attract flows and β3 an impedance factor reflecting the rate of increase of the friction of distance. If an area is functionally polycentric and the places are spatially interdependent, then network structures of commuting, trade, shopping, and other types of functional relations within this area should be solely determined by the size of the places and the distance between them. In other words, once the size of places and distance between places are controlled for, in an equilibrium situation there should be no additional flows or interactions.

With regard to spatial interdependencies, one would expect that the interdependencies between places are two-sided (or exchange) and crisscross (periphery–periphery; Burger et al. 2011) in character: places should be both sender and receiver of relationships and interdependencies between places at different levels of the original urban hierarchy (e.g. core–periphery relationships) should not be stronger than the interdependencies between places at the same level of the hierarchy (e.g. core–core relationships or periphery–periphery relationships). The degree of spatial interdependencies within an area can be determined by assessing to what extent a region functions as one place. If this would be the case, we would see that controlling for size and distance, interdependencies within places (or between places within one part of the region) should not be stronger than interdependencies between places (or places across different parts of the region).

## 4 Estimation of the Gravity Model

By taking logarithms of both sides of gravity equation and including a disturbance term, the multiplicative form can be transformed into a linear stochastic form. It results in an equation that is testable using ordinary least squares, in which the disturbance term $\varepsilon_{ij}$ is assumed to be identical and independently distributed (i.i.d):

$$\ln I_{ij} = \ln K + \beta_1 M_i + \beta_2 M_j - \beta_3 d_{ij} + \varepsilon_{ij}$$

The model above can be extended to a panel data framework, so that it becomes possible to study the development of spatial interactions over time (see e.g. De Goei et al. 2010). In addition, the empirical gravity model can be easily augmented to include other factors than size and distance. Most notably, dummy variables that reflect the type of relationship between places (e.g. core-periphery vs crisscross; or within a subregion vs. between subregions; see Fig. 2), can be included in the model to test the degree of functional polycentricy and spatial interdependencies in a region. Also barriers between places, like lack of physical accessibility, or language and cultural differences between places, can be introduced to test whether these hamper or stimulate interaction.

The models can be estimated using OLS, but the application of a linear regression model often results in inefficient, inconsistent, and biased estimates (Flowerdew and Aitkin 1982) since the underlying assumptions of normal distribution and homoskedasticity are often not satisfied. For this reason, the use of alternative regression techniques such as count data model is then judged more appropriate. Applications of count data model in assessing spatial structure can be found in the work of De Goei et al. (2010), Van Oort et al. (2010) and Hanssens et al. (2014). A

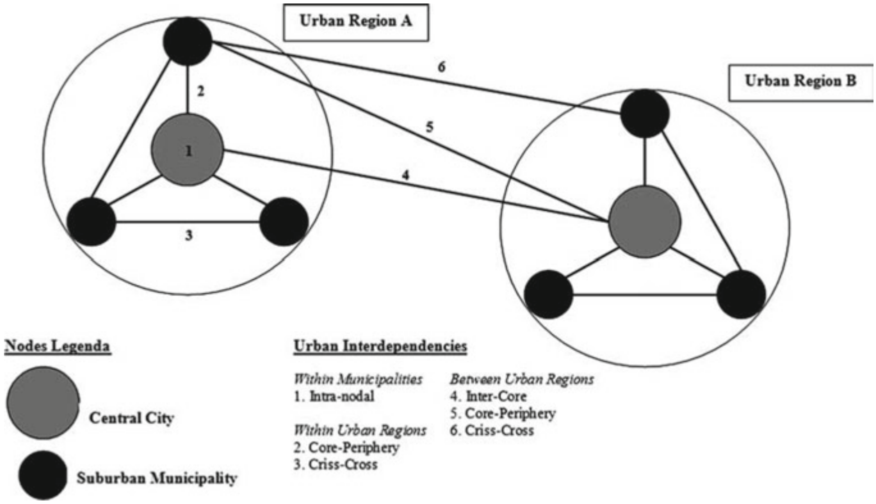


**Fig. 2** Example of different spatial interdependencies within a region *Source* Van Oort et al. (2010)

more elaborate account of the estimation of gravity models can be found in Burger et al. (2009) and Broekel et al. (2014).

## 5 Concluding Remarks

Although the gravity model provides a framework to simultaneously assess different aspects of functional spatial structure, a difficulty in the assessment of both functional polycentricity and spatial interdependencies still constitutes the multiplexity of urban networks (Burger et al. 2014b) and integration (Meijers et al. 2018) as well as individual-level heterogeneity (Burger et al. 2014a). First, the spatial structure of different types of functional relationships is not necessarily identical and a region can, therefore, appear to be polycentric or spatially integrated based on the analysis of one type of functional linkage but loosely connected based on the analysis of another type of functional linkage (Burger et al. 2014a). Second, spatial interdependencies between different centres could have institutional and cultural dimensions besides functional dimensions (Meijers et al. 2018). Third, even when a single type of flow is taken into account, there may be a wide variety in spatial interaction patterns that can be attributed to differences among people or firms (Burger et al. 2014a). Addressing this heterogeneity is important, as networks of flows are built up by heterogeneous individual and group behaviour, and structural changes and policies that benefit one group may harm another.

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