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THREE ESSAYS ON URBAN SPATIAL STRUCTURE IN BOGOTA D.C.

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1. General Summary

Cities are physical, economic and social systems characterized by a high spatial concentration of population and employment. Although the configuration of urban systems offers important peculiarities around the world, the economy has achieved relative success in organizing a conceptual structure that allows for the identification and explanation of some forces that lead to a spatial population concentration. Works by William Alonso, Richard Muth and Edwin Mills constitute some of the most important contributions to the systematization of general ideas from which urban structures may be explained. Among others, the most important ones refer to the reverse relationship between densities, land price and the capital/land ratio, with regard to distance from the city center. This systematization process has given way to what is now known as New Urban Economy (NUE). Although studies on urban structure are deeply rooted in the North American context, during the last twenty years, and given the increase in information, other cities in Europe and in developing countries have sparked the interest of investigators, not only as an intellectual exercise searching for proof on the general predictions of mathematical models arising from the work of the abovementioned authors, but also as a practical exercise from which urban planning policy instruments are strengthened .

The research papers I am presenting in hopes of obtaining a Doctorate Degree in Applied Economics from the Universitat Autònoma de Barcelona, seeks to contribute to the creation of new knowledge on urban structures in cities within the Latin American context. The case study object for urban context analysis for this research paper is the city of Bogota D.C., the capital of Colombia. In addition, the urban regularity involved in the analysis is the reduction of employment density and land price as distance increases, not only to the traditional city center (CBD), but to other areas of economic activity concentration that define the polycentric nature of the city today. There are few NUE studies applied to this city. During the last decade, changes to the urban transportation system, or the Trasnmilenio system, have sparked the interest of local investigators searching to explain its effects on population density, land prices and urban development within the city. These studies have helped fill the existing gap on the city´s economic analysis in current specialized literature. However, these studies focus on transport infrastructure, which is only one of the structural spatial elements, and ignores the role of employment subcenters.

The urban structure of a city is largely determined by the pattern in which economic activities are located. Starting from a monocentric model, and the exogenous polycentric models suggested by the NUE, in the first document of this thesis, a nonparametric method is implemented that allows for a high level of objectivity in the identification of employment subcenters. Changes generated from an economic activity decentralization process are manifest in a city thru the creation of new centers for employment in the shape of sub centers. Therefore, more than a process defined by general employment dispersion the example is still concentrated, and therefore agglomeration economics must still prevail.

In the second document, an analysis on economic relationships between the CBD and the employment subcenters in Bogota is presented. By combining the NUE, the New Economic Geography (NEG) and the new paradigm on Networked cities, a conceptual framework is created that explains the economic relationship between the elements of an urban structure. This framework allows us to determine if the employment subcenters are substitutes of the CBD or if they complement it. The abovementioned is achieved based on three methodological perspectives. In first place, by defining the specialty or diverse nature of the employment subcenters, based on the process of identifying them as such. In second place, by comparing the value of the density gradient for each subcenter and keeping in mind its location relative to the CBD and the remaining urban area. Lastly, some sort of regularity in the geographic location of the subcenters is identified. The main result is that complementary relationships rule the city's urban structure, and thus has political implications. For example, complementarity implies that the transportation system must have a strong mainstreaming component that represents better access conditions, not just to a subcenter, but to the network it forms.

In the last document an empirical exercise is performed in order to prove one of the main theoretical predictions of the polycentric NUE models, which is that employment sub centers have significant effects on the prices of land, and define a spatial pattern characterized by a loss in value as the distance to the sub centers and the CBD increases, thus compensating for the additional cost in transportation that households must assume.

The document not only considers urban structure, but also the fact that geographic layout of the city subcenters implies that the influence of the main arteries on the price of land must also be taken into account. Therefore, the analysis considers both the city´s subcenters and its road infrastructure. The main result is that land prices respond to agglomeration economies generated by the concentration of economic activities in the shape of sub centers, and not just simply to infrastructure. In fact, it can be proven that employment sub centers in Bogota exert a greater influence on land prices than that of the main arteries on which they are located.

Resumen General.

Las ciudades son sistemas físicos, económicos y sociales caracterizados fundamentalmente por una elevada concentración espacial de población y empleo. Aunque la configuración de los sistemas urbanos presenta importantes particularidades alrededor del mundo, la economía ha logrado, con relativo éxito, organizar una estructura conceptual que permite identificar y explicar algunas fuerzas que conllevan a la concentración espacial de la población. Los trabajos de William Alonso, Richard Muth y Edwin Mills constituyen una de las más importantes contribuciones para sistematizar las ideas generales a partir de las cuales se pueda explicar las generalidades de la estructura urbana. Entre estas, las más importantes se refieren a la relación inversa entre densidades, precios del suelo y ratio capital/suelo, con respecto a la distancia al centro de la ciudad. El proceso de sistematización ha dado lugar a lo que se ha denominado Nueva Economía Urbana. Aunque los estudios sobre la estructura urbana de las ciudades tiene un fuerte arraigo en el contexto norteamericano, durante los últimos 20 años y ante la creciente disponibilidad de información, otras ciudades en países en Europa y también en países en vías de desarrollo han despertado el interés de los investigadores, no sólo como un ejercicio intelectual que busca probar la generalidad de las predicciones del modelo matemático que surge de los trabajo de los autores mencionados, sino también como ejercicio práctico a partir del cual se refuercen los instrumentos de política del planeamiento urbano.

El trabajo de investigación que presento para optar al título de Doctor en Economía Aplicada de la Universitat Autònoma de Barcelona busca contribuir en la generación de nuevo conocimiento sobre la estructura urbana de las ciudades en el contexto latinoamericano. En el caso de este trabajo de investigación, el contexto urbano objeto de análisis es Bogotá, D.C., la capital de Colombia. A su vez, la regularidad urbana involucrada en el análisis es la disminución de la densidad del empleo y de los precios del suelo a medida que aumenta la distancia, ya no sólo al centro tradicional (CBD) sino a otras concentraciones de actividad económica que definen el carácter policéntrico de la ciudad actual. Existen pocos estudios basados en la Nueva Economía Urbana (NEU) aplicados a esta ciudad. En la última década, los cambios en el sistema de transporte urbano de la ciudad, materializados en el sistema Transmilenio, han despertado el interés de los

investigadores locales por explicar sus efectos sobre las densidades de población, el precio del suelo y el desarrollo urbano de la ciudad. Estos estudios han contribuido a llenar el vacío que sobre el análisis económico de la ciudad existe en la literatura especializada. No obstante, estos trabajos se enfocan en la infraestructura de transporte, que es tan sólo uno de los elementos estructuradores del espacio, dejando de lado el papel de los subcentros de empleo.

La estructura urbana de una ciudad está determinada en buena medida por el patrón de localización de la actividad económica. Partiendo del modelo monocéntrico y de los modelos policéntricos exógenos de la NEU, en el primer documento de esta tesis se implementa una metodología no-paramétrica que permite un elevado grado de objetividad en la identificación de los subcentros de empleo. Los cambios generados por el proceso de descentralización de la actividad económica se manifiestan en la ciudad por medio de la generación de nuevos centros de empleo en forma de subcentros. Por lo tanto, más que un proceso caracterizado por la dispersión generalizada del empleo, el empleo sigue presentándose de forma concentrada, por lo que las economías de aglomeración deben seguir actuando.

En el segundo documento se presenta un análisis de las relaciones económicas entre el CBD y los subcentros de empleo en Bogotá. Combinando los aportes teóricos de la NEU, la Nueva Geografía Económica (NGE) y del nuevo paradigma de Ciudad en Red, se genera un marco conceptual para explicar las relaciones económicas entre los elementos de la estructura urbana. Este marco permite determinar si los subcentros de empleo son sustitutos o complementarios del CBD. Lo anterior se logra a partir de tres perspectivas metodológicas. En primer lugar definiendo el carácter especializado o diversificado de los subcentros de empleo desde el proceso de identificación de los mismos. En segundo lugar, comparando el valor de los gradientes de densidad para cada subcentro teniendo en cuenta su localización relativa frente al CBD y al resto del área urbana. Por último, se busca identificar alguna regularidad en el patrón de localización geográfica de los subcentros. El resultado principal es que las relaciones de complementariedad rigen la estructura urbana de la ciudad, lo cual tiene implicaciones de política. Por ejemplo, la complementariedad implica que el sistema de transporte debe tener un fuerte componente de transversalidad que signifique mejores condiciones de accesibilidad, no sólo a un subcentro, sino a la red que conforman.

En el último documento se lleva a cabo un ejercicio empírico para comprobar una de las principales predicciones teóricas de los modelos policéntricos de la NEU. Esta es, que los subcentros de empleo tienen efectos significativos sobre los precios del suelo y definen un patrón espacial caracterizado por la caída de su valor a medida que aumenta la distancia a los subcentros y al CBD, para así compensar el costo de transporte adicional en que deben incurrir los hogares. En el documento no sólo se tiene en cuenta la estructura urbana, también se considera el hecho de que la disposición geográfica de los subcentros en la ciudad implica tener en cuenta la influencia de los ejes viales sobre los precios del suelo. Por lo tanto, el análisis tiene en cuenta tanto los subcentros como la infraestructura vial de la ciudad. El resultado principal es que los precios del suelo responden a las economías de aglomeración generadas por la concentración de la actividad económica en forma de subcentros, y no sólo al simple acceso a la infraestructura. De hecho, para Bogotá se comprueba que los subcentros de empleo ejercen un papel más importante sobre los precios del suelo que aquel que logran los ejes viales principales sobre los cuales se localizan.

Employment Subcenter Identification in Bogota D.C.

ABSTRACT

Although employment has become increasingly decentralized in recent decades, urban structure still matters. Researchers have developed different methodologies to identify employment subcenters in metropolitan areas, and McMillen´s two-stage procedure is an easily reproducible technique to identify potential subcenters. The first stage identifies candidate subcenters as significant positive residuals in a smooth employment density function. The use of the ordinary least squares (OLS) employment density function in the second stage allows for the selection of subcenters as sites that provide significant explanatory power. This paper's main contribution is empirical rather than methodological. McMillen´s procedure is applied to Bogota census tract data for the years 1990 and 2001 to identify the city's employment subcenters. This information was used to test the polycentric hypothesis of the New Urban Economic framework for a city in a developing country. Studies on this subject are scarce but of general interest to policy makers and researchers.

Keywords: subcenters, employment density, nonparametric, urban structure.

1. Introduction

This study employs the two-stage methodology proposed by McMillen (2001) to identify employment subcenters in Bogota, Colombia. It allows for polycentrism testing and identifies subcenters more objectively than other methods do. Subcenters are geographically bounded employment hotspots outside a central business district (CBD). They share the advantages and disadvantages of agglomeration economies, such as those of a CBD, but have reduced land and commuting costs for firms and workers.[1] Due to developments over the last thirty years, the monocentric city paradigm has become a conventional way to describe the urban form. Most of the important contributions to our understanding of urban structure have come from studies on American (U.S.) metropolitan areas, and the main academic goal of these studies has been the identification of employment centers outside CBDs, with a focus on cities developed around highways.

[1]The papers by McDonald and McMillen (1999) and Small and Song (1994) are important contributions toward understanding the effects of subcenters on non-CBD employment density, housing prices, land rents and population density.

These new centers constitute a polycentric city, which McMillen (2001, p. 448) defined as a city with "one or more employment subcenters beyond the traditional CBD. In contrast, a monocentric city can have decentralized employment, but non-CBD employment is not grouped into subcenters." Los Angeles is considered a prototypical polycentric city and is widely referenced in studies of polycentric metropolitan spatial structures. Giuliano and Small's (1991) seminal work on the Los Angeles metropolitan region is the reference point to explain and define "subcenters." Previous studies have also considered other cities, including Hartshorn and Muller (1989) on Atlanta; McDonald and Prather (1994) on Chicago; Wadell Shukla (1993) on Dallas-Forth Worth; White et al. (1993) on Milwaukee; Clark and Kuijpers (1994) on Randstad and Los Angeles; Muñiz et al. (2002a, 2002b, 2005, 2008) on Barcelona; and Suarez and Delgado (2009) on Mexico.

McMillen's (2001) two-stage nonparametric procedure to identify subcenters can be implemented for a variety of cities and tract sizes. In the first stage, a nonparametric estimator is used to smooth the employment density of each census tract. A weighted least square (WLS) regression is then estimated for each observation to give more weight to nearby observations (McMillen and McDonald, 2004). Potential subcenters are sites with significant positive residuals, and an employment subcenter is a site that has a high employment density even after controlling for spatial trends.

The second stage of the procedure entails a parametric or semiparametric regression to determine whether the potential subcenters have a significant effect on employment density. This regression controls for CBD distance, which allows significant subcenters to stand out. It also accounts for the prediction by Alonso (1964), Muth (1969) and Mills (1972) that distance from a city explains the spatial variation of variables such as employment density. This stage estimates the proximity effects of subcenters on employment density, which is the basic input data used to analyze agglomeration economies. This procedure seeks to capture that a subcenter is an area with a significant employment density that is higher than that obtained by controlling for CBD distance alone.

This paper uses total employment data to apply McMillen's procedure to Bogota. This study contributes to an understanding of the spatial structure of employment in cities with economic characteristics that differ from those of U.S. cities. Likewise, it tests the relevance of the methodology in a different spatial structure, demonstrating its replicability. Finally, this research estimates the optimal window size using the cross-validation method.

This methodology was originally used by McMillen to identify employment subcenters in six U.S. metropolitan areas. Arguably, the most significant previous urban economic studies on employment subcenters in Bogota are Dowall and Treffeisen (1991) and Lee (1982); the former is one of the few studies on the identification of employment subcenters and polycentrism in the cities of developing countries.

The remainder of the paper is organized as follows. The next section provides a brief description of the methodologies used to identify subcenters. The third section explains the analytical framework, and the fourth section describes the data and data sources. The fifth section presents the results, subcenter locations and evidence that subcenters have a significant effect on employment densities. The last section presents the conclusions.

2. Subcenter Identification Procedures

Identifying the key characteristics of subcenters has been a challenging research aim. From the seminal works of McDonald (1987), Giuliano and Small (1991) and Greene (1980) to the empirical and analytical contributions of Bogart and Ferry (1999), Cervero and Wu (1997), Craig and Ng (2001), Gordon and Richardson (1996), Heikkila et al. (1989), McDonald and McMillen (1990), McMillen and McDonald (1998) and Small and Song (1994), the search for criteria to define and identify a subcenter has led to major academic controversies. The main controversy is related to the methodology used for subcenter identification. However, a clear definition of a subcenter allows for its identification within the urban structure and thus the analysis of its effects on employment. Based on the research mentioned above, McMillen (2001, p. 448-449) argues that "a reasonable working definition of a subcenter is a site (1) with significantly larger employment density than nearby locations that has (2) a significant effect on the overall employment density function". This definition has been accepted in the academic community and responds to the theoretical assumptions of the New Urban Economics (NUE), but it involves two fundamental problems for empirical work. The first problem is related to measuring the "larger employment density," chiefly how to define a change in employment density that distinguishes it from neighboring locations. The second problem is related to the concept of "nearby" and the difficulty of spatially defining local and global contexts. Both problems respond to the presence of spatial effects and spatial heterogeneity, which are essential factors behind the existence of spatial econometrics.

The use of spatial econometric techniques results in less subjective methods that reduce the need for a diverse knowledge of the study area. The density threshold methodology proposed by Giuliano and Small (1991) defines a subcenter as a set of contiguous sites, each having a minimum employment density of 10 employees per acre (4,047 square meters) and a total of at least 10,000 employees. Using this methodology, Bogota would have had 9 subcenters in the year 2001. However, spatial and economic characteristics, especially those related to the employment distribution in urban areas, may require changes in the cutoff points to produce reasonable results.[2] Consequently, the selection of appropriate cutoff points would require a mix of local knowledge and employment statistics.

Threshold-based criteria for subcenter identification have been applied to particular units of observation. Giuliano and Small (1991) used finely scaled geographical data to study the Los Angeles metropolitan area. The study region consisted of 1,146 "transportation analysis zones" (TAZs), which were based on commutes to and from work and covered an area of 9,158 square kilometers. McMillen (2001) used the same unit of observation for Chicago, Houston, Dallas, Los Angeles, New Orleans and San Francisco. McMillen and McDonald (1998) utilized U.S. census data to provide employment figures for each quarter section of suburban Chicago; a quarter section is an area of a quarter square mile or 0.64 square kilometers. In this case, the study region consisted of 14,290 tracts in an area of 9,254 square kilometers. For Bogota, census tract data from the National

[2] McMillen and McDonald (1998) used the same procedure and cutoff points to identify 15 subcenters in Chicago; because one subcenter had more than 400,000 employees and covered an area extending from the O'Hare Airport in the northwest suburbs to Lake Michigan and into Lake County, McMillen and McDonald raised the cutoff points to 20 employees per acre (4,047 square meters) and 20,000 total employees.

Census Bureau (DANE) were used, which are population-based and not directly related to work commutes.[3] The data correspond to 621 tracts in 40,137 hectares or 401.5 square kilometers. These tracts only cover Bogota's urban space, which is not an official metropolitan area, although DANE estimates that this area could support 9.6 million inhabitants and 17 municipalities. The geographical differences in the study areas and especially in the observation units lead to a widely recognized geographical problem known as the modifiable areal unit problem (MAUP);[4] while it is less significant in the methods used in urban economics to measure and test proximity effects, it does directly influence the number of subcenters determined in a metropolitan area or city. As stated by McMillen (2001), a small tract size leads to many cartographical areas with no employment in otherwise high density locations. On the other hand, large tract size data smooth over local employment peaks and may result into fewer subcenter sites than those resulting from extensively disaggregated data.

Cervero (1989), Giuliano and Small (1991) and McDonald (1987) laid the groundwork for applied research in identifying the phenomenon of employment subcenters in the U.S. Job-related empirical research on employment subcenters has focused on three particular aspects. First, it has focused on defining and identifying subcenters. The most important contributions in this field include McDonald (1987), Giuliano and Small (1991), Craig and Ng (2001) and McMillen (2003). Second, it has examined the effects of subcenters on land values and variables related to the housing market; the main contributors are Waddell et al. (1993), McMillen and McDonald (1998) and McMillen (2004). Finally, Small and Song (1994), McMillen and McDonald (1998) and McMillen (2004) are the major sources regarding the effects of subcenters on the spatial distribution of employment and population in cities.

According to earlier studies, subcenters are areas in which the employment density is twice the urban average (Greene, 1980). McDonald (1987) and McDonald and McMillen (1990) defined a subcenter as a set of locations with a gross employment density greater

[3]TAZs are aggregates of census blocks, but their areas are determined by functional characteristics, and they do not include a fixed population (Giuliano and Small 1991). This can lead to problems in identifying employment subcenters from observation units that were configured for mapping and census purposes without relation to economic links and commuting.

[4]The MAUP problem was originally proposed by Gehlke and Biehl (1934), and an extensive description of the problem can be found in Reynolds (1998).

than that of all adjacent areas. This approach is appropriate for urban areas with larger geostatistical units but can also identify smaller locations surrounded by areas with little or no level of employment as subcenters (McMillen and McDonald, 1998). The methodology of Giuliano and Small (1991) and Small and Song (1994) referenced earlier provides a measure that controls both absolute and relative levels for defining a subcenter.

Heikkila et al. (1989) offered more formal measures for identifying subcenters. They evaluated a stepwise regression to assess the individual significance of the variables (subcenter distances) introduced in each stage of the model and observed the estimated value of land prices. Subcenters are identified as sites having explanatory power. McDonald and Prather (1994) used a model to analyze monocentric employment density and defined subcenters as geographical areas with significant positive residuals. These methods are more objective than earlier methods and do not rely on detailed local knowledge of the city in question. They also allow for the joint analysis of employment subcenters and economies of agglomeration.

Gordon et al. (1986) were pioneers in proposing two-stage procedures for identifying potential subcenters. For the identification stage, they visually inspected density maps, a method used to select subcenter locations based on hotspot sites. McMillen and McDonald (1998) used Giuliano and Small's (Giuliano and Small, 1991) methodology to identify 20 candidate subcenters in Chicago and calculated maximum likelihood estimations, obtaining 17 subcenters that provided significant explanatory power for the employment density function. Both methodologies rely on an arbitrary definition of subcenter locations. Craig and Ng (2001) estimated a nonparametric quantile regression procedure using Koenker et al.'s (1994) quantile smoothing splines to obtain smoothed employment density estimates for Houston; however, their methodology is better suited to identifying rings of high employment density than to identifying subcenters.

A 1981 publication by Ingram and Carroll is the most important urban employment and population reference in the context of Bogota and other Latin American cities. This work used census data to construct population and employment statistics for Latin American cities to describe and explain spatial transformations and to compare these with those of North American cities. For Bogota, this transformation was mainly explained by population dispersion. Lee (1982) worked extensively on Bogota using a bid-rent theoretical framework to explain the spatial descentralization of manufacturing employment locations. He observed a steady outward movement of jobs away from central areas, with employment subcenters located at peripheral locations. The main result was the new decentralized spatial structure in Bogota. Both publications used census data, although Ingram and Carroll (1981) analyzed the overall distribution of employment and population while Lee (1982) used industry-level data to analyze changes in employment location patterns across the urban rings resulting from Bogota´s zone system. These papers did not identify employment subcenters but were the first available references in the academic urban planning literature to describe spatial changes in Bogota. They also provided evidence of a trend toward employment decentralization while comparing that trend to patterns and processes in older urban areas in the developed world.

Literature from the seventies and eighties on multinucleation in urban areas included papers by Greene (1980), Ogawa and Fujita (1980), Griffith (1981), Gordon et al. (1986), McDonald (1987) and Heikkila et al. (1989). These papers were the source of the theory used by Dowall and Treffeisen (1991) to explain and define a subcenter. The authors did not emphasize unanimous criteria for identifying employment subcenters. The publication by Dowall and Treffeisen (1991) used McDonald's definition (cited above) as an essential reference for identifying subcenters in Bogota. However, spatially disaggregated employment data for Bogota were not available for use with McDonald's approach to identifying subcenters. Instead, Dowall and Treffeisen used administrative and historical information to identify obvious candidate subcenters. They chose "a set of eleven urban zones classified like neighborhoods which correspond[ed] to local peaks in employment, commerce, and/or land values." (Dowall and Treffeisen, 1991, p. 207)

Regardless of the lack of data for identifying Bogotan employment subcenters, Dowell and Treffeisen's (1991) publication is a general reference for applied work on employment subcenters in Latin American cities and the most important benchmark for identifying employment subcenters in Bogota.

3. Nonparametric Procedure Description: McMillen's two-stage procedure

According to McMillen (2001), the ideal procedure should be reproducible for a variety of cities and should not require detailed local knowledge. Such a procedure should also be appropiate for different units of analysis, allow for local variations on urban surfaces, control for distance from a CBD and provide statistical significance on surface changes in employment density.

A two-stage nonparametric procedure meets the first four of these objectives. The final objective can be achieved by changing the econometric specification, particularly the subsample size required for keeping the structure of local employment density intact (Redfearn, 2007).

In the first stage of the procedure, a locally weighted regression (LWR) is estimated to smooth the natural logarithm of employment over space. The basic nonparametric equation is

$$y_i = m(x_i) + \mu_i \quad (1)$$

where y_i is the natural logarithm of the gross employment density, x_i is a set of explanatory variables and $m(x)_i = \alpha + x_i\beta$ is a first-order expansion. The idea behind nonparametric estimation is an arbitrarily close approximation of $m(x)$. Stone (1977) and Cleveland (1979) suggested an estimator for $m(x)_i$ that minimizes

$$\sum_{i=1}^{n}(y_i - m - (x_i - x)\beta(x^*))^2 K(\frac{x_i - x}{h}) \quad (2)$$

with respect to m and $\beta(x^*)$. K_i determines the weight given to observation i to articulate the prediction at x. (x^*) is a number lying between x_i and x, representing the expansion point of $E(y_i \mid x = x_i) = m(x_i)$ around x. The expected result is $m(x_i) = m(x) + \frac{\delta(m)}{\delta(x)}(x^*)(x_i - x)$; it is also clear that $\beta(x^*) \equiv \frac{\delta(m)}{\delta(x)}(x^*)$. This estimate can be obtained by running a standard weighted least squares (WLS) regression estimate for each observation. The estimates $\hat{\beta}(x^*)$ are the coefficients obtained from the regression of $K_i^{1/2}y_i$ on $K_i^{1/2}$ and $K_i^{1/2}(x_i - x)$, while $\hat{m}$ is the predicted value at point (x). The expansion point captures the logic of linear local regression smoothing (Pagan and Ullah, 1999), which minimizes the residual sum of squares using only the observations close to x_i = x.

The explanatory variables in McMillen´s two-stage method are the distances to the CBD in the east (x_1) and north (x_2) directions. The equation describing the basic models is

$$y_i = m + \beta_1(x^*)(x_{1i} - x_1) + \beta_2(x^*)(x_{2i} - x_2) \quad (3)$$

where (x_{1i}) and (x_{2i}) are the due east and north distances to the CBD for each observation i, while x_1 and x_2 are the target points and (x^*) is the expansion point. The target point is the CBD's latitude and longitude.

Nonparametric models commonly use the kernel function K_i = $K((x_i - x)/h)$. For this application, K_i is a function of the distance between $x(i)$ and x . Distance has a natural geographic definition in spatial modeling (Brunsdon et al., 2002), and K_i is a function of distance between observation i and the target point, meaning, for example, that $(x_i - x)$ is the distance $d_i(x)$ between a census tract centroid and a CBD centroid. The variable h is the bandwidth or window size capturing the basic idea that relatively more weight is placed on sample observations as compared to "nearby" observations in the spatial data sample. Common kernel functions include the tricube:

$$K_i = \left(1 - \left(\frac{d_i(x)}{d_q(x)}\right)^3\right)^3 I(d_i(x) < d_q(x)) \quad (4)$$

where $I()$ is an indicator function that equals 1 when the condition is true. K_i forms the weight matrix, where all of the observations beyond the window q are given zero weight in the estimation, while the observations closer to each other receive more weight. McMillen's procedure used a large window size; 50% of the nearby observations for a site receive some weight in estimating the smoothed value of y. However, there is a problem in identifying outliers, because the estimation of y at a site uses half of the observations, substantially obscuring the topography of local employment (Redfearn, 2007). To avoid this problem, h is determined using a cross-validation procedure often used in local linear regression models (LeSage, 2004). A score function takes the following form:

$$\sum_{i=1}^{n}\left[y_i - \hat{y}_{\neq i}(h)\right]^2 \quad (5)$$

which is minimized with respect to h, where $\hat{y}_{\neq i}(h)$ denotes fitted values of y_i with observations for point i omitted from the calibration process. The variable h is an integer q representing the number of nearby neighbors for the tricube kernel. This number can vary across x. In this case, the bandwidth is defined as the window size. There are some differences between working with a fixed bandwidth and a comparably variable window size for which the values of x are evenly distributed across its value range (McMillen, 2010). Certainly, cities may have different spatial trends in their urban areas. For example, if the employment density gradient is larger on one side of the city, the number of neighbors must be higher than in an area with a smaller density gradient. In this case, it is better to estimate the employment density using a small subsample that will keep the structure of local employment density intact.

In this paper, the cross-validation method was used to determine the optimal window size. In contrast to McMillen's procedure, it resulted in a smaller window size (0.36). The objective of the first stage was to identify candidate subcenters. The list of potential subcenters was comprised of sites with residuals significantly greater than 0 at a significance level of 5%: $(y_i - \hat{y}_i)/\hat{\sigma}_i > 1.96$ where y_i is the LWR estimate of y at site i (Equation1) (McMillen, 2001, p. 452) and $\hat{\sigma}_i$ is the prediction's estimated standard error. Pagan and Ullah (1999) estimated the variance of the predicted value of the log employment density at location x using Equation 1. The second moment is defined as $\sigma^2(x) = E(y - i^2 \mid x) - (m(x))^2$. The variance is the first diagonal element of the following expression:

$$\sigma(x)^2\left(\sum_{i=1}^{n} z_i w_i z_i'\right)^{-1}\left(\sum_{i=1}^{n} z_i w_i^2 z_i'\right)\left(\sum_{i=1}^{n} z_i w_i z_i'\right)^{-1} \qquad (6)$$

where $z_i = (1, x_{1i} - x_1, x_{2i} - x_2)$ and $w \equiv K_i^{1/2}$. McMillen (2001) estimated $\sigma(x)^2$ as the predicated value derived from a kernel regression $(y_i - \hat{m}(x))^2$ on x_1 and x_2. This formulation accounts for heteroscedasticity and allows the variance to differ across space, specifically as

$$\hat{\sigma}^2(x) = \frac{\sum_i \omega_i e_i^2}{\sum_i \omega_i} \qquad (7)$$

where $\omega_i = h^{-2}\phi((x_{1i} - x_1)/h)\phi((x_{2i} - x_2)/h)$ and $\phi()$ is the standard normal density function. To avoid including many nearby sites as subcenters when significant residuals cluster together, McMillen's procedure narrows down the list of potential subcenters to those sites with higher predicted log employment densities among all of the observations with significant positive residuals in a radius of 4.2 kilometers (McMillen, 2001).[5]

It is clear that the choice of window size h is important for LWR estimation results. An extremely small window size can produce a nearly perfect fit, leading to the absence of significant residuals even when a subcenter has caused a local rise in density. Excessive smoothing can lead to positive residuals even when there is no local increase in the density (McMillen, 2001). The optimal range of bandwidth or window size remains an issue of research, despite the voluminous literature on bandwidth selection (McMillen, 2010). Regardless, kernel choice is less important in a nonparametric estimation.

The advantage of LWR analysis lies in its ability to detect local rises in the employment density function, even after accounting for broad spatial trends and only estimating given nearby observations with more weight. Controlling for spatial trends means taking local variations into account for the density gradient (east and north distances), including the CBD distance, and using the initial smoothing of the data as a benchmark. The initial smoothing process can be a simple OLS or LWR with a relatively large window that produces a moderate amount of smoothing, keeping a very small number

[5]Although the chosen radius is arbitrary according to the urban map, the radius of the cluster census tract with significant residuals is never greater than 4.5 kilometers. This is consistent with the idea that a subcenter leads to a local peak in the employment density function radius.

of observations, for example, half of the nearby observations, from receiving undue weight in the calculation of $\hat{y}(x)$ (McMillen, 2010).

After identifying candidate subcenter sites, the second stage uses a semiparametric procedure to assess their significance. The equation used for estimation is

$$y_i = \delta_0 + \delta_1(f(DCBD_i)) + \sum_{j=1}^{s}(\delta_{1j}D_{1j}^{-1} + \delta_{2j}D_{1j}) + \mu_i \quad (8)$$

where D_{ij} is the distance between observation i and the candidate subcenter site j, $DCDB_i$ represents the distance from observation i to the central business district, and S is the number of candidate subcenter sites. Equation 8 accounts for the effect of the $DCDB$ on the employment surface, allowing one to conduct a classical hypothesis test for the coefficients of interest, $\delta_2 D_{1j}{}^{-1}$ and $\delta_2 D_{2j}$. The variables representing distances to the subcenter enter the equation in both level and inverse forms. The first form captures the significant effects of subcenters over urban areas. The latter form is better for modeling a subcenter with more local effects. All subcenter candidates are included in calculating Equation 8, but the employment density corresponding to these sites is omitted to eliminate the bias introduced by including endogenously chosen sites as explanatory variables.

The flexible Fourier form is used to estimate *f(DCBD)* for this paper. In order to implement the procedure, the variable DCBD is first transformed to lie between 0 and 2π,

$$f(CBD_i) \approx \lambda_0 + \lambda_1 z_i + \lambda_1 z_i^2 + \sum_{q=1}^{Q}(\gamma_q cos(qz_i) + \delta_q sin(qz_i)) \qquad (9)$$

where z is the transformed variable. The Schwarz information criterion was used to choose the value for Q.

Estimating Equation 8 using a considerable number of candidate subcenters leads to severe multicollinearity problems. In this process, the subcenter variable with the lowest t value is deleted, and Equation 8 is estimated again. The equation is reduced until all of the subcenter distance variables are significant at the 10% level. The final list of subcenters includes sites with negative (positive) coefficients for D_j (D_j^{-1}) or both at the end of the regression procedure. McMillen (2001) envisioned a reproducible methodology for other studies. Certainly, his efforts to avoid criteria based on local knowledge, planning or historical background represent an advanced approach in urban economics. The important work of Anas et al. (1998) reveals that finding a more objective definition and criteria requires continuous empirical and theoretical research in geography, economic theory and econometric techniques. It is clear from the geographic perspective that the number of employment subcenters and their boundaries are quite sensitive to statistical definition. The urban landscape is highly irregular when viewed at a fine scale, and the manner in which one averages local irregularities determines the appearance of the resulting pattern. From an economic perspective, patterns occurring on different distance scales are influenced by different types of agglomeration economies. Such economies are based on interaction mechanisms with particular spacial proximity requirements for which a theoretical relationship between impact and policy variables must be developed. This involves the choice of specific functional forms relating these variables to others as controls.

4. Data

The data were based on census tracts from the National Census Bureau of Colombia (DANE) and were obtained from the Urban Planning Office of Bogota, which has a geographic information system (GIS) that maps coverage tracts of the city, making it possible to acquire the perimeter and location of each census tract. ArcGIS® was used to measure the area of each census tract in hectares. Centroids were obtained to measure the Euclidean distances from the CBD as well as the distances between the census tracts. Census tracts with employment have an average size of 58 hectares, with a sum of 31,780 hectares. The total urban area of the city is approximatley 380 square kilometers or 147 square miles, while its maximum length and width are 30 km and 17 km, respecively.

There is no distinction between formal and informal employment data for either 1990 or 2001, including street vending jobs.[6] Hence, the total employment figures given by the census tract data are used to evaluate the model. A summary of the data is provided in Table 1.

[6]DANE's definition of informal employment relies on four main features related to plant size and productivity: self-employed workers without professional or technical backgrounds, unpaid family workers, household workers and firms with up to 5 employees.

Table 1. City characteristics.

Variable	1990	2001
Population	4,948,000	6,300,000
Employment	1,884,000	2,698,000
Formal Employment	979,680	1,214,100
Census Tracts	608	608
-With Employment	543	543

Source: DANE.

Extensively disaggregated geographic levels appeared with similar kinds of results regardless of the size of cartographic area being analyzed. As explained in the previous section, one of the objectives regarding the two-stage procedure is to reduce the sensitivity of results to the tract size of the data set. The labor market in Bogota is defined by duality. This concept characterizes urban labor markets with two different employment sectors: the primary sector, whose firms offer stable employment and relatively high wages, and the secondary sector, which lacks these characteristics (Smith and Zenou, 1997). The share of secondary or informal employment in the city was approximately 50% for the years 1990 and 2001.

5. Significant Subcenter Locations

The first panel in Table 2 presents standard monocentric employment density estimates for Bogota. It also shows the natural log of the gross employment density for the years 1990 and 2001 as dependent variables with the distance from the CBD as an explanatory variable. The OLS estimation leads to excessive smoothing that identifies significant residuals even when there is no local rise in density. Employment density gradients were higher in the year 1990 compared to the year 2001. This shows that the traditional CBD is no longer the only broad spatial trend determinant among employment densities. A corresponding decrease in R^2 and t values on the CBD gradient shows that the CBD no longer defines employment densities in Bogota.

Table 2. Regressions Results.

	Log Employment Density	
	1990	2001
Constant	5.02	5.11
	(41.97)	(36.63)
CBD gradient	-0.19	-0.17
	(14.64)	(11.8)
OLS R^2	0.28	0.20
Observations	542	542
LWR and semiparametric estimation:		
Number of significant		
-LWR residuals	7	15
Number of subcenters*	5	7
R^2 Semiparamtric Eq.8	0.46	0.44
Fourier expansion length (Q)	0	0
Window size	33%	36%

Absolute t values are in parentheses.
*Subcenters with statistically significant effect on the overall shape of employment density function.Eq.7

The second panel indicates an improvement in explanatory power due to a semiparametric estimator (Equation 8) that uses subcenters identified by a LWR estimation in the first stage (the estimation of Equation 2 for selecting candidate subcenters). Equation 8 can be evaluated by the OLS method because the Fourier expansion method does not involve technical problems for the OLS estimator. The R^2 value obtained from estimating Equation 8 is generally much higher than the R^2 value resulting from a simple model, which is another indication that the city is no longer monocentric. The first-stage LWR estimation identifies 7 significant positive residuals in the year 1990 and 15 in the year 2001.

In the second stage, candidate subcenter sites are omitted in the evaluation of Equation 8. Limiting estimation to the neighborhood of observation i while allowing nonlinearity eliminates much of the heteroscedasticity and autocorrelation that is endemic to spatial data (McMillen and McDonald, 2004). This advantage arises from choosing a bandwidth value that retains the local structure of the employment data. It is important to recognize that the optimal window size is likely to be much larger when estimating the marginal effect of x on y rather than directly predicting y. Estimating the marginal effect of distance from the CBD in identifying subcenters is thus a logical choice.

Significant subcenters are displayed in Figure 1. Both maps show subcenters identified using the procedure of Giuliano and Small (GS, hereafter), in which a potential subcenter site is the census tract with the highest employment among a group of contiguous tracts with at least 25 employees per hectare and a total minimum of 25,000 employees. These cutoffs would be equivalent to Giuliano and Small´s cutoff (1 hectare $\approx$ 2.5 acres).

The triangles represent sites identified by the (GS) criteria. The hexagons indicate sites charaterized by both (GS) and McMillen´s two-stage procedure. For the year 1990, the (GS) procedure identified 5 potential subcenter sites. Two of these sites were determined by the first-stage nonparametric procedure. These subcenters have a significant effect on the employment density functions estimated by OLS. Significant subcenter sites from McMillen's two-stage procedure are identified by circles. Both procedures detect sites in zones west and north of the CBD (identified by a circumference). The greatest difference is that the two-stage procedure identifies sites in distant locations with respect to the CBD, located to the southwest and far north. These are sites with significant local effects on employment density and, in some cases, have spillover effects on a larger area. However, these subcenters do not exceed the total employee requirement of 25,000 in the set of contiguous census tracts.

Figure 1. Employment subcenters under GS and two stage procedure in Bogota.

1990 2001

Source: own elaboration.

The GS procedure identified nine subcenters for the year 2001. Three of them were identified by LWR with significant effects on OLS (Equation 8). The first 3 subcenters located on the north axis of the CBD in both 1990 and 2001 are evidence of changes in the spatial structure of employment. Two of these subcenters had a significant effect on the employment density function (Equation 8) in the year 1990, but both lost their significance in 2001. Subcenter (Chile Av.), located in the middle of the two previous subcenters, became significant. Depending on the subcenter location zones, the overall tendency of the spatial structure of employment is similar to that of the year 1990. There is also evidence of emerging new employment sites in the central-west area of the city. The advantages of the two-stage procedure become apparent when identifying subcenters in urban areas with low overall levels of employment density. These subcenters turn out to be important determinants of local densities. The localization of subcenters on the northern axis of the CBD accounts for a lower gradient in absolute terms on the north side of the city (coefficient of D_j).

Moreover, the eastern gradient is lower than the northern gradient for both years. The decentralization of employment toward the north of the city creates a continuous urban area with defined employment concentrations. Additionally, the northern gradient increases its value in the year 2001, which suggests that densities do not decrease as rapidly with distance from the CBD.

Two new subcenters in the south-west region are outcomes of road network development. The main road system of the city was not complemented by local streets, leading to the emergence of unplanned central places developing where roads crossed former mass transit lines. Figure 1 shows a subcenter location similar to that shown by Dowall and Treffeisen (1991, p. 208) Although their identification methodology is based on local knowledge and official figures, it is the only leading reference for Bogota.

The pattern of new subcenter emergence also shows that a policy on transportation infrastructures should not be planned in a strictly hierarchical manner, but should instead seek a kind of transversality that would support the network economies that emerge from the decentralization of employment in the form of subcenters.

5.1 Effects of Subcenters on Employment Densities.

NUE predicts that employment subcenters would have significant effects on land values, population and employment densities. This paper seeks to determine the extent to which a variable measuring proximity to subcenters improves the fit of the standard exponential employment density function. A simple exponential function is $y_i = \beta_0 + \beta_1 DCBD_i + \mu_i$, where y_i is the natural logarithm of employment. The results of the standard function are presented in the second and third columns of the first panel in Table 2. This paper employs a gravity variable for modelling the effects of multiple subcenter proximities, as used by Shukla and Waddell (1991). The estimation equation is

$y_i = \beta_0 + \beta_1 DCBD_i + \beta_2 Gravity_i + \mu_i$, and a positive value of β_2 implies that the proximity of subcenters corresponds to an increasing employment density (McMillen, 2001).

The gravity variable for observation i is similar to that of the standard gravity model:

$$Gravity_i = \sum_{j=1}^{S} \frac{\hat{f}(x_j)}{D_{ij}^{\alpha}} \quad (10)$$

where S is the number of subcenters in the metropolitan area, D_{ij}^{α} is the distance between observation i and subcenter j, α is a parameter representing the decay rate, and $\hat{f}(x_j)$ is the estimated density of observations at the subcenter site. Weighting terms for the gravity variable due to their estimated densities places less weight on proximity to more remote subcenters with large tract sizes but that are likely to be near tracts with little or no employment (McMillen, 2001). The parameter α varies between 0.25-2, stopping when the lowest residual sum of squares has been reached. Equation 10 is a convenient way of summarizing the effects of many variables such as the subcenter distance.

Table 3. Gravity variable regressions.

	Log Employment Density	
	1990	2001
Constant	1.14	1.78
	(8.37)	(8.52)
CBD Gradient	-0.04	-0.03
	(5.04)	(2.64)
Gravity	0.43	0.35
	(34)	(17.62)
R2	0.76	0.5
DW	1.8	2.08
Observations	537	535
(α)	0.5	0.75

Absolute t values are in parentheses.

Table 3 presents results from Equation 10. The employment density rises near the subcenters, even after controlling for the distance from the CBD. Nevertheless, the distance from the CBD is an important determinant of employment densities in Bogota. The large t values of gravity variables and corresponding increases in R^2 shown in Tables 2 and 3 obtained while estimating employment density functions are evidence regarding the importance of assuming a polycentric city. These findings suggest that a traditional CBD is no longer the critical determinant of overall formal employment density in Bogota.

6. Conclusion

This paper shows that a polycentric model effectively explains the spatial employment structure of Bogota. Rather than using the CBD, this study implements McMillen's procedure, specifically first-stage LWR, which is an objective methodology to identify candidate subcenter sites for spatial research on urban employment structure. The procedure adapts to local structures rather than using a monocentric city structure and is less sensitive to units of measurement than other procedures are. The two-stage methodology produces reasonable results for Bogota and shows the advantages of identifying sites away from the CBD and other traditional centers of activity. Methodologies such as (GS) do not identify these sites. However, (GS) is a benchmark and the seminal reference for identifying subcenters.

Bogota`s CBD is an important determinant of density in the city, but the presence of other subcenters in 1990 and 2001 indicates a polycentric urban structure. These subcenters also have a significant effect on the overall shape of the employment density function, even after controlling for distance from the CBD. LWR estimation (first-stage) identifies subcenters that depart from the spatial pattern of those "close" to the CBD and those located "far away" from areas of high economic activity. These subcenters have an important effect on local employment density. The first stage of the procedure can identify the unexpected sites that turn out to be important determinants of density.

When the gravity variable (representing proximity to subcenters) is included, the results obtained support the importance of a polycentric city model. Employment densities tend to be grouped in relation to distance from the CBD but emerge near subcenters. McMillen noted that if the two-stage procedure fails to identify an expected important site in the first stage, then the distance from that site can be added in the second stage. Similarly, if the procedure identifies exceedingly small sites as subcenters, they can be deleted in the second stage. This decision may require local knowledge, however, and initial smooth estimations can drive the identification process, along with level inspection and employment estimates for each census tract.

The procedure identified 5 and 7 subcenters for the years 1990 and 2001, respectively, with significant effects as defined by standard hypothesis testing. Thus, the two-stage procedure treats subcenters as a statistical concept in which proximity is an important determinant of employment density. However, it is necessary to test the sensitivity of the results to the average tract size of the data set. The geographical unit for Bogota is a census tract, but it is possible to have more disaggregated information, such as census block data. Aggregated information provides smoother estimates than disaggregated data do, which means that, in the former case, the number of candidate subcenter sites and significant sites falls. It is also expected, however, that the results would be comparable within the same range of distance. Testing these results for different analysis units can strengthen the first objective of the ideal procedure, although the procedure meets the objectives of statistical significance conditioned by distance from the CBD. This approach allows for local variations in the effect of distance from the CBD on employment density (different gradients over urban area). Further research is needed to account for the persistent labor market duality in cities, such as Bogota, in developing countries.

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Polycentrism in Bogota. The relationships between the subcenters and the CBD: Substitutive or complementary?

ABSTRACT

The importance of the Central Business District (CBD) in an urban structure of the cities demonstrates analytical relevance of the basic predictions of monocentric model. However, the dynamic nature of cities has generated a process of employment decentralization, at least during the last 50 years. This is characterized by a pattern of economic concentration in the form of subcenters in different zones of an urban area. This paper uses a nonparametric procedure to identify employment subcenters using sector-specific information for the year 2008. CBD along with subcenter form a polycentric urban structure. However, the proximity is still important for the economic activity, i.e. employment subcenters have significant effects on the employment density according to the theoretical prediction of the polycentric model of New Urban Economy. This research provides evidence in favor of this prediction in Bogota (Colombia). This is an urban context which is different from those discussed in the literature. Identification of subcenters is the first step to economic analysis of the urban structure. The next step is to define their roles. This research aims to characterize the subcenter based on economic relationship with CBD, the localization pattern and the sectoral composition. The results show that the subcenters have complementary links with CBD which are consistent to the localization pattern and characterized by the functional division of space and the sectoral specialization. Therefore, the employment decentralization follows a polycentric location model and is characterized by a specialized geography of the subcenters.

Keywords: subcenters, employment density, location, polycentric models.

1. Introduction

Numerous studies have addressed the polycentric nature of American cities (Los Angeles: Giuliano and Small, 1991; Chicago: Mcdonald, 1987; McMillen and McDonald, 1997; McMillen, 2003; Dallas: Shukla and Waddell, 1991; Phoenix: Leslie and Ó hUallachain, 2006, Canadian cities: Shearmur and Coffey, 2002; European cities: (Barcelona: Muñiz et. al., 2008; Muñiz et. al., 2003; Roca et. al., 2009; Dijon: Baumont et. al., 2004; Paris: Gilli, 2009), Middle Eastern cities (Tel-Aviv: Alperovich and Deutsch, 1994), Asian cities (Tokyo:Zheng, 1991) and Latin American cities (Concepción: Rojas et.al., 2009; Mexico City: Suarez and Delgado, 2009; Bogota: Dowall and Treffeisen, 1991). The geographic scope of these studies suggests that polycentrism is an urban model that can be found across the entire planet. We can define polycentrism as the existence of significant concentrations of employment outside the CBD which structure the metropolitan space and affect land value, the intensity of land use (density), the location of agents and mobility patterns. This definition addresses not only the existence of several different employment centers but also the role that they play in the metropolitan system. Unfortunately, even though numerous studies have been devoted to identifying the subcenters using a rigorous, replicable, objective methodology, few have actually researched the role that the subcenters play in relation to the CBD and the other subcenters.

This study addresses the issue of the substitutability or complementarity of the subcenters in the city of Bogota. Other recent studies have analyzed this issue (Craig, Steven and Kohlhase, 2010); Anderson and Bogart, 2001; Gilli, 2009; Leslie and Ó hUallachain, 2006). The novel contribution of this study is that it simultaneously addresses the topic from three different perspectives: checking whether they specialize in any particular sector, comparing the value of the estimated density gradient for each subcenter according to whether it is estimated in the direction of the CBD or in any other direction, and looking for some regularity in their pattern of geographic location. Should the hypothesis of substitutability be proven, it would be expected that the subcenters have similar sectorial compositions, which would also be similar to the composition of the CBD. It would also be expected that the employment density gradient would have similar values in all directions, and that the pattern of geographic location would reflect the regularities inherent in a Christallerian system. However, the empirical evidence for the case of Bogota veers in the opposition direction, so the subcenters seem to play a complementary role.

The results are interesting from a theoretical perspective, since they may be expressing the importance of specific agglomeration economics in each sector (localization economies) in the processes of employment decentralization. They also point to the advisability of bearing in mind history more, since the local economic base may explain the specialized nature of the subcenters. All of this implies understanding the city not so much as a hierarchical, symmetrical tree structure but as an increasingly horizontal and asymmetrical network where the relations of complementarity win out over those of substitutability. On a practical level, the results suggest the advisability of supporting the localization economies of each subcenter through specific economic-regional policies oriented at the locally dominant branch of activity. The results also point out that a policy on transportation infrastructures that is not planned strictly hierarchically but instead seeks a kind of transversality would enable the network economies that emerge from the complementarity to be maximized, which would in turn notably improve the overall efficiency of the system.

This paper is organized in following order. Second section provides detailed theoretical framework supporting transition of monocentric model to polycentric for better explanations regarding urban structure. Third section presents data and methodology for identifying employment subcenters. Fourth section contains results regarding their identification and characterization as well as economic relationships with CBD. The last section presents main conclusions of the investigation.

2. The hypothesis of the substitutability of subcenters: Theoretical coverage and methodological consequences.

2.1. Polycentric models of the New Urban Economics (NUE) and the New Economic Geography (NEG).

Even though the Monocentric City Model continues to describe the form of many cities with reasonable accuracy, there is a vast number of large urban areas for which one of the fundamental assumptions of the model, the total concentration of jobs in the CBD, is far from the reality. The spatial dispersion of employment associated with the processes of decentralization could fit the basic parameters of the Monocentric City Model assuming that part of this employment is located outside the CBD under decreasing density conditions from the center to the periphery, similar to the pattern of population density. However, this is a solution that is often unsatisfactory, especially when employment is located on the periphery, forming density lumps.

This led to the need to reformulate the theoretical model in order to allow it to accommodate the existence of polycentric urban structures. Polycentrism has been addressed in the New Urban Economics by selectively modifying some of the assumptions used in the monocentric model, yet without breaking with the compensatory logic that emerges from assigning a land value according to the transportations costs entailed in each location. The fundamental change consisted of introducing a centrifugal force in the guise of agglomeration diseconomies to explain the decentralization of some of the firms, along with a centripetal force in the guise of agglomeration economies which explain the reconcentration of part of the employment on the periphery of the city. Two families of polycentric models coexist within the New Urban Economics: exogenous and endogenous. Exogenous models, both the older and the newer ones, concur in acknowledging from the start the existence of subcenters and then later concentrating on the implications of these subcenters on the behavior of the population and/or employment. In contrast, endogenous models are static models lacking history yet which are capable of endogenously explaining the appearance of subcenters as one of the possible balances within a general equilibrium model (Richardson, 1988).

While endogenous models make it possible to debate on externalities, market failures and the gap between individual and collective optimality, exogenous models are designed to analyze the implications of the decentralization of employment. Even though the former are more interesting from an eminently theoretical standpoint, the latter have a formal structure that is particularly well adapted to the analysis of dynamic situations whose process is closer to the real world. Both dovetail in predicting that the employment and population densities decrease as the distance to the employment subcenters increases (Muñiz et al., 2008)

From a different theoretical framework and a larger spatial scale, the theoretical models of the New Economic Geography (NEG) are another of the basic referents when studying polycentrism. These models can be viewed not as an alternative approach to NUE but as a complementary framework that enables a more deeply examination of certain aspects that are somewhat neglected in the NUE, such as the issue of urban hierarchy or the pattern of spatial location of the subcenters. To do this, they start with an approach in which the internal economies of scale and product differentiation play a fundamental role, along with transportation costs and consumers' preferences (Anas et.al., 1998; Fujita and Mori, 1997; Fujita et.al., 1999) .[1]

[1] Fujita and Mori (1997) proposed an evolutionary approach regarding theory of urban systems. It explains that current urban structure is the result of historical process. Fujita et al. (1999) went step ahead by introducing more than one good provision in the model to manage emergence of urban centers of different hierarchical order.

2.2. The literature on polycentrism in view of the question of the substitutability or complementarity of subcenters.

Generally speaking, the exogenous polycentric models of the NUE work under the assumption of the substitutability between the subcenters and the CBD. The studies by White (1976) and Sullivan (1986) are good examples of this tendency. However, in some cases, complementarity is accepted. For example, in Sasaki (1990) the agglomeration economies which arise in the CBD have both a local and a global impact, while those in the subcenters exert only a local effect, which entails a relationship of complementarity. The case of Fujita et al. (1997) is particularly interesting since its development gives rise to diverse equilibriums, which in turn imply different levels of complementarity.

In contrast, the exogenous polycentric models of the NUE have focused on the complementarity of the subcenters with regard to the CBD. Fujita and Ogawa (1982) posit a model in which the agglomeration economies appear in the company output function through a potential localization function which depends on the volume of employment weighed by distance. Even though this is not an issue to which they devote much attention, the way they introduce agglomeration economies into the model implies complementarity. The same holds true in Lucas and Rossi-Hansberg (2002), where externalities in the output function are introduced as an efficiency parameter which depends on the average employment in the other locations weighed by distance.

Contrary to the diversity of options adopted by the NUE models, the NEG models generally assume a relationship of substitutability between the CBD and the subcenters. This is logical given that one of its explicit objectives is to reproduce the hierarchy inherent in a Christallerian system, a hierarchy which is supported on assumptions such as the substitutability between the CBD and the subcenters.

2.2.1 Polycentric Employment Density function

In the empirical realm, the issue of the substitutability or complementarity of the subcenters has been present, but only as an implicit assumption associated with the different estimation techniques of polycentric density functions, not as a relevant issue in itself which deserves to be developed in further depth.

To estimate the polycentric population and employment functions, different functional functions have been proposed that in turn imply a given relationship – of either complementarity or substitutability – between the subcenters and the CBD. The additive density function implies complementarity (Gordon et.al., 1986; Small and Song, 1994), but it assumes that the centers have a very small impact for long distances. The multiplicative density function corrects this problem, so in theory it is the function that captures the principle of complementarity the most broadly. However, the econometric problems associated with the correlation between the numerous distances considered in the model made it recommendable to find some way to lower their radius of action. With this goal in mind, some studies introduced not direct distance but the inverse of the distance to the subcenters, thus lowering the multicollinearity of the model, albeit at the cost of limiting the implicit degree of complementarity between subcenters and the CBD (McDonald and Prather, 1994); McMillen and McDonald, 1998). The extreme case of implicit substitutability arises in the polycentric density function, which only considers the distance (or the inverse of the distance) to the closest subcenter (McDonald and Prather, 1994; McMillen and McDonald, 1997; McMillen and Lester, 2003 ; McMillen, 2004).

In short, even though some theoretical NUE models use the hypothesis of complementarity between the CBD and the subcenters, they do not tend to inquire into the consequences of this with regard to the sectorial composition of the NUE and NEG polycentric models. The hypothesis of complementarity has neither been particularly developed under the coverage of these theoretical cornerstones of polycentrism nor has it been regarded as a sufficiently interesting hypothesis to be explicitly tested, with the exception of studies by Craig and Koolhase (2010) and Anderson and Bogart (2001). These works addressing complementarity feature between CBD and subcenters certainly do not fall under NUE or NEG models.

2.2.2 Complementary subcenters under approaches alternative to the NUE and NEG

European territory has been occupied and exploited in a sedentary fashion for centuries, so today's urban systems (national, regional, and local) partly capture the hallmarks of an ancient geography which emerged from much more severe restrictions on transportation than the ones today, in which the prevailing output was agricultural and the main economic function of cities was to supply more or less specific personal services to the people. With industrialization and the subsequent decentralization of the population and employment, the traditional Christallerian equilibriums were altered. Today, for quite a few cities in Europe, a large urban center's sphere of influence overlaps with the spheres of medium-sized cities which are located between 20 and 50 km from the main center and often have centuries or even millennia of history behind them and are contributing to forming a polycentric urban system, which has only recently been integrated thanks to improvements in transportation.

This functional integration or metropolitanisation leads to a reinterpretation of the inherited urban system in a less hierarchical way. As the previously disconnected market areas become functionally integrated, the possibility arises that the different centers will complement each other in their quest for the advantages of specialization. Today, urban centers, which were previously oriented towards supplying population services, can more deeply reap the advantages of specialization without having to sacrifice a diverse economic base on a larger regional scale (Camagni and Salone, 1993; Capello and Camagni, 2000; Batten, 1995; Dematteis, 1990, 1994; Boix and Trullén, 2007).

Starting from a totally different place, Anderson and Bogart (2001) have developed a discourse on the functioning of a polycentric urban system similar to the theoreticians of the urban network. Through a variety of studies (Bogart and Ferry, 1999; Bogart, 1998; Anderson, 1999), they apply the fundamental lessons of the theory of international trade to the logic of a polycentric urban system. They suggest interpreting employment centers as countries which can gain efficiency in an open economy by concentrating their production on a single sector in order to explore a comparative advantage or the specific economies of scale of a given sector (or localization economies) without having to sacrifice the variety in consumption. Translated to a metropolitan discourse, even though the subcenters are specialized, the urban region has enough variety to generate "network economies". The interaction among agents within the urban region occurs not just locally but also on a metropolitan scale. Hence, it is crucial to guarantee the integration of the system through communication infrastructures which make possible the interactions (technological or pecuniary) among subcenters needed to achieve agglomeration economies on a metropolitan scale (network economies).

Both the Italian literature on network economies and Anderson and Bogart's approach concur in positing a kind of polycentrism very different to the Christallerian kind. Instead of self-contention, they propose integration; instead of generic agglomeration economies, they propose localization economies and network economies; instead of a sectorial structure similar to the CBD, they propose more unique and specialized profiles; and instead of the substitutability of the subcenters with regard to the CBD, they suggest complementarity.

2.3. Complementarity versus substitutability: Testable implications

The purpose of this study is to explicitly test whether the subcenters in Bogota behave in a complementary or substitutive way with regard to the CBD. To accomplish this, three different ways are explored: a) the possible existence of singularities in the sectorial composition of the subcenters; b) the symmetry or asymmetry of the subcenter density gradient; and c) the pattern of spatial location of subcenters. The existence of sectorial singularity, a lower density gradient towards the CBD and a spatially imbalanced location pattern would be considered evidence in favor of the hypothesis of complementarity. On the contrary, a sectorial composition similar to the CBD, a gradient of the same value in any direction and Christallerian-style location pattern would point to the substitutability of subcenters.

2.3.1 Sectorial specialization

According to the formal update of the Christallerian model proposed by the New Urban Geography theoretical models in which the subcenters replicate the role played by the CBD on their immediate periphery but on a smaller scale, the economies that come into play are general; that is, they are not specific in any particular sector. This approach attaches a great deal of importance to the knowledge externalities that require frequent face-to-face contact, which would fit with the fact that the CBD and the subcenters concentrate much of the employment in the Producer Services (PS) sectors and in some population and production oriented service sectors such as Finance Insurance and Real Estate (FIRE). To the contrary, in the approach to polycentrism common in the literature on network cities, the employment centers complement each other as two different kinds of agglomeration economies come into play. The first have a local scope and are specific to a given sector (localization economies), while the second, which have a regional scope, emerge from the size and diversity in the entire urban system (network economies).

2.3.2 The symmetry of the value of the gradient of the subcenter

The complementarity or substitutability of subcenters has implications not only on their sectorial structure but also on the economic value of the land around them and the corresponding population and employment density. If subcenters substitute the CBD, the agents (people and firms) preferably interact with a single employment center from which they get the goods and services they need. Therefore, the value of a given location depends solely on access to a single employment center. Conversely, if the subcenters are complementary to each other and with regard to the CBD, the agents value access to diverse employment centers since each one provides different goods and services. Bearing in mind that the CBD has traditionally concentrated a large percentage of jobs and that despite recent widespread decentralization it is still the site of the most jobs, the hypothesis of complementarity implies that the value of the gradient of the subcenter should be significantly lower when it is estimated between the subcenter and the CBD than in any other direction, since for the same distance to the subcenter locations closer to the CBD would be more highly valued by the agents.

Craig and Kolhase (2010) estimate polycentric population density and employment functions for the metropolitan region of Houston, Texas, with the purpose of checking whether there are significant differences in the value of the gradient associated with each subcenter when estimated in the direction towards the CBD. Their results confirm that the "slope" of the function (density gradient) is significantly lower when estimated in the direction of the CBD, which can be interpreted as evidence in favor of the hypothesis of complementarity.

2.3.3 Spatial equilibrium

The Christallerian model, which some models of the New Economic Geography attempt to reproduce in today's formal framework, that is, including the presence of agglomeration economies and increasing returns, is characterized by outlining not only the number of subcenters corresponding to each hierarchical order but also a pattern of spatial location which tends to occupy the territory in a balanced fashion. Fujita et.al., (1997) hold that if the decentralization of employment occurs as part of a process of horizontal disintegration in which decentralized companies perform similar activities, the resulting geography is typically Christallerian with substitutive subcenters distributed in a balanced fashion throughout the metropolitan area. To the contrary, if the process of employment decentralization is more similar to a vertical disintegration process, these spatial balances will not necessarily occur, generating a less hierarchical and more spatially imbalanced urban system (Gilli, 2009).

Some studies confirm alternative location patterns to the Christallerian patterns in subcenters with pronounced specialization. The subcenters whose economic base is preferably oriented towards services for individuals tend to be especially close to the CBD (Leslie and O'hUallachain, 2006). With regard to manufacturing subcenters, they tend to take advantage of locations with good access to the main transportation hubs, so it should come as no surprise that metropolitan corridors arise that string together beads of small subcenters (Kolko, 2010).

3. Data used and methodology to identify subcenters

3.1. Data

Urban Planning Office of Bogota provided the data used in this research which consists of census tract information of formal employment per economic sector for 2008. Census Bureau Office of Colombia (DANE) collected and developed this information from the population census of 2005 and was updated using economic information provided by Secretary Finance of Bogota (SHD) and the Chamber of Commerce of the city (CCB). Bogota urban census tracts cover an area of 380 square kilometers (sq. km) or 147 square miles (sq. mi) while maximum length and width are 30km and 17km respectively. Total area of Bogota D.C. is 1.587 sq. km (613 sq. mi.) which covers rural and sparsely populated locality of Sumapaz (5,667 inhabitants in 2007), and rural areas of Ciudad Bolívar and Usme, which are not included in this study. The city has 607 census tracts. Each economic classification of formal employment namely; total, manufacturing, retail, services and "other", has 576, 562, 552, 546 and 571 census tracts, respectively. Although number of the employment census tracts change per economic sector, but statistical summary for the areas remain the same, which is as follows: Average and median tract sizes of 0.62sq.km and 0.45sq.km, with standard deviation of 0.7sq.km. Minimum and maximum tract sizes are 0.06sq.km and 7.03sq.km, respectively.

Statistical summary is provided in Table 1. Total formal employment was around 1,3 million for 2008. This figure for the city was 3,4 million for the same year with informal employment rate of 62%. However, the informal employment was 1,8 million (Camara de Comercio de Bogota, 2008) for 2008 with the rate of 53%. In addition, the formal employment was 1,6 million. The difference between the figures used in this work, and those reported by Chamber of Commerce is due to exclusion of around 250.000 jobs with no spatial reference.

Urban Planning Office provided the geographic information. Specialized software (ArcGIS®) was used to associate the employment information with specific spatial reference (census tracts) to measure area for each tract (in hectare) and to provide coordinates for the centroids. Spatial weight matrix was created for each observation using these coordinates to measure the distance to CBD.

Table 1. Formal Employment according to Census Tract of 2008**.**

Employment	Total Formal	Manufacturing	Retail	Services	Other
Total	1,302,888	220,557	284,810	445,544	351,977
Mean	2261.96	392.45	515.96	816.01	616.42
Median	1116	120	215.50	260.50	317
Standard dev.	3211.48	868.27	807.49	1810.73	965.94
Min	7	1	1	1	2
Max	27782	8000	6066	19454	9330
Cummulative Emp. Share(2.5km)	0.13	0.09	0.19	0.14	0.9
Density	**Total Formal**	**Manufacturing**	**Retail**	**Services**	**Other**
Total	36.5	6.3	8.4	13.1	10
Mean	53.04	8.45	12.45	19.41	14.68
Median	28.77	3.20	5.27	6.32	7.76
Standar dev.	72.84	14.71	21.15	43.01	22.28
Min	0.13	0.00	0.01	0.01	0.08
Max	426.92	115.30	236.39	289.91	173.23

Source: Own elaboration from (DANE) data. Employment and densities are expressed in jobs and jobs-per-hectare, respectively

The information available does not allow us to break down the employment into more than three sectors (manufacturing, retail and services). The information on the miscellaneous sectors makes no reference to any kind of activity in particular, so it was not taken into account when identifying the subcenters by sector.

3.2. Methodology used to identify subcenters

The empirical research on modeling urban spatial structure has focused on developing objective, flexible methods that yield the best possible representation of cities' complex spatial structure (Redfearn, 2007). From the cluster methods proposed by Giuliano and Small (1991) to the technical parameters of McDonald (1987) and the more technically refined approaches of McMillen (2001) and Redfearn (2007), the methodological development to identify subcenters has been a crucial contribution to the analysis of polycentric urban structure.

However, cluster methods and parametric techniques have certain methodological limitations in metropolitan contexts characterized by a polycentric structure. Cluster methods are highly sensitive to the unit of analysis and require broad knowledge of the local context. In turn, parametric techniques do not take into account the local variations in employment according to distance from the CBD, they assume a linear functional form which scarcely represents today's urban structures, and they entail problems of multicollinearity as they include many variables which represent the distance to different employment concentrations. Quite a few studies have recognized the problems with identifying employment concentrations within cities using cluster methods or parametric techniques (McDonald and Prather, 1994; Small and Song, 1994; Shukla and Waddell, 1991; Wadell and Shukla, 1993; Dowall and Treffeisen, 1991; McDonald and McMillen, 1990; Heikkila et al., 1989).

McMillen (2001) presents a procedure to identify subcenters; though it is grounded upon the studies by Gordon et al. (1986), Craig and Ng (2001), and McMillen and McDonald (1998), it is a pioneer in systematically presenting a solution to the limitations of the cluster methods and parametric techniques. The procedure has two characteristics that reinforce its objectivity. The first is that it makes the identification of employment subcenters endogenous, and the second is that it makes possible to determine whether the subcenters have significant effects on the employment density.

According to McMillen (2001), subcenters are identified in two stages. The first stage consists of estimating the employment density using the Locally Weighted Regression (LWR) estimator.

This stage has two characteristics that overcome the limitations of the cluster method and parametric techniques. First, it takes into account the local variations in employment density which do not depend on the unit of analysis used (census sectors, post codes, etc.) and are instead conditioned by the distance to the CBD. Secondly, the weighing scheme enables the local employment structure to be maintained. These characteristics reduce the problems of specification in the econometric model. These problems are the symmetry entailed in the monocentric model with regard to the CBD and the fact of giving the same weight to all the observations in the spatial structure. The objective function for the LWR estimator solves these problems.

$$\sum_{i=1}^{n}\left(y_i-\alpha-\beta_1(x)(x_{1i}-x_1)+\beta_2(x)(x_{2i}-x_2)\right)^2 K_i \qquad (1)$$

Then the function is minimized with respect to α, β_1 and β_2, as the β coefficients are the gradients of density associated with point x, with the east and north coordinates equal to x_{1i} and x_{2i}, respectively. The coordinates of the CBD are x_1 and x_2. The model takes into account the changes in the employment density that take place on either side of the CBD controlled by their distance from each observation. Therefore, no symmetry with regard to the CBD is assumed. K_i represents the tri-cube weight function.

$$K_i=\left(1-\left(\frac{\delta_{ij}}{d_i}\right)^3\right)^3 I\left(\delta_{ij}<d_i\right) \quad (2)$$

in which d_i is the distance of the qth observation closest to i, δ_{ij} is the Euclidean distance between observations i and j, and is $I(\bullet)$ an indicator function which has the value of 1 when the condition is met. The number of nearby neighbors chosen for each local regression (window size) is yielded by the method called *cross-validation*(CV)[2] (Härdle and Linton, 1994). In this weighing scheme, the closest observations are given

[2] For the behavior of the weighing scheme the choice of q is more important than the functional form of the function K_i (Clark, 1977).

more weight than those which are located further away in each local regression. Therefore, the local structure of employment density remains the same and the spatial relations between observations are not assumed to have the same weight over the urban area.[3]

The potential employment subcenters are the observations with positive and significant residues at 5% [$(y_i - \hat{y}_i / \hat{\sigma}_i) > 1.96$]; y_i is the natural logarithm of the employment density in observation *i*; $\hat{y}_i$ is the LWR estimate of y_i; and $\hat{\sigma}_i$ is the estimated standard error for the prediction (Pagan and Ullah, 1999). To prevent there form being many potential places, only those with the highest estimated value in a radius of four kilometers are chosen.

The statistical significance of the subcenters is determined in the second stage. One of the main predictions of the polycentric models of the NUE is that the subcenters should exert a significant effect on the employment density. To check this prediction, we estimated the semi-parametric function;

$$y_i = f\left(DCBD_i\right) + \sum_{j=1}^{s}\left(\beta_{1j} D_{ij} + \beta_{2j} D_{ij}^{-1}\right) + u_i \qquad (3)$$

in which D_{ij} is the distance between observation *i* and subcenter *j*. To capture the local effect of each subcenter, their distance also enters into the equation inversely. Then the distance to the CBD is transformed so that it has values in the range of 0 to 2π and a Fourier expansion[4] is estimated, represented by *f(DCDB$_i$)*. This enables to take into account the non-linearities entailed in the distance function to the CBD (Gallant, 1981). The estimate of equation 3 includes all the potential subcenters, but the observations where they are located are omitted to eliminate the bias implied in introducing subcenters chosen endogenously as explanatory variables (McMillen, 2001). To avoid problems of multicollinearity, the *stepwise regression* procedure is used, which consists of eliminating the variable with the lowest value of the statistical *t* in each regression. The procedure is repeated until all the variables that represent the distances to the

[3] The weighing scheme for each local regression solves several of the problems inherent to the parametric techniques applied to spatial data (McMillen and McDonald, 1997). First of all, they enable the local regressions in each observation to reflect the local curvatures of the employment density function. What is more, the problems of multicollinearity are lowered by avoiding the estimate of larger polynomials to represent the changes in employment on the urban area. Even though the exclusion of variables leads to the estimation of biased values, the magnitude of the problem is lower given that the procedure is adapted to the local employment density. Finally, the complexity of the urban area should be borne in mind when assuming a non-linear and more flexible functional form than the negative exponential function.

[4] The number of parameters of the extension is determined by the Schwarz information criterion.

subcenters are significant at 20%. The final list of subcenters corresponds to the places which show a negative coefficient over D_{ij} and/or a positive coefficient over D_{ij}^{-1}. The identification process is repeated using the employment data from each economic sector.

4. Results

4.1. Identification of Subcenters

Subcenters are identified using McMillen's procedure (McMillen, 2001), with one exception. In our case, just like in the majority of studies, one group of subcenters is identified using the total employment figures. However, a sectorialized identification is also carried out in which only the figures on one sector (in our case, industry, services, and retail) are taken into account. Studies like Coffey and Shearmur (2002), Muñiz and García-López (2010), and Leslie and O'hUallachain (2006) have also examined the possible specialized nature of the subcenters in this same identification phase.

The first panel of table 2 presents standard negative exponential function of employment density in the framework of monocentric city. Dependent variables are the natural logarithm of formal employment density per sector while the explanatory variable is the distance from CBD. The employment density gradients are similar for total employment, services and retail sectors. The steepest gradient in 2008 is for the sector of manufacturing. All CBD gradients and their t-values suggest that CBD still is an important determinant of urban structure. The ordinary least square (OLS) R^2 indicates that the distance from CBD only explains an average of 12 percent variation in employment. Second panel of the table indicates additional explanatory power of modeling the city into polycentric framework. Second row (LWR residuals) of this panel shows significant residuals identified in the first stage of nonparametric procedure (equation 1). Third row shows subcenters with significant effects on employment density in accordance to *stepwise regression* R^2 of equation 3.

Fourier expansion terms do not restrict OLS estimation. In addition, traditional R^2 is available for semiparametric regression. The expansion length is 0, hence only the transformed distance variable remains at each stepwise regression of second stage. As expected, semiparametric functional form fits better than parametric negative exponential form. This result is due to endogenous identification of subcenters at first stage of the analysis. CV score indicates that 84, 65, 100 and 65 are the numbers of nearest census tracts for total formal employment, manufacturing, services and retail sectors receiving some weight in each local regression, which accounts average span of 0.15[5].

Table 2. Monocentric and LWR Polycentric Regressions, 2008.

	Total Formal Employment	Manufacturing	Services	Retail
Log formal employment density				
OLS gradient	-0.127	-0.157	-0.134	-0.132
	-9.751	-9.900	-7.860	-8.217
OLS intercept	4.218	2.316	2.766	2.567
	33.977	15.254	17.061	16.837
N	575	561	545	551
OLS R^2	0.14	0.15	0.10	0.11
LWR and semiparametric estimation-Log formal employment density				
LWR significant residuals	14	15	13	10
Number of subcenters	3	4	4	4
R^2 semiparametric regression	0.4	0.3	0.33	0.26

t statistics below coefficients

Based on the application of the procedure using the total employment figures, three subcenters are identified. The sectorialised breakdown of the employment figures also enables us to identify four using the data from industry, four more using the data on employment in the services sector, and four more in retail. The final list of employment centers thus includes not only the CBD but also eleven subcenters (four locations were identified using figures from more than one sector).

4.2. Employment density functions under the assumptions of complementarity or substitutability

Tables 3 and 4 show the main results of the employment density functions estimated under the substitutability and complementarity hypotheses, respectively. The figures on Table 3 show the OLS estimate of the coefficients corresponding to equation 4, where only the distance to the closest subcenter is taken into account (substitutability hypothesis).

$$y_i = \beta_0 + \beta_1 DCBD_i + \beta_2 DNEAR_i + \mu_i \qquad (4)$$

[5] A window size of observations less than 30% generally keeps the local structure of the data intact with negligible bias (Cleveland and Devlin, 1988).

in which y_i is the gross employment density in census sector *i* and $DNEAR_i$ is the distance to the subcenter closest to census sector *i*. Equation 4 starts with the assumption that subcenters are substitutive, so the economic agents only value access to one of them. This assumption implies that each subcenter identified has the capacity to replicate the functions of the CBD, albeit with a noticeably smaller radius of influence.

Table 3. OLS estimates of equation 4: Substitution hypothesis

	Total Employment	Manufacturing	Services	Retail
CBD gradient	-0.10	-0.19	-0.05	-0.05
	-8.65	-12.88	-2.41	-2.60
DNEAR gradient	-0.30	-0.27	-0.24	-0.26
	-11.54	-9.74	-7.80	-8.04
Intercept	4.90	3.88	3.19	3.01
	40.70	18.65	19.95	20.12
R^2	0.32	0.28	0.20	0.20
N	572	557	541	547

t values below coefficients.

Below, Table 4 shows the results of equation 5 (complementarity hypothesis):

$$y_i = \beta_0 + \beta_1 DCBD_i + \sum_{j=1}^{s} \beta_j DSC_{j,i} + \mu_i \qquad (5)$$

where not only is distance to the CBD included, but so is the distance to each of the 11 subcenters identified based on the total employment data and the sectorial data. Both the gradient associated with distance to the CBD and the gradient associated with the distance to each subcenter identified show the right sign and are significant at standard levels.[6]

Table 4 also shows that of all the subcenters identified, only three exert a significant effect on total employment. Of them, the Av. Chile subcenter stands out in that not only does it have a global scope but both the value and significance of its gradient are also particularly high, which distinguishes it from the other subcenters. The statistical prominence of the Av. Chile subcenter is important in the discussion on the economic relations between the subcenters and the CBD in Bogota. No other subcenter exerts such an important and significant effect on the city's urban structure. Therefore,

[6] The subcenters Av. 26-Av.Cali, Sevillana, and Restrepo are significant at 15%, and the CBD is significant at 10% in the case of the services sector. However, in the procedures of identifying the subcenters, these levels are tolerable (McMillen, 2001).

there is a possibility that in the forthcoming years Av. Chile will occupy the highest rank in the urban system, perhaps even above the CBD.

Even though the R^2's obtained under the substitutability assumption are lower than those obtained under the complementarity assumption, the analysis of the economic relations between the subcenters and the CBD are still unsatisfactory in at least two respects. First, the negative exponential function described in equation 5 incorporates the distance to the CBD and to each of the 11 previously identified subcenters, generating overlaps in the different subcenters' areas of influence. The confluence of different gradients makes it difficult to distinguish the effect of each subcenter on the employment density. Secondly, estimating the density function with the distance of each census sector to each subcenter implies accepting the hypothesis of gradient symmetry, which is incompatible with the hypothesis of complementarity of the subcenters with regard to the CBD.

Table 4. OLS equation 5 estimations: Complementarity hypothesis.

	Total Formal Employment	Manufacturing	Services	Retail
Dist CBD (*)	-0.05	-0.11	-0.05	-0.05
	-3.13	-5.91	-1.77	-2.21
Dist Av.Chile (*)	-0.16		-0.18	
	-8.20		-6.39	
Dist Av.26-Av.Cali (*)	-0.03			
	-1.53			
1/Dist Sevillana	1.11	0.47		
	4.19	1.52		
1/Dist Inv. Alamos		1.02		
		2.90		
D ist Zona Industrial Outlets (*)		-0.20		
		-6.96		
1/Dist Toberín		2.37		
		6.90		
1/Dist El Lago			0.72	1.13
			2.76	6.13
1/Dist Auto.Norte. Calle 127			1.23	
			2.80	
1/Dist Restrepo			0.54	1.23
			1.52	4.07
Dist Salitre (*)				-0.15
				-7.30
1/Dist Unicentro				1.78
				3.66
Intercept	5.07	2.94	3.24	2.37
	30.37	13.35	10.94	9.24
R^2	0.35	0.30	0.34	0.26
N	572	557	541	547

T values below Coefficients
(*) direct distance (global effect)

4.3. Contrasting the hypothesis of substitutability versus complementarity.

4.3.1. Symmetry of the gradient of the subcenters in the direction towards the CBD

Craig and Kohlhase (2010) developed a methodology to identify the kind of tie that exists between each subcenter at the CBD. This empirical approach takes into account the spatial changes in the economic activity around the subcenter, always controlling for the distance from each subcenter to the CBD. The idea is to perform estimates of exponential functions centered on each subcenter, but allowing for the existence of two gradients. The former reflects the intensity of the economic activity between the subcenter and the CBD, while the latter reflects the intensity between the subcenter and the urban limit (Craig and Kohlhase, 2010). The estimated function for each subcenter is:

$$Density = \beta_0 + \beta_n NEAR \bullet DISTANCE + \beta_a AWAY \bullet DISTANCE + \mu \qquad (6)$$

The endogenous variable is the gross employment density around a particular subcenter, *DISTANCE* is the distance in kilometers to the subcenter, *NEAR* is a dummy variable which has a value of 1 if the census sector falls between the subcenter and the CBD and *AWAY* is another dummy variable which has a value of 1 if the census sector is in any other direction. The estimate is restricted to the zones of influence around each subcenter; this zone is defined as a concentric area with a radius of *r* around each subcenter in which *r* is the distance between the subcenter and the CBD.

If β_n is equal in magnitude to β_a, the agents consider the subcenter a substitute for the CBD since they do not detect any significant advantages of having good access to both the CBD and the subcenter. To the contrary, if the gradients are different and the gradient toward the CBD (β_n) is flatter – lower in absolute value than β_a – the agents value accessibility to both the subcenter and the CBD. To examine whether the gradients on each side of the subcenter are equal or different, a statistical test is applied to the 11 subcenters identified.

The results on Table 5 support the hypothesis of complementarity between the subcenters and the CBD. All the gradients are negative and significant for the areas furthest from the CBD (β_a).In turn, the estimated gradients between the subcenters and the CBD (β_n) are generally negative, significant and flatter. The test of the equality of the coefficients shows that in all the subcenters except Av. Chile, Av.26-Av.Cali and Restrepo, the absolute value of the gradients associated with the *NEARDISTANCE* variable are significantly lower compared to the gradients for the *AWAYDISTANCE* variable, which implies complementarity between the CBD and the subcenters.

The results for the subcenters Av. Chile and Av.26-Av.Cali are favorable to the hypothesis of complementarity for all the sectors except manufacturing. This could be due to the fact that the small companies located around the subcenter have no ties with the companies located in the CBD. However, to prove this hypothesis we would need more detailed information on employment on a sectorial level. One alternative explanation could be the proximity between subcenter Av. 26-Av.Cali and the city airport, one of the leading airports in the country and the Andes region. Bearing in mind this subcenter's proximity to the logistical infrastructures of the airport, it is likely that the manufacturing companies value access to the subcenter but not to the CBD. The same holds true of the manufacturing companies located between the Restrepo subcenter and the CBD.

Table 5. Employment Density Functions for Individual Subcenters by Sector: A Methodology for identify economic links between subcenters and CBD.

	Endogenous Vble.	Total Jobs			Manufacturing			Retail			Services		
Subcenter		Constant	Near CBD	AwayCBD	Constant	Near CBD	AwayCBD	Constant	Near CBD	AwayCBD	Constant	Near CBD	AwayCBD
Av.Chile	Parameter	4.830	-0.147	-0.181	2.513	-0.064	-0.078	3.252	-0.120	-0.177	3.809	-0.176	-0.206
	Std. Error	0.430	0.016	0.070	0.126	0.016	0.024	0.141	0.023	0.017	0.506	0.018	0.026
	N/Test Near=Far	303	Different**		247	Same		270	Different***		270	Different*	
Av. 26-Av. Cali	Parameter	4.083	-0.107	-0.181	2.605	-0.093	-0.135	2.384	-0.055	-0.128	2.439	-0.057	-0.130
(Dorado Plaza)	Std. Error	0.123	0.013	0.023	0.149	0.017	0.030	0.137	0.015	0.027	0.124	0.014	0.024
	N/Test Near=Far	384	Different***		246	Same		234	Different***		303	Different***	
Salitre	Parameter	4.420	-0.157	-0.218	2.930	-0.150	-0.182	2.740	-0.106	-0.161	2.700	-0.094	-0.154
	Std. Error	0.118	0.013	0.017	0.146	0.019	0.023	0.137	0.017	0.021	0.125	0.016	0.019
	N/Test Near=Far	384	Different***		288	Different*		324	Different***		303	Different***	
Zona Ind. Outlets	Parameter	4.523	-0.180	-0.257	3.018	-0.176	-0.214	2.859	-0.131	-0.193	2.787	-0.115	-0.181
	Std. Error	0.117	0.019	0.140	0.145	0.020	0.026	0.140	0.019	0.024	0.128	0.018	0.022
	N/Test Near=Far	380	Different***		287	Different**		324	Different***		303	Different***	
El Lago	Parameter	4.768	-0.132	-0.222	2.500	-0.057	-0.115	3.178	-0.107	-0.201	3.730	-0.160	-0.240
	Std. Error	0.126	0.016	0.023	0.137	0.017	0.026	0.131	0.016	0.023	0.135	0.017	0.025
	N/Test Near=Far	333	Different***		264	Different***		296	Different***		296	Different***	
Unicentro	Parameter	4.518	-0.072	-0.28	2.25	-0.016	-0.167	3.018	-0.065	-0.225	3.64	-0.105	-0.28
	Std. Error	0.144	0.013	0.026	0.154	0.014	0.033	0.146	0.013	0.027	0.153	0.014	0.029
	N/Test Near=Far	377	Different***		288	Different***		321	Different***		324	Different***	
Toberín	Parameter	3.55	0.007	-0.37	1.6	0.029	-0.205	2.268	-0.003	-0.252	2.73	-0.019	-0.291
	Std. Error	0.155	0.012	0.078	0.163	0.012	0.137	0.162	0.012	0.105	0.173	0.013	0.108
	N/Test Near=Far	372	Different***		288	Different*		321	Different**		324	Different**	
Auto. Norte 127	Parameter	4.6507	-0.085	-0.328	2.250	-0.018	-0.188	2.967	-0.064	-0.243	3.554	-0.101	-0.297
(Santa Sofía)	Std. Error	0.13	0.010	0.030	0.140	0.010	0.030	0.130	0.010	0.020	0.160	0.010	0.030
	N/Test Near=Far	368	Different***		288	Different***		321	Different***		324	Different***	
Alamos	Parameter	3.0585	0.139	-0.273	1.686	0.128	-0.161	1.822	0.127	-0.267	1.973	0.058	-0.237
	Std. Error	0.068	0.018	0.043	0.075	0.022	0.116	0.067	0.023	0.035	0.067	0.016	0.062
	N/Test Near=Far	324	Different***		252	Different**		279	Different***		264	Different***	
Sevillana	Parameter	3.8635	-0.084	-0.128	2.367	-0.065	-0.098	2.392	-0.056	-0.098	2.357	-0.041	-0.095
	Std. Error	0.122	0.014	0.016	0.131	0.015	0.018	0.126	0.014	0.017	0.122	0.015	0.016
	N/Test Near=Far	384	Different***		287	Different**		324	Different***		303	Different***	
Restrepo	Parameter	3.7587	-0.100	-0.209	2.209	-0.068	-0.173	2.267	-0.045	-0.200	2.451	-0.109	-0.238
	Std. Error	0.191	0.042	0.066	0.258	0.054	0.102	0.229	0.054	0.077	0.230	0.053	0.076
	N/Test Near=Far	75	Different**		67	Same		64	Different**		63	Different**	

Different*, **, *** indicate the near and away coefficients are significantly different at 10%, 5% and 1% level respectively, using and F test.

The results of estimating equation 6 for the Toberín subcenter show that the gradients for the *NEARDISTANCE* variable are lower in absolute value than the gradients for the *AWAYDISTANCE* variable. However, this difference is not statistically significant except for the gradient associated with the manufacturing sector. Toberín is located at the outskirts of the city, so it is separated from the CBD by a large distance. This zone is the home to three subcenters (Unicentro, El Lago and Av. Chile). The employment level that they concentrate means that the gradient towards the CBD is positive, though not significant, while the spatial changes are prominent. The same explanation is also valid for the Alamos subcenter.

4.3.2. Sectorial specialization of the subcenters and pattern of spatial location

If subcenters reproduce CBD’s functions and only influence the surrounding area (hypothesis of substitution), the only logical explanation is that CBD and subcenters have similar composition. In this case, the identification of subcenters with total jobs should result in a list of locations identical to the ones exclusively used for the employment data related to manufacturing, services and retail sectors. Conversely, specialized profile of subcenters that is clearly different from that of CBD suggests complementary relationship between the two. It is not necessary that employment subcenters identified using total employment are same as those identified by using sectoral data.

The identification with sectorial data enables the subcenters to be classified according to whether they are identified with the data on a single sector or more than one sector (Figure 1). There is a first group of subcenters specialized in manufacturing (Toberín, Alamos, Zona Industrial-Outlets, and Sevillana), a second group specialized in the services sector (Av. Norte-Calle 127, El Lago, Av. Chile and Restrepo), a third group specialized in retail (Unicentro, El Lago, Salitre and Restrepo), and a fourth group made up of localities that are identified as subcenters with the employment data in both services and retail (Restrepo, El Lago). These results confirm the specialized, unique nature of the subcenters, the segregation of industrial activities from other activities, and the convergence (at least in two subcenters) of both services and retail.

Figure 1. Subcenters location by sector. (formal and manufacturing)

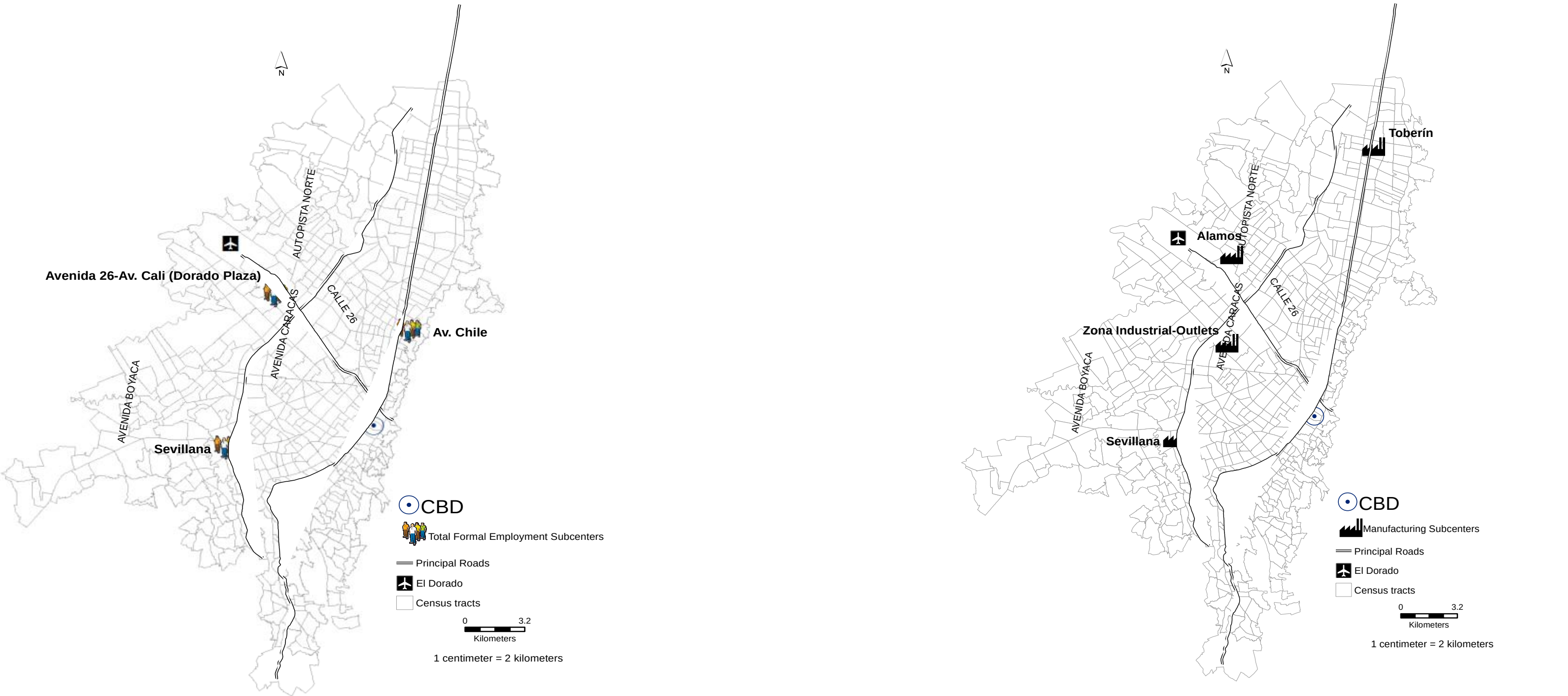
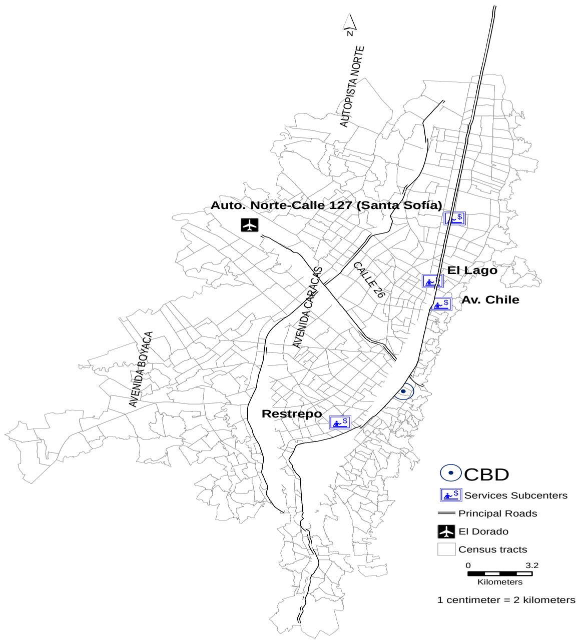
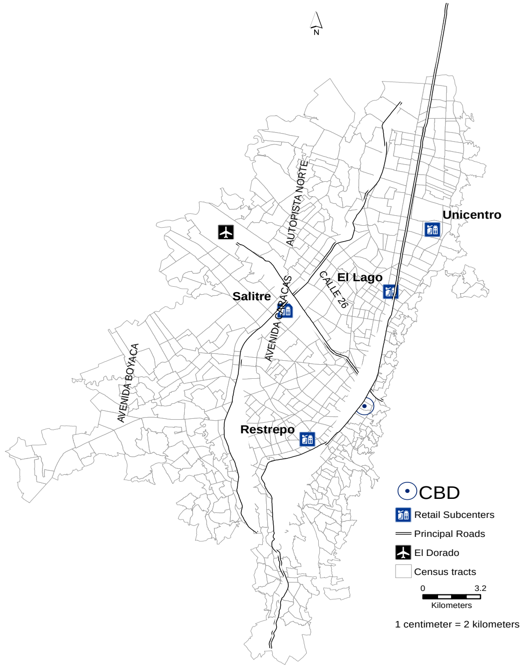


Figure 1 continuation (services and retail)





Source: Own elaboration.

In addition to this clarification oriented based on sectorial data, the subcenters identified with the total employment figures have a different meaning. The three subcenters identified, Av. Chile, Av. 26-Av. Cali (Dorado Plaza), and Sevillana, would play a special role in articulating the metropolitan space. Av. Chile and Av. 26-Av. Cali also exert a global effect, which confers on them a special status. Sevillana, in contrast, only has a local effect.

Far from the balanced layout inherent in a Christallerian model, the employment subcenters in Bogota show different spatial logics. The manufacturing subcenters are located along the outer north-south axis, establishing a kind of wall between the inner zone, where most of the people and jobs are, and the western extra-radius, which is less dense and plagued with unoccupied spaces. This location pattern partly reflects the advantages entailed in being located near the airport and the availability of more land, as well as the zoning policies which have separated the people from the most highly polluting manufacturing activities. The services subcenters are located along the entire north-south axis, closely following the population location pattern, especially the higher per capita income population who live in the northern part of the urban area. With regard to the retail subcenters, they follow a pattern similar to that of the services subcenters, with the unique feature that they also reveal the importance of the east-west axis which emanates out from the CBD.

5. Conclusions

Bogota has a polycentric urban structure which is the outcome of a process of employment decentralization which has not followed a random or chaotic model; rather it is articulated based on concentrations of jobs outside the CBD which we call subcenters. Eleven employment subcenters have been identified (in addition to the CBD) using both the overall employment figures and a breakdown into three sectors (manufacturing, services and retail). The study was oriented towards answering a fundamental question: are the subcenters in Bogota substitutive or complementary with regard to the CBD? According to the information obtained on the symmetry of the gradient value, the sectorial specialization of the subcenters, and their model of spatial location, the answer to the question is that the subcenters in Bogota are complementary with regard to the CBD. These results highlight the importance of agglomeration economies specific to one sector (localization economies) in the process of the vertical disintegration of the manufacturing process, as well as the advisability of not viewing the city as a strongly hierarchical system but instead as an open web where complementarity is the norm more than the exception.

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The effect of urban structure and mobility axes on land prices in Bogota

Abstract: Urban land prices were analyzed from three main perspectives: urban structure, urban regulation, and hedonic prices. From the first perspective, this study investigates the effect of a polycentric urban structure on land prices. Unlike most studies, in the present paper, mobility axes are used as a control variable, and the effects of this variable and the urban structure can vary depending on the spatial extent (local or global) of the effects. Using data from Bogota, this study contributes to the analysis of land prices and their relationship to urban structure in Latin American cities. The results demonstrate that, while employment subcenters are relevant locally and globally to land prices, mobility axes are only relevant at the local level.

Keywords: Land prices, polycentrism, mobility axes, agglomeration economies.

1. Introduction

The significant concentration of employment outside the traditional central business districts (CBDs) of cities on every continent (Leslie and ÓhUallachain, 2006; McMillen, 2001; Muñiz and Garcia-López, 2010; Suarez and Delgado, 2009; Zheng, 1991) (Rojas Quezada et al., 2009) has made polycentrism one of the most dynamic areas of research in urban studies in recent decades. As evidence of this interest, a new generation of polycentric theoretical models has emerged that correct, expand, and improve the standard monocentric model (Anas et al., 1998), along with extensive literature dedicated to homogenizing and improving methods to identify employment subcenters (Leslie, 2010; McMillen, 2003; McMillen, 2001; Nagle, 2010; Redfearn, 2007; Roca et al., 2009). The importance that polycentrism has acquired as an alternative to dispersion has obscured other possible alternative urban structures to monocentrism. These other models can also structure a metropolitan area, particularly the model of linear growth through axis corridors. Since the 1930s, authors such as Hoyt (1933) have proposed a star-shaped spatial structure as an alternative to the monocentric model; in the star-shaped model, economic activity is decentralized along the axes and transport nodes, thus exploiting the accessibility offered by these locations. More recently, studies such as that by Baum-Snow (2007) have provided the necessary theoretical background, and studies such as those by Steen (1986) and García-López (2012) appear to confirm the structural capacity of transport routes.

This paper contrasts the impact on land prices of two specifications in the urban structure of Bogota, one polycentric and the other linear. By comparing the significance of the estimated parameters and the overall explanatory power of the model, it is possible to discern which urban structure is better able to predict price behavior. This question is important because correctly capturing the urban structure is a prerequisite to correct urban planning.

To classify subcenters, the relevant literature has established three criteria. The first criterion is that a subcenter should, above all, contribute significantly to employment and in a manner different from that of the traditional CBD, and thus, the subcenter should be sufficiently far from the CBD. The second criterion is that families and businesses should positively value the proximity of the subcenter, which affects land value, population density, and employment. That is, the employment subcenters should exhibit "structural capacity". The third and most controversial subcenter criterion is that the subcenter should be morphologically similar to the CBD, meaning that the subcenter should have a circular aspect.

However, the method by which subcenters are identified ignores the possibility that subcenters can assume forms that are not circular, such as a linear form. Let us imagine that, by applying the standard identification methods, a number of subcenters are identified along a road. However, the values for density, the number of jobs, and so on that are determined for the zones close to the subcenters are not significantly different from the values found for the subcenters themselves. Logically, the following question arises: are the subcenters the structural elements of an urban space or are they transport routes? The literature on polycentrism offers different examples of subcenters that are located on an axis corridor such as in Houston along the Ship Channel (Craig and Ng, 2001), in Los Angeles on Wilshire Boulevard (Giuliano and Small, 1991), and in Barcelona along Highway AP-7 (Font and Vecslir, 2008). Therefore, the definition of a subcenter is interesting not only from a purely theoretical standpoint but also because subcenters potentially appear in a large number of cities.

This paper is divided into five sections, including the brief introduction to urban structure and transport infrastructure. The second section reviews the literature related to the relationship of the urban structure to land prices, followed by a brief description of Bogota. The fourth section presents the data and method used. The results and the study's conclusions are provided in the fifth section.

2. Land prices and urban structure

Studies of the behavior of land prices in an intra-metropolitan context can be divided into three groups. The first group comprises studies that focus on the urban structure, analyzing changes in land prices based on the distance from the CBD and other employment subcenters. Among these studies, we note those by McDonald and Bowman (1979), McMillen (1996), McDonald and McMillen (1990), McMillen et al. (1992), Kau and Sirmans (1979), and Yeates (1965) for Chicago; Colwell (1997) for Cook County (Illinois, USA); and Dowall and Treffeisen (1991) for Bogota. The second group of studies focuses on the effects of zoning on land prices. The studies by McMillen and McDonald (1991, 1993, 1999) and McDonald and McMillen (1998) for Chicago are good examples. The third group includes studies that explain the effect of urban structure from a hedonic price standpoint while controlling for the characteristics of housing and neighborhoods. In this group, the most relevant contributions include studies by Bender and Hwang (1985) and Berry (1976) for Chicago; Daniels (1975) for Oakland; Kain and Quigley (1970) for St. Louis; Lapham (1971) for Dallas; and Clapp et al. (2001) for Washington, D.C. Other notable studies include that by Peiser (1987), which analyzes the price of non-residential land, and Schmenner (1981), in which land prices are explained based on the spatial structure of industrial land. The present paper belongs to the first group of studies.

2.1 Polycentrism and land prices

The results from studies that explain spatial variation in land prices confirm the main predictions of the monocentric model. That is, there is a slight decrease in land value with increasing distance from the CBD. However, the explanatory power of the monocentric model appears to have decreased over time (McDonald and McMillen, 1990; McMillen et al., 1992; McMillen, 1990; Mills, 1969). This decrease may be due to the impact of new employment centers other than the CBD in a context of strong employment decentralization.

Given the gradual failure of the monocentric model, studies related to the analysis of land prices and urban structure have recently evolved according to two complementary approaches. The first approach consists of the use of more flexible functional forms than the standard negative exponential function, which can capture the presence of peripheral employment concentrations. For example, McDonald (1979) and McDonald and Bowman (1979) show that, in the case of Chicago, a fourth-degree polynomial best explains the behavior of land prices based on distance from the CBD. Similarly, McMillen (1996) uses completely flexible functions that are adaptable to spatial variations in land prices estimated using non-parametric methods.

The second approach is characterized by incorporating into the price functions the distance not only from the CBD but also from the employment subcenters (McDonald and McMillen, 1990; Heikkila et al., 1989). This type of study is in agreement with studies in which the effects of a polycentric structure on population density or housing prices are contrasted (Cervero R., 1997; Cervero & Wu, 1998; Craig, Steven and Kohlhase, 2010; Dowall and Treffeisen, 1991; Gordon et al., 1986; Griffith, 1981; McDonald and McMillen, 1990; McDonald and Prather, 1994; McMillen and McDonald, 1998; Muniz et al., 2008; Richardson et al., 1990; Small & Song, 1994). These studies share an explicit connection with polycentric theoretical models from the new urban economy (Brueckner, 1987), which predict a decrease in land value (and in population density and employment opportunity) with increasing distance from employment subcenters (significant concentrations of employment under sufficient density conditions).

In theoretical terms, land values should decrease according to the distance from the subcenters for the same reasons land values decrease with distance from the CBD in the standard monocentric model: families value proximity to subcenters because of the possibility of decreasing the costs of the required mobility, and companies value proximate access to the low-cost specialized services that are found in subcenters.

An interesting question about polycentrism concerns the different spatial impacts that subcenters can have. Empirical evidence demonstrates that there are subcenters with impacts that extend throughout the urban region, whereas other subcenters have a significantly smaller spatial impact. The first type of polycentrism would be classified within a reticular urban system with subcenters specialized by sector. The second type would be part of a hierarchical system such as Christaller's model, in which the subcenters only support the immediate surroundings. Methodologically, the changes adopted in the function of land prices (or density) to estimate with the goal of decreasing the spatial impact of the subcenters (Christaller's focus) have mainly consisted of using the inverse of the distance from the subcenters or considering only the distance to the closest subcenter. Alternatively, including the direct distance to each subcenter identified in a multiplicative function implicitly posits complementarity between subcenters, i.e., a network focus (Craig, Steven and Kohlhase, 2010; Heikkila et al., 1989; Meijers, 2005, 2007, 2008).

2.2 Polycentrism and transport axes

One of the most evident limitations of the standard monocentric model is that the city cannot extend over an indefinite number of radii from the center to the periphery. The city's extension toward the exterior over a limited number of axes implies a distortion in the iso-density and iso-value curves that values the areas closest to the transport axes (Steen, 1986). The theoretical models of Anas and Moses (1979) and Baum-Snow (2007) adapt a standard monocentric model that incorporates transport axes. The results of these models show a decrease in land value and density with increasing distance from transport axes. Studies such as those by Steen (1986), McMillen and McDonald (1998), Baum-Snow (2007) and García-López (2012) confirm the distorting effect of the proximity to transport routes on land value and density.

As a hybrid of the linear growth models and polycentric models, the theoretical studies by White (1976) and Ross and Yinger (1995), which consider ring-shaped subcenters, deserve special attention. The unique element of these studies is that the subcenters do not exhibit a circular shape similar to the shape of a CBD.

Studies on polycentrism adapted to different cities show that, on numerous occasions, the subcenters are located on an axis or corridor. For example, in Houston, Craig and Ng (2001) identified three subcenters along the Ship Channel; in Los Angeles, Giuliano and Small (1991) identified five subcenters on Wilshire Boulevard; and in Barcelona, Muñiz et al. (2003) and Font and Vecslir (2008) grouped all of the subcenters in six and seven corridors, respectively. Furthermore, according to Giuliano et al. (2011), the subcenters close to the main transport routes are more dynamic in terms of employment.

The existence of multiple subcenters along a transport axis raises an interesting question: What structures an area, the subcenters (several points), the transport axis (a line), or a mixture of the two? In the first case, the transport axis would facilitate the emergence of the subcenter but would not affect its form (circular). In the second case, the subcenters identified along the road would be an inexact representation of the structural elements of the territory, which result from the imposition of identification techniques designed for circular subcenters. In the third case, roads and subcenters would jointly contribute to the organization of the territory.

Few studies have linked polycentrism with intra-metropolitan variations in land prices in Bogota. The study by Dowall and Treffeisen (1991) is the most important in terms of the number of citations in specialized journals. Based on official data, the authors *a priori* identify subcenters in the city and show that land prices are more adequately explained by a polycentric model than by a monocentric one. From an analytical perspective linked to transportation economy, the studies by Rodríguez and Targa (2004), Bocarejo et al. (2012), Mendieta and Perdomo (2007), Perdomo (2011), and Rodríguez and Mojica (2008) analyze the effects of a massive transport system on land value. These studies show a positive effect of the proximity to the massive transportation system "Transmilenio" (a bus service that serves an important part of urban area) on the value of land and housing.

An examination of the list of subcenters proposed by Dowall and Treffeisen (1991) (we will later present our own list, which is based on more objective and readily replicable methods) for the urban area of Bogota appears to be linked to the layout of the road network. The subcenters in the eastern zone of the city, where the CBD is located, are distributed along the highway corridor formed by Avenida (Av.) Caracas and Autopista Norte. The former is the main mobility axis for the city's southeastern zone, where a large portion of the low-income population and some local commerce is located. By contrast, the Autopista Norte is the main mobility axis for the city's northern area and for connection to the surrounding region. Much of the middle- and high-income population is located in the northeastern zone. The area's economic activity is mainly high-end services.

The Calle 26 corridor connects the CBD with the El Dorado Airport. Regional and national public and private institutions are located along this axis. Since the mid- 1990s, many of the undeveloped properties next to the road have become occupied by companies tied to the high-end hotel, logistics, and business service sectors, forming a strategic high-value area for the city's development. Along this corridor, undeveloped areas remain that will likely continue to attract economic activity in the future.

The corridor of Av. Boyaca fulfills the function of urban and regional integration in a manner similar to that of the corridor of Av. Caracas-Autopista Norte. The economic activity of the portion of the corridor that is south of Calle 26 is characterized by ties to manufacturing activity. This zone's population comprises people with low and middle income. North of Calle 26, residences for people with middle and upper-middle incomes predominate.

3. The urban area of Bogota

Bogota is Colombia's chief city. Bogota's urban primacy in Colombia's city system strengthened in the 1990s, when Bogota's population exceeded 5 million. Since the 1990s, the city's urban area has concentrated approximately 21% of the country's population and 25% of its economic activity. In 2008, Bogota's population reached 7.2 million. Between 2001 and 2008, the rates of participation, occupation, and unemployment were approximately 65%, 56.5% and 13.5%, respectively (Secretary of District Planning -

Secretaría de Planeación Distrital - SDP-, 2009). For this same period, the average shares of industry, services, trade, and construction in the city's GDP were 16%, 59%, 13%, and 4%, respectively (SPD, 2009). The labor market is characterized by high informality, which typified 50.8% of the city's employment (SPD, 2009).

Studies of the urban structure of Bogota are necessarily limited to the city's urban territory. Although there is economic information on the suburban areas adjacent to the city's urban perimeter, this information is not generated and organized by the territory's metropolitan area because this form of territorial organization is not institutionalized for the city. The urban area of Bogota is 380 km^2. However, the total area of the Capital District is 1,584 km^2, which includes the town of Sumapaz and the rural areas of Ciudad Bolívar and Usme. The length of this urban area is 36 km, and the maximum east-west distance is approximately 17 km. These distances refer to the developable area of the Capital District's urban territory.

The new transportation system, the city's economic growth, and the smaller quantity of available land have caused substantial changes in the price of urban land. Although in 2004, 70% of the urban land had a value below $300,000 per square meter (114 USD), in 2010, only 20% remained in that range[1] (Alcaldía Mayor de Bogota, 2011).

4. Method and data

4.1. Method

Different methods have been proposed to identify employment subcenters. The first studies used measures based on official and historical information, the number of jobs, commuting flows, and the ratio of workers to residents (Cervero, 1989; Giuliano and Small, 1991; Greene, 1980; Griffith, 1981). With increases in available information and better geographic coverage, studies performed in the past 20 years have used employment density as a fundamental variable to identify subcenters (McDonald, 1987; McMillen and McDonald, 1997; McMillen, 2001). In this type of study, a subcenter is defined as a significant concentration of jobs that affects the local or global density pattern.

[1] In 2009 Prices

To identify the employment subcenters in Bogota, the procedure of McMillen (2001) was adapted in two stages. In the first stage, the subcenter candidates were identified. A locally weighted regression (LWR) estimator was used with a spatial weighting scheme based on the tri-cubic kernel function. The endogenous variable was the gross employment density. The exogenous variables were the east and north distances between each census tract and the CBD. Unlike the procedure used by McMillen, in this study, the non-parametric estimation of the employment density maintains the local structure of the employment density. Therefore, fewer observations were used in each local regression. To determine the number of census tracts that receive weight in the regression, a cross-validation method was used. The subcenter candidates were groups of adjacent census tracts that together exhibit values at 5% significance. In the second stage, a multiplicative polycentric density function was estimated (Anas et al., 1998). In this function, the endogenous variable was gross employment density, and the exogenous variables were the distances from all subcenter candidates to the CBD. While the original procedure in McMillen (2001) used total employment data, our case used sectoral employment data (total, manufacturing, services, and trade), which enabled us to incorporate the specialized nature of certain subcenters in the identification process.

Once the employment subcenters were identified, polycentric multiplicative functions were estimated to examine a main theoretical prediction of the NEU polycentric models: the impact of employment subcenters on ground rent (Anas et al., 1998; Dowall and Treffeisen, 1991; McDonald and McMillen, 1990). The endogenous variable became the value of the land, and the exogenous variables were the distances from the subcenters to the CBD. According to the geographic layout of the employment subcenters in the territory, polycentric multiplicative estimates were performed that control for the distance to the main roads in the city.

4.2. Data and specifications

The estimates of the polycentric density functions were based on data from the Administrative Department of the District Cadastre (Departamento Administrativo de Catastro Distrital - DACD) and the District Secretary of Planning (Secretaría Distrital de

Planeación - SDP) for 2008. The unit of observation was the census tract. Bogota includes 607 census tracts. The employment subcenters in the city were identified from total and sectoral formal employment data[2].

The data on land prices were from 2008 and geo-referenced for each census tract in the city. The information regarding road infrastructure was supplied by the city's SDP and was updated to 2008. The real average price per square meter in the city in 2008 was $430,000 (USD 219), with a maximum and minimum value of $2,600,000 (USD 1,322) and $5,000 (USD 2.54) respectively. The standard deviation of price in the city was $331,000 (USD 169)[3].

In the identification process, the endogenous variable was the total employment and the sectoral employment (industrial, services, and trade). The explanatory variables were the distances north and east from the centers of each census tract to the CBD. Once the significant residuals were identified at 5% for all census tracts, the exogenous variables were the direct and inverse distances from each center to the CBD with significant residues. The first variable seeks to capture subcenters with a global impact on the gross density function, whereas the second variable captures subcenters that have a local effect (McMillen, 2001). The basic regression is

$$y_i = \beta_0 + \beta_1 DCDB_i + \sum_{j=1}^{S}\left(\beta_{3j} Dist_{ij}^{-1} + \beta_{4j} Dist_{ij}\right) + \varepsilon_i \quad (1)$$

where y_i is the natural logarithm of the gross employment density, $DCBD_i$ is the distance in kilometers of each census tract from the CBD, $Dist_{ij}^{-1}$ is the inverse of the distance in kilometers between the census tract i and subcenter j, $Dist_{ij}$ is the distance in kilometers between the census tract i and subcenter j, and ε_i is an error term with a normal distribution. The subcenters eventually identified are those with positive coefficients on -$Dist_{ij}$ or $Dist_{ij}^{-1}$ and a significance level of 20% (McMillen, 2001). However, there were

[2] Vendor street jobs and informal employment are not included. DANE's definition of informal employment relies on four main features related to plant size and productivity: self-employed workers without professional or technical backgrounds, unpaid family workers, household workers and firms with up to 5 employees.

[3] The average exchange rate for 2008 was $1.966 pesos pesos per dollar. The land prices come from cadaster local office and not necessarily reflect the market land prices in the city.

certain subcenters for which there was no land price information. Therefore, of the 11 identified employment subcenters, only the subcenters with complete price information were considered. In this case, there were seven subcenters, including the CBD.

Once the employment subcenters were identified, polycentric price functions were estimated by ordinary least squares (OLS). In these regressions, the endogenous variables were the 2008 land values, and the exogenous variables were the subcenters identified with a global or local reach. The basic regression of the polycentric model is

$$Land\,\mathrm{Pr}\,ice_i = \delta_0 + \delta_1 DCDB_i + \delta_2 DNearSubc_i + \upsilon_i \quad (2)$$

where *LandPrice*$_i$ is the natural logarithm of the value of urban land in census tract *i* in 2008, *DNearSubc*$_i$ is the distance in kilometers from census tract *i* to the closest subcenter, and υ_i is an error term with normal distribution. The other variables are equal to those specified in Equation 1.

Last, polycentric price functions were estimated while controlling for distance to main roads.

$$Land\,\mathrm{Pr}\,ice_i = \delta_0 + \delta_1 DCDB_i + \delta_2 DistNearInfra_i + \varsigma_i \quad (3)$$

$$Land\,\mathrm{Pr}\,ice_i = \delta_0 + \delta_1 DCDB_i + \sum_{j=1}^{S}\left(\delta_j Dist_{ij}^{-1} + \delta_j Dist_{ij}\right) + \delta_5 DistNearInfra_i + \mu_i \quad (4)$$

where *DistNearInfra*$_i$ represents the distance from the center of each census tract to the closest major road and μ_i and ς_i are error terms with normal distribution. It is expected that the coefficients δ_{2j} and δ_{5j} will have a negative sign.

5. Results

5.1 Urban structure: employment subcenters and transportation axes

Table 1 shows the level of employment for each major economic sector in each subcenter. Considering total employment, the identified subcenters account for 8.5% of employment in Bogota. Manufacturing and service employment is more highly concentrated in the subcenters than employment related to retail trade. In the last column, the geographic scope of the subcenters is shown for the variable with the greatest statistical significance between the direct distance (global effect) and the inverse (local effect) for each subcenter evaluated in Equation 1.

Figure 1 shows the employment subcenters identified by the two-step method of McMillen (2001) and the major highways along which much of the city's economic activity occurs. Av. 26 can be considered a road axis that divides the city into northern and southern zones, which have clear functional differences regarding economic activity. The financial service business and major private firms are located in the northeastern zone (subcenters Av. Chile and Unicentro). However, there is also a manufacturing subcenter on the city's northern edge. Meanwhile, trade and service activities are located in the southern zone, as well as local services (subcenter Restrepo) and heavy industrial activities with a global effect (subcenter Sevillana).

The subcenter Salitre has emerged as an employment concentration over the last 15 years. Most of the economic activity that is located along Av. 26 corresponds to high-end urban trade and service firms. In summary, the northeastern zone and Calle 26 show a tendency toward high-end services, whereas the southern zone specializes in local services and large-scale manufacturing activities.

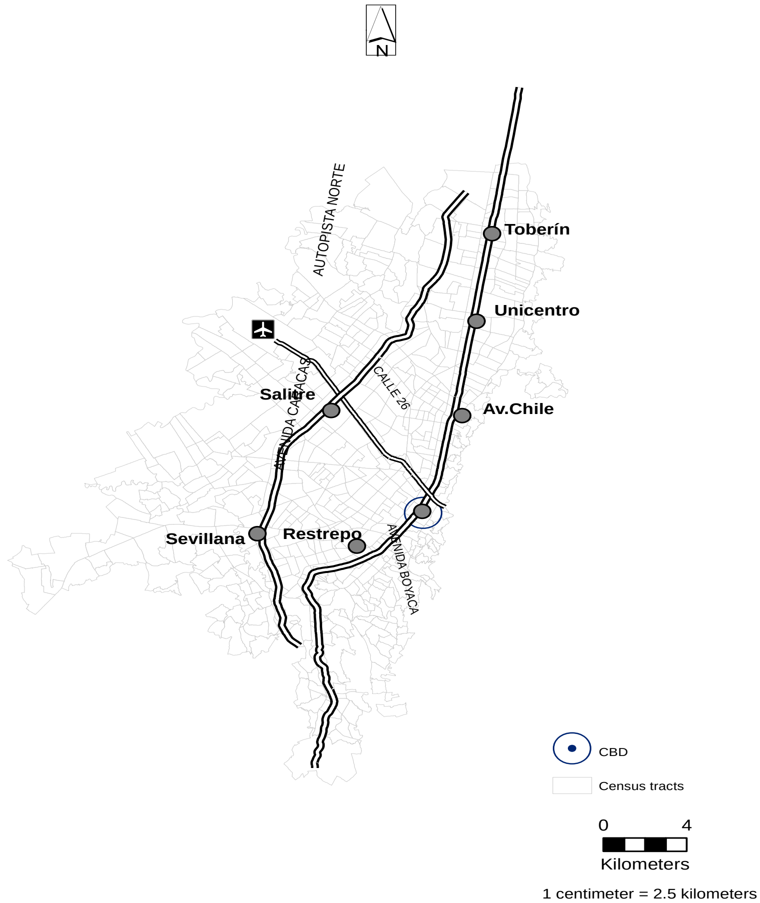
Table 1. Sectoral employment by employment subcenter.

Subcenter	Total Formal Employment	Manufacturing Employment	Retail Employment	Services Employment	Other Employment*	Average Density	Effect on Employment Density
Salitre	35635	15466	5706	11294	3169	154	Global
Av. Chile	16226	585	3259	10327	2055	423	Global
CBD	15156	525	3263	9969	1399	427	Global
Restrepo	8700	1098	3322	3359	921	191	Local
Sevillana	2639	1261	357	793	228	758	Local
Toberín	11364	4158	2214	3333	1659	15	Local
Unicentro	20170	1636	5019	9078	4437	337	Local
Total	109890	24729	23140	48153	13868	329	
City**	1302888	220557	284810	445544	351977	53	

*Includes agriculture, construction, and mining.

**The Bogota Chamber of Commerce reports a total of 1.6 million formal jobs (jobs that comply with all legal requirements, such as social security, employment contracts, etc.). However, the data available for this study only show 1.3 million jobs geo-referenced by census tract.

Figure 1. Subcenters and main transportation routes in Bogota.

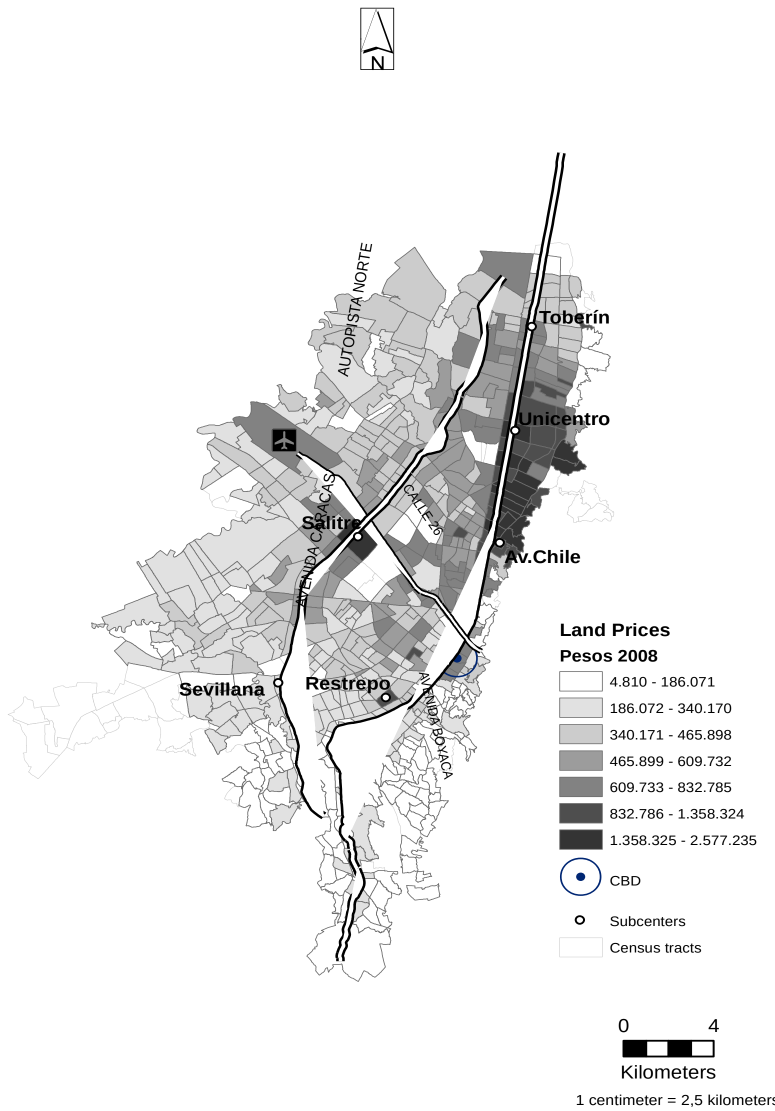


Source: Elaborated by the author.

5.2 The pattern of land prices

A simple visual inspection of Figure 2 reveals a moderately specific pattern of land prices. First, the highest values are found north of the CBD, particularly along Av. Caracas-Autopista Norte. Second, the pattern of land prices departs substantially from the predictions of the monocentric model. We do not observe the typical circles of decreasing density from the CBD toward the periphery. Third, the subcenters exhibit land values that are substantially higher than those of the surrounding areas.

Figure 2. Land prices in Bogota (census tracts).



Source: Elaborated by the author.

5.2.1 The effect of the urban structure on land prices

Table 2 shows the results of different estimates of the price function for alternative urban structures. The second column shows the results for the monocentric model. The third column shows the results for the restricted polycentric models, which only include the distance to the CBD and the distance to the closest subcenter. Therefore, the estimate includes the assumption of substitutability between subcenters. The fourth column shows the results for the restricted linear model, where, in addition to the distance to the CBD, the distance to the closest axis is added. Therefore, this model implies that the land value of a census tract should only be affected by the distance that separates the census tract from the CBD and the closest axis, excluding the possibility that the price is affected by other axes that are more distant. The fifth column corresponds to the estimate for the restricted complete model, which includes the distances to the closest subcenter and the closest axis as explanatory variables. The sixth column shows the coefficients obtained by estimating the complete polycentric model without controlling for the proximity to transport axes. In this case, the direct and inverse distances to the six identified subcenters are included as explanatory variables. The model considers the possible complementarity between subcenters, a possibility that would be confirmed if significant gradients for the direct distances were obtained. Additionally, this model considers the possibility that the subcenters have a more local effect, which can be captured using the inverse distance to each subcenter. The model allows us to obtain more information regarding each subcenter individually. The seventh column corresponds to the complete polycentric model while controlling for the distance to the closest axis.

Table 2. Effects of the urban structure and roads on land price (OLS).

Regressors	Dependent variable: Ln Land Prices 2008					
	1	2	3	4	5	6
dist_cbd_km	0	0.05	0.01	0.05	-0.13	-0.13
	0.05	6.13	1.69	6.18	-3.46	-3.35
dist_near_sc		-0.21		-0.20		
		-13.12		-11.91		
dist_near_corridor			-0.14	-0.02		-0.04
			-5.24	-0.84		-1.83
dist_Chile					-0.07	-0.07
					-1.24	1.43
dist_Unicentro					-0.00	0.02
					-0.1	0.3
dist_Toberin					0.00	-0.01
					0.11	-0.3
dist_Salitre					0.00	-0.01
					0.22	-0.43
dist_Sevillana					-0.12	-0.12
					3.90	3.90
dist_Restrepo					0.26	0.26
					5.76	5.7
1/dist_Chile					0.13	0.3
					0.6	1.79
1/dist_Unicentro					1.14	1.27
					2.86	3.24
1/dist_Toberin					0.35	0.26
					1.50	1.12
1dist_Salitre					0.49	0.29
					1.23	0.71
1/dist_Sevillana					0.05	-0.02
					0.25	-0.1
1/dist_Restrepo					1.20	1.2
					5.82	5.89
Constant	12.7	4.6	12.8	13	12.83	12.92
	174.5	37.01	172.07	188.97	36.88	37.15
N	568	561	567	561	532	531
R2	0	0.24	0.05	0.23	0.60	0.61

T-values below coefficients.

The first notable result is the apparent null effect of proximity to the CBD on land prices. Although the result is not singular (see Bertaud for a list of cities with null or positive gradients for distance to the CBD), two considerations are necessary. The first consideration is that, in other studies of the urban structure of Bogota, a slight but significant effect of the distance to the CBD on population density and employment was observed (Avendaño, 2008; Dowall & Treffeisen, 1991). Thus, the “problem” appears limited to prices. The second consideration is that the value of this parameter is substantially affected by the spatial scale. In our case, a restricted urban limitation that does not include information on surrounding municipalities that compose the wider Bogota metropolis largely explains the result.

The third important result is that the model's explanatory power was significantly improved by incorporating the distance to the closest subcenter as an explanatory variable (column 3). The value, the significance of the parameter, and the overall adjustment capacity confirm that the pattern of land prices in Bogota is better explained by a polycentric structure than a monocentric structure.

Fourth, compared with the monocentric model (column 3), the restricted linear model (column 4) operates significantly better. The gradient of the distance to the axis is significant and of the expected sign, and the capacity for overall adjustment reaches 5%. Therefore, the transportation axes play an important role in structuring the urban space. However, when the distance to the closest subcenter and the closest axis (column 5) are combined as regressors, the coefficient of the distance to the axis is not significant. Therefore, the overall results indicate that the urban structure in Bogota that best fits the pattern of land prices is the polycentric model, not the linear model.

Fifth, the estimated coefficients of the distance (direct and inverse) for each subcenter for the complete polycentric model (which includes the distance to the CBD, the direct distance to each subcenter, and the inverse distance to each subcenter as explanatory variables) were of the appropriate signs in most cases, although only certain results were significant (column 6). Nevertheless, the overall explanatory power of the model reaches 60%. However, the coefficients of the inverse distances are more significant than the coefficients of the direct distances, which indicates that the subcenters have a restricted geographic impact on land prices, with Sevillana as an exception to the rule. After adding the distance to the closest axis as a regressor (column 7), even with the appropriate sign, the result was not significant. However, the coefficients of the distances to the subcenters remain stable, which confirms the small structuring capacity of the axes once the presence of the subcenters is considered.

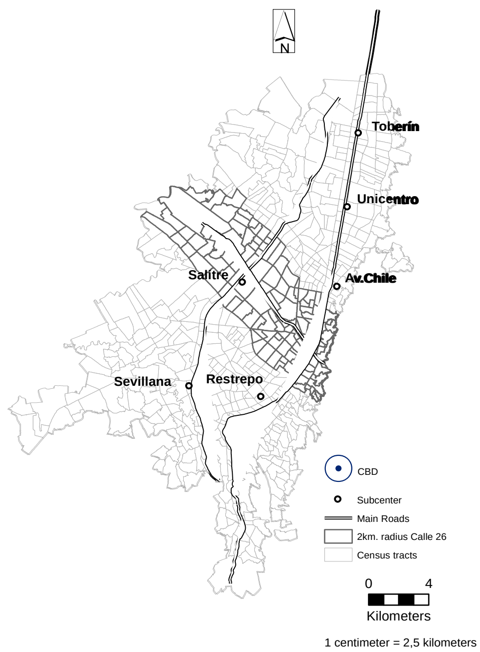
The above table showed the results for a model that attempted to explain the value of land prices throughout the city. Below are the results of a model in which only the census tracts located within 2 km of the transport axes are considered (Figure 3). The aim is to limit the area of influence of the subcenters and transport axes to the immediate surroundings. If the urban structure's impact has a localized effect, this circumstance should increase the significance of the estimated parameters compared with the previous model. In addition, estimating the three different specifications for each axis enables us to observe in greater detail the effect of the urban structure on the pattern of land prices in each individual axis.

Figure 3. Areas located within 2 km of the main transport routes.

2 km radius from Av. Boyaca.

2 km radius from Av. Caracas-Autopista Norte.

Figure 3. continuation.



2 km radius from Av. 26.

Table 3. Local effects of the urban structure and transport routes on land prices (OLS).

Regressors	Dependent variable: Ln Land Prices 2008					
	1	2	3	4	5	6
dcbdkm	0.01	0.02	0	-0.02	0.05	0.04
	1.31	0.46	-0.24	-1.49	2.9	1.41
dist. Eje Av. Caracas-Auto. Norte.	-0.13	-0.09				
	-1.84	-2.16				
dist. Eje Av. 26			-0.17	-0.11		
			-2.17	-1.45		
dist. Eje Av. Boyaca					-0.1	-0.02
					-1.36	-0.38
Chile		-0.09				
		-1.65				
Unicentro		-0.08				
		-1.00				
Toberín		0.04				
		0.94				
Salitre				-0.14		-0.14
				-2.38		-7.15
Sevillana						0.07
						3.99
Restrepo		0.05				
		1.56				
1/dist..Chile		0.08				
		0.47				
1/dist. Unicentro		0.29				
		0.66				
1/dist. Toberín		0.01				
		0.04				
1/dist. Salitre				-0.9		-0.6
				-1.27		-1.21
1/dist. Sevillana						0.75
						3.07
1/dist. Restrepo		0.66				
		3.21				
Constant	12.81	13.08	13.23	14.14	12.29	12.65
	110.26	36.4	102.83	30.43	64.88	43.33
N	310	289	119	118	211	209
R^2	0.02	0.68	0.04	0.10	0.05	0.47

t values below coefficients.

By examining each axis separately, the results regarding the impact of the distance to transport routes are obtained. The coefficient of the distance to the axis without controlling for the existence of subcenters is negative and significant for the corridors Av. Caracas-Autopista Norte and Av. 26. In the case of the corridor Av. Boyaca, although negative, the result was not statistically significant. However, the overall explanatory power of the model is poor (between 2% and 5%). After including the distance to the subcenters located in each axis, the overall explanatory power substantially improves. However, the significance of the distances to the subcenters remains low. The main result of the estimate is the decreasing value and significance of the parameter of the distance to the axis after including the distance to the subcenters located in each corridor. Again, this outcome suggests the limited structural capacity of the transport routes compared with the employment subcenters. Nevertheless, despite the decrease in this parameter's value, the value remains reasonably significant for two corridors (Av. Caracas-Autopista Norte and Av. 26). Thus, the distance to the axis helps explain land prices. Taken together, the results suggest that transport axes play a structuring role. However, this role is localized and has a smaller impact than that of the employment subcenters.

6. Conclusion

The urban structure, i.e., the urban organization of employment, determines the spatial configuration of land prices in Bogota. As for the type of urban structure, the results show that the pattern of land prices in the city is best explained by a polycentric rather than a monocentric urban structure. Additionally, agglomeration economies based on access to infrastructure shared by agents significantly affect land prices. However, unlike employment subcenters, the transport routes have more localized effects on the urban area.

The exclusively local effect of the mobility axes on land prices implies that there are mobility problems that hamper access to the network of subcenters. That is, the road infrastructure does not facilitate connectivity in the city, which has a significant impact on land prices. The continuity of the main roads in the city is interrupted by local roads that do not possess an efficient access system. Furthermore, although the employment subcenters are located along the city's main roads, the employment subcenters do not play as important a role in structuring land prices in the city as the subcenters. Therefore, physical proximity is more important than mere access to infrastructure. In fact, while Av. Caracas, Autopista Norte, and Calle 26 are relevant for explaining land prices, this relevance is limited to the local scale. Proximity to subcenters is valued by agents throughout the urban area.

Although this paper shows the importance of the urban structure in explaining land prices, two important factors should be further studied to reinforce the analysis. First, it is necessary to estimate land price according to land use to determine if there are synergies between firms according to different uses, which would allow us to distinguish between economies of urbanization and localization. For example, it is desirable to analyze whether commercial land prices respond to the distance from manufacturing subcenters. Second, future research should examine the absence of a generalized effect of roads on land prices. Land prices may be more influenced by the income and amenities associated with a locality than the accessibility of the transportation network that connects the employment subcenters.

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