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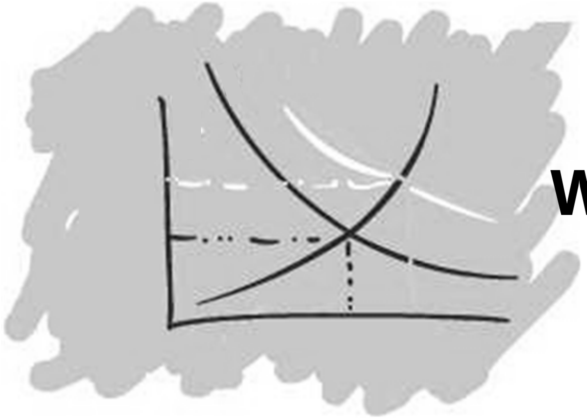

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Angel M. Prieto, José L. Zofío and Inmaculada Alvarez

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Urban patterns, population density and optimal city dimension: The case of public infrastructure

Angel M. Prieto[a], José L. Zofío[b, *] and Inmaculada Álvarez[b]

[a] IRNASA-CSIC. *Instituto de Recursos Naturales y Agrobiología, Consejo Superior de Investigaciones Científicas, Cordel de Merinas 40-52, E-37008 Salamanca, Spain.*

[b] *Departamento de Análisis Económico: Teoría Económica e Historia Económica, Universidad Autónoma de Madrid, E-28049 Cantoblanco, Madrid, Spain.*

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Abstract

Determination of the optimal city size underlies the economic rationality of infrastructure provision by local governments. We investigate the existence of decreasing average costs resulting from economies of scale, associated with larger urban dimensions in terms of population and housing, and economies of density, brought about by reductions in urban dispersion, and calculate optimal population densities when providing basic infrastructure. The methodology relies on novel definitions of scale and density economies and their estimation by way of flexible translog cost functions, extensively applied in the literature dealing with the provision of services—i.e., utilities, but extended here to their supporting infrastructure. Our results unveil the existence of latent economies of scale and density resulting in a cost excess in the provision of infrastructure due to the effect of urban sprawl that translates into suboptimal city sizes. Based on these findings several policy guidelines rationalizing urban development are suggested. The model is illustrated using Spanish statistical data collected from the nationwide local infrastructure and equipment survey, and prices from a new database that uses engineering cost benchmarks.

Keywords: Urban patterns, Scale and density economies, Optimal urban density, Translog cost function.

JEL Classification: C3, D24, H1, H4, R53

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[*] Corresponding author: José L. Zofío. Voice: +34 914972406; fax: +34 914976930, e–mail: jose.zofio@uam.es
Ángel M. Prieto. Voice: +34 923219606; fax: +34 923219609; e-mail: alpiste@usal.es
Inmaculada Álvarez. Voice : +34 914972858; fax: +34 914976930; e–mail: inmaculada.alvarez@uam.es

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1. Introduction

The search for an optimal city dimension when proposing policies toward the rationalization of public expenditure at all provision levels, ranging from urban infrastructure to social services, is the main reason motivating early spatial-based theoretical modeling balancing in equilibrium the costs of governmental provision and the utility perceived by users through accessibility (e.g., Bramley, 1990; ch. 4), as well as the most basic econometric studies providing supporting evidence (e.g., Easton and Thomson, 1987). Today, despite the fact that the local provision of public goods—infrastructure and services—is complex in nature, and subject to ever-changing preferences and legislation, there seems to be an agreement among urban and fiscal economists that, for the case of urban infrastructure provision, a greater city dimension reducing urban dispersion is desirable. This stylized fact is based upon the existing evidence showing that the provision of these goods is subject to economies of scale and density, whose realization leads to more cost efficient patterns of development. [1] Intuitively, the provision of basic physical infrastructure such as water distribution, sewerage collection or road networks must be characterized by the existence of large economies of scale and density, as it is the production of their service utilities counterparts. However, evidence is almost nonexistent, narrow in terms of methodologies and techniques, and focused on single sectors. By applying a common analytical framework to a wide set of public utilities and relevant infrastructure variables, we study systematically the existence of these economies and relate them to particular urban patterns, thereby obtaining, for the first time, a measure of optimal population density.

Clearly not all infrastructure is equally affected by the spatial distribution patterns of population and dwellings. A clear distinction has to be made between "network" infrastructure as the one we study, and "hub" infrastructure such as schools, local hospitals or police stations. Providing the former carry larger costs than the latter for equal population and number of dwellings (i.e., in *per capita* and *per house* terms) as water distribution, sewerage collection and street paving and lighting is done on a door-by-door basis, while the latter normally implies a single infrastructure—building. Moreover we need to differentiate between city size measured as the number of inhabitants and dwellings within an administrative limit —i.e., *scale* in terms of these latter variables, and the *density* of those variables in space, i.e., the degree of urban sprawl. While the provision costs for local

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[1] See RERC (1974) and Frank (1989) for early reviews of the literature from an urban planning/land use (UP&LU) engineering perspective, and Schmalensee (1978) in the context of a model of natural monopoly, for determining the cost of providing physical infrastructure as well as the cost of producing the service utility that it supports

governments of network infrastructure is greatly affected by dispersion, this is not the case for hub infrastructure.

This study intends to make novel contributions to the existing literature in several ways. First, to our knowledge, this is the first attempt to define economies of population, housing and urban density in the provision of basic *infrastructure* using advanced econometric techniques pertaining to the production and cost theory literature. As our review of previous research on this subject shows, while the estimation of flexible costs functions in *services* production has been extensively applied when studying utility industries to determine optimal production size (e.g., water distribution, sewage, urban roads,…), this literature has neglected the provision of the supporting physical infrastructure. In extending the scope of analysis we discuss in depth how the existing definitions of economies of scale and density in the econometric literature dealing with service production, must be redefined when taking into account infrastructure provision. urban

Second, we study these size economies in terms of the population and housing addressed by the infrastructure provision, while taking into account variables reflecting the compact or sprawled pattern of a jurisdiction. This allows us to determine the effect that population density has on provision costs and identify optimal city dimension in terms of that magnitude. Ordinary least squares regression analysis based on semilog specifications has been performed by Ladd (1992) and more recently, Carruthers and Ulfarsson (2003), to estimate the cost of public services in terms of urban built environment and controlling for political, socioeconomic and geographical location. However, the relatively simple specifications used by these authors prevent them from determining an optimal city dimension as defined in our study. Nevertheless, their results show that the elasticity of urban dispersion on the costs of providing several public *services* varies across sectors.

Third, our analysis not only allows us to extend well known results on service production to physical infrastructure provision and determine optimal city sizes, but also to introduce and control for the effect that urban dispersion has on them. By adopting two complementary measures of urban sprawl as the number of dispersed clusters—reflecting scattered population developments[2]—and the urban area, which can be associated respectively to horizontal and vertical density economies, we can test one of the main concerns of the literature that acknowledges a U-shaped expenditure function. Our results show that one of the basic facts regarding the negative effects that an extensive and small sized-low density urban morphology has on the cost-effectiveness provision of some public services (Altshuler and Gómez-Ibáñez, 1993; Kaiser et al. 1995), is unambiguously observed when dealing

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[2] As discussed in section 3, these variables capture the concept of urban sprawl as a low-density settlement configuration characterized by excessive and discontinuous spatial expansion of land use.

with basic infrastructure. Anticipating some conclusions, this implies that from the perspective of the optimal size of jurisdictions and consolidation of local governments, sprawled urban forms increase the unit cost—per capita or per dwelling—of infrastructure development, and therefore policies favoring “smart growth” management programs based in larger city sizes, more compact forms and higher density, result in lower average costs.[3] Summarizing the purpose of this paper we explore the relationship between city size—in terms of population and housing—and urban structure—in terms of the compact or dispersed pattern of a jurisdiction— and the cost of providing basic infrastructure, resulting in the estimation of the optimal city dimension in terms of population density. We accomplish this goal by estimating three separate cost equations that allow us to determine these optimal values for the most important urban infrastructure sectors: Water supply (S1), Sewerage and cleansing of residual waters (S2) and Paving and lighting (S3).

This article is structured as follows. In the next section we present a comprehensive survey on the literature studying economies of scale and density in these sectors from a service production perspective, and the existing differences with our infrastructure standpoint. In section 3 we model the behavior of public officials and resource managers when providing urban infrastructure by way of the translog cost function. The definitions of economies of population scale and urban density, as well as the analytical determination of the optimal city size in terms of population density are also discussed in that section. We exemplify our analysis using data on the Spanish region of Castilla y León, portraying a large and diverse typology of city sizes and urban patterns. In section 4 we introduce the different databases that we use to construct our series of capital stock in urban infrastructure. We also comment on a novel database on engineer prices that is used to determine the cost of the provision variables. In section 5 we present our estimates of the scale and density economies and emphasize the underlying rationality to the optimal size of jurisdictions and consolidation of local governments.. We also determine the ideal city size that minimizes the average provision cost function in terms of population density, while controlling for the remaining variables. The results are compared with those recently obtained in utilities industries and the urban planning/land use literature We conclude in section 6 by drawing the main conclusions and discussing the policy implications derived from optimal city sizes and urban patterns, resulting in “smart growth” practices.

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[3] See Carruthers (2002) for the US case representing a developed country, and Jenks and Burgess (2000) for developing countries

2. Evaluating cost efficiency in service provision

2.1. Evidence of economies of size: scale and density

As anticipated, in relation to the sectors that we study there is previous research that mainly focuses on the service management side of production, but neglects the associated supporting infrastructure. Starting from the Water distribution sector (S1), González-Gómez and García-Rubio (2008) undertake a comprehensive bibliographical review. Because of data availability, the most abundant bibliography can be found by far in the United States. If we select those studies that share with ours the estimation of a parametric cost function, it is worth citing Mann and Mikesell (1976), Clark and Stevie (1981), Hayes (1987), Kim and Clark (1988), Bhattacharyya et al. (1994), Bhattacharyya et al. (1995), Torres and Morrison (2006) and Garcia et al. (2007). In other countries we find studies by Ford and Warford (1969), Ashton (2000, 2003) and Bottasso and Conti (2009) in the United Kingdom, Kim and Lee (1998) in South Korea, Fabbri and Fraquelli (2000) in Italy, Sabbioni (2008) in Brazil, Garcia and Thomas (2001, 2003) in France, and, finally, Mizutani and Urakami (2001) in Japan. With regard to the sector of Sewerage and cleansing of residual waters (S2), it is commonly studied together with water supply, as it is its by-product. This potentially allows to test for the existence of scope economies in both sectors. Examples of this work are Hunt and Lynk (1995), Saal and Parker (2000) and Nauges and van den Berg (2007). All these studies generally conclude the existence of relevant economies of scale and density in both sectors, suggesting that serving larger city sizes and higher densities—compactness—would be desirable, favoring processes of mergers and acquisitions among firms, though up to a certain level as not to incur in diseconomies—which nevertheless are not seen. Finally, in the sector of Paving and lighting (S3) the empirical evidence with regard to scale economies is relatively scanty. Deller et al. (1988) classic reference limits itself to rural low-volume roads, where economies of scale in operating service costs are identified. In the provision of street lighting service sector we find Prado and García (2007).

In this literature the effect of urban dispersion defined as the density of population or housing on service production costs is limited. However, there are two notable exceptions by Torres and Morrison (2006) and Bottasso and Conti (2009) in the water supply sector. Following Schmalensee (1978), the former take into account the “nature of the network” by considering the effect of a change in the number of customers per square mile and differentiate between vertical economies (i.e., costumer density as in high density-high rise building urban patterns) and horizontal network density diseconomies associated to low density-extensive service areas. The latter authors determine the effect on production costs of the density of operations as the ratio between population and the length of the water mains. In contrast, the literature studying the effect of urban dispersion—density economies—on expenditure functions by way of semi-log regressions is limited to the contributions mentioned in the previous sections and dealing with all the above sectors, either jointly as in Ladd (1992) or sector by sector as in Carruthers and Ulfarsoon (2003). They find economies of density up to a certain value of number of people or jobs per acre, but depending on the specific nature of the production sector, i.e., network versus hub provision, they eventually change to diseconomies.

2.2. Infrastructure versus service provision

As previously remarked, this study complements the existing studies on the production of services by focusing on the underlying infrastructure. This is accomplished by (i) defining costs functions associated with the physical provision of the stocks of infrastructure supporting utilities' delivery[4], and (ii) considering population and housing as the main output served by the different inputs materializing in the aggregate stocks of urban infrastructure. The separate nature of service production and infrastructure provision determines our theoretical approach to define and measure the cost-effectiveness associated with the magnitude of economies of scale (city size in terms of population and housing) and density (urban morphology). Generally, cost effectiveness is assessed in different ways depending on whether one deals with infrastructure provision (investments accumulated in urban infrastructure stocks) or service production (utility flows). When dealing with infrastructure, cost effectiveness is determined as in the present study by the minimum average cost of providing it. As a result of their public good nature, basic urban infrastructure developments are normally financed by way of subsidies—i.e., tax revenues (Lee, 1981)—explaining why they are normally owned by local authorities, while the production of services and their pricing is left to the market. In the case of infrastructure provision the number of inhabitants and dwellings not only represent natural measures of city size[5], but they are also the target variables (outputs) produced by the different inputs materialized in the infrastructure stocks, which can be expressed in per capita or per dwelling terms.[6]

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[4] Since Bradford et al. (1969) one can differentiate two complementary dimensions in the provision of local goods and services. On one hand "D-outputs" as goods and services *directly* produced by local governments — as would be the physical provision of infrastructure, which deserves in itself a detailed individual study— and, on the other, those "C-outputs" consumed by the *citizens*.

[5] The consideration the population as the variable upon which determine the existence of size economies is not new in the field of regional science and urban economics. Eberts and McMillen (1999:1,481) survey diverse contributions where population is a standard measure of city size. In a widely cited work, Rosenthal and Strange (2004) show as main results that productivity increases between 3% and 8% when city population doubles.

[6] The selection of these two variables as the outputs of the infrastructure is reinforced by the fact that they constitute the reference criteria when distributing grants at the city—municipal—jurisdictional level from higher Administrations.

The studies on utilities previously mentioned have analyzed in depth the cost structure of service production, regarding the infrastructure stock as an input of the production process[7]. On the contrary we regard the infrastructure stock as the output necessary to reach population and housing when delivering utilities. This infrastructure is the result of investment flows accumulated throughout the years, constituting a publicly owned stock, which is valued as if new by using current best practice engineering prices, i.e. a gross capital stock concept. Our approach therefore complements the results obtained in the services literature by shedding light upon the infrastructure side of the provision.

3. Economies of scale, density and optimal city dimension

The model assumes that public officials in local governments minimize provision costs subject to a minimum stock level constraint ensuring that the supported service (e.g., water supply) can reach both population and individual dwellings in a satisfactory way. Within their jurisdiction public officials, assisted by their technical staff, have discretion in deciding how resources are allocated amongst the individual physical provision variables (*e.g, water tanks, pipes, mains*,…) making up each infrastructure sector, and given their cost minimizing behavior, this results in optimal input demands. The minimum stock level is equivalent to the output constraint in the standard cost minimization problem and we interpret it as the target (output) population and housing that is produced (served) by the infrastructure stock. Therefore, the long run total provision costs correspond to the capital stock accumulated throughout the years in the individual urban areas (normally grouped under a jurisdiction generically termed as city or municipality).

Even when population and housing in two urban areas are the same, many factors that translate into a wide range of prices for a particular infrastructure as well as network characteristics, will finally result in different provision costs. Examples among the former are the hardness of the soil when opening ditches, or the orography and relief of the terrain when paving roads and streets. Among

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[7] Even if the distinction between the provision of the supporting infrastructure and the production of the service is conceptually clear, their differentiation in empirical applications when defining production or cost functions can be hampered by data availability. In the utilities literature estimating flexible cost functions, the usual measure for the flows of capital services departs from the favored concept of productive capital stock. OECD (2001:51-52) states that "*Because flows of the quantity of capital services are not usually directly observable, they have to be approximated by assuming that service flows are in proportion to the stock of assets after each vintage has been converted into standard "efficiency" units. The so-computed stock is referred to as the "productive stock" of a given type of asset. Thus, the importance of capital stock measures in productivity analysis derives from the fact that they offer a practical tool to estimate flows of capital services".* In reality, as there is no information available on capital services' flows, the majority of studies inappropriately use the infrastructure capital stock as proxy of the capital input. This is to stress that the stock of urban infrastructure that constitutes our dependant variable should not be confused with the intermediate input employed in the above mention literature.

the network characteristics stand out the already mentioned urban compactness or dispersed patterns of the jurisdiction, which makes it necessary to control for the number of population clusters that it comprises as well as their extension (e.g., the less dense and more disperse is population and housing, the higher is the cost of supplying water as the network length increases). All these issues result in diverse endowments of urban infrastructure or *provision stock*, whose final value will differ between urban areas as a result of physical, legal, and institutional factors, as well as the historical patterns in settlement behavior.

3.1. The translog cost function

To allow flexibility in the underlying production function when determining the optimal urban dimension by way of the scale and density economies, we specify a translog cost function that accommodates the case of multi-output production in population and housing. This function was introduced by Christensen et al. (1971, 1973) and we can easily derive from it the alternative sources of scale and density economies. For each of the three provision sectors, public officials optimizing behavior results in an econometric specification of the cost function (1) that includes the cost of infrastructure provision (C) as the dependent variable and the following regressors: (i) the infrastructure provision targets—outputs, Y_g—corresponding to the number of inhabitants and number of dwellings: Y_1 and Y_2; (ii) prices of the relevant infrastructure—input—physical variables, denoted by P_i –see Table 2 for their particular definition, and (iii) two density variables Z_k reflecting the compact or disperse pattern of a jurisdiction, which is captured by the number of urban clusters, Z_1 and the dimension of the urban area, Z_2.

Given these variables the translog cost function C is written as[8]:

$$\begin{aligned}\ln C = \alpha_0 &+ \sum_{g=1}^{Y}\alpha_g \ln Y_g + \sum_{i=1}^{P}\beta_i \ln P_i + \sum_{k=1}^{Z}\delta_k \ln Z_k + \\ &+ \frac{1}{2}\left[\sum_{g=1}^{Y}\sum_{h=1}^{Y}\alpha_{gh}\ln Y_g \ln Y_h + \sum_{i=1}^{P}\sum_{j=1}^{P}\beta_{ij}\ln P_i \ln P_j + \sum_{k=1}^{Z}\sum_{l=1}^{Z}\delta_{kl}\ln Z_k \ln Z_l\right] + \\ &+ \sum_{g=1}^{Y}\sum_{i=1}^{P}\varphi_{gi}\ln Y_g \ln P_i + \sum_{g=1}^{Y}\sum_{k=1}^{Z}\theta_{gk}\ln Y_g \ln Z_k + \sum_{i=1}^{P}\sum_{k=1}^{Z}\omega_{ik}\ln P_i \ln Z_k .\end{aligned} \tag{1}$$

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[8] Ensuring that (1) is positive linearly homogeneous in provision prices and crossed effects' symmetry requires, respectively, the following restrictions: $\sum_{i=1}^{P}\beta_i = 1$; $\sum_{i=1}^{P}\beta_{ij} = 0, j = 1,...,P$; $\sum_{i=1}^{P}\varphi_{gi} = 0, g = 1,...,Y$; $\sum_{i=1}^{P}\omega_{ik} = 0, k = 1,...,Z$, and $\alpha_{gh} = \alpha_{hg}, g,h = 1,...,Y$; $\beta_{ij} = \beta_{ji}, i,j = 1,...,P$; $\delta_{kl} = \delta_{lk}, k,l = 1,...,Z$.

Additional information relative to the cost minimizing demand equations can be introduced into the estimation by using Shephard’s lemma:

$$\frac{\partial \ln C}{\partial \ln P_i} = \frac{\partial C}{\partial P_i (P_i / C)} = \frac{P_i X_i}{C} = S_i \ , \tag{2}$$

where X_i is the i-th physical provision variable and S_i is its share in total provision cost. The set of demand equations that is obtained given the translog functional form is[9]:

$$S_i = \beta_i + \sum_{j=1}^{P} \beta_{ij} \ln P_j + \sum_{g=1}^{G} \varphi_{gi} \ln Y_g + \sum_{k=1}^{Z} \omega_{ik} \ln Z_k , \quad i = 1,...,P \tag{3}$$

3.2. The sources of density economies associated to urban compactness

We now discuss in depth the concepts of population and housing density within a jurisdiction taking into account the two variables reflecting the compact or dispersed pattern of the urban areas it may comprise. Our first variable (Z_1) captures the disperse distribution of population and housing among the existing total number of population centers or clusters,[10] while the second variable (Z_2) corresponds to the urbanization area (Km.^{2}).

The relevance of these two variables characterizing urban structure is their complementary interpretation when revealing the sources of density economies associated to reductions in urban dispersion. To unveil the economic and technological reasons behind them we discuss both variables separately. Because we want to study cost behavior when population and housing densities *increase* (i.e., keeping the number of inhabitants and dwellings constant in the numerator, while reducing the number of dispersed settlements and urban extension in the denominator, e.g., Y_1/Z_1), we interpret their elasticities with reversed sign, so to obtain the magnitude of cost reduction when density is increased by *reducing* the number of clusters or the surface area. Starting with Z_1, reducing the number of population and housing clusters while keeping constant the urban area (Z_2) would be equivalent to their relocation by clustering them in a lower number of centers (whose joint urban area remains constant). That is, reducing the number of population settlements, *ceteris paribus* Z_2 and the target variables Y_g, implies that the density ratios Inhab./Km^2 and Dwell./Km^2 remain constant, but the discontinuous urban development associated to urban scatterness—“leap-frog” settlements—is

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[9] The system of equations formed by the cost function (1) and factor demands (3) can be estimated by maximum likelihood techniques, as they constitute a system of seemingly unrelated regression equations, *SURE*, (Zellner, 1962). All variables have been mean-corrected prior to estimation, i.e. each variable is divided by its mean. Proceeding this way, first order coefficients can be regarded as elasticities evaluated at the sample means.

[10] A population cluster—normally a low density area such as a village or hamlets that may be relatively far away from the main core urban area—is formally defined by the Spanish National Statistical Office, INE, as an area encompassing ten or more buildings forming an urban layout (i.e. a grid conformed by streets, squares, etc.).

reduced. If the cost elasticity of the number of clusters: $\varepsilon_{C,Z_1} = \partial \ln C \ / \ \partial \ln Z_1$ is less than one, one percent proportional *reduction* in the number of clusters reduces cost to a lower extent. With regard to the cost elasticity associated with the traditional size variable Z_2 representing the urban area, its associated elasticity $\varepsilon_{C,Z_2} = \partial \ln C \ / \ \partial \ln Z_2$, implies a proportional change in the square kilometers of urban surface that increases the density ratios Inhab./Km^2 and Dwell./Km^2, allowing us to study area density economies. If ε_{C,Z_2} is less than one, *reducing* the urban extension by one percent reduces the cost to a lower percent. As a result we depart from the normal interpretation of the elasticities associated to density variables that can be found in the literature—more noticeably recent contributions by Torres and Morrison (2006) and Bottasso and Conti (2009), which would reflect the cost increase associated to reducing population and housing densities by increasing the number of clusters and/or the urban area. Therefore, in our empirical section we interpret the sign and magnitude of economies of urban density in an equivalent—but reversed—way so as to better capture the effect of urban density *increases* on provision costs.

Correspondingly, lessening the scattered pattern within a jurisdiction by *reducing* the number of clusters reduces the cost of providing basic infrastructure as a result of the associated reduction in the network extension connecting individuals and dwellings to the utility sources, e.g., in the water supply sector all pipes and mains necessary to reach dispersed settlements are not longer necessary. As the number of population clusters summarize best the urban sprawl characteristics of a given urban area by capturing tract dispersion (separation between non-contiguous development tracts, also known as "skipped-over" development) we associate ε_{C,Z_1} to density economies associated to urban sprawl reductions. Comparing this density elasticity with those presented in recent studies on network utilities, it better matches the definition of "(dis)economies of horizontal network expansion" in Torres and Morrison (2006) and "spatial density" in Bottasso and Conti (2009). However, this precise concept cannot be explicitly captured by these authors in their studies as they miss an urban sprawls variable such as Z_1,[11] i.e., the adverse effect on costs of an extensive urban pattern with population owning large individual lots and settling in normally disperse and disconnected clusters that require longer network infrastructure.[12]

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[11] When defining their conceptually equivalent economies of horizontal network expansion and spatial density, Torres and Morrison (2006) and Bottasso and Conti (2009) respectively use the number of customers (contracts) and properties connected to the network, which can be associated in both cases to the number of dwellings that we employ.

[12] Nevertheless, Bottasso and Conti (2009: 145) try to tackle the issue of disperse population settlements by introducing a variable defined as population per Km. of network length, which can be considered as a proxy of urban sprawl.

Complementarily, *densifying* the existing settlement clusters by *decreasing* the urban area (i.e. interpreting the elasticity with reversed sign), carries provision cost reductions, and these savings result from the possibility of serving the same number of individuals and dwellings with shorter networks resulting from smaller urban areas. In this sense $-\varepsilon_{C,Z_2}$ captures the effect of reducing the Km^2 of urban extension—within the existing number of clusters—on urban density ratios, thereby increasing population densities and reducing the average cluster extension. This density variable better correlates with the concept of "(dis)economies of vertical network expansion" in Torres and Morrison (2006) and "customer density" in Bottasso and Conti (2009), as they reflect the effects on costs of favoring high density urban areas in terms of population residing in high-rise buildings and apartment blocks associated with a large number of dwellings, e.g., urban areas as New York City, requiring shorter piping and mains than those necessary in extensive urban configurations where there are large individual lots and single housing, e.g., as in Los Angeles.[13]

The complementary nature and therefore necessary distinction between these two variables associated to density patterns is illustrated in Table 1 and Figure 1. It is assumed, Table 1a, that jurisdictions A and B have the same number of inhabitants (500), dwellings (250) and city size (40), distributed among several urban clusters as shown in the white boxes. Therefore, even if they have the same population and dwellings density, their spatial configuration clearly differs as A exhibits a horizontally dispersed morphology including four clusters: $Z_1 = 4$, while B is compact, $Z_1 = 2$. As a result, focusing solely in the traditional surface area Z_2 (Km^2), would miss the urban form associated with the number of populating clusters (number of white areas), which is a key factor in the provision cost of basic infrastructure, making it necessary to introduce in the model a variable capturing this urban pattern. Consequently, exploring the effect of urban structure on the cost of urban infrastructure provision by solely looking at the urban extension would be misleading, and population and housing density economies associated to the extension of the urban area in the existing clusters Z_2, must be complemented with its urban dispersed counterpart, which is better captured by the number of dispersed clusters Z_1. Moreover, as discussed below and illustrated in Figure 1a, we can stress that ε_{C,Z_1} captures cost network economies *between* clusters in the total jurisdictional area—i.e., within the grayed area. By comparing cluster densities, Table 1a and Figure 1a show that reducing the number of clusters—as would be the case if jurisdiction A were to adopt the urban pattern of city B—increases

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[13] Finally, our economies of density reflecting cost behavior when both the number of dispersed clusters and the urban area are simultaneously reduced, would correspond to the size economies presented in Torres and Morrison (2006) as their definition corresponds to a joint reduction in the two variables reflecting the density characteristics of the urban pattern when producing water distribution.

population and housing densities per cluster, but area densities remain unchanged. Complementarily, ε_{C,Z_2} captures the cost economies associated with urban density *within* the existing clusters, i.e., considering only dwellings per square kilometer of urban area, as represented by the white areas in Table 1b and Figure 1b. In this case, reducing the urban area from 50 to 40 within the existing clusters (Z_1 = 4)—with jurisdiction B now adopting the urban pattern of city A—increases all area densities (inhabitants and dwellings), but leave cluster densities unchanged.

Table 1 and figure 1. Economies of density and urban patterns.

Figure 1.a. Urban patterns

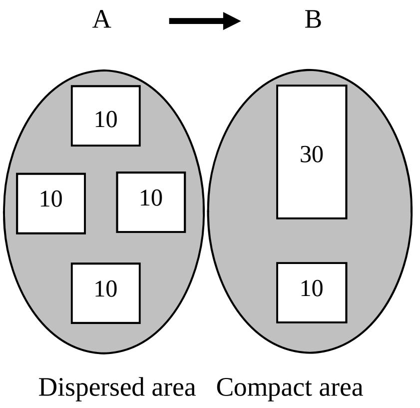

Table 1.a. Economies of density (ε_{C,Z_1}): Reducing nº urban clusters

		Cities A and B			
Variables	A	Clusters densities			B
Urban clusters (C) (Z_1)	4	125	Inhab./ C.	250	2
Inhabitants (nº)	500	62.5	Dwell./ C.	125	500
Dwelling (nº)	250	10	Km^2/ C.	20	250
Urban area (Km^2) (Z_2)	40	Cet. par.: Inh./Km^2, Dwell./Km^2			40

Figure 1.b. Urban patterns

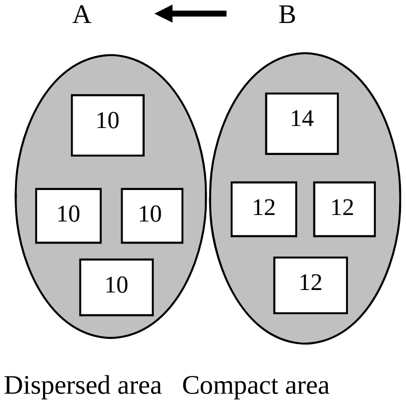

Table 1.b. Economies of density (ε_{C,Z_2}): Reducing the urban area

	Cities A and B				
Variables	A	Urban area densities			B
Urban clusters (nº) (Z_1)	4	12.5	Inhab./ Km^2	10	4
Inhabitants (nº)	500	6.25	Dwell./ Km^2	5	500
Dwelling (nº)	250	10	Km^2/ C.	12.5	250
Urban area (Km^2) (Z_2)	40	Cet. par: Inhab./C, Dwell./C,			50

Source: Own elaboration.

3.3. Measures of economies of scale and density

We now recall the model represented by the system of equations formed by the cost function (1) and factor demands (3) to formally define the notions of economies of (i) population and housing scale and (ii) urban density. As anticipated, we propose two complementary measures that portrait cost behavior when population and density *increase* in the territory, either by increasing these magnitudes while keeping constant the variables representing the sprawled pattern of the jurisdiction (i.e., number of clusters Z_1 and the urban surface Z_2), or vice versa, by *reducing* these latter variable while keeping constant the number of inhabitants and dwellings.

The particular definition that we make of the population and housing scale economies allows answering the fundamental question relative to the cost structure of infrastructure provision relative to the most relevant variables of size by informing about the effect that an equal change in the number on inhabitants (Y_1) and dwellings (Y_2) would have on current provision cost, holding the variables capturing the urban configuration and extension unchanged. Given the provision variables Y_g, $g = 1, 2$, scale economies define as:

$$\begin{aligned}&\text{SCE} = \sum_{g=1}^{Y} \frac{\partial \ln C}{\partial \ln Y_g} = \\ &= \left[\sum_{g=1}^{Y} \alpha_g + \sum_{g=1}^{Y}\sum_{h=1}^{g-1} \alpha_{gh} \ln Y_h + \sum_{g=1}^{Y} \alpha_{gg} \ln Y_g + \sum_{g=1}^{Y}\sum_{h=g+1}^{Y} \alpha_{gh} \ln Y_h + \sum_{g=1}^{Y}\sum_{i=1}^{P} \varphi_{gi} \ln P_i + \sum_{g=1}^{Y}\sum_{k=1}^{Z} \theta_{gk} \ln Z_k \right]\end{aligned} \tag{4}$$

When SCE is less, equal to, or greater than one, economies associated to the size—scale—of a jurisdiction in terms of population and housing are increasing, constant or decreasing (scale diseconomies). In the case that economies of scale existed, this would imply that an equiproportional increase in these variables brings lower provision cost increases. Therefore, given equal municipal characteristics relative to urban density, Z_k, increasing the values of Y_g by one percent translates into a lower provision cost in the magnitude signaled by the sum of their elasticities: SCE = $\varepsilon_{C,Y_1} + \varepsilon_{C,Y_2}$.

Next we define economies of urban density as the change that takes place in the provision cost when both variables reflecting urban sprawl are *reduced* by one percent, Z_k, $k = 1, 2$. As already discussed, when interpreting the elasticities with reversed sign, it is expected that increasing population and housing density by reducing the number of dispersed urban clusters, Z_1, along with a reduction in the square kilometers of urban area, Z_2, would carry lower provision costs—ceteris paribus the number of inhabitants and dwellings. Hence, economies of density coming from urban dispersion reductions at the existing levels of the provision variables Y_g read as follows:

$$\begin{aligned}&\text{DNE} = -\sum_{k=1}^{Z} \frac{\partial \ln C}{\partial \ln Z_k} = \\ &= -\left[\sum_{k=1}^{Z} \delta_k + \sum_{k=1}^{Z}\sum_{l=1}^{k-1} \delta_{kl} \ln Z_l + \sum_{k=1}^{Z} \delta_{kk} \ln Z_k + \sum_{k=1}^{Z}\sum_{l=k+1}^{Z} \delta_{kl} \ln Z_l + \sum_{g=1}^{Y}\sum_{k=1}^{Z} \theta_{gk} \ln Y_g + \sum_{i=1}^{P}\sum_{k=1}^{Z} \omega_{ik} \ln P_i \right]\end{aligned} \tag{5}$$

If increasing urban density—considering the elasticities of Z_1 and Z_2 with reversed sign—brings a reduction in the provision cost, (5) will be negative, and economies of density exist. In this case negative values smaller than −1, i.e. DNE $\in$ (−∞,−1), indicate increasing economies of density (increasing the density reduces the cost in a larger proportion as the sum of the elasticities: $-\varepsilon_{C,Z_1}-\varepsilon_{C,Z_2}$ is greater than one in absolute values, whereas negative values equal or greater than −1, i.e. DNE $\in$ (−1, 0], imply that constant or decreasing density economies are observed (increasing the density reduces the cost in a lower proportion as the sum of the elasticities is smaller than one in absolute values). For DNE = −1, constant economies if density exist. Therefore, when density economies exist, reducing the number of population clusters and the extension of the urban area (*e.g.*, promoting densification by means of a single urban area and reducing single housing by favoring apartment buildings with multiple housings units), would reduce the cost of providing infrastructure. In this way (5) establishes that the provision of infrastructure to population and housing carries lower costs as territorial density increases, e.g., when they locate in one single cluster with high-rise buildings, as opposed to rural zones characterized by single and dispersed housings located in numerous clusters.[14]

3.4. Optimal city dimension

The final aim of the foregoing section is the determination of the ideal urban dimension in terms of the actual variables upon which public officials take action when planning urban infrastructure investments. Not surprisingly, from a political perspective, the most relevant variable when allocating intergovernmental grants devoted to infrastructure is urban population, proxy of the number of voters, while from the urban planning/land use perspective rationalizing investments according to economic criteria concerning this study, it is population density the variable that better captures cost efficiency when providing public infrastructure. We therefore consider population Y_1 and city size Z_2 as the key dimension variables whose optimal values minimizing average provision cost should be determined.

We analytically obtain the ideal dimension for which average provision cost is minimum by generalizing the approach set out by Mizutani and Urakami (2001) for water utilities, and extend it to the determination of the minimum cost in the case of multiple outputs within our infrastructure provision framework. When particularly referred to population density the expression for the minimum provision cost can be calculated by taking the antilogarithm of (1) and dividing by

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[14] The definitions that we present of economies of scale (4) and density (5) correspond to those originally introduced by Panzar and Willig (1977) and adopted by Torres and Morrison (2006), and they are the inverse of those later suggested by Caves et al. (1984, 1985), that in turn are favored by Batasso and Conti (2009). Nevertheless, whether the scale and density economies are defined as the inverse of the sum of the elasticicities or not does not change any conclusion, but just their numerical interpretation.

population Y_1 and by the urban area Z_2. The first-order conditions (FOC) that jointly minimize average provision cost with respect to these two variables yield the number of inhabitants and urban area (Km^2) that allow us to establish optimal population density by dividing the former by the latter (Inhab./Km^2, i.e., Y_1 / Z_2). Starting out with the FOC relative to the number of inhabitants, it can be obtained by taking the antilogarithm of (1) and dividing by Y_1:

$$\begin{aligned}\mathrm{AC}_{Y_1} &= C / Y_1 = (1 / Y_1) \cdot \exp(\ln C) = \\ &= (1/Y_1) \cdot \exp\Bigg[\alpha_0 + \sum_{g=1}^{Y} \alpha_g \ln Y_g + \sum_{i=1}^{P} \beta_i \ln P_i + \sum_{k=1}^{Z} \delta_k \ln Z_k + \\ &+ \frac{1}{2}\left[\sum_{g=1}^{Y}\sum_{h=1}^{Y} \alpha_{gh} \ln Y_g \ln Y_h + \sum_{i=1}^{P}\sum_{j=1}^{P} \beta_{ij} \ln P_i \ln P_j + \sum_{k=1}^{Z}\sum_{l=1}^{Z} \delta_{kl} \ln Z_k \ln Z_l \right] + \\ &+ \sum_{g=1}^{Y}\sum_{i=1}^{P} \varphi_{gi} \ln Y_g \ln P_i + \sum_{g=1}^{Y}\sum_{k=1}^{Z} \theta_{gk} \ln Y_g \ln Z_k + \sum_{i=1}^{P}\sum_{k=1}^{Z} \omega_{ik} \ln P_i \ln Z_k \Bigg].\end{aligned} \qquad (6)$$

Differentiating this average cost function with respect to first provision variable Y_1 and equating it to zero gives us the following FOC:

$$\begin{aligned}\frac{\partial \mathrm{AC}_{Y_1}}{\partial Y_1} = \frac{\partial (C / Y_1)}{\partial Y_1} &= (1/Y_1^2) \cdot \Big[\exp(\ln C) \cdot \Big[\alpha_1 + \alpha_{11} \ln Y_1 + \sum_{h=1}^{Y-1} \alpha_{1h} \ln Y_h + \sum_{i=1}^{P} \varphi_{1i} \ln P_i + \sum_{k=1}^{Z} \theta_{1k} \ln Z_k \Big] \\ &\quad - \exp(\ln C) \Big] = 0.\end{aligned} \qquad (7)$$

Since $Y_1 \neq 0$ and exp(ln$C$) $\neq$ 0, the minimum of the average cost function requires the following equality:

$$\alpha_1 + \alpha_{11} \ln Y_1 + \sum_{h=1}^{Y-1} \alpha_{1h} \ln Y_h + \sum_{i=1}^{P} \varphi_{1i} \ln P_i + \sum_{k=1}^{Z} \theta_{1k} \ln Z_k - 1 = 0 \qquad (8)$$

Following the same procedure we can obtain the expression for the optimal value of the density variable Z_2 minimizing average costs. The counterpart to equation (8) corresponding to $\partial \mathrm{AC}_{Z_2} / \partial Z_2 = \partial (\mathrm{C} / Z_2) / \partial Z_2 = 0$, is:

$$\delta_2 + \delta_{22} \ln Z_2 + \sum_{l=1}^{Z-1} \delta_{2l} \ln Z_l + \sum_{g=1}^{Y} \theta_{g2} \ln Y_g + \sum_{i=1}^{P} \omega_{i2} \ln P_i - 1 = 0 \qquad (9)$$

We use equations (8) and (9) to jointly determine the optimal values for the provision and density variables that allow us to establish the optimal population density ratio Y_1/Z_2 (Inhab./Km^2). In our empirical application, once we estimate for each provision sector the cost system including equations (1) and (3), we solve the above system of equations assuming that all variables for which we are not optimizing remain constant at the sample mean.

4. Databases: LIES and cost based engineering prices

4.1. Physical variables, prices and the cost of the urban infrastructure stock

The physical variables X_i that we use to construct our novel database in urban infrastructure stock come from the Spanish Local Infrastructure and Equipment Survey dated in 2005, *Encuesta de Infraestructura y Equipamientos Locales*, EIEL 2005. This inventory is designed by the Ministry of Public Administration (MAP, 2005) and local governments at the provincial level–*Diputaciones*–are responsible for executing it. The inventory lists all infrastructure and equipment that must be provided in each jurisdiction according to the legal framework represented by the Spanish law, 7/85 *Ley de Bases de Régimen Local*[15].

For this study we have also produced a second database using engineering cost prices of the different provision variables as technically defined in the inventory. We calculate unit provision prices that are the result of weighing each input price: labor, capital, intermediate consumptions,…, by its cost share in the production of that particular provision variable–e.g., 1 meter of water distribution network. Additionally, the unit provision price also incorporates other costs regarding single unit inputs (pipelines, water street chests and wells, hydrants, drains, hatch valves, etc.), as well as other auxiliary input units (sand, mortar, concrete, curb, trench refilling, ground compacting, etc.)[16]. This methodology takes into account technological characteristics and incorporates all those elements that are part of each of the representative tasks that are necessary to produce one unit of infrastructure.[17] Once the parametric price for each provision variable is determined, it is in turn weighted by the relevant geo-structural variables characterizing the particular urban location in which the civil work takes place: lithology/geology, altitude and distance to the closest commercial hub representing a proxy to transportation costs.[18] All these ancillary variables allow us to establish urban area factor that

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[15] As provision levels and conditions may change with time as services deteriorate or are improved, the inventory is periodically updated. Its importance resides in the fact that it constitutes a dynamic statistical source that can be used to evaluate local provision levels and conditions to allocate the intergovernment grants funds.

[16] These and other individual task prices that we have used to determine unit prices for the remaining provision variables can be looked up in the Castilla y León database of construction prices, *Instituto de la Construcción de Castilla y León*: www.iccl.es, BPCCL (2004).

[17] For this purpose we have gathered information from the technical engineering staff of the provincial governments whose expert opinion on the components and prices of the different civil works —provision variables— is critical. These public works' supervisors plan, organize, oversee, coordinate and review a comprehensive program of public works construction, maintenance and repair of urban infrastructure, which includes water supply, sewerage collection and paving and lighting.

[18] The weight capturing the lithological and geological characteristics of a municipality reflects soil hardness when executing a work. The information provided by the lithological map of Castilla y León, SIEMCALSA (1997) allows us to classify urban areas in thirteen distinctive categories and six levels of soil hardness. As for the altitude, we have considered four levels taking as reference for a particular urban area that of its largest population cluster. Finally, when the closest city head of a commercial area coincides with the administrative capital city, the distance can be found in the 1993 Nomenclator produced by the Spanish National Statistical

renders the single provision price more accurate as these weights allow us to modify the parametric price taking into account the characteristics of a particular geographic location.[19]

The cost of provision that we obtain by multiplying the prices P_i by the existing physical infrastructure X_i can be considered as the provision stock of urban infrastructure. Given that the year in which a particular infrastructure was constructed is unknown—as well as the their current condition or quality level (note that repairs are also programmed and budgeted)—we are forced to value the existing stock at current provision prices. This corresponds to the usual definition of gross capital stock, which prices assets at their current acquisition value.[20]

With regard to the target provision variables for which infrastructure investment is planned: inhabitants Y_1 and dwellings Y_2, we have considered a population figure that considers all people residing in any population cluster belonging to a jurisdiction—municipality—below 50.000 inhabitants, INE (2004). This information, collected at the cluster level as defined in footnote 11, includes all urban developments of various extensions: cities, towns, villages, hamlets, as well as their surrounding subdivisions and other residential areas. Residential areas comprise housing intended for a permanent or seasonal use. The reason behind this choice is that urban infrastructure levels must be planned according to its potential number of users at any moment in time. This means for example that urban areas with a high degree of second (seasonal) residences will experience unused infrastructure capacity, but it is clear that basic urban infrastructure –e.g., water distribution or sewerage collection and disposal, must be provided on a door-by-door basis regardless of the intensity of use. Both variables, gathered and listed by municipalities, which is the benchmark jurisdictional level, come from the 2001 Spanish Census of Population and Dwellings, INE (2001). As reflected by INE, this concept of population "is believed to reflect a more accurate estimation of the real level of population to whom the municipality must provide infrastructure".

Finally, the already discussed variables capturing the compact or dispersed pattern of the urban area are the number of urban clusters, Z_1, coming from the 2005 EIEL survey, and the dimension of the urban area, Z_2, as given by the Spanish Property Assessment Office (*Catastro Inmobiliario Urbano*), that aggregates the land surface of all individual clusters.

Office, INE (2003), while the distances to alternative commercial cities have been calculated using the information database given by the National Center of Geographical Research, CNIG (2001) and the Commercial Atlas of Spain published by the Spanish savings bank, laCaixa (2000).

[19] These weights are commonly used in studies on production of urban utilities, e.g. Coelli and Walding (2005) for water supply, Rubiera (2007) in studies testing central place, hierarchy, and location theories, Deller et al. (1988) for rural low-volume roads, all of which obtain provision prices by means of engineering costs analyses.

[20] A methodological discussion summarizing the conclusions of the Camberra group on capital stock measurement, with regard to the concepts of gross, net and productive capital stocks can be found in OECD (2001). See also footnote 7.

4.2. Data description

The number of municipalities included in the estimation of the cost functions corresponding to each provision sector of urban infrastructure, as well as the descriptive statistics relative to provision costs, inhabitants and dwellings as well as provision prices are shown in Table 2. Out of the total number of municipalities: 2,238, it is possible to see that the scarcity and deficiency of reliable data forces us to dismiss some observations. [21] With regard to provision costs, the third sector of Paving and lighting constitutes the largest infrastructure stock on average, reaching €2,001,118. In relation to the prices of all eight provision variables, P_i, we highlight the biggest unit value corresponding to the installation of a single street lamp whose cost is €540.4. With regard to the variables related to density, the average number of clusters Z_1 by municipality ranges amongst 1.6 (S1) and 2.2 (S3), whereas average urban surface situates around 0.25 square kilometers. Finally, by sectors, the highest cost share in Water supply (S1) corresponds to the distribution network, representing a proportion of 69.6% on average. With regard to the sector of Sewerage and cleansing of residual waters (S2), the sewerage collection network presents the highest share, 48.9%, while in Paving and lighting (S3) the provision representing the highest share is paving with 92.6%.

5. Magnitude and significance of the economies of scale and density

5.1. Cost function estimates

The estimation of the system of equations corresponding to each provision sector yields the results presented in Table 3. In general we observe a reasonable goodness of fit when considering both the test for joint significance of the parameters F, as well as of the R^2 coefficient. Likewise, the set of the first order parameters are statistically significant and exhibit positive values. Focusing on the joint value of the population (Y_1) and housing (Y_2) coefficients in each sector, they are systematically smaller than one showing that an increase in one of these two target provision variables by one percent would increase the provision cost to a lower extent, and reflect the existence of economies of scale. Nevertheless, their individual values in each provision sector greatly differ, showing the different technological characteristics pertaining to each provision sector as well as average population and housing features. For example, the sewerage and cleansing infrastructure (S2) is mostly dependant on the number of inhabitants, explaining why its associated coefficient is four times larger than the dwellings' coefficient—in fact water cleansing plants are dimensioned according to population, while

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[21] The loss is small in Water supply (S1) and more severe in Paving and lighting (S3), while in the Sewerage and cleansing of residual waters sector (S2) as many as 1,099 observations are missing from the database, simply because despite regulations requiring compulsory systems to cleanse residual waters, they have not installed any.

Table 2. Descriptive statistics by provision sector.

S1. Water supply (n = 1,793)

Variables	Mean	Std.	Min.	Max.
C_i - Cost (Stock)	763,089.0	1,132,196.0	37,066.0	21,304,711.0
Y_1 - Inhabitants (nº)	463.4	1,149.7	12.0	30,875.0
Y_2 - Dwellings (nº)	338.9	634.7	11.0	12,785.0
P_1 - High capacity piping (€/m)	27.6	4.1	22.1	38.6
P_2 - Distribution network (€/m)	89.8	5.7	83.9	113.8
P_3 - Water tanks (€/m3)	431.5	9.1	382.8	449.9
Z_1 - Population clusters (nº)	1.6	1.2	1.0	6.0
Z_2 - Urban area (Km.^{2})	0.3	0.6	0.007	8.6
S_1^* - High capacity piping	0.131	0.123	0.001	0.820
S_2^* - Distribution network	0.696	0.164	0.119	0.983
S_3^* - Water tanks	0.173	0.115	0.008	0.802

S2. Sewerage and cleansing of waters (n = 1,139)

Variables	Mean	Std.	Min.	Max.
C_i - Cost (Stock)	694,760.1	727,924.8	47,176.5	7,039,996.0
Y_1 - Inhabitants (nº)	441.5	639.8	22.0	7,141.0
Y_2 - Dwellings (nº)	246.6	322.1	16.0	4,241.0
P_1 - Sewerage network (€/m)	86.6	6.1	80.2	112.2
P_2 - High disposal netw. (€/m)	83.6	6.8	68.2	103.5
P_3 - Treated flow (€/m3)	9.6	0.9	5.8	10.9
Z_1 - Population clusters (nº)	2.1	2.3	1.0	19.0
Z_2 - Urban area (Km.^{2})	0.2	0.2	0.01	4.6
S_1^* - Sewerage network	0.489	0.178	0.008	0.948
S_2^* - High disposal network	0.108	0.096	0.001	0.867
S_3^* - Treated flow	0,403	0,152	0,002	0,892

S3. Paving and lighting (n = 1,311)

Variables	Mean	Std.	Min.	Max.
C_i - Cost (Stock)	2,001,118.0	2,694,889.0	186,552.2	36,500,000.0
Y_1 - Inhabitants (nº)	703.4	2,168.6	52.0	37,020.0
Y_2 - Dwellings (nº)	474.0	1,145.0	66.0	21,537.0
P_1 - Paving (1) (€/m2)	31.4	3.1	20.9	40.0
P_2 - Lighting (€/lamp)	540.4	53.1	379.7	675.1
Z_1 - Population clusters (nº)	2.2	2.5	1.0	19.0
Z_2 - Urban area (Km.^{2})	0.3	0.6	0.02	8.6
S_1^* – Paving	0.926	0.056	0.677	0.992
S_2^* - Lighting	0.074	0.056	0.008	0.323

(1) Urban road surface (streets, squares and other roads)

* $S_\#$: Cost shares in each provisions sector.

Source: Own elaboration from LIES and Price Databases.

this relationship reverses in the Water supply sector (S1) where the coefficient corresponding to the number of dwellings is twice that of population, as the capillary network is dimensioned according to the former, which in turn explains its relevance when explaining the provision cost. With regard to the price elasticities, P_i, they reflect the particular cost shares that have been observed in each provision sector as presented in Table 2. Finally, we highlight the values of the different variables representing the pattern and extension of the urban areas, Z_k. They behave as expected in all three sectors both regarding their values and signs, while being statistically significant. When interpreted with reversed sign, reducing the number of clusters (Z_1) and the urban area (Z_2) would reduce provision cost even if to a lower extent, anticipating the existence of economies of density.

5.2. Economies of scale and density

We now recall the definitions presented in the third section concerning scale (SCE) and density (DNE) economies as presented in eqs. (4) and (5), and show their magnitudes in Table 4. The values of economies of scale and density can be estimated not only for the whole set of observations, but also for successive data subsets divided according to our target urban planning variable relative to population density upon which we establish the optimal urban dimension (i.e., Inhab./Km^2, Y_1/ Z_2). This is done by dividing the set of observations in three subsets that allow enough degrees of freedom to perform reliable estimations. In Table 4 we present the estimated values for the whole set of observations and for different subsets that yield statistically significant estimates.

The results show that in all three sectors there exist significant economies of scale and density for the whole dataset. From our calculations, a one percent increase in the number of inhabitants and dwellings in the Water supply sector (S1), would increase the cost of infrastructure provision by 0.603%. The SCE magnitudes for S2 and S3 reach remarkable values: 0.493 and 0.188, suggesting important average cost savings in terms of urban scale—population and housing. In spite of the variability in the SCE values obtained as a result of segmenting the sample, there is a significant upward trend in SCE in all three sectors as population density increases, signaling that these economies tend to wear out, i.e., as the optimal city dimension in terms of population density is approached.

Table 3. Cost determinants of urban infrastructure (parameter estimates).

		S1. Water supply		S2. Sewerage and cleansing of waters		S3. Paving and lighting	
Variables	Parameters	Coefficients	T-Stat.	Coefficients	T-Stat.	Coefficients	T-Stat.
Constant	α_0	0.078	4.450	0.085	6.540	0.157	6.260
$\ln Y_1$	α_1	0.213	7.050	0.374	11.290	0.107	1.750
$\ln Y_2$	α_2	0.390	14.120	0.119	4.080	0.081	1.660
$\ln P_1$	β_1	0.116	34.210	0.475	73.280	0.927	45.140
$\ln P_2$	β_2	0.703	153.960	0.108	31.250	0.073	35.670
$\ln P_3$	β_3	0.182	55.630	0.416	73.320	—	—
$\ln Z_1$	δ_1	0.152	7.830	0.417	17.520	0.447	9.460
$\ln Z_2$	δ_2	0.201	9.110	0.062	5.160	0.236	9.750
$(\ln Y_1)^2$	α_{11}	-0.091	-0.960	0.363	3.070	-0.147	-0.770
$(\ln Y_2)^2$	α_{22}	0.100	1.500	0.018	0.210	-0.192	-2.120
$\ln Y_1 \ln Y_2$	α_{12}	-0.114	-0.820	-0.282	-1.830	0.264	1.290
$(\ln P_1)^2$	β_{11}	0.013	0.920	0.270	6.190	-0.003	-0.600
$(\ln P_2)^2$	β_{22}	-0.181	-4.180	0.002	0.080	-0.003	-0.600
$(\ln P_3)^2$	β_{33}	-0.123	-5.170	0.173	6.250	—	—
$\ln P_1 \ln P_2$	β_{12}	0.022	1.140	-0.049	-1.950	0.003	0.600
$\ln P_1 \ln P_3$	β_{13}	-0.035	-2.790	-0.220	-7.210	—	—
$\ln P_2 \ln P_3$	β_{23}	0.158	5.290	0.048	2.970	—	—
$(\ln Z_1)^2$	δ_{11}	-0.096	-2.310	-0.110	-1.090	-0.107	-0.810
$(\ln Z_2)^2$	δ_{22}	0.122	1.760	0.019	0.590	-0.003	-0.080
$\ln Z_1 \ln Z_2$	δ_{12}	0.057	0.900	0.214	3.200	-0.039	-0.490
$\ln Y_1 \ln P_1$	φ_{11}	-0.058	-6.870	-0.088	-4.340	-0.030	-4.960
$\ln Y_1 \ln P_2$	φ_{12}	0.080	7.080	-0.002	-0.170	0.030	5.000
$\ln Y_1 \ln P_3$	φ_{13}	-0.022	-2.720	0.090	5.090	—	—
$\ln Y_2 \ln P_1$	φ_{21}	0.033	4.030	-0.016	-0.850	-0.006	-1.250
$\ln Y_2 \ln P_2$	φ_{22}	-0.073	-6.690	-0.025	-2.460	0.006	1.260
$\ln Y_2 \ln P_3$	φ_{23}	0.040	5.020	0.042	2.500	—	—
$\ln Y_1 \ln Z_1$	θ_{11}	0.137	2.580	-0.130	-1.340	0.044	0.310
$\ln Y_1 \ln Z_2$	θ_{12}	-0.033	-0.700	-0.055	-1.260	-0.110	-2.190
$\ln Y_2 \ln Z_1$	θ_{21}	-0.037	-0.920	0.108	1.430	0.013	0.160
$\ln Y_2 \ln Z_2$	θ_{22}	-0.035	-0.810	-0.042	-1.090	0.126	2.870
$\ln P_1 \ln Z_1$	ω_{11}	-0.003	-0.560	0.121	7.330	0.032	6.490
$\ln P_2 \ln Z_1$	ω_{21}	-0.004	-0.470	-0.006	-0.680	-0.032	-6.540
$\ln P_3 \ln Z_1$	ω_{31}	0.007	1.230	-0.115	-7.990	—	—
$\ln P_1 \ln Z_2$	ω_{12}	0.048	8.420	-0.064	-7.230	0.016	6.580
$\ln P_2 \ln Z_2$	ω_{22}	-0.031	-4.080	0.045	9.510	-0.016	-6.630
$\ln P_3 \ln Z_2$	ω_{32}	-0.016	-2.950	0.018	2.400	—	—
F-test		8.77*E+11		4,358.4		16,794.5	
R^2		0.854		0.933		0.709	
Observations		1,793		1,139		1,311	

Source: Own elaboration.

Economies of density (DNE) also present notable values, thereby showing their importance as potential sources of allocative efficiency in reducing average costs. As discussed in previous sections, in Table 4 density economies are reported with negative values to show explicitly the effect that reducing urban sprawl would have on provision costs. As a result, a one percent reduction in the number of clusters Z_1, simultaneous to the same proportional reduction in the extension of urban areas, Z_2, i.e., a densification of population and housing on the territory, brings a cost reduction equal to –0.353% in S1 (DNE = –0.353 = $-\varepsilon_{C,Z_1} - \varepsilon_{C,Z_2}$ = –0.152–0.201), and showing the savings in the provision of urban infrastructure that brings a reduction in urban dispersion by drawing together population and housing in fewer (urban) clusters with less single housing in large lots, and more inhabitants and dwellings living in apartment complexes. Our results remarkably concur with the existing evidence from the urban planning/land use literature, showing that the degree of urban dispersion, measured by spatial attributes defined from an engineering perspective such as lot size, tract dispersion, and distance from "upstream" (source) and "end-of the pipe" facilities, have a positive correlation with the cost of providing infrastructure. For example, Speir and Stephenson (2002) report that reducing the lot size within a given tract by 100% from 0.5 acres to 0.25 acres, reduces water supply and sewerage costs per dwelling in a range between –20% and –38%, depending on tract dispersion and distance to the source or end infrastructure. The magnitudes of the elasticities associated to our variables capturing the effect on costs of reducing urban dispersion by 100% yield values within that range: –35.3% in S1, –47.9% in S2, and –68.3% in S3.

Moreover, by comparing the two sources of density economies associated to urban sprawl reductions, as presented in the last two columns of Table 4 reporting their relative weights in the DNE economies, we learn that reducing the number of clusters Z_1 results in larger cost reductions than reducing the extension of the existing urban areas Z_2, while they are more balanced in the first sector. It is then possible to conclude that reducing dispersion by exploiting horizontal or spatial network economies, is more relevant than the density economies coming from a reduction in the service extension within the existing clusters—exploiting vertical or customer network savings.

Finally, by jointly considering the effect of increasing density by *increasing* the number of inhabitants or dwellings, combined with a simultaneous *reduction* in the number of clusters or the urban area within the jurisdiction, we learn that this would result in greater average cost savings than those associated to the population or housing elasticities. We can illustrate this in terms of our target population density variable reflecting optimal urban dimensions: Inhab./Km^2 (Y_1/Z_2)—whose values are presented in the next section—and, therefore, consider the average cost function in terms of the number of inhabitants as already defined in (7). First, we know from the estimated elasticity ε_{C,Y_1} = α_1

< 1 that increasing the number of inhabitants reduces average cost—illustrated by a movement along the downward sloping average cost function. Second, we need to establish the effect that a change in the density variable Z_2 has on the average cost function, which is determined by the sign of $\partial \mathrm{AC}_{Y_1} / \partial Z_2$. Since $\partial \mathrm{AC}_{Y_1} / \partial Z_2 = \partial (C / Y_1) / \partial Z_2 = 1/Y_1 Z_2 \cdot [\exp(\ln C) \cdot \partial \ln C / \partial \ln Z_2]$, where $\exp(\ln C) = 1$ and $\partial \ln C / \partial \ln Z_2 = \delta_2$ once the expression is evaluated at the sample mean. Therefore, since both Y_1 and Z_2 have positive values we conclude that the sign of $\partial \mathrm{AC}_{Y_1} / \partial Z_2$ depends on the sign of $\partial \ln C / \partial \ln Z_2$, and given our parameter estimate of δ_2 presented in Table 3, $\partial \mathrm{AC}_{Y_1} / \partial Z_2 > 0$. Thereby, *reducing* the urban area results in a downward shift of the average cost—the partial derivative is consistently interpreted, once again, with reversed sign. The same average cost behavior is observed if we focus on the effect of changes in the sprawled pattern of the jurisdiction represented by the number of clusters Z_1, since reducing it also brings a downward shift in the average costs function, i.e., $\partial \mathrm{AC}_{Y_1} / \partial Z_1 > 0$. Moreover, comparable results would be obtained if average costs were defined in terms of the number of dwellings: $\partial \mathrm{AC}_{Y_2} / \partial Z_1 > 0$ and $\partial \mathrm{AC}_{Y_2} / \partial Z_2 > 0$.

We conclude from our results that the average cost of providing urban infrastructure in *per capita* or *per dwelling* terms reduces as the number of inhabitants and dwellings increase—as reflected by the scale economies, and that this reduction is reinforced if the density of provision within a jurisdiction is increased by reducing urban configurations associated to dispersed settlements, and by promoting their compactness—as signaled by the corresponding density economies. A relevant urban policy “smart growth” implication that can be learnt from comparing scale and density economies is that if public officials want to increase the allocative efficiency of the budget invested in basic urban infrastructure, they should not only be concerned with increasing the number of inhabitants and dwellings in a jurisdiction, but also take into account the magnitude and relative values of the density economies. In fact, relative cost savings due to sprawl reductions are not negligible. Therefore favoring urban patterns that exploit horizontal or spatial network economies, as well as vertical or costumer economies, can be even more important than trying to achieve the optimal municipal size in terms of the number of inhabitants and dwellings. This suggests that public officials should promote first higher population and housing densities by discouraging disperse and disconnected clusters (discontinuous developments as captured by Z_1) and encouraging high-rise building within the urban areas Z_2, rather than focusing only in supporting larger municipal sizes in terms of population and housing. These results are particularly in line with those recently obtained for service production in utility industries by Bottaso and Conti (2009: Table 2) with regards to the “spatial” elasticity related to the extension of the urban area in Km^2, which is larger than the elasticity associated with the amount of output delivered (M^3)—as presented in Table 2, meaning that *reducing* the extension of the urban area would reduce production costs to a larger extent than reducing output production itself.

Table 4. Scale and density economies by population density (Inhab./Km^2).

S1. Water supply

Size	Scale Economies, SCE	Density Economies, DNE	Weights in DNE	
			Z_1	Z_2
All obs. (nº = 1,793)	0.603 (0.041)*	-0.353 (0.029)*	0.431	0.569
Q1	0.776 (0.155)*	-0.140 (0.126)*	0.162	0.838
Q2	0.880 (0.390)*	-0.330 (0.387)*	0.457	0.543
Q3	0.992 (0.387)*	-0.652 (0.370)*	0.616	0.384

S2. Sewerage and cleansing of residual waters

Size	Scale Economies, SCE	Density Economies, DNE	Weights in DNE	
			Z_1	Z_2
All obs. (n = 1,139)	0.493 (0.044)*	-0.478 (0.027)*	0.871	0.129
Q1 y Q2	0.332 (0.082)*	-0.624 (0.070)*	0.926	0.074
Q3	0.763 (0.473)*	-0.281 (0.454)*	0.742	0.258

S3. Paving and lighting

Size	Scale Economies, SCE	Density Economies, DNE	Weights in DNE	
			Z_1	Z_2
All obs. (nº =1,311)	0.188 (0.078)*	-0.684 (0.053)*	0.654	0.346
Q1 y Q2	0.050 (0.308)*	-0.892 (0.290)*	0.770	0.229
Q3	0.415 (0.253)*	-0.507 (0.225)*	0.446	0.554

Notes: Standard errors in parenthesis (see Bohrnstedt y Goldberger (1969) for calculation details).
* Significant at the 5% level.
Source: Own elaboration.

5.3. Optimal city dimension in terms of population density

The discussion above suggests that both scale and density economies are important sources for cost reduction when providing urban infrastructure. In this section we combine both concepts so as to analytically obtain an optimal urban dimension defined in terms of population density, which confidently represents the most accepted variable from an urban planning/land use perspective based on economic criteria, MFOM (2002). These values have been obtained by solving for the system of equations comprising (8) and (9). As presented in section 3 this system jointly determines the number of inhabitants and urban area that minimize average provision costs, allowing us to calculate the optimal population density corresponding to the ratio of both magnitudes. For all three sectors, these values are presented in Table 5, along with the density corresponding to the different tertiles in which the dataset has been previously divided. Results show that optimal population density ranges from 2,801.0 Inhab./Km^2 in the Paving and lighting sector (S3) and 4,429.7 Inhab./Km^2 in Sewerage and cleansing of residual waters (S2). These values situate in the upper part of the distributions of observed densities in all sectors, showing that in region of *Castilla y León* current population densities are well below these benchmarks. This is confirmed by the percentage of jurisdictions presenting population densities below these optimal values, that is around 90% in the first two sectors and 76% in the last sector. In fact average population density for all 2,238 surveyed urban areas is 349.8 Inhab./Km^2. It is then clear then that the existing urban areas in *Castilla y León* are on average noticeably smaller than the optimal size obtained when estimating our cost functions.

Table 5. Optimal population density when providing urban infrastructure (Inhab./Km^2).

Sector	Optimal Density	Q1	Q2	Q3	# cities below optimum density
S1. Water supply	3,098.4	1,566.4	2,232.5	5,175.8	1,612 (89.9%)
S2. Sewerage and cleansing of waters	4,429.7	2,445.4	3,340.4	5,097.2	1,038 (91.1%)
S3. Paving and lighting	2,801.0	1,943.9	2,545.6	8,503.2	995 (75.9%)

Source: Own elaboration.

We can now think about the implications of the results presented in Tables 4 and 5 and how to make use of them so as to rationalize infrastructure provision and provide guidelines for urban planning and fund allocation in infrastructure investments. From Table 4 we concluded that public officials could substantially reduce provision costs by promoting denser urban areas in terms of populations and housing (scale economies) while discouraging dispersed urban cluster settlements and extensive developments (density economies). Taken together, these two urban planning guidelines result in larger population densities, whose optimal values can be analytically determined as reported in Table 5. These values confirm that current population densities are well below the desired level, given rise to the existing economies of scale and density calculated in this study.

6. Conclusions

In this study we introduce new definitions of urban scale and density economies and their corresponding estimates when analyzing the cost of providing urban infrastructure. We adopt a standard but relatively unexploited approach where the target provision outputs are the number of inhabitants and dwellings benefiting from the existing infrastructure (see Eberts and McMillen, 1999), and quantify cost elasticities associated to population and housing increases, resulting in larger jurisdictions (scale economies), and as well as to urban sprawl reductions, including the reduction in the number of clusters and the urban area (density economies). In doing so we adopt a cost minimizing behavior on the part of public officials, which is modeled by way of a flexible translog cost function system. We illustrate our proposed methodology for the case of the most important sectors in terms of investment levels: Water supply, Sewerage and cleansing of residual waters, and Paving and lighting, and illustrate them using data from the Spanish region of Castilla y León.

Our main findings show that relevant scale and density economies exist, and that the cost savings associated to the latter are not negligible. Particularly, those coming from urban dispersion reductions associated with a decreasing number of clusters—i.e., horizontal or spatial density economies reflecting network length savings *between* clusters—normally neglected in previous studies, are even more important than those associated to density increases *within* clusters by reducing the extension of urban areas (Km^2), i.e., vertical network economies. Moreover, in the sectors of Water supply and Sewerage and cleansing of residual waters density economies match the magnitudes corresponding to scale economies deriving from larger city sizes in terms of population and housing, showing their importance as sources of cost allocative efficiency.

Taking advantage of the existing scale and density economies would result in urban areas with higher population and housing densities than those currently observed. This can be easy illustrated with some statistics describing the dispersed pattern of the urban areas in Castilla y León. In this region there are 2,238 municipalities with 5,800 population clusters, resulting in an average of 2.6 clusters per municipality. Additionally the average extension of the urban area per population cluster is 0.13 Km^2, a rather low figure that is half the size of the urban area extension that is observed in municipalites without any clusters beyond the main settlement. These values clearly show the potential savings that can be obtained in infrastructure provision costs if the dispersed and extensive pattern of urban settlements within the existing jurisdictions were reduced. Depending on the particular sector, the values minimizing average provision cost confirm that optimal densities situate around 3.500 Inhab./km^2, which is about ten times higher than the observed average population density in the municipalities of Castilla y León, and matches prescribed densities in planning guidelines for urban areas. For example the Spanish *Ministerio de Fomento* responsible for urban planning, construction and infrastructure investment recommends that population settlements should range between 3,333 and 5,000 inhab./Km^2, MFOM (2000).

Although it is not possible to perform a direct comparison of our results with those obtained in the literature reviewed in the second section, as they deal with the production of services in utility industries and neglect the supporting urban infrastructure, it is clear that both sets of results are complementary. As in these studies focused on the production of services based on network infrastructures, for the provision of the supporting physical infrastructure we find significant scale and density economies, being the latter as relevant as the former due to of urban sprawl diseconomies (horizontal or spatial network effects associated with disperse population settlements in clusters) or surface area economies (vertical or customer network effects associated with city size in terms of properties, consumers or dwellings). The existence of these latent scale and density economies results in unrealized cost efficiency gains, and this inefficient outcome is due to suboptimal city sizes in terms of population density. Moreover, both types of economies are complementary when promoting lower provision costs, as shown when jointly considering the effect of *increasing* the number of inhabitants or dwellings, along with a simultaneous *reduction* in the number of clusters or the urban area within a given jurisdiction.

If the main policy implication of the studies focused on the production of services is that in order to reap the benefits of the existing cost economies, mergers and acquisitions increasing average firm sizes should be encouraged, our main result concerning urban development guidelines calls for parallel prescriptions. Public officials designing new urban developments and allocating investment funds devoted to the construction of infrastructure should promote larger and denser city sizes in terms of population and housing and prevent discontinuous developments, thereby realizing latent scale and density economies. Particularly, the fact that density economies are as relevant as their scale counterparts in some sectors suggests that the first step to rationalize urban growth and funds allocation should be preventing isolated developments that would increase the number of clusters within the existing jurisdictions, while favoring an increase the number of inhabitants and dwellings per square kilometer of urban area. As a result, “smart growth” urban planning policies should strongly discourage urban sprawl in the form of disperse and disconnected (skipped-over) population clusters, while promoting higher population and housing densities.

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