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Diverse cities or the systematic paradox of Urban Scaling Laws

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ABSTRACT

Scaling laws are powerful summaries of the variations of urban attributes with city size. However, the validity of their universal meaning for cities is hampered by the observation that different scaling regimes can be encountered for the same territory, time and attribute, depending on the criteria used to delineate cities. The aim of this paper is to present new insights concerning this variation, coupled with a sensitivity analysis of urban scaling in France, for several socio-economic and infrastructural attributes from data collected exhaustively at the local level. The sensitivity analysis considers different aggregations of local units for which data are given by the Population Census. We produce a large variety of definitions of cities (approximatively 5000) by aggregating local Census units corresponding to the systematic combination of three definitional criteria: density, commuting flows and population cutoffs. We then measure the magnitude of scaling estimations and their sensitivity to city definitions for several urban indicators, showing for example that simple population cutoffs impact dramatically on the results obtained for a given system and attribute. Variations are interpreted with respect to the meaning of the attributes (socio-economic descriptors as well as infrastructure) and the urban definitions used (understood as the combination of the three criteria). Because of the Modifiable Areal Unit Problem (MAUP) and of the heterogeneous morphologies and social landscapes in the cities' internal space, scaling estimations are subject to large variations, distorting many of the conclusions on which generative models are based. We conclude that examining scaling variations might be an opportunity to understand better the inner composition of cities with regard to their size, i.e. to link the scales of the city-system with the system of cities.

1. Introduction

At the age of big data, working with decennial Census data may seem out-dated. Shouldn't we use the profusion of new data sources and the capacity of computation newly available to produce new research and solve new questions? This debate is on-going, unresolved and potentially irrelevant. First because there might be complementary research to be done at the intersection of small and big data Batty (2015). Second, because today's (Census) small data are also yesterday's big data[1] and so there might be no radical shift in paradigm involved Barnes and Wilson (2014), Taylor, Schroeder, and Meyer (2014). Third, because one could very well admit that cutting-edge research is not a direct function of cutting-edge data, and that the quality of the questions asked and the adequacy of data used to answer them is the important subject – so that Census data can still be the relevant data for some contemporary research design. Our final point is that, in the same way that urban data are big with interactions Batty (2015), Census data can become “big” for combinatorial reasons.

Indeed, because Census data systems – and the geographies at which the information is collected – are a legacy of the past and because they take a long time to adapt to the moving socioeconomic geographies, there are few cases in which Census data are readily usable for spatial analysis at the scale of interest. Aggregations of local areal units are the rule rather than the exception, especially in the field of urban studies. However, in order to preserve the social, economic, and spatial patterns of the data and match meaningful definitions of cities, no single aggregation is optimal, and we propose as an alternative to build systematic aggregations for which we explore the outcomes with respect to the combination of definitional parameter values. The choice of one of the multiple possible aggregations determines the spatial extents of the cities considered, the measurement of their population size, and most probably the way we observe the urban system's response to size West (2014). The systemic property related to size is known as scaling and is used to study the quantitative variation of cities' characteristics (for instance the number of people of a certain economic category, or the quantity of a certain infrastructure) with respect to their size (population for example). The exhaustivity of Census data clearly is a

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[1] “The Population census was in fact one of the only systematic catalogues of data produced on a continuing basis until national accounts and related economic data began to be collected seriously and routinely in the 1920s (Bos, 2011). But right from the start, data were always big with respect to the available means by which it could be manipulated” [Batty (2015), p. 2]

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strong advantage for relating one variable to another, and the combinatorial increase of possible representations of the system does challenge computing, analytic and visualisation capacities.

Urban scaling laws have fostered urban researchers' interest over the last decade because they provide powerful summaries of the variations of urban attributes with city size.[2] Indeed, when considering the variation of an absolute urban quantity Y against total population P in a city i, there is almost always a covariation between the two Shalizi (2001), frequently in the mathematical form of a power law

$$Y_i = a * P_i^{\beta}$$

where a represents a time dependent normalisation constant, and β the scaling exponent under enquiry. Superlinear relationships (i.e.: $\beta > 1$) indicate positive returns to scale, i.e. larger amounts of Y per capita in larger cities; whereas sublinearity ($\beta < 1$) is associated with economies of scale, i.e. smaller amounts of Y per capita in larger cities. Linear scaling ($\beta \approx 1$) means that the quantity per capita is constant across city size. Scaling exponents β estimated from empirical data have been interpreted as static or evolutionary properties, respectively by Bettencourt, Lobo, and Strumsky (2007) and Pumain, Paulus, Vacchiani-Marcuzzo, and Lobo (2006). Bettencourt (2012) developed models of network interactions predicting an exponent of 5/6 for infrastructural variables and of 7/6 for socioeconomic variables. However, even though most estimations lay in a range commensurable with these values, they are subject to variations, as attested by the meta-analysis of estimates for $CO2$ emissions by Rybski et al. (2013) or the sensitivity analysis of a large pool of variables with city definitions by Arcaute et al. (2015). These two studies question the validity of a universal interpretation.

For example, despite the existence of theoretical models to predict the value of urban scaling from local interactions Bettencourt (2012), Lobo, Bettencourt, Strumsky, and West (2013), Ortman, Cabaniss, Sturm, and Bettencourt (2014), an easy way to argue against the universality of scaling exponent values is to look at their variation with city definition Fragkias, Lobo, Strumsky, and Seto (2013), Rybski et al. (2013), Arcaute et al. (2015). For instance, in France, there are two definitions of cities defined by the statistical office INSEE (cf. Table 2 and Fig. A1 in Appendix A):

- Urban Units or *Unités Urbaines* (UU), which correspond to the aggregation of local units (*communes*) sharing a continuous built-up area of less than 200 m between buildings, and
- Metropolitan areas or *Aires Urbaines* (AU), defined as the aggregation of a central Urban Unit and all the *communes* with more than 40% of active commuters to the centre.

Comparing scaling results from those two official definitions, we find not only marginal discrepancies between expected values and estimated exponents, but evidence of different scaling regimes when we compare morphological and functional city delineations (Table 1) with similar goodness of fits (i.e. quite low for manufacturing jobs and relatively high for the other attributes). In one case, say employment in the manufacturing sector, the number of jobs grows more than proportionally with the population of density-defined Urban Units, whereas the number of such jobs per capita decreases with the size of functionally-defined Metropolitan Areas. The paradox obtained from the comparison of city definitions can question the very motivation for using urban scaling and its empirical analysis. However, even though

Table 1
Scaling exponents for two city definitions in France.

Urban Attribute	City Definition	β	CI* (95%)	R^2	N
Manufacturing	UU	1.175	[1.13; 1.22]	0.543	2226
	AU	0.849	[0.81; 0.89]	0.691	771
Vacant Dwellings	UU	1.051	[1.03; 1.07]	0.797	2233
	AU	0.902	[0.88; 0.92]	0.928	771
Basic Services	UU	1.086	[1.07; 1.10]	0.892	2233
	AU	0.956	[0.94; 0.97]	0.965	771
Education	UU	1.215	[1.19; 1.24]	0.778	2230
	AU	0.981	[0.96; 1.00]	0.922	771

Source of the data: French Census, 2011. UU: density-based Urban Units. AU: functionally defined Urban Areas. *N*: Number of cities in the regression. *CI: confidence interval.

there seems to be no point in trying to fit absolute scaling parameters, the variations in scaling estimation are of theoretical interest because of what they say about the relation between intra-urban spaces (micro-scale), city definitions (meso-scale) and urban scaling (macro-scale).

Indeed, we suggest that the variations in scaling estimations between dense cities definitions and metropolitan areas are not a failure of a robustness test, but the expression of the different nature of urban spaces implied by the two definitions: the former describes the population within a dense environment of social interactions and infrastructural elements; the latter refers to a much larger functional space of economic interactions. Both can be called cities but they are not equivalent. For example, if one was interested in modelling the development of industry locations, one would consider different strategies in the central and suburban parts of the city, because of differentiated opportunities to locate certain types of buildings, because of housing rent gradients or because of the different urban atmospheres available in the different parts of the city. Therefore, where the boundary is set to observe cities with respect to scaling is of crucial importance, because it defines the level of morphological and socioeconomic diversity included in the concept of city under enquiry. The boundary concept applies to the spatial extent as well as to the minimum population required to call a population aggregate urban: there might be differences of nature (and quality) between small towns and large metropolises with respect to certain indicators.

An additional motivation to explore multiple city definitions comes from the fact that official definitions rely on the choice of unique thresholds (e.g. distance between buildings, the percentage of commuters or a minimum population). Those have proven useful to describe urbanisation over time, but their precise value contains a share of arbitrariness that we want to evaluate in order to strengthen or question conclusions based on these definitions. Finally, varying definitional criteria will eventually produce a picture of scaling estimates that lies in between the two official definitions for France and this will help us understand better the discrepancies observed empirically, as well as to compare studies performed on a large number of cities with studies that look at the upper part of the urban hierarchy only.

In this paper, we analyse the observed transitions from one scaling regime to another when varying city delineations. We do so by generating a whole range of city delineations; in other words, by aggregating local Census units in multiple ways following the systematic variation of definitional parameter values (Section 2). We analyse the variation of urban scaling estimates with respect to the parameter values used to delineate such cities, and argue that variations are not random (Section 3.1). Instead, they can inform our knowledge of cities and of the different areas they are composed of. We suggest a way to describe these discrepancies and provide potential explanations (Section 3.2). Section 4 concludes by stressing the importance of using urban scaling along with complementary explanations of the genesis of city systems (regional integration, path-dependent processes, etc.) to better understand the socioeconomic and morphological complexity of cities and systems of cities.

[2] Although some authors focus on intra-urban scaling (by investigating the fractal distribution of transportation networks or the scaling of the height of buildings within a city Longley and Mesev (2002), Kim, Benguigui, and Marinov (2003), Carvalho and Penn (2004), Batty et al. (2008), Niedzielski, Horner, and Xiao (2013), Masucci et al. (2015), our interest here lies at the inter-urban scale only. We only consider the variation of an aggregated quantity with city population at the scale of a country or region.