An evolutionary theory for the spatial dynamics of urban systems worldwide

J. Raimbault[1,2,3*], E. Denis[3] and D.Pumain[3]
j.raimbault@ucl.ac.uk

[1]CASA, UCL
[2]UPS CNRS 3611 Complex Systems Institute Paris
[3]UMR CNRS 8504 Géographie-cités

ECTQG 2019
Co-evolution of cities and networks
September 8th 2019

How to explain urban growth?

- Apparent direct **causes** : intentions/actions from urban actors (policies, locational strategies from firms, residential migrations . . .)
- But **statistical observation** (thousands of cities, over centuries) : each city has a probability of growing similar to other cities belonging to the same territorial system

$\rightarrow$ "distributed growth" on the long run with many local and temporal fluctuations

Gibrat's model

"Proportional" growth = growth rates are equiprobable for any city size and not correlated with previous rate

Good fit $\rightarrow$ double explanatory gain:

- Persistancy of urban spatial patterns and hierarchies
- The statistical shape of urban sizes distribution (Zipf's law or lognormal $\simeq$ H. Simon $\neq$ P. Krugman) as generated from growth process

[Gibrat, 1931] [Robson, 1973] [Pumain, 1982]

Gibrat's model

A satisfying proxy but some empirical contradiction

1. The observed distributions of city sizes (actually: settlement sizes including hamlets, villages, towns and SMAs) are lognormal (evidence from [Robson, 1973], [Pumain, 1982], [Eeckhout, 2004], [Decker et al., 2007])
2. Gibrat's growth model leads to a lognormal distribution of city sizes
3. but Gibrat's growth model hypothesis are rejected (correlation between growth rates and city size, correlation between successive growth rates)

Evolutionary urban theory

Innovation diffusion and spatial integration of urban systems

- In new urban systems, as in USA, there is a spatial filling process that occur through waves of urban growth (urban Frontier) corresponding to the diffusion of economic cycles
- In mature urban systems, like in France, the innovations diffusion reaches cities that are not spatially regularly arranged but already experienced other growth periods according to distinct cycles of urban specialisation

Evolutionary urban theory and scaling laws

Linking scaling laws to a geographical model of urban growth with spatial interaction and innovation cycles

- We suggest to replace a generic statistical model of growing independent entities (Gibrat's urban growth model) by a model of spatially and temporally interdependent entities (i.e. the geographical concept of "system of cities" or "settlement system")
- It reproduces the observations on differential scaling parameters for urban activities according to their age in innovation cycles [Favaro and Pumain, 2011]
- It also makes explicit the multilevel dynamics of interurban competition for capturing innovation, which may itself generate new innovation through interurban emulation, within an evolutionary perspective

Testing the evolutionary urban theory

How are stylized facts on systems of cities robust and general ?

$\rightarrow$ empirical study with the new Global Human Settlement layer dataset

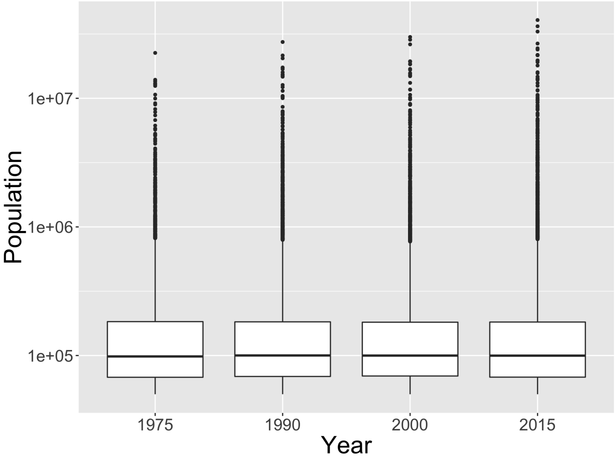
How can dynamical models of urban systems be applied in the context of the evolutionary urban theory ?

$\rightarrow$ test of six dynamical models, based on geographical interactions between cities but different dimensions, on different systems of cities and worlwide

A new source of data on global urbanization

- GHSL (Global Human Settlement Layer) : GEO Human Planet Initiative (European Commission)
- Built up area from satellite images 40 m + population data 250 m $\rightarrow$ 1 km2 grid
- 13 000 urban areas $>$ 50 000 inhab.
- Surface, population in 1975, 1990, 2000, 2015
- GDP, Green surfaces, Pollutants 1990-2015

Population distributions



Temporal stability of the shape of global population distribution

Urban systems summary

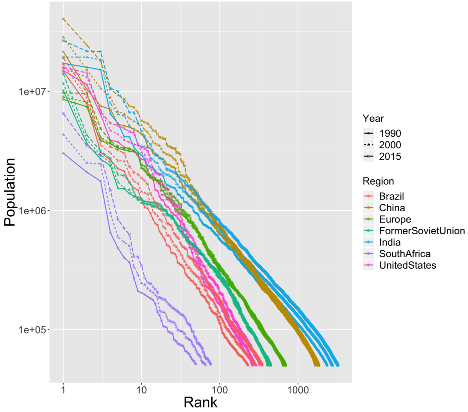
Summary statistics in 2015 for urban systems [Pumain et al., 2015]

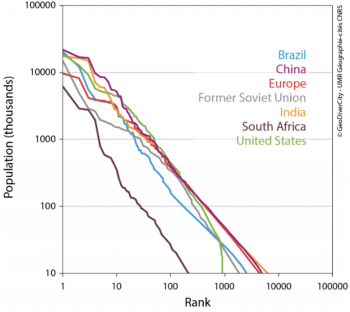
System	Population	Cities	Primacy	Rank-size	R2
Europe	188Mio	693	1.01	0.94 ± 0.0026	0.994
China	567.2Mio	1850	1.66	0.91 ± 0.0011	0.997
Brazil	111.7Mio	349	1.95	0.99 ± 0.0026	0.998
India	703.1Mio	3248	1.22	0.78 ± 0.0009	0.996
South Africa	25.3Mio	77	1.85	1.05 ± 0.020	0.974
US	153Mio	324	1.12	1.16 ± 0.0054	0.992
FSU	120.3Mio	450	3.27	0.92 ± 0.0062	0.979

Country	Number of cities*	Rank-size slope	Primacy index (P1/P2)	Number of macrocephalic cities	Total urban population (millions)
Brazil	2615	0.88	2	2	161
FSU	1929	1.10	3	0	173.5
India	5121	0.95	1.1	3	427
China	9294	0.80	1.3	0	481
South Africa	220	1.15	2	4	25
Europe	4413	0.96	1.2	2	291
United States	909	1.23	1.5	0	287

Urban systems hierarchy

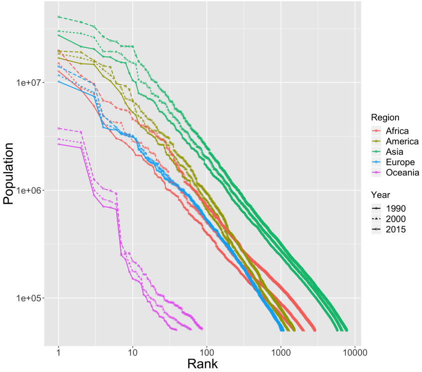
Reproducing results of [Pumain et al., 2015] for large urban systems

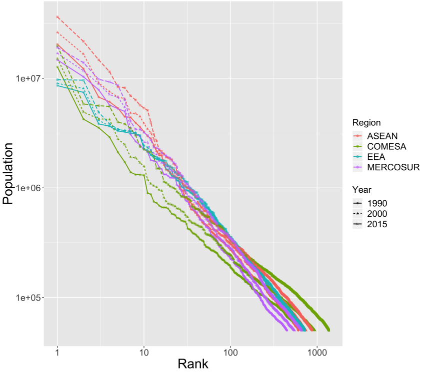




→ **Robustness of qualitative stylized facts to the database**

Rank-size by continents or trade areas





→ **Possibility to extend analysis to other consistent geographical ensembles**

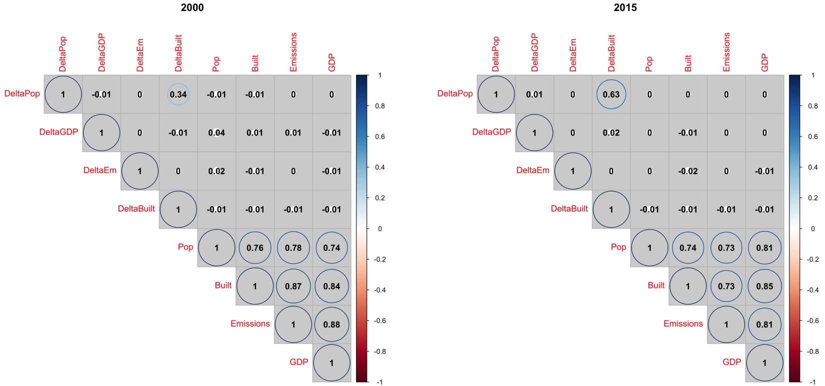
Rank-size by continents or trade areas

System	Population	Cities	Primacy	Rank-size	R2
Europe	288Mio	1067	1.45	0.93 ± 0.003	0.991
America	547Mio	1521	1.02	1.02 ± 0.002	0.996
Asia	2143Mio	7737	1.12	0.87 ± 0.0004	0.998
Africa	585Mio	2876	1.70	0.78 ± 0.0008	0.997
Oceania	19Mio	86	1.08	0.91 ± 0.027	0.926

System	Population	Cities	Primacy	Rank-size	R2
ASEAN	293Mio	874	1.67	0.92 ± 0.003	0.993
MERCOSUR	220Mio	657	1.37	1.00 ± 0.0016	0.998
COMESA	252Mio	1367	3.39	0.72 ± 0.0014	0.995
EEA	194Mio	720	1.01	0.94 ± 0.0026	0.994

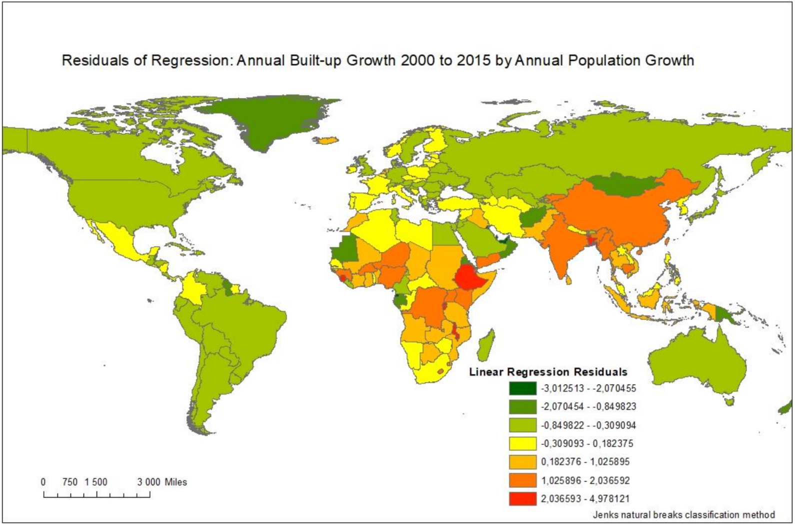
$\rightarrow$ similar qualitative patterns, but different thematic questions can be tackled

Correlations between urban indicators



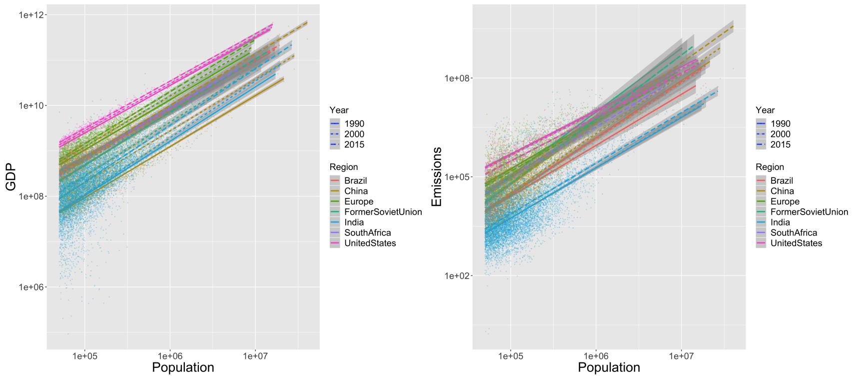
$\rightarrow$ no apparent deviation to Gibrat's law with this dataset (importance of definition of cities in scaling laws [Cottineau et al., 2017])

Linking urban growth and built-up area growth

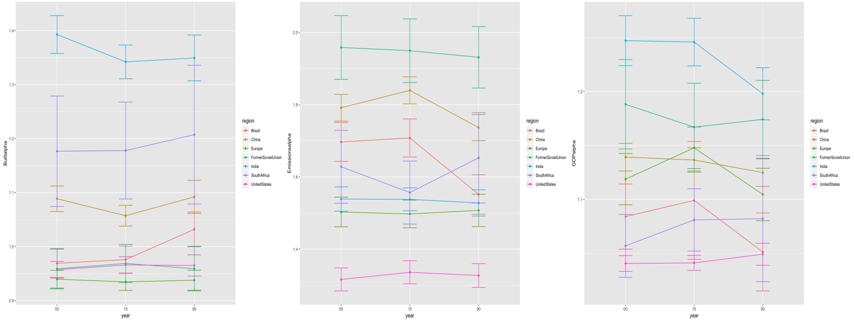


Geographical structure in the relation between population growth and built-up area growth

Scaling laws



Evolution of scaling exponents



All indicators are stable in their confidence range

Summary of scaling exponents

System	Built-up area	GDP	Emissions
Europe	0.93 ± 0.016 (0.83)	1.15 ± 0.019 (0.83)	1.50 ± 0.038 (0.69)
China	1.06 ± 0.019 (0.62)	1.14 ± 0.011 (0.85)	1.84 ± 0.037 (0.57)
Brazil	0.98 ± 0.025 (0.81)	1.10 ± 0.055 (0.54)	1.71 ± 0.053 (0.75)
India	1.34 ± 0.031 (0.36)	1.25 ± 0.022 (0.50)	1.54 ± 0.031 (0.42)
S. Africa	1.18 ± 0.090 (0.69)	1.08 ± 0.028 (0.95)	1.56 ± 0.087 (0.81)
US	0.97 ± 0.015 (0.92)	1.04 ± 0.069 (0.99)	1.34 ± 0.03 (0.84)
FSU	0.97 ± 0.035 (0.63)	1.17 ± 0.041 (0.65)	1.95 ± 0.088 (0.52)

$\rightarrow$ more general, more or less consistent study of scaling ("basic" indicators but on consistent and global geographical areas)

Scaling by continents or trade areas

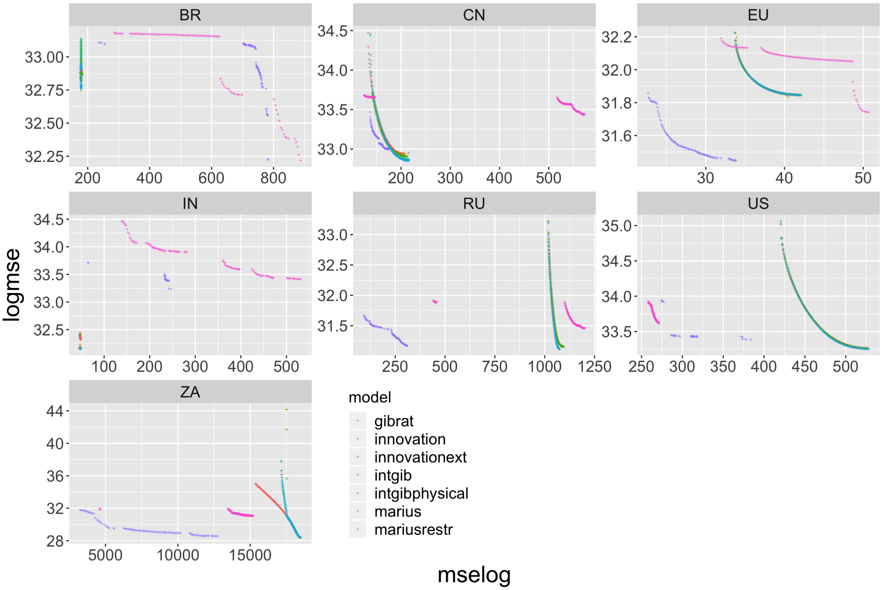
System	Built-up area	GDP	Emissions
Europe	0.93 ± 0.016 (0.76)	1.12 ± 0.024 (0.67)	1.58 ± 0.039 (0.61)
America	1.11 ± 0.030 (0.48)	1.23 ± 0.027 (0.57)	1.69 ± 0.041 (0.53)
Asia	1.32 ± 0.022 (0.32)	1.30 ± 0.016 (0.47)	1.78 ± 0.024 (0.42)
Africa	1.57 ± 0.049 (0.26)	1.45 ± 0.043 (0.29)	2.04 ± 0.054 (0.33)
Oceania	2.56 ± 0.44 (0.28)	1.95 ± 0.32 (0.33)	2.97 ± 0.44 (0.34)

System	Built-up area	GDP	Emissions
ASEAN	1.26 ± 0.049 (0.43)	1.23 ± 0.041 (0.51)	1.75 ± 0.067 (0.44)
MERCOSUR	1.04 ± 0.040 (0.50)	1.15 ± 0.035 (0.62)	1.72 ± 0.050 (0.64)
COMESA	1.65 ± 0.074 (0.26)	1.52 ± 0.072 (0.26)	1.93 ± 0.085 (0.28)
EEA	0.93 ± 0.015 (0.84)	1.15 ± 0.019 (0.83)	1.50 ± 0.037 (0.69)

Testing interaction-based dynamical models for urban growth

- The Favaro-Pumain model for the diffusion of innovation [Favaro and Pumain, 2011]
- The Marius model family based on economic exchanges [Cottineau, 2014]
- An interaction model including physical transportation networks [Raimbault, 2018]

Calibration of dynamical models on regional systems



Worldwide calibration of models

Discussion

Statistical predictibility of city growth and size on short time periods
Largest metropolises are not « monstruopolises »
Complexity $\rightarrow$ proactive adaptive strategies are necessary (imitation, or anticipation and risk), emulation (co-opetition)
Robustness, variation and sustainability of urban systems (neither norm nor optimum)

Conclusion

Reserve Slides

Description of models

Network interaction model

- Endogenous growth
- Interactions inducing growth through gravity potential
- Static physical network taken into account (geographical shortest path with topography)

Favaro-Pumain model

- Endogenous growth
- Innovation emerge and diffuse in cities
- Growth rates adapted according to utility of innovation and level of adaptation

Marius model

- Cities produce economic goods
- Economic exchanges are estimated according to gravity flows
- Populations grow depending on final economic balances

Models settings

$\rightarrow$ Work under Gibrat independence assumptions, i.e. $\mathrm{Cov}[P_i(t), P_j(t)] = 0$. If $\vec{P}(t+1) = \mathbf{R} \cdot \vec{P}(t)$ where $\mathbf{R}$ is also independent, then $\mathbb{E}\left[\vec{P}(t+1)\right] = \mathbb{E}[\mathbf{R}] \cdot \mathbb{E}\left[\vec{P}\right](t)$. Consider expectancies only (higher moments computable similarly)

$\rightarrow$ With $\vec{\mu}(t) = \mathbb{E}\left[\vec{P}(t)\right]$, we generalize this approach by taking $\vec{\mu}(t+1) = f(\vec{\mu}(t))$

Network model

Direct network interaction model [Raimbault, 2018]:

Let $\vec{\mu}(t) = \mathbb{E}\left[\vec{P}(t)\right]$ cities population and (d_{ij}) distance matrix

Model specified by

$$f(\vec{\mu}) = r_0 \cdot \mathbf{Id} \cdot \vec{\mu} + \mathbf{G} \cdot \mathbf{1} + \mathbf{N}$$

with

- $G_{ij} = w_G \cdot \frac{V_{ij}}{<V_{ij}>}$ and $V_{ij} = \left(\frac{\mu_i \mu_j}{\sum \mu_k{}^2}\right)^{\gamma_G} \exp\left(-d_{ij}/d_G\right)$
- $N_i = w_N \cdot \sum_{kl} \left(\frac{\mu_k \mu_l}{\sum \mu}\right)^{\gamma_N} \exp\left(-d_{kl,i}\right)/d_N$ where $d_{kl,i}$ is distance to shortest path between k, l computed with slope impedance $(Z = (1 + \alpha/\alpha_0)^{n_0}$ with $\alpha_0 \simeq 3)$

Innovation diffusion

Favaro-Pumain model [Favaro and Pumain, 2011]:

1) Diffuse innovations according to

$$\delta_{c,i,t} = \frac{\sum_j p_{c,j,t-1}^{s_c} \exp\left(-\lambda_s d_{ij}\right)}{\sum_c \sum_j p_{c,j,t-1}^{s_c} \exp\left(-\lambda_s d_{ij}\right)}$$

2) Update population with G_{ij} (see network model) such that

$$V_{ij} = \frac{p_i p_j}{\left(\sum_k p_k\right)^2} \exp\left(-\lambda_m d_{ij} \prod_c \delta_{c,i}^{\phi_c}\right)$$

with $\phi_c = \sum_i p_{i,c} / \sum_{i,c} p_{i,c}$

3) Introduce innovation with utility $s_{c+1} = g_0 \cdot s_c$ in a randomly chosen city with a hierarchy parameter α_I, if global adoption share ϕ_c is larger than a threshold θ_I. Initial utility s_0 is a parameter. New innovation has an initial penetration rate r_I in the city.

Economic exchanges

Marius model [?]:

Initial wealth as a power law of population (exponent α_W)

1) Update supply and demands as superlinear functions of population (exponents α_S, α_D)

2) Exchange goods according to a gravity potential of interaction (distance decay d_M), supplies and demands; update wealth accordingly

3) Update population such that population difference is a power law of wealth difference (economic multiplier e_M and exponent α_P)

Benchmarked models

1. Gibrat model: 1 param. r_0
2. Direct interaction model (geographical distance): 4 param. r_0, w_G, γ_G, d_G
3. Physical network interaction model (topographical distance: 4 param. r_0, w_G, γ_G, d_G
4. Innovation diffusion model (simplified): 4 param. $r_0, w_I, \lambda_s, \lambda_m$ (other parameters at default values from [Favaro and Pumain, 2011])
5. Innovation diffusion model (full): 9 param. $r_0, w_I, \lambda_s, \lambda_m, s_0, g_0, r_I, \alpha_I, \theta_I$
6. Restricted Marius model: 4 param. $e_M, \alpha_S, \alpha_D, d_M$
7. Marius model: 6 param. $e_M, \alpha_S, \alpha_D, d_M, \alpha_W, \alpha_P$

References I

Cottineau, C. (2014).
L'évolution des villes dans l'espace post-soviétique. Observation et modélisations.
PhD thesis.

Cottineau, C., Hatna, E., Arcaute, E., and Batty, M. (2017).
Diverse cities or the systematic paradox of urban scaling laws.
Computers, environment and urban systems, 63:80–94.

Decker, E. H., Kerkhoff, A. J., and Moses, M. E. (2007).
Global patterns of city size distributions and their fundamental drivers.
PLoS One, 2(9):e934.

Eeckhout, J. (2004).
Gibrat's law for (all) cities.
American Economic Review, 94(5):1429–1451.

References II

Favaro, J.-M. and Pumain, D. (2011).
Gibrat revisited: An urban growth model incorporating spatial interaction and innovation cycles.
Geographical Analysis, 43(3):261–286.

Gibrat, R. (1931).
Les inégalits économiques.
Sirey.

Pumain, D. (1982).
La dynamique des villes.
Economica.

Pumain, D., Swerts, E., Cottineau, C., Vacchiani-Marcuzzo, C., Ignazzi, C. A., Bretagnolle, A., Delisle, F., Cura, R., Lizzi, L., and Baffi, S. (2015).
Multilevel comparison of large urban systems.
Cybergeo: European Journal of Geography.

Raimbault, J. (2018).
Indirect evidence of network effects in a system of cities.
Environment and Planning B: Urban Analytics and City Science, page 2399808318774335.

Robson, B. (1973).
Urban growth: an approach, methuen & co.
Ltd., London.