A systematic comparison of interaction models for systems of cities

J. Raimbault[1,2,*]

juste.raimbault@polytechnique.edu

[1]Complex Systems Institute, Paris, UPS CNRS 3611 ISC-PIF
[2]UMR CNRS 8504 Géographie-cités

CCS 2018

Session Infrastructure, Planning and Environment

Thessaloniki

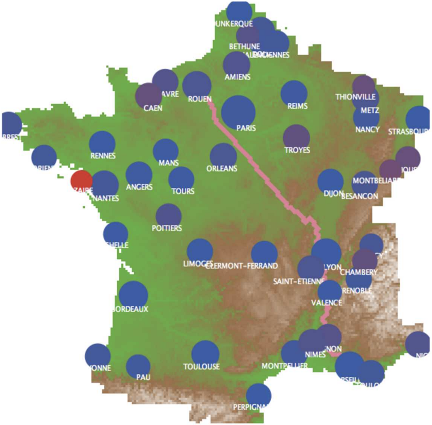
September 24th 2018

The long time memory of urban systems

Source: Wikipedia

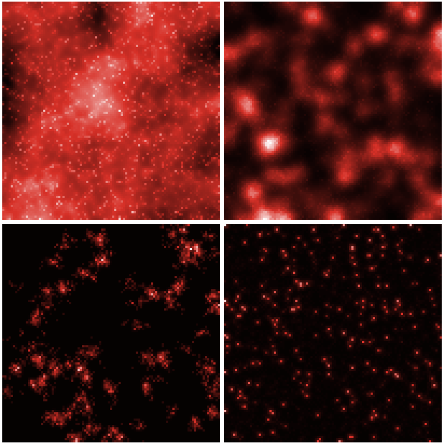
Modeling urban growth

Macroscopic urban system



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

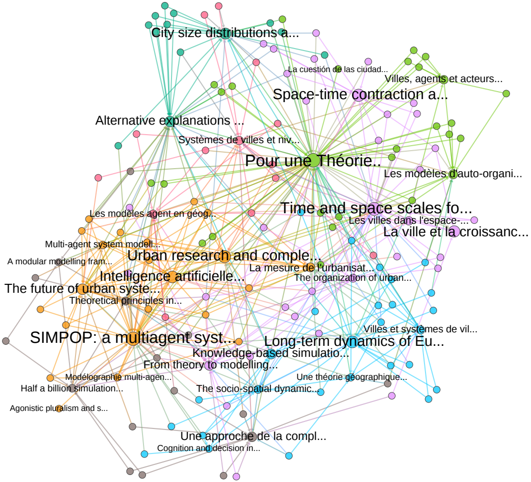
Mesoscopic territorial systems



Raimbault, J. (2018). Calibration of a density-based model of urban morphogenesis. PloS one, 13(9), e0203516.

An evolutionary urban theory

From [Pumain, 1997] to [Pumain, 2018]: systems of cities as co-evolutive systems in which interactions are crucial



[Raimbault, 2017] Citation network analysis of core publications in the evolutionary urban theory

Towards a systematic model comparison

→ several models in this context have been introduced, but never compared (e.g. in terms of explanative power)

→ multidimensionality of urban systems and the potential complementarity between very different processes

Research objective : *Benchmark interaction models for systems of cities developed in the frame of the evolutionary urban theory, on several comparable systems of cities.*

Urban systems interaction models

Comparison of three approaches based on the evolutionary urban theory [Pumain, 1997] capturing different dimensions of urban systems:

- 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, 2018b]

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

Datasets

Dataset

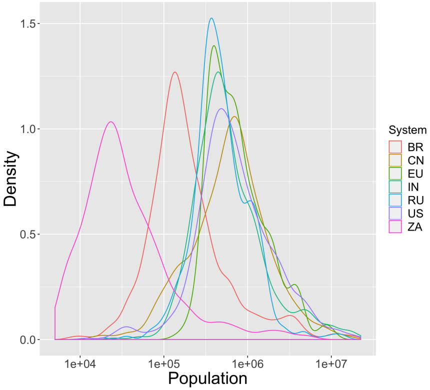
Harmonized dataset, explored in particular by [Pumain et al., 2015] (built in the context of Geodivercity ERC): Urban systems for Europe, United States, Brazil, China, India, South Africa, Russia, consistent and comparable between 1960 and 2010 each 10 years.

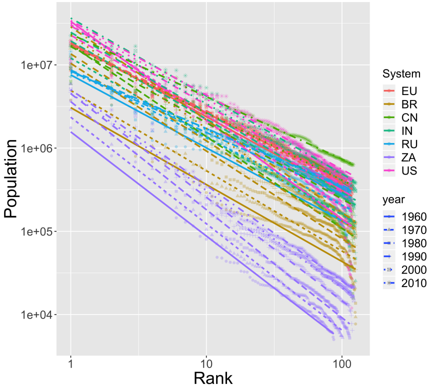
Data preprocessing

- Remove small cities and medium-sized cities ([Adam, 2006] for definition of medium-sized) for scalability of simulations
- Shortest paths matrices (direct and taking into account topography, using the EEA world DEM) computed a priori and cached (*no evolution of the network*)

Stylized facts

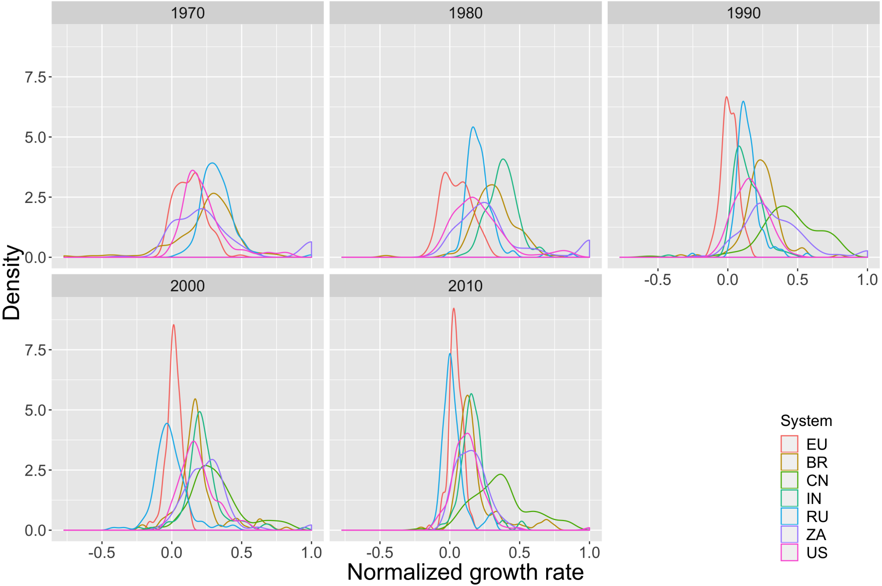
Population distributions mainly log-normal (75% with KS-test, all with AIC); consistent hierarchies in time.





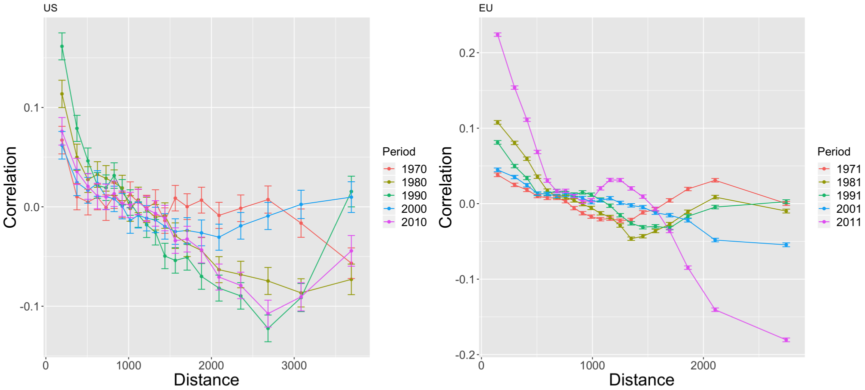
Stylized facts

Growth rates distributions evolve considerably in time



Stylized facts

Correlation as a function of distance: long-range correlations in several systems



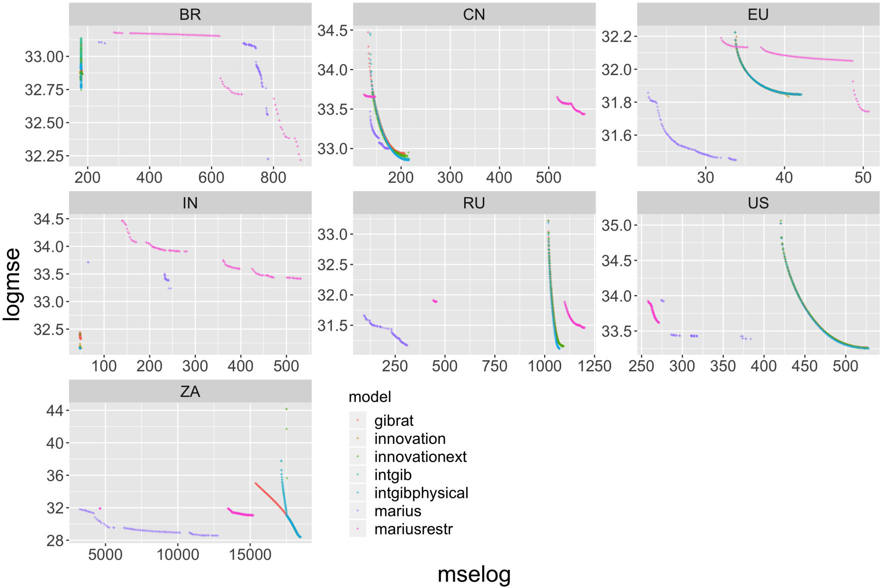
Model calibration

Bi-objective calibration of 7 models for 7 city systems $\rightarrow$ use of genetic algorithms on grid, made smooth with the OpenMOLE software `https://next.openmole.org/`

OpenMOLE: (i) embed any model as a black box; (ii) transparent access to main High Performance Computing environments; (iii) model exploration and calibration methods.

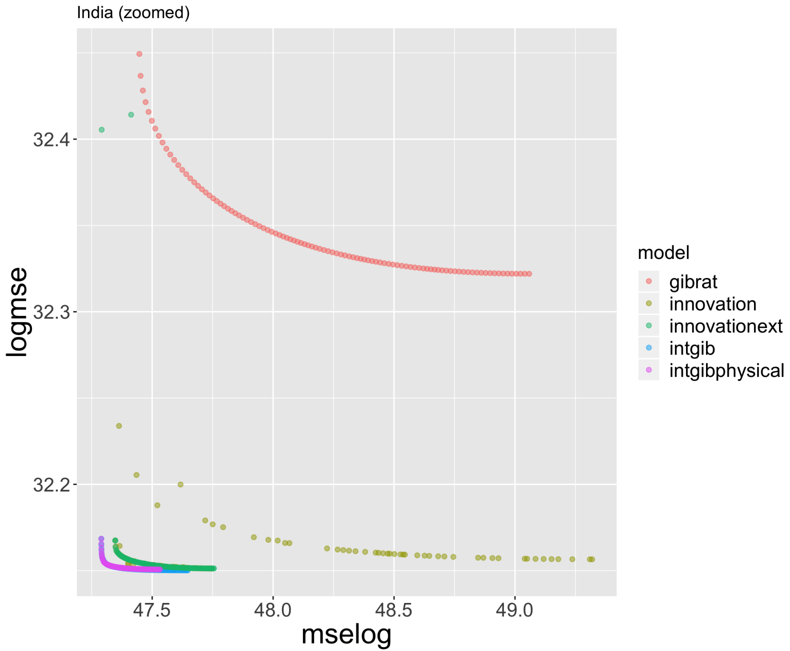
Come to the Satellite on Wednesday, and apply to the summer school ! (`https://exmodelo.org/`)

Comparison of models on all systems

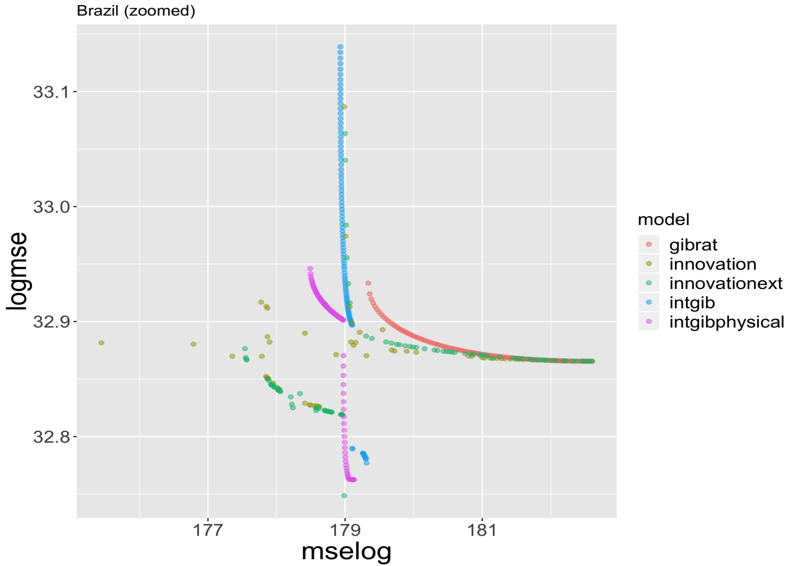


Systems driven by economic exchanges: EU, US, RU, ZA

Indian urban system: direct interactions

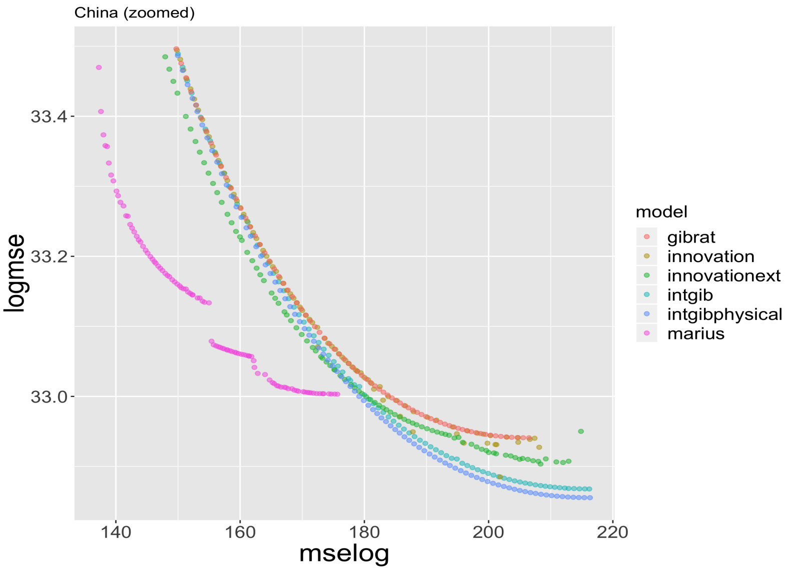


Brazilian urban system: multiple factors



Importance of topography; innovation processes mostly.

China: a tight competition



No clear best model: other processes in play ? (strong top-down planning)

Results: empirical AIC

Comparing Gibrat and Network model by correcting for the number of parameters [Raimbault, 2018b]: additional parameters actually improve the fit (but not always)

System	ΔAIC (log)	ΔBIC (log)	ΔAIC (mse)	ΔBIC (mse)
ZA	33.82658	29.40496	-838.07184	-842.49347
CN	20.67713	16.78273	13.40767	9.51327
BR	-263.27003	-267.71575	-407.55220	-411.99792
IN	-85.01949	-89.24206	-188.16703	-192.38960
RU	50.60535	46.24233	104.94806	100.58503

Discussion

Implications

→ Complementarity of economic, innovation and direct interaction processes

→ High dimensionality of urban systems

Developments

→ Still points on robustness to be investigated: influence of stochasticity, convergence of GA, saturation of parameters, number of cities.

→ Towards integrated models coupling these different components ?

→ Compare on synthetic systems of cities with appropriate indicators [Raimbault, 2018c].

→ Calibrate at the second order (correlations), non-stationary in time.

→ More elaborated method to compare models in a "fair" way (correcting for additional parameters, open question for models of simulation): model reduction ?

Conclusion

→ First step towards systematic benchmarks and multi-modeling. **Need for more systematic model exploration.**

→ Model integration and multi-scalarity ? **Need for more integrated models.**

→ Multiple perspectives on urban systems ? **Need for more interdisciplinarity.**

Related works

Raimbault, J. (2018). Indirect evidence of network effects in a system of cities. Environment and Planning B: Urban Analytics and City Science, 2399808318774335. `https://halshs.archives-ouvertes.fr/halshs-01788559`

Raimbault, J. (2018). Modeling the co-evolution of cities and networks. *Forthcoming in Handbook of cities and networks, Rozenblat C., Niel Z., eds.* arXiv:1804.09430.

Raimbault, J. (2018). Caractérisation et modélisation de la co-évolution des réseaux de transport et des territoires (Doctoral dissertation, Université Paris 7 Denis Diderot). `https://halshs.archives-ouvertes.fr/tel-01857741`

Open repository at `https://github.com/JusteRaimbault/UrbanGrowth`

Acknowledgments: thanks to the *EGI* for access to the infrastructure.

Reserve Slides

Models settings

→ Work under Gibrat independence assumptions, i.e. $\text{Cov}[P_i(t), P_j(t)] = 0$. 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)

→ 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, 2018b]:

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 [Chérel et al., 2015]:

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. $e_M, \alpha_S, \alpha_D, d_M, \alpha_W, \alpha_P$

Model calibration

Genetic algorithm NSGA2:

- Around 40000 generations (4e6 model runs)
- Population $\mu = 100$
- Convergence tested with hypervolume relative variation

References I

Adam, B. (2006).
Medium-sized cities in urban regions.
European Planning Studies, 14(4):547–555.

Chérel, G., Cottineau, C., and Reuillon, R. (2015).
Beyond corroboration: Strengthening model validation by looking for unexpected patterns.
PLoS ONE, 10(9):e0138212.

Cottineau, C. (2014).
L'évolution des villes dans l'espace post-soviétique. Observation et modélisations.
PhD thesis, Université Paris 1 Panthéon-Sorbonne.

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.

References II

Pumain, D. (1997).
Pour une théorie évolutive des villes.
Espace géographique, 26(2):119–134.

Pumain, D. (2018).
An evolutionary theory of urban systems.
In *International and Transnational Perspectives on Urban Systems*, pages 3–18. Springer.

Pumain, D., Swerts, E., Cottineau, C., Vacchiani-Marcuzzo, C., Ignazzi, 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. (2017).
An applied knowledge framework to study complex systems.
In *Complex Systems Design & Management*, pages 31–45.

References III

Raimbault, J. (2018a).
Calibration of a density-based model of urban morphogenesis.
PloS one, 13(9):e0203516.

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

Raimbault, J. (2018c).
Unveiling co-evolutionary patterns in systems of cities: a systematic exploration of the simpopnet model.
arXiv preprint arXiv:1809.00861.