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]

Testing the evolutionary urban theory

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

→ 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 ?

→ 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

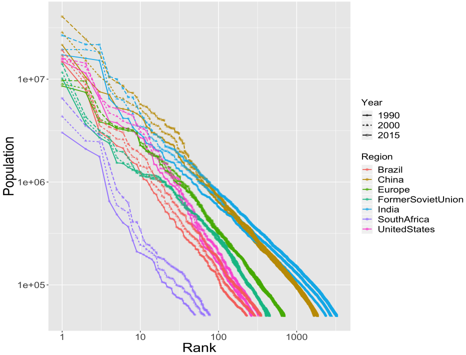
Urban systems summary

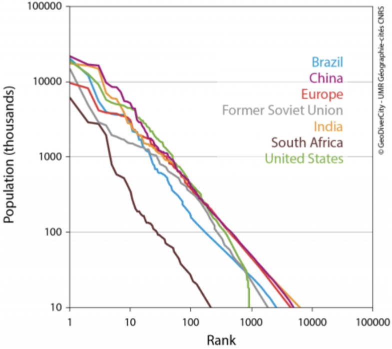
Summary statistics in 2015 for urban systems [Pumain et al., 2015]

System	Pop (M)	Pop geodiv.	Cities	Rank-size
Europe	188	291	693	0.94
China	567	481	1850	0.91
Brazil	112	161	349	0.99
India	703	427	3248	0.78
South Africa	25	25	77	1.05
US	153	324	287	1.16
FSU	120	174	450	0.92

Urban systems hierarchy

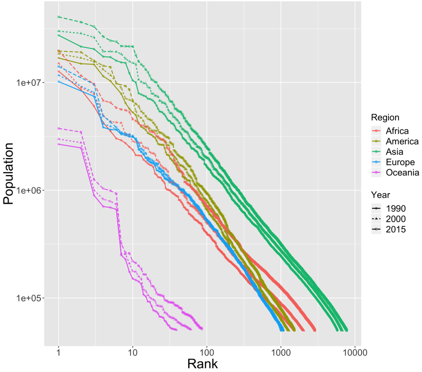
Reproducing results of [Pumain et al., 2015] for large urban systems

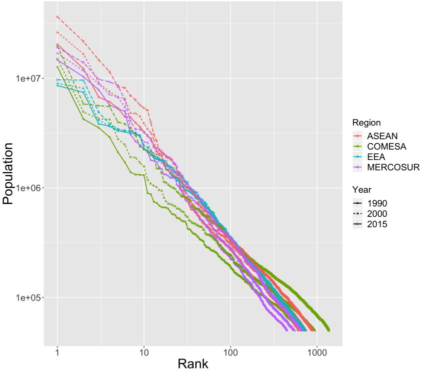




→ **Robustness of qualitative stylized facts to the database**

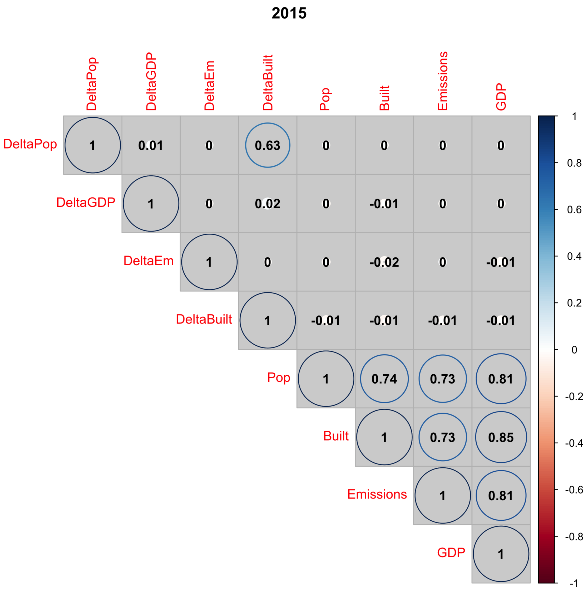
Rank-size by continents or trade areas



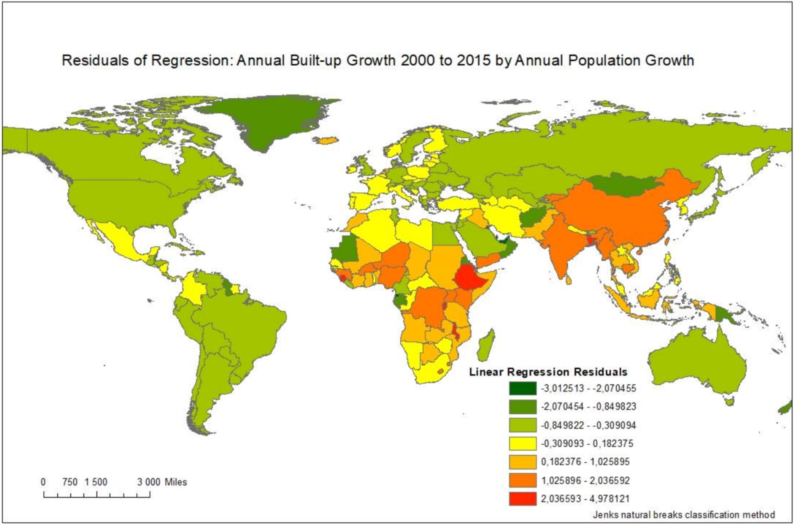


→ **Possibility to extend analysis to other consistent geographical ensembles**

Correlations between urban indicators

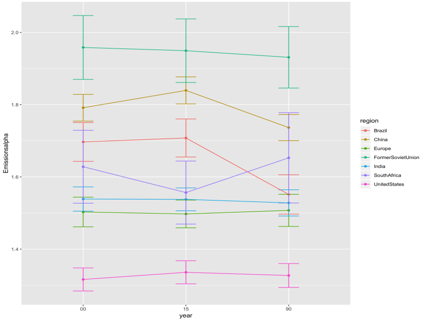


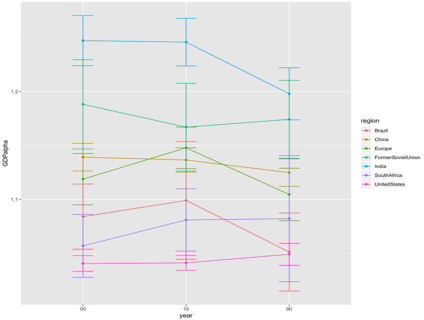
Linking urban growth and built-up area growth



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

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)

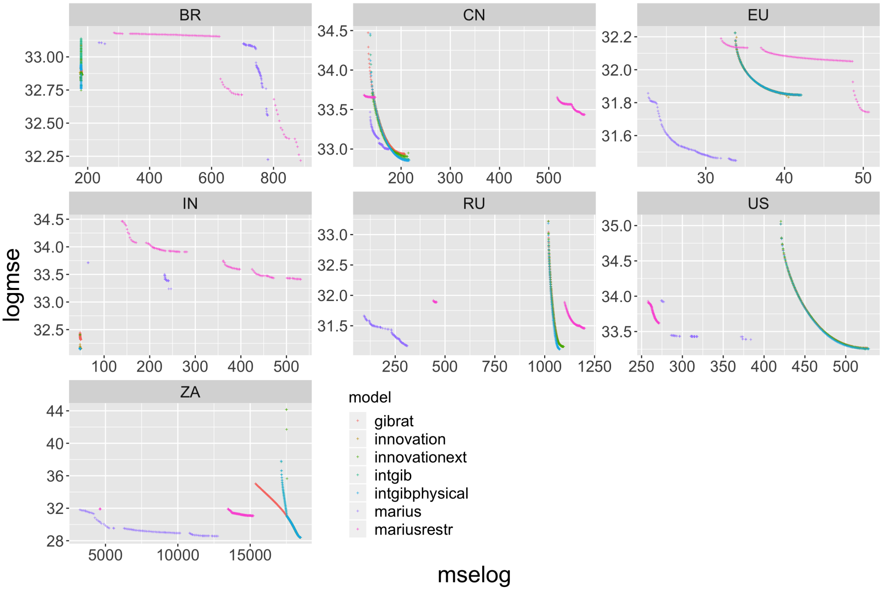
$\rightarrow$ more general, more or less consistent study of scaling ("basic" indicators but on consistent and global geographical areas)

Dynamical models of urban growth

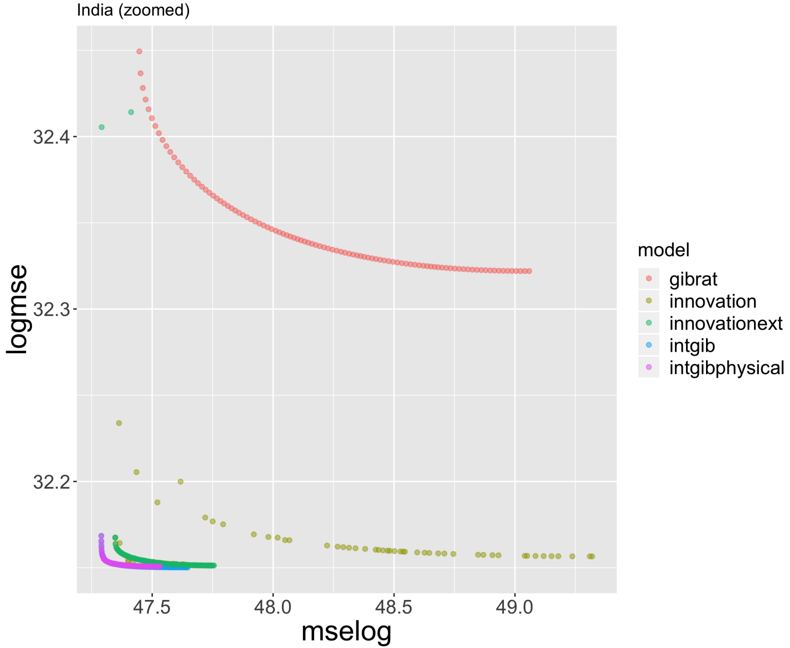
Testing interaction-based dynamical models for urban growth

- 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]

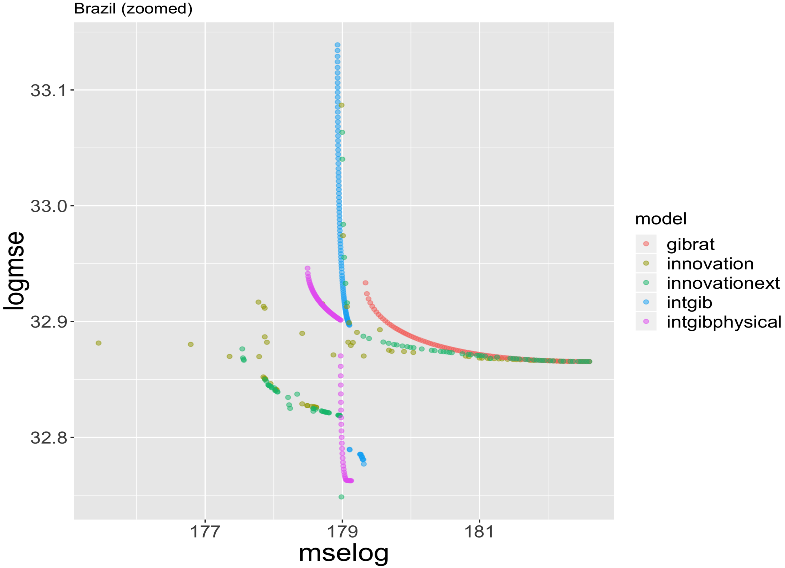
Calibration of dynamical models on regional systems



Indian urban system: direct interactions

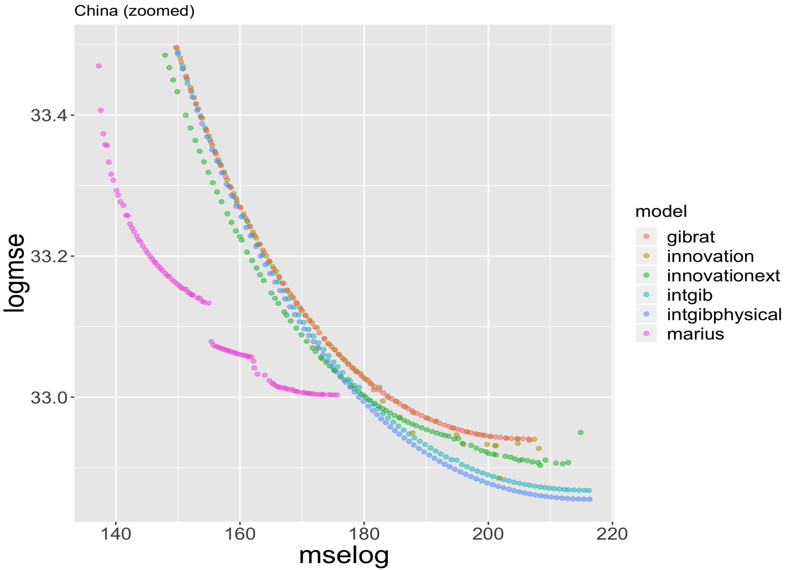


Brazilian urban system: multiple factors



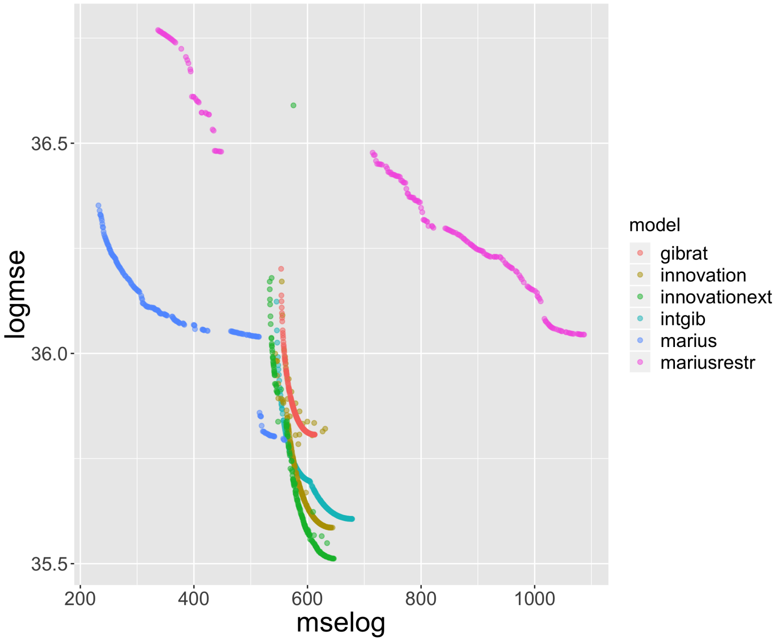
Importance of topography; innovation processes mostly.

China: similar models



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

Worldwide calibration of models



Discussion

Synthesis
→ robustness of stylized facts, and of theoretical constructions
→ complementarity of processes and models
→ importance of the historical/political/geographical context, path-dependency

Open questions:
→ linking urban scaling and dynamical models
→ endogenous consistent urban systems
→ multiscale models

Applications
→ Statistical predictability of city growth and size on short time periods
→ Largest metropolises are not "monstruopolises"
→ Transfer to practitioners: 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

→ Robustness of results regarding data sources, multiple models. **Need for more systematic model exploration and sensitivity analysis.**

→ Model complementarity. **Need for more integrated models.**

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

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

Acknowledgments: thanks to the *European Grid Infrastructure* for access to the infrastructure.

Reserve Slides

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

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)

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 $\alpha_0 \simeq 3)$

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

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