

A multi-scalar model for system of cities

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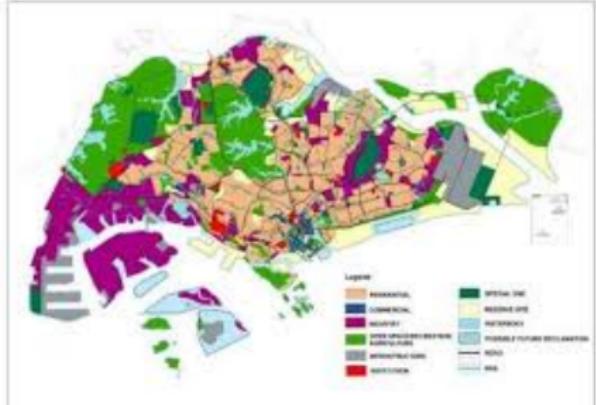
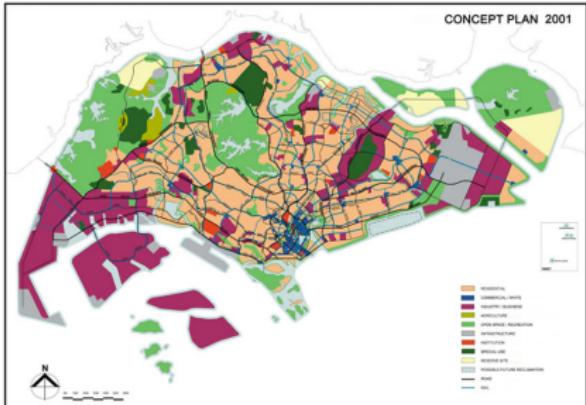
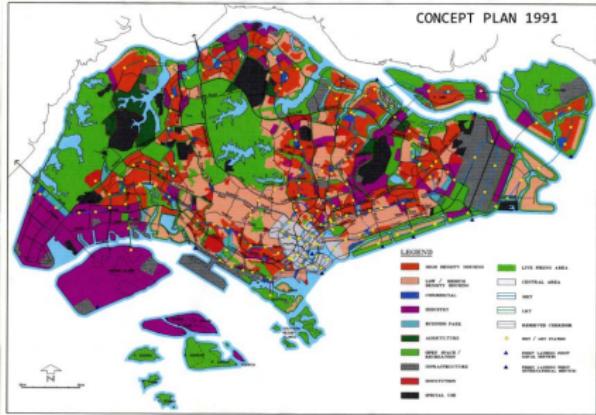
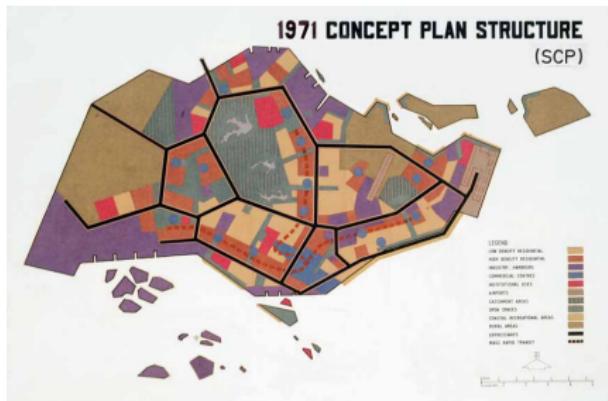
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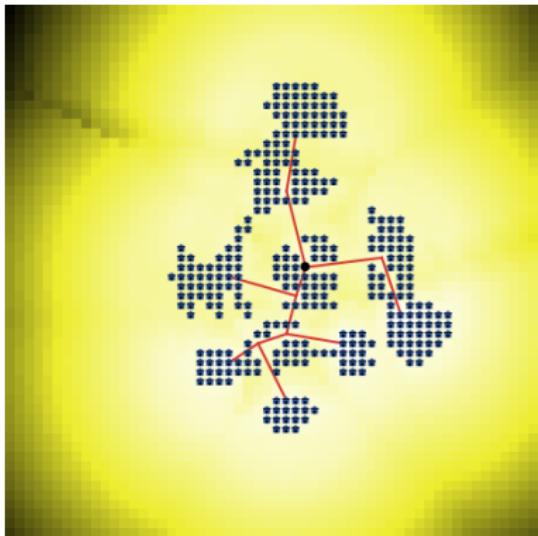
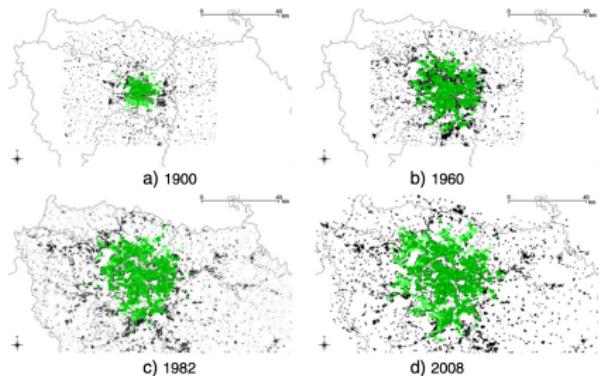
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Urban Complexity
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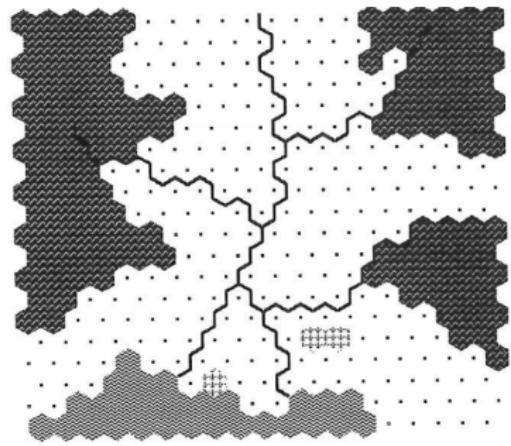
Urban growth across time and scales



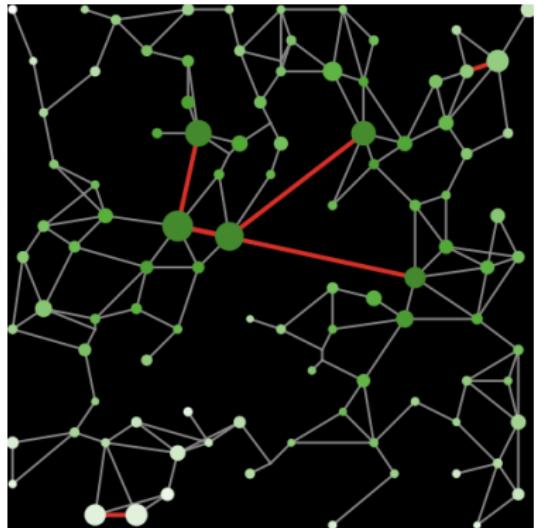


Land-use transport models
[Viguié et al., 2014]

Hybrid urban morphogenesis model
[Raimbault et al., 2014]

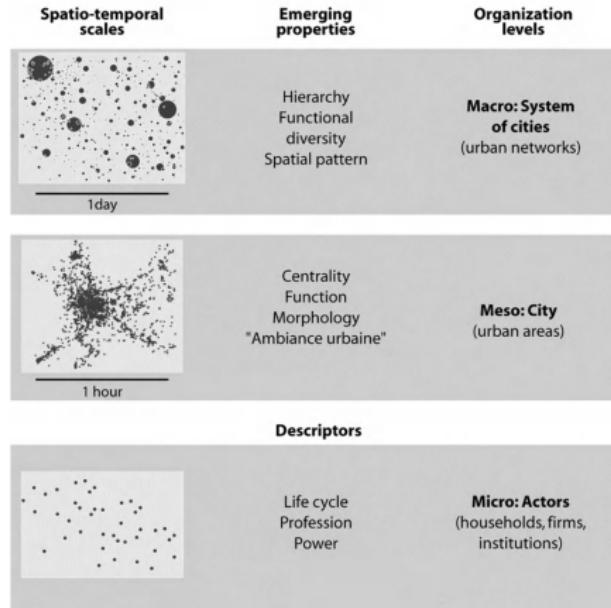


— River
▨ Sea
■ Mountain
▨▨▨ Swamp



The series of Simpop models: from Simpop1 [Sanders et al., 1997] to SimpopNet [Schmitt, 2014]

Towards multi-scalar models



Scales of urban systems of systems described by the evolutionary urban theory [Pumain, 2018]

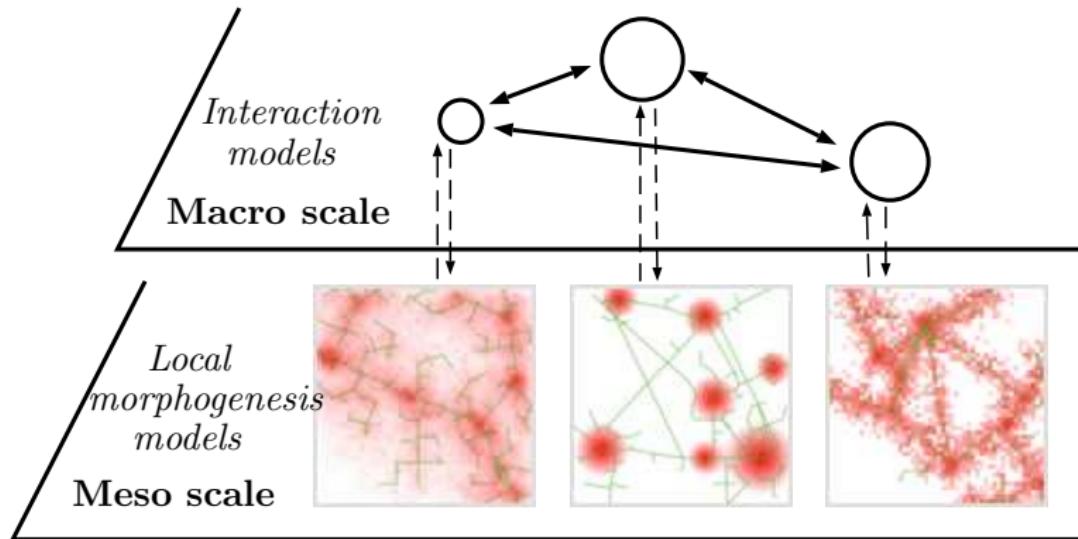
- Distinct processes and objects within each different scale
- Weak inter-scale coupling, such as progressive resolution for land-use model, does not consider emergence and autonomous scales
- An integrated model, or strongly coupled, would be *a new model extending the two coupled models in the sense that it includes them in some parameter settings or limit conditions*

Urban multi-scalar complexity must be captured by a strongly coupled model

- no strongly coupled multi-scalar model in the literature (few examples such as [Murcio et al., 2015] but without distinct ontologies)
- need to however consider “simple” models to be able to understand their behavior and extract knowledge from them

Research objective:

Investigate a strong coupling of a simple urban system interaction network at the macroscopic scale with an urban morphogenesis model at the mesoscopic scale



Model scales and objects:

- Cities as agents at the macroscopic scale
- Cities as population density grids at the mesoscopic scale

Processes:

- Interaction flows between cities and endogenous growth
- Urban sprawl and aggregation within urban areas
- **Downward feedback** Adaptation of urban form parameters to population and accessibility growth (“policy response”)
- **Upward feedback** Adaptation of city interaction range depending on internal performance (congested flows)

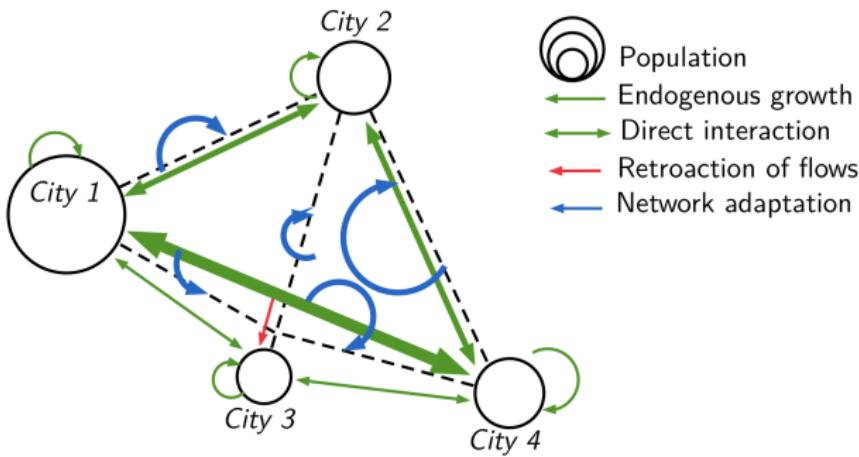
At each time step:

- 1 Macroscopic population are evolved with the interaction model
- 2 Population and accessibility differences modify the mesoscopic parameter of diffusion (sprawl) and aggregation (metropolization)
(downward feedback)
- 3 Urban forms are evolved for each city at the mesoscopic scale to match population increases
- 4 City interaction ranges are modified according to the internal performance of each city (congested flows) *(upward feedback)*

Macroscopic model

System of cities interaction model including network evolution; production of multiple co-evolution regimes and calibration for France.

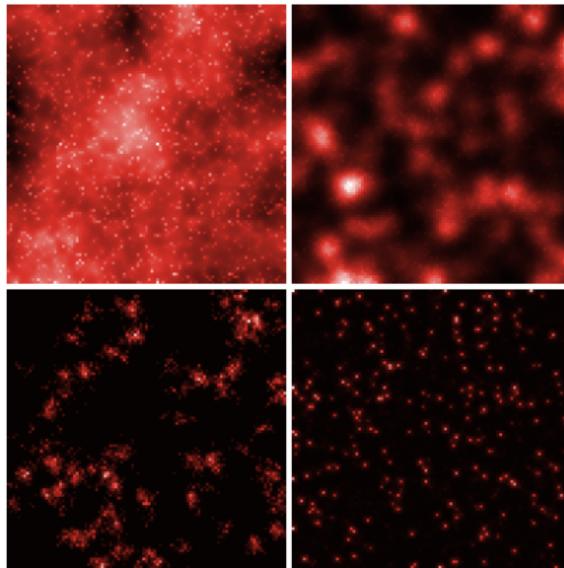
[Raimbault, 2018b]



Indicators at the macroscopic scale: distributions of population, accessibilities, centralities (summarized by average, hierarchy, entropy)

Mesoscopic model

Aggregation-diffusion model at the mesoscopic scale, covering most existing urban forms in Europe [Raimbault, 2018a]



Indicators at the mesoscopic scale: urban form captured by Moran index, average distance, hierarchy, entropy

Model parameters

Type	Parameter	Process	Range
Macro	$g_i = g_0$	Endogenous growth	[0; 0.05]
	$w_i = w_G$	Interactions weight	[0; 0.01]
	$\gamma_i = \gamma_G$	Interactions hierarchy	[0; 5]
	d_i	Interactions decay	[0; 1000]
Meso	α_i	Aggregation	[0; 5]
	β_i	Diffusion	[0; 0.1]
	t_m	Urban growth speed	{1; 20}
	n_d	Diffusion steps	[1; 5]
Multiscale	$\delta\alpha$	Metropolization (downward)	[-0.2; 0.2]
	$\delta\beta$	Sprawl (downward)	[-0.2; 0.2]
	δd	Efficiency (upward)	[-0.2; 0.2]
	λ	Congestion cost (upward)	[0; 10]

Performance constraints: simulate N mesoscopic morphogenesis models in parallel (macroscopic interactions are efficient as based on matrices)

→ model implemented in `scala` and integrated within a broader library (including implementations of [Raimbault, 2018b] [Raimbault, 2018a] [Favaro and Pumain, 2011] [Cottineau et al., 2015])

Large number of parameters and output indicators

→ integration into the OpenMOLE model exploration open source software [Reuillon et al., 2013]



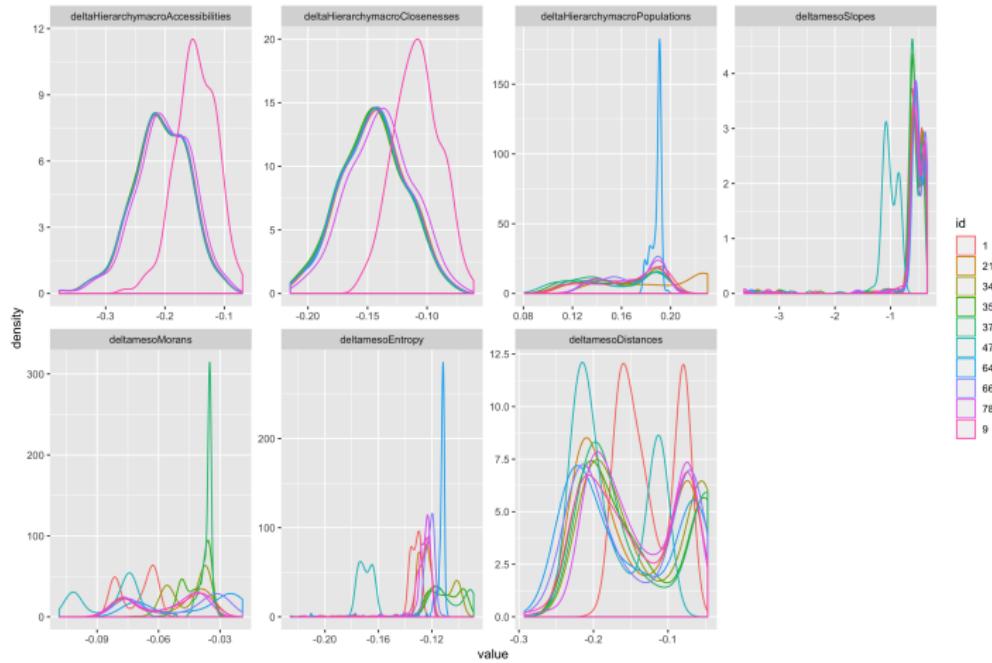
Enables seamlessly (i) model embedding; (ii) access to HPC resources; (iii) exploration and optimization algorithms

Come to the satellite *New Methods and Epistemologies to Explore Simulation Models* tomorrow afternoon in LHN-TR+05

Model applied on synthetic systems of cities:

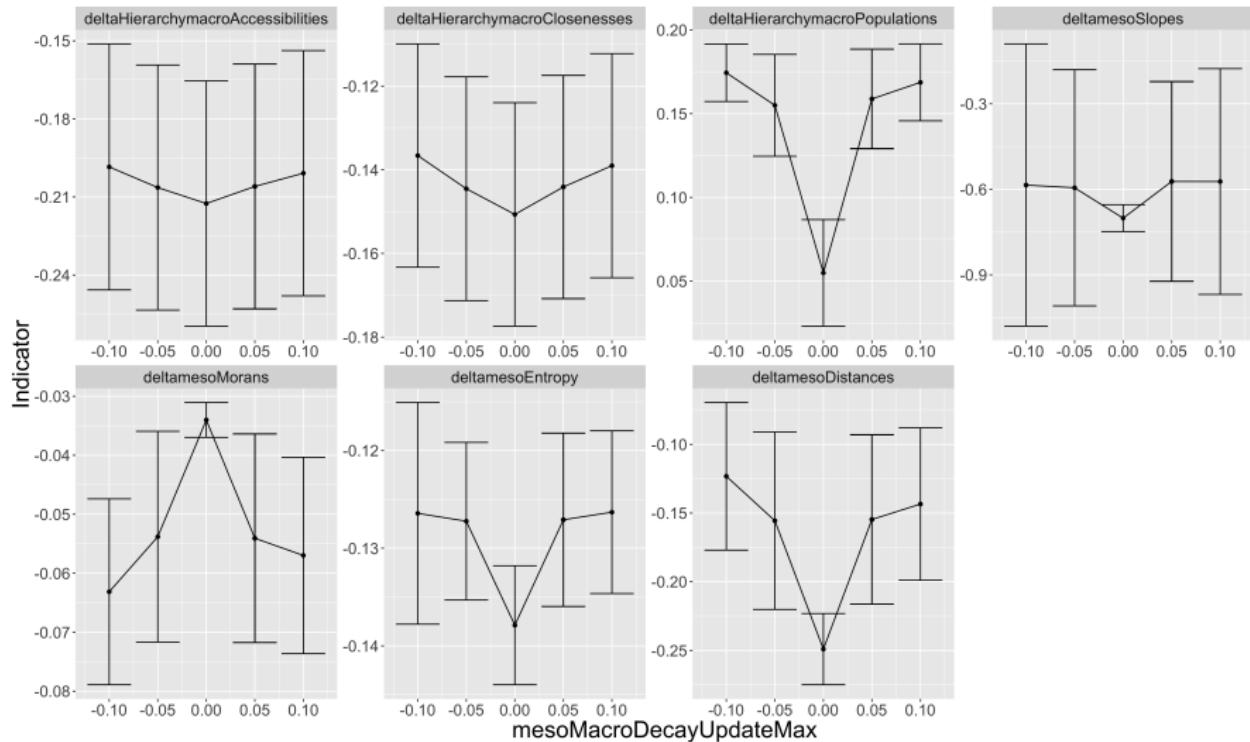
- random positions and rank-size hierarchy ($\alpha = 1.0$ and $P_0 = 100,000$)
- countrywide urban system scale: 500km and 20 cities
- initial population grids as monocentric (grid of size 50 and center cell density 1000 units)
- simulated for 20 macroscopic time steps (order of magnitude of half a century)

Statistical consistency



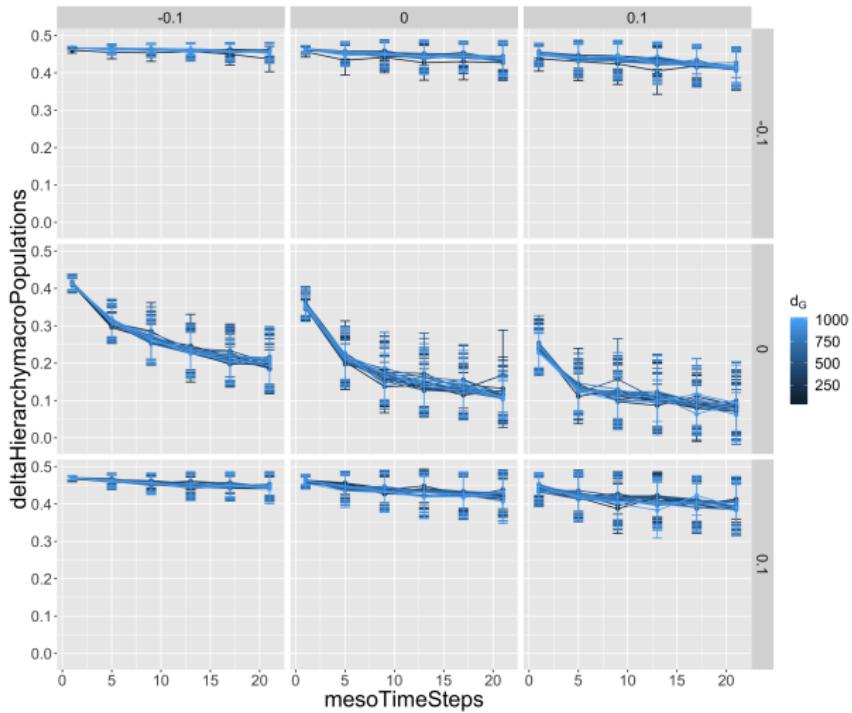
For all indicators, median sharpe ratios computing for a parameter point across repetitions are all larger than 1.6

Model exploration



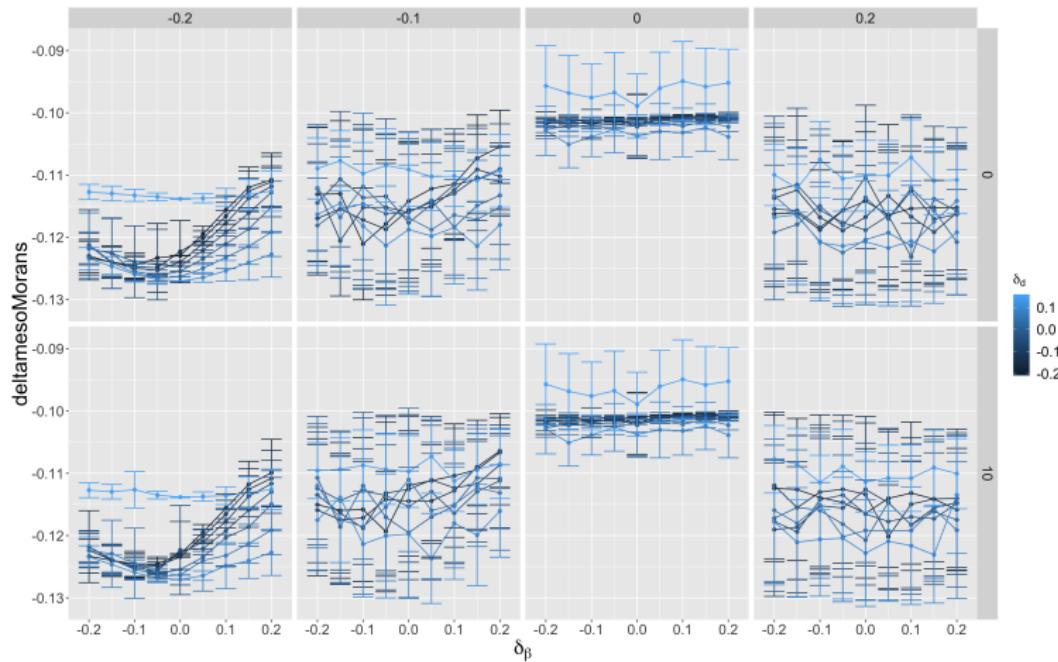
U-shape behavior of both macroscopic and mesoscopic indicators as a function of δd

Model exploration



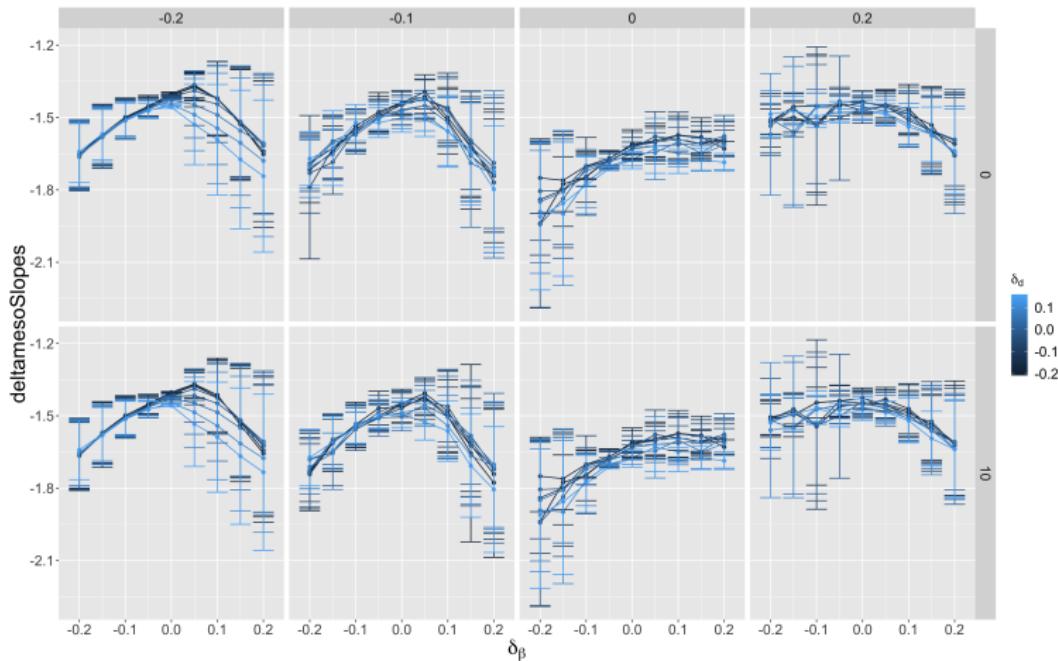
Non-trivial influence of coupled feedbacks on the different scales

Impact of policy parameters



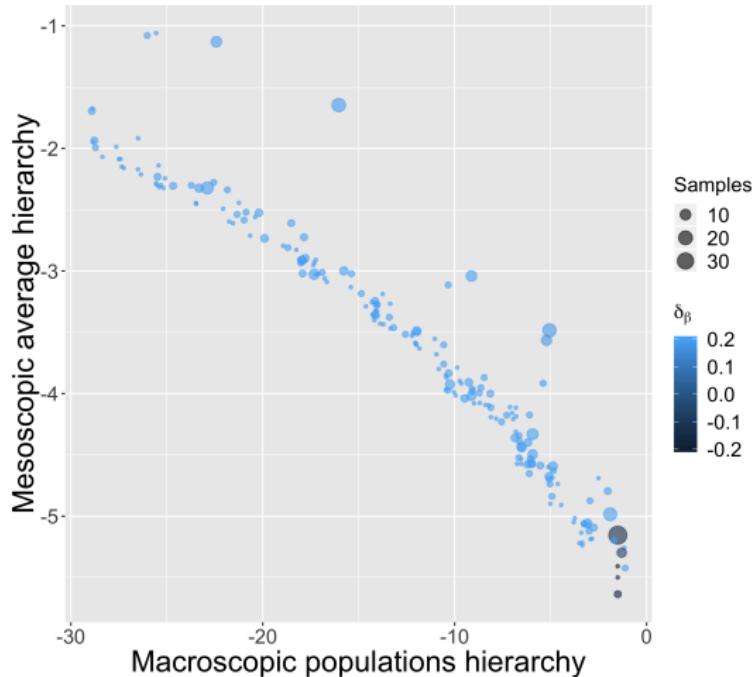
Mesoscopic centralization appears at a $\delta\beta$ critical value for low $\delta\alpha$; influenced by upward feedback

Impact of policy parameters



Mesoscopic hierarchy has a U-shape of $\delta\beta$ in negative $\delta\alpha$, but has a plateau for positive values

Multiscale optimization



Pareto front obtained with Genetic Algorithm optimization for two contradictory objective of macroscopic and mesoscopic hierarchies

Theoretical and practical implications

- model effectively captures an interaction between downward and upward feedback: weak emergence [Bedau, 2002]
- coupling “simple three parameters models” yield a complicated and complex simulation model: necessity of complexity and simulation models to understand urban complexity?
- progressive integration towards models for policy?

Developments

- diversity search algorithm to find e.g. regimes with the strongest effect of feedback
- parametrization on real systems; possibly calibration
(see [Raimbault, 2019] forthcoming presentation at ILUS)

- A first step towards *strongly* multi-scalar models to capture urban complexity towards policy models
- Towards integrative models and theories for urban systems
[Raimbault and Pumain, 2019]

Open repositories for

- Model: <https://github.com/JusteRaimbault/UrbanGrowth-model>
- Project: <https://github.com/JusteRaimbault/UrbanGrowth>
- Simulation data: <https://doi.org/10.7910/DVN/IRHMQK>

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

Reserve Slides

- Grid world with cell populations $(P_i(t))_{1 \leq i \leq N^2}$.
- At each time step:
 - 1 Population growth with exogenous rate N_G , attributed independently to a cell following a preferential attachment of strength α
 - 2 Population is diffused n_d times with strength β
- Stopping criterion: fixed maximal population P_m .
- Output measured by morphological indicators: Moran index, average distance, rank-size hierarchy, entropy.

Macroscopic interactions

$$P_i(t+1) = P_i(t) \left(1 + \Delta t \cdot \left(g_i + \frac{w_i}{N} \cdot \sum_j \frac{V_{ij}}{\langle V_{ij} \rangle} \right) \right) \quad (1)$$

where the gravity interaction potential is given by

$$V_{ij} = \left(\frac{P_i P_j}{\sum_k p_k^2} \right)^{\gamma_G} \cdot \exp \left(-\frac{d_{ij}}{d_i} \right) \quad (2)$$

Accessibility given by

$$Z_i = \sum_j \frac{P_j}{\sum_k P_k} \cdot \exp - d_{ij}/d_i \quad (3)$$

- Mesoscopic growth rate $N_G^{(i)}(t+1) \Delta P_i / t_m$
- Sprawl parameter (population pressure)

$$\beta_i(t+1) = \beta_i(t) \cdot \left(1 + \delta\beta \cdot \frac{\Delta P_i t}{\max_k \Delta P_k(t)} \right) \quad (4)$$

- Aggregation parameter (metropolization process)

$$\alpha_i(t+1) = \alpha_i(t) \cdot \left(1 + \delta\alpha \cdot \frac{\Delta Z_i t}{\max_k \Delta Z_k(t)} \right) \quad (5)$$

Congested flows within the mesoscopic zones:

$$U_i = \sum_{kl} \left(\frac{P_k P_l}{P^2} \cdot \frac{1}{d_{kl}} - \lambda \left(\frac{P_k P_l}{P^2} \cdot \frac{1}{d_{kl}} \right)^2 \right) \quad (6)$$

Update the macroscopic interaction distance accordingly

$$d_i(t+1) = d_i(t) \left(1 + \delta d \cdot \frac{U_i}{\max_k |U_k|} \right) \quad (7)$$

- 1 Rank-size slope γ , given by $\ln(P_{\tilde{i}}/P_0) \sim k \gamma \cdot \ln(\tilde{i}/i_0)$ where \tilde{i} are the indexes of the distribution sorted in decreasing order.
- 2 Entropy of the distribution:

$$\mathcal{E} = \sum_{i=1}^M \frac{P_i}{P} \cdot \ln \frac{P_i}{P} \quad (8)$$

- $\mathcal{E} = 0$ means that all the population is in one cell whereas $\mathcal{E} = 0$ means that the population is uniformly distributed.
- 3 Spatial-autocorrelation given by Moran index, with simple spatial weights given by $w_{ij} = 1/d_{ij}$

$$I = M \cdot \frac{\sum_{i,j} w_{ij} (P_i - \bar{P}) \cdot (P_j - \bar{P})}{\sum_{i,j} w_{ij} \sum_i (P_i - \bar{P})^2}$$

- 4 Mean distance between individuals

$$\bar{d} = \frac{1}{d_M} \cdot \sum_{i < j} \frac{P_i P_j}{P^2} \cdot d_{ij}$$

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