Modeling urban evolution and co-evolution in systems of cities

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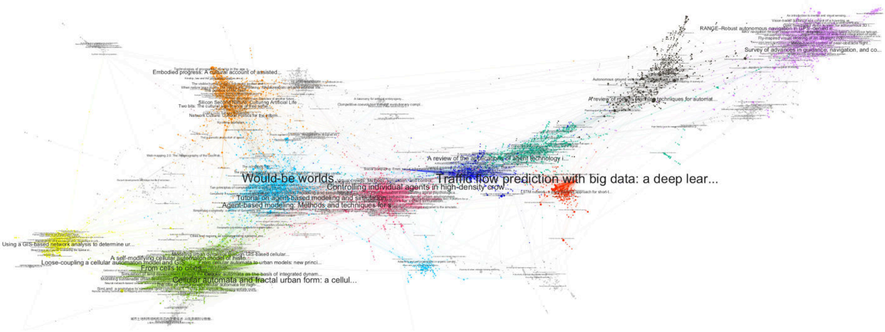
Urban Genome Project seminar
University of Toronto, School of Cities
December 9th 2020

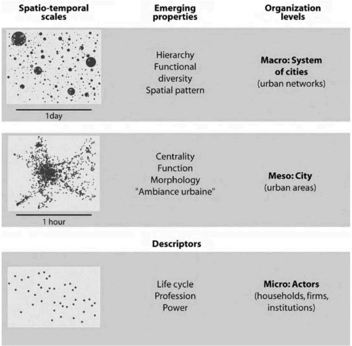


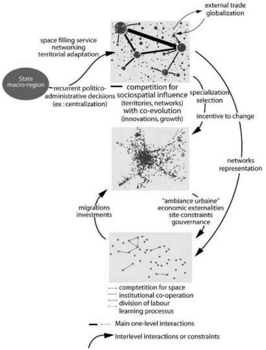
Citation network of ALife studies of urban systems [Raimbault, 2020a] arXiv:2002.12926

Transfer of concepts: Urban morphogenesis, bio-inspired design, urban ecology, autopoiesis [Batty and Marshall, 2009]

Urban Evolution

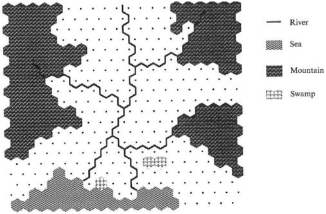
Urban evolution extending cultural evolution, cities as agents with their proper genome and evolutionary dynamics?



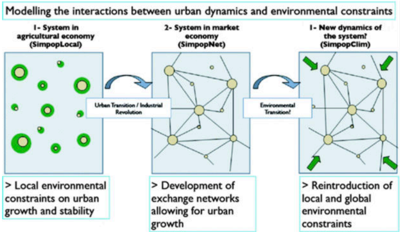


An evolutionary urban theory considering cities as systems within systems of cities; co-evolving urban systems in which interactions are crucial [Pumain, 2018] [Pumain, 1997] [Pumain, 2008]

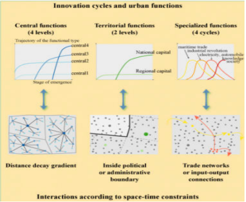
The series of Simpop models [Pumain, 2012a]



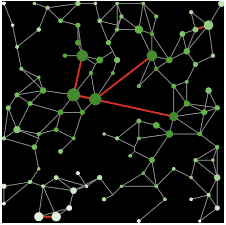
Simpop 1 model [Sanders et al., 1997]



From SimpopLocal to SimpopClim [Pumain, 2012a]

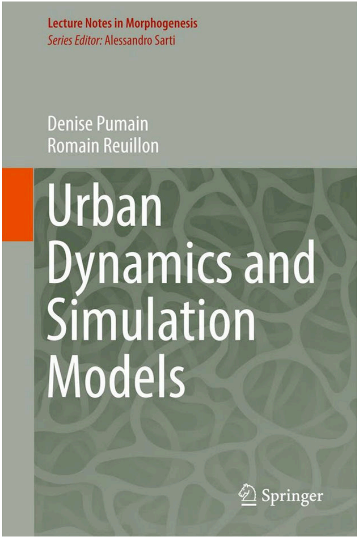


Simpop 2 model [Bretagnolle et al., 2006]



SimpopNet model [Schmitt, 2014]

Towards new practices: ERC Geodivercity



→ Recurrent stylized facts on main systems of cities
→ Construction of simulation models (with an explicative purpose)
→ Tools and methods to explore simulation models

OpenMOLE

Theories and models

Historical succession of epistemologies in the case of systems of cities [Varenne, 2018]:

1. Deduction from theory (top-down): Christaller
2. Induction from the empirical (bottom-up): Berry
3. Towards an abductive epistemology (iterative interaction theoretical-empirical): Pumain

$\rightarrow$ simulation allows synthesis

Geographical systems and complexity

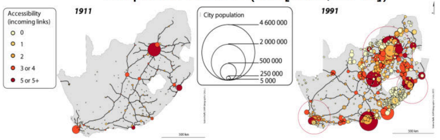
Necessity of simulation models in geography induced by complexities of these systems ?

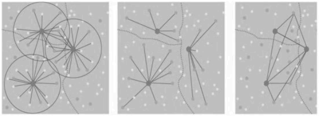
- Ontological complexity [Pumain, 2003]
- Dynamical complexity: non-ergodicity and path-dependency [Pumain, 2012b]
- Complexity and co-evolution [Raimbault, 2019b]
- Complexity and emergence [Bedau, 2002]

Construction of Knowledge across Domains

Databases
(ex. [Swerts, 2017])

Empirical studies (ex. [Baffi, 2016])

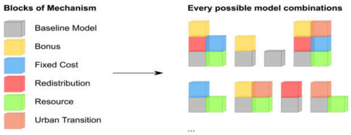




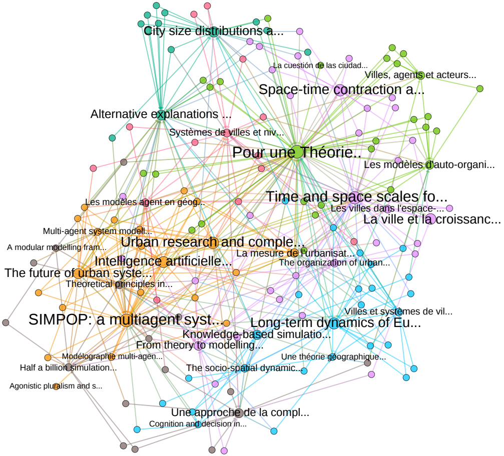
Models (ex. [Pumain, 2008])

Tools (ex. [Reuillon et al., 2013])

Theory
[Pumain, 1997]
[Pumain, 2010]



Methods (ex. [Cottineau et al., 2015])



Citation network analysis of key publications

Raimbault, J. (2017). An Applied Knowledge Framework to Study Complex Systems. In Complex Systems Design & Management (pp. 31-45).

OpenMOLE software

Urban simulation models integrated into the OpenMOLE open source software for model exploration and validation

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

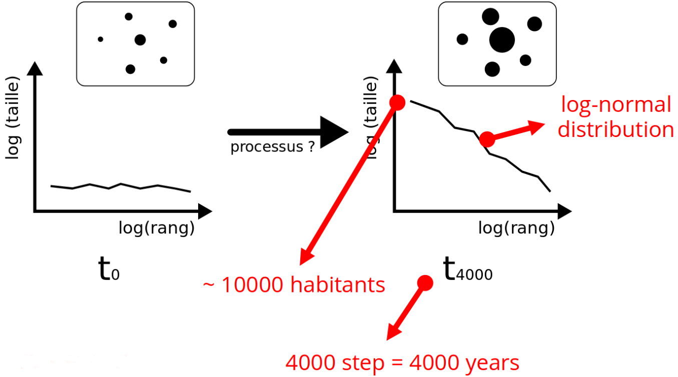
`https://openmole.org/`

Applications for the summer school (May 30th-June 4th 2021) are open! `https://exmodelo.org/`

Reuillon, R., Leclaire, M., & Rey-Coyrehourcq, S. (2013). OpenMOLE, a workflow engine specifically tailored for the distributed exploration of simulation models. Future Generation Computer Systems, 29(8), 1981-1990.

Calibration of SimpopLocal model

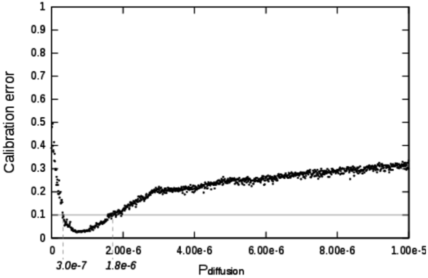
SimpopLocal model calibrated with distributed NSGA2 on grid

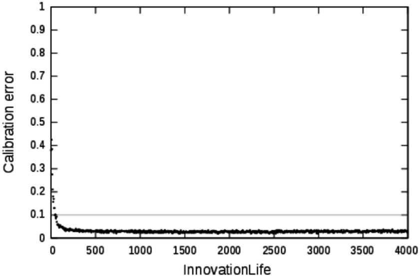


Schmitt, C., Rey-Coyrehourcq, S., Reuillon, R., & Pumain, D. (2015). Half a billion simulations: Evolutionary algorithms and distributed computing for calibrating the SimpopLocal geographical model. Environment and Planning B: Planning and Design, 42(2), 300-315.

SimpopLocal and calibration profile

Computes the best calibration at fixed steps along one dimension.

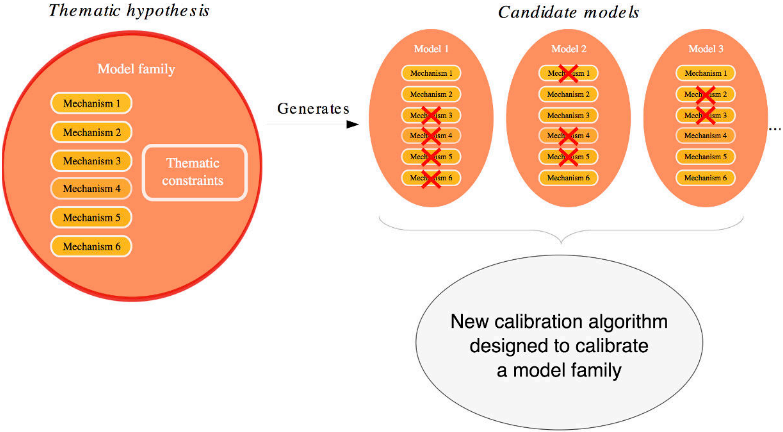




Reuillon, R., Schmitt, C., De Aldama, R., & Mouret, J. B. (2015). A new method to evaluate simulation models: the calibration profile (cp) algorithm. Journal of Artificial Societies and Social Simulation, 18(1), 12.

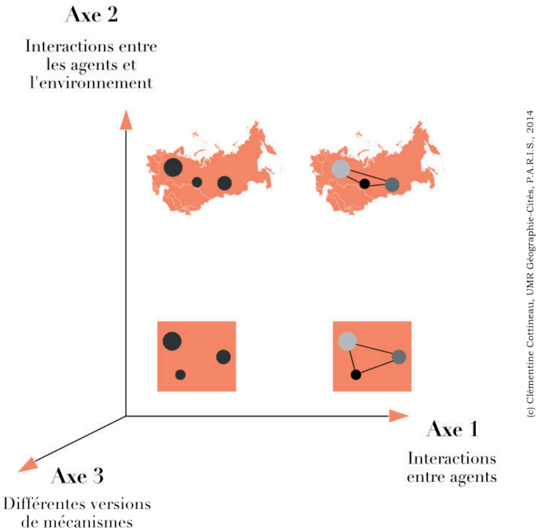
Unicity of mechanisms: multi-modeling

Automate the confrontation of alternative hypothesis / mechanisms



Cottineau, C., Reuillon, R., Chapron, P., Rey-Coyrehourcq, S., & Pumain, D. (2015). A modular modelling framework for hypotheses testing in the simulation of urbanisation. Systems, 3(4), 348-377.

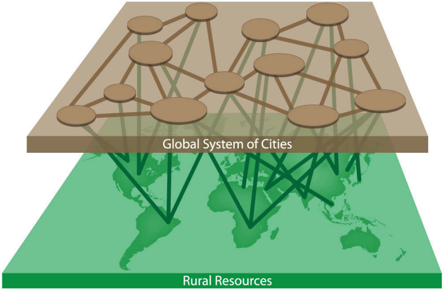
Multi-modeling (64 models)



Exemple of concurrent hypothesis

Exchange mechanism: market vs centralized

City growth: interurban interactions vs environmental situation



Calibration of model family

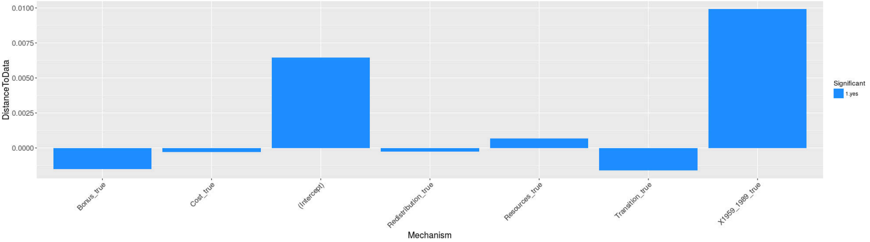
Compute the best set of parameters for all 64 models.

Contribution of mechanisms to the quality of simulation (closeness to data)

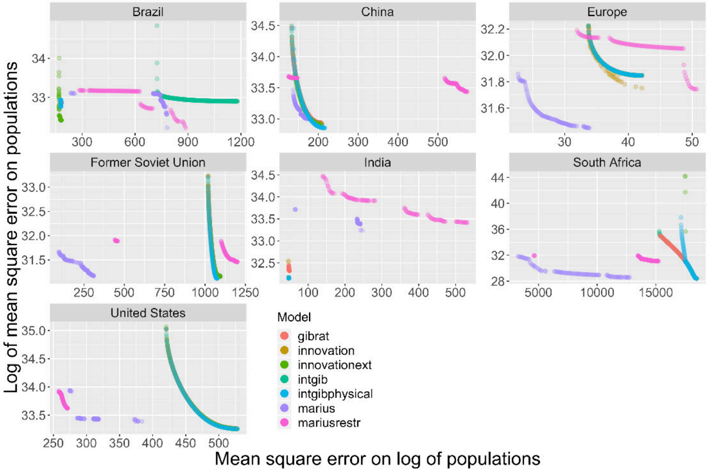
Models with different combination of mechanisms have been calibrated intensively against empirical data, using generic algorithms for more than 100000 generations. This plot shows the results of a regression explaining one measure of the quality of models (a small difference between simulated and empirical urban trajectories) by their mechanisms composition (the fact that any of the supplementary mechanisms is activated or not" Each bar represents the value of the estimated coefficient for each activated mechanism, in comparison with the same model structure without this mechanism, everything else being equal.

Statistical Significance (% of error)

0 1 10

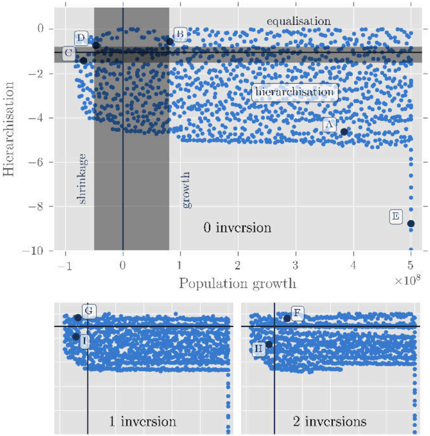


Other example of multi-modeling



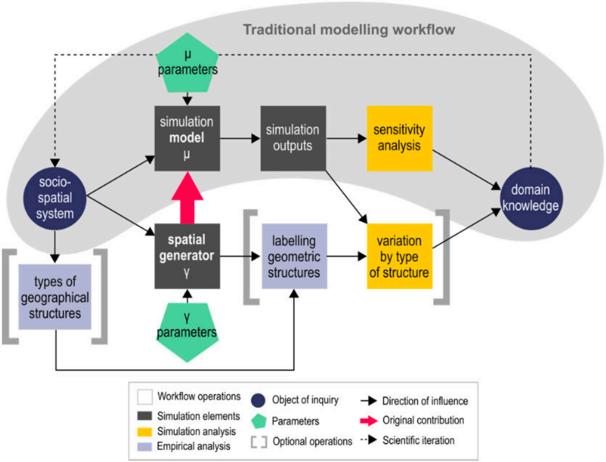
Raimbault, J.; Denis, E.; Pumain, D. (2020). Empowering Urban Governance through Urban Science: Multi-Scale Dynamics of Urban Systems Worldwide. Sustainability 2020, 12, 5954.

Diversity of urban systems dynamics produced by the MARIUS model



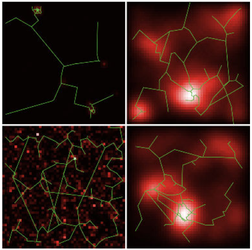
Chérel, G., Cottineau, C., & Reuillon, R. (2015). Beyond corroboration: Strengthening model validation by looking for unexpected patterns. PloS one, 10(9), e0138212.

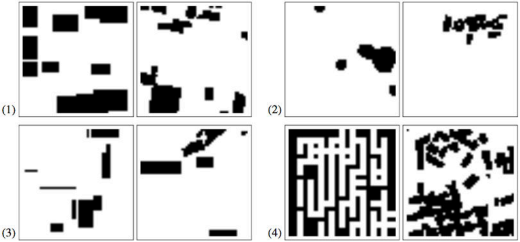
Spatial sensitivity analysis



Raimbault, J., Cottineau, C., Le Texier, M., Le Nechet, F., & Reuillon, R. (2019). Space Matters: Extending Sensitivity Analysis to Initial Spatial Conditions in Geosimulation Models. Journal of Artificial Societies and Social Simulation, 22(4).

Spatial sensitivity analysis: synthetic data





Raimbault, J. (2019). Second-order control of complex systems with correlated synthetic data. Complex Adaptive Systems Modeling, 7(1), 1-19.

Raimbault, J., & Perret, J. (2019). Generating urban morphologies at large scales. In Artificial Life Conference Proceedings (pp. 179-186).

Innovation diffusion

→ **Innovation diffusion** is a crucial process in artificial life evolutionary systems and open-ended evolution [Bedau et al., 2000]

→ Artificial societies used to study the dynamics of innovation [Zenobia et al., 2009]

→ Innovations diffuse hierarchically in systems of cities [Hagerstrand et al., 1968], potential explanation of urban scaling laws [Pumain et al., 2006]

Innovation diffusion as a privileged entry to understand urban evolution

Model objective

$\rightarrow$ Concepts of urban evolution do not necessarily capture essential processes (transmission and transformation) in the literature

$\rightarrow$ Need for simple models with explicit urban genome at the system of cities scale

Research objective:

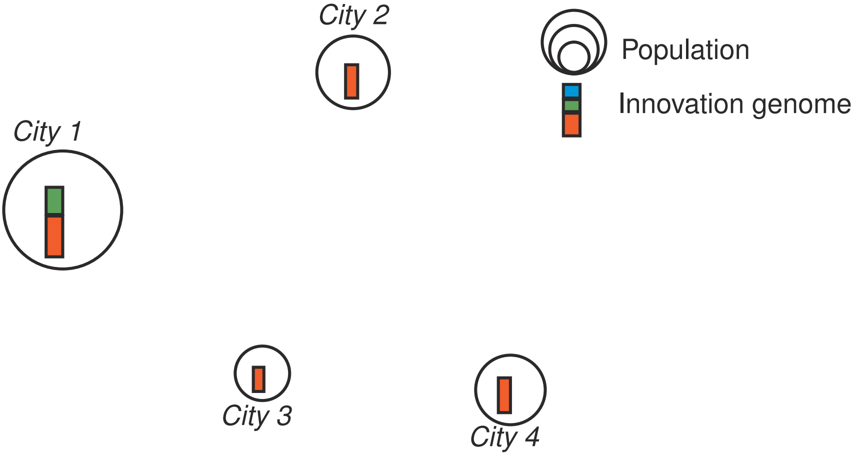
Describe and systematically explore an urban evolution model based on innovation diffusion, for urban dynamics at the macroscopic scale

Raimbault, J. (2020). A model of urban evolution based on innovation diffusion. Artificial Life Conference Proceedings 2020 NO. 32, 500-508.

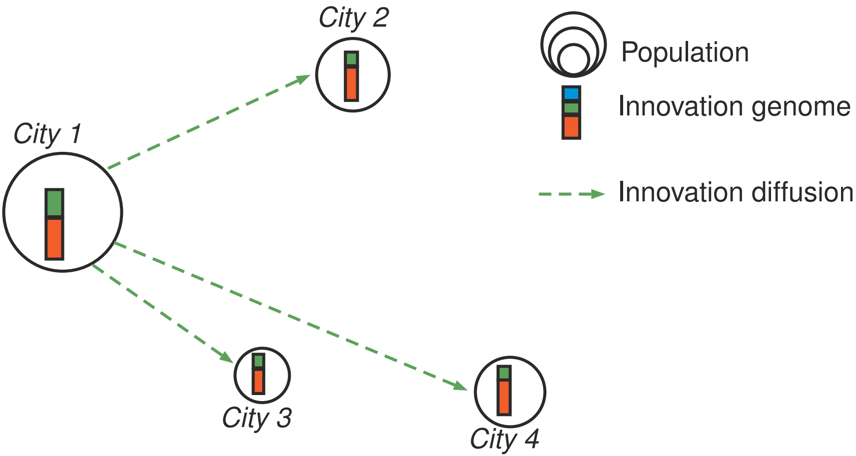
Model rationale

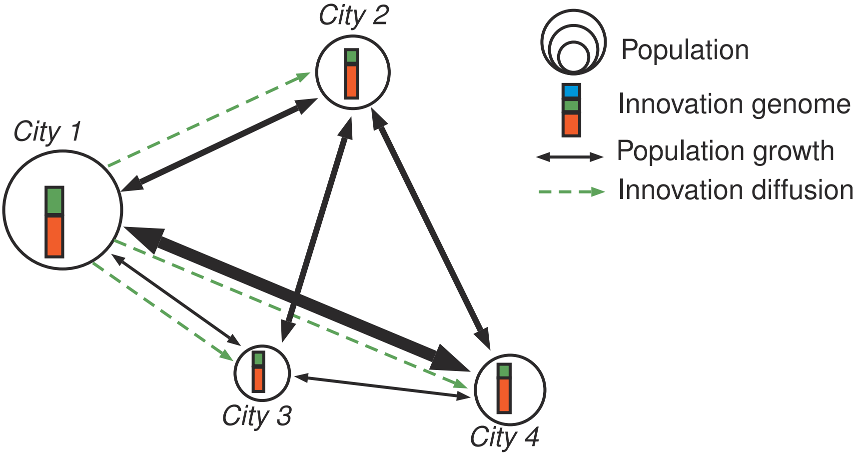
- Agents are cities, macroscopic scale (regional, country, continental) and long time scales (century)
- Cities characterized by their size in terms of population; genome as adoption proportions of innovations (social or technological) for each city (one single dimension to simplify)
- Following [Favaro and Pumain, 2011], attractivity of cities due to level of innovation drive their population growth through spatial interactions; innovation diffuse through an other spatial interaction model [Fotheringham and O'Kelly, 1989]
- Mutations occur in cities as new innovations appear

Model description

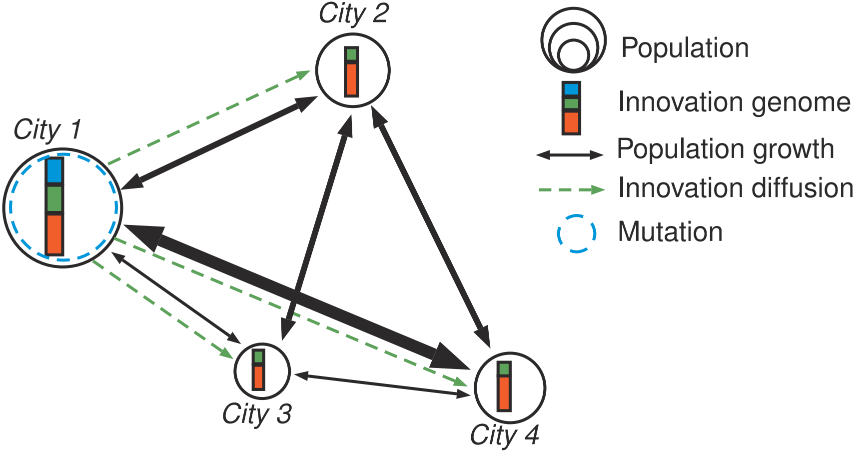


Model description




City 2
City 1
City 3
City 4
Population
Innovation genome
Population growth
Innovation diffusion

Model description



Model formalization

At each time step, with $P_i\left(t\right)$ population, $\delta_{c,i}\left(t\right)$ genome, u_c utility of innovation, $p_{c,i,t}$ share of total population adopting innovation c in city i

1. Crossover through the diffusion of innovations

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

2. Population growth through spatial interactions $P_i\left(t\right) - P_i\left(t-1\right) = w_I \cdot \sum_j \frac{V_{ij}}{<V_{ij}>}$ with

$$V_{ij} = \frac{P_i\left(t-1\right) \cdot P_j\left(t-1\right)}{\left(\sum_k P_k\left(t-1\right)\right)^2} \cdot \exp\left(-\frac{d_{ij}}{d_G} \cdot \prod_c \delta_{c,i,t}^{\phi_{c,t}}\right)$$

   and $\phi_{c,t} = \sum_i \delta_{i,c,t} \cdot P_i\left(t-1\right) / \sum_{i,c} \delta_{i,c,t} \cdot P_i\left(t-1\right)$

3. Mutations with innovations introduced with probability $\beta \cdot \left(P_i\left(t\right) / \max_k P_k\left(t\right)\right)^{\alpha_I}$ and an initial penetration rate r_0; new utility u_c randomly distributed (normal or log-normal) with average current average utility and standard deviation a given parameter σ_U

Model indicators

- Average diversity

$$D = \frac{1}{t_f+1}\sum_{t=0}^{t_f}\left(1 - \sum_{i,c}\left(p_{c,i,t}\right)^2\right)$$

- Average utility

$$U = \frac{1}{t_f + 1}\sum_{t=0}^{t_f}\sum_{i,c}\delta_{c,i,t}u_c$$

- Innovatitivity

$$I = \frac{\max c}{N \cdot \left(t_f + 1\right)}$$

- Population trajectories, summarized by final hierarchy [Raimbault, 2020d]

Synthetic configurations

Model applied on synthetic systems of cities (so that conclusions are independent of geographical contingencies [Raimbault et al., 2019]):

- random positions and rank-size hierarchy $P_i\left(0\right) = \frac{P_{max}}{i^{\alpha_0}}$ with $\alpha_0 = 1.0$ and $P_{max} = 100,000$
- regional urban system scale: $N = 30$ cities
- simulated for $t_f = 50$ macroscopic time steps (order of magnitude of a century)

Model parameters

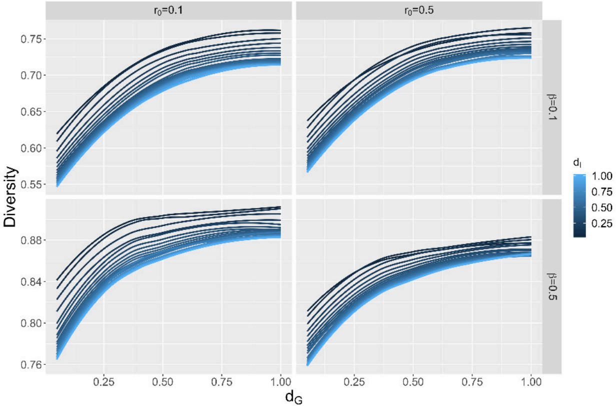
Parameter	Not.	Process	Range	Def.
Number of cities	N	Spatial scale	$10; 100$	30
Initial hierarchy	α_0	System of cities	$0.5; 2.0$	1
Initial population	P_{max}	System of cities	$10^4; 10^7$	10^5
Simulation steps	t_f	Temporal scale	$10; 100$	50
Growth rate	w_I	Pop. growth	$0.001; 0.01$	0.005
Gravity range	d_G	Crossover	$0; 2$	1
Innovation range	d_I	Crossover	$0; 2$	1
Innovation rate	β	Mutation	$0; 1$	0.5
Innovation hierarchy	α_I	Mutation	$0; 2$	1
Innov. utility std.	σ_U	Mutation	$\left[0.7; 2\right]$	1
Penetration rate	r_0	Mutation	$\left[0.1; 0.9\right]$	0.5
Utility type	-	Mutation	{n;ln}	ln

Statistical consistency

- Latin Hypercube Sampling of 100 parameter points, 1000 replications for each
- Sharpe ratios have high values for all indicators and all parameters (minimum 1.7 for utility)
- Average and median relative distances defined as $\Delta_{ij} = 2\frac{\left|\mu_i - \mu_j\right|}{\sigma_i + \sigma_j}$ larger than one for all indicators: 50 repetitions in further experiments

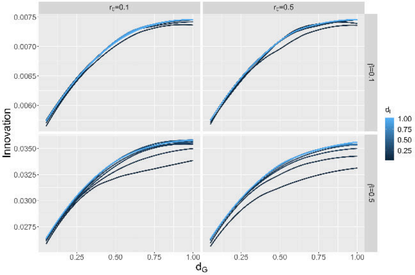
Model exploration: diversity

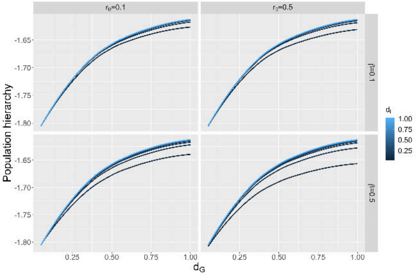
Grid sampling of the parameter space (23,168 points, 50 replications) with a finer grid on d_G and d_I; plots shown at $\alpha_I = 1$ and $\sigma_U = 1$



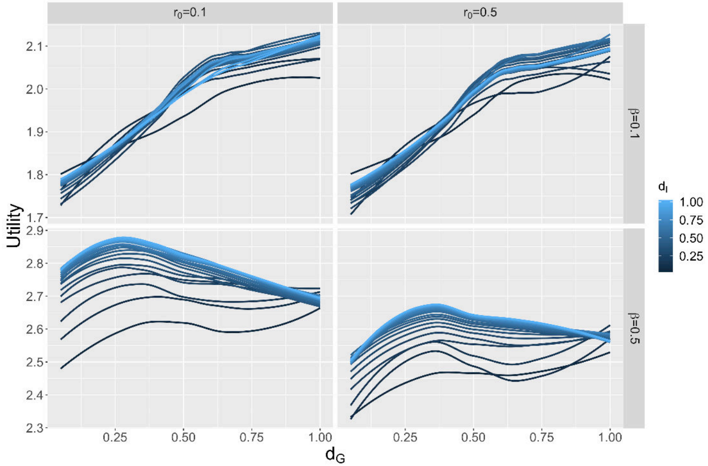
Diversity increases with interaction span with a plateau behavior, decreases with innovation diffusion span

Model exploration: innovation and hierarchy



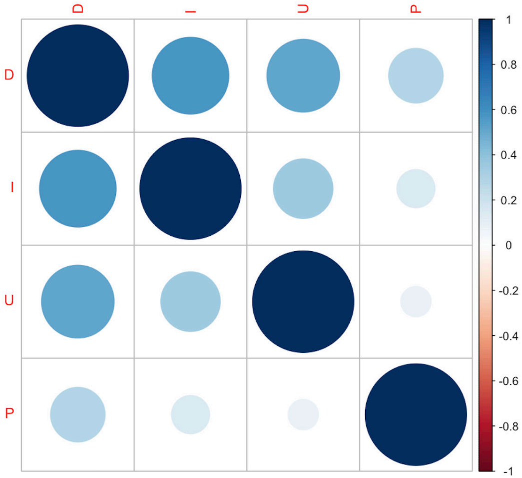


Systems with more interactions and diffusion are less unequal and innovate more



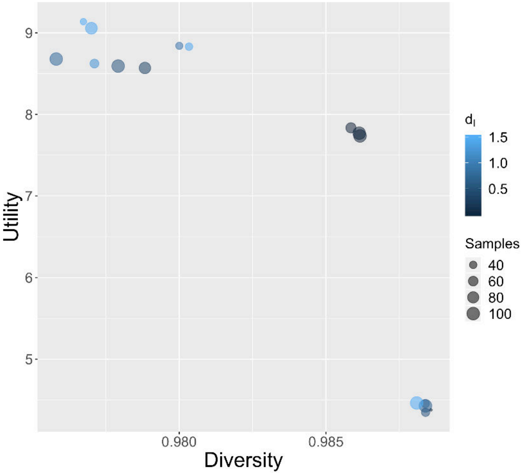
Piecewise behavior for low innovation rates; maximum as a function of d_G for high innovation: emergence of regional innovation clusters?

Correlations



Correlation matrix estimated over the whole exploration: innovation and population are not strongly correlated; 91% of variance on first two components

Model optimization



NSGA2 algorithm to simultaneously optimize utility and diversity: emergence of three compromize regimes; intermediate regime with low level of innovation diffusion

Discussion

Empirical and theoretical implications

$\rightarrow$ Global integration of cities is not necessarily optimal in terms of overall utility

$\rightarrow$ Urban evolution simulation model including explicit evolution processes and an urban genome

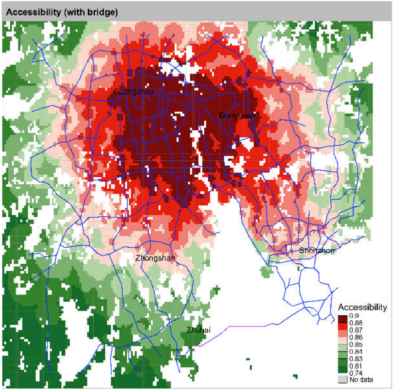
Future work and extensions

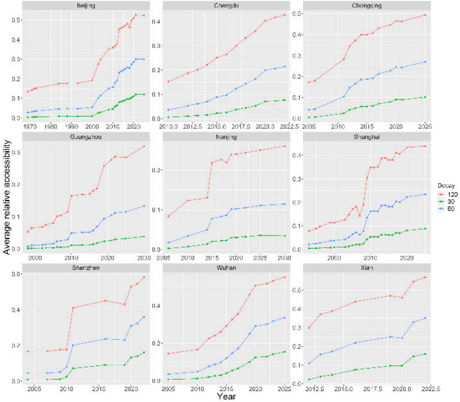
$\rightarrow$ Multi-dimensional urban genome to capture multi-dimensionality of urban dynamics [Hidalgo et al., 2007]

$\rightarrow$ Application to real systems of cities [Raimbault et al., 2020]: patent data as possible proxy for innovation dynamics [Bergeaud et al., 2017]

$\rightarrow$ Processes at other scales, towards multi-scale models [Raimbault, 2019a]

Interactions between networks and territories





Accessibility as part of complex processes of co-evolution between transportation networks and territories.

Raimbault, J. (2019). Evolving accessibility landscapes: mutations of transportation networks in China. In Aveline-Dubach, N., ed. *Pathways of sustainable urban development across China - the cases of Hangzhou, Datong and Zhuhai*, pp 89-108. Imago. ISBN:978-88-94384-71-0

Definition of co-evolution [Raimbault, 2019b]

Objects:

- Cities and territories seen from the *Evolutionary Urban Theory* viewpoint
- Transportation networks as realisation of “transactional projects”, following the *Territorial Theory of Networks* [Dupuy, 1987]

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Processes:

A three-level definition for co-evolution:

1. at the agent level
2. at the agent population level (niches)
3. at the global system level

Definition of co-evolution [Raimbault, 2019b]

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Processes:

A three-level definition for co-evolution:

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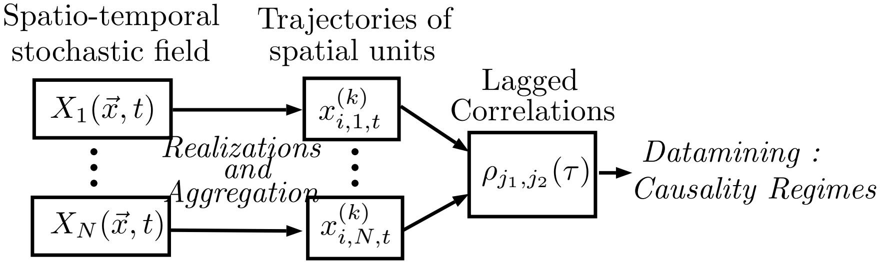
2. at the agent population level (niches)
3. at the global system level

Corresponding approaches:

1. Empirical studies (microscopic level)
2. Urban morphogenesis modeling (niche level)
3. Urban evolutionary theory models (macroscopic level)

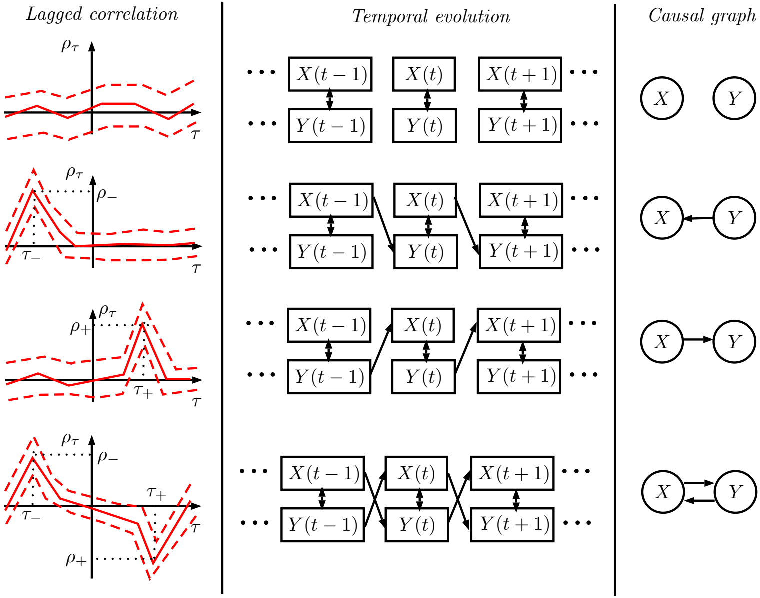
Raimbault, J. (2019). Modeling interactions between transportation networks and territories: a co-evolution approach. arXiv preprint arXiv:1902.04802.

Measuring co-evolution

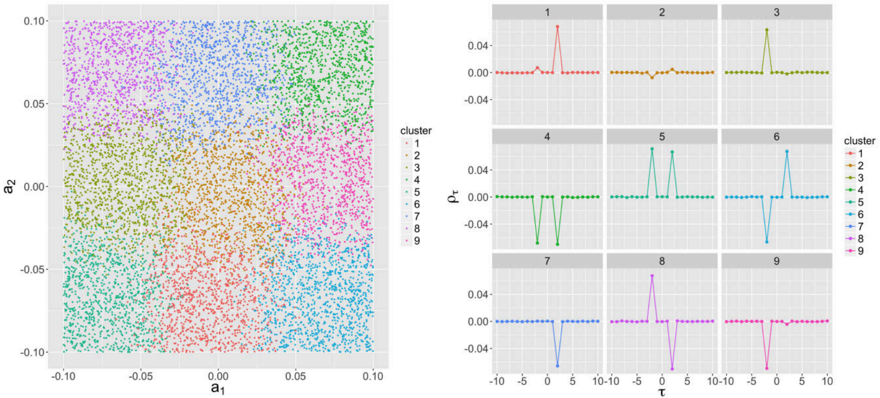


Raimbault, J. (2017). Identification de causalités dans des données spatio-temporelles. SAGEO 2017 Proceedings. *Translated as arXiv:1709.08684*

Illustration of the method

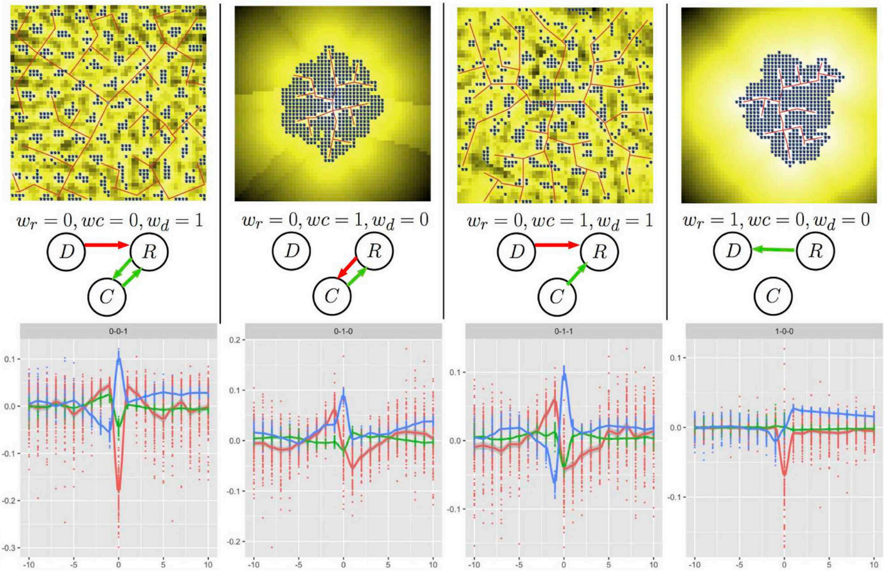


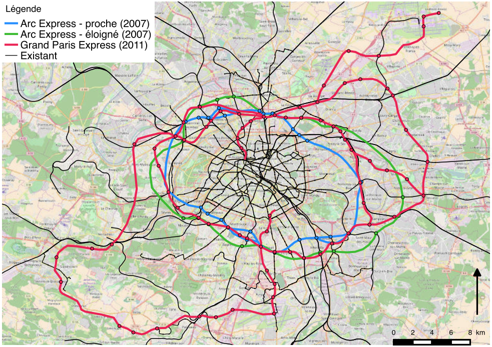
Method validation

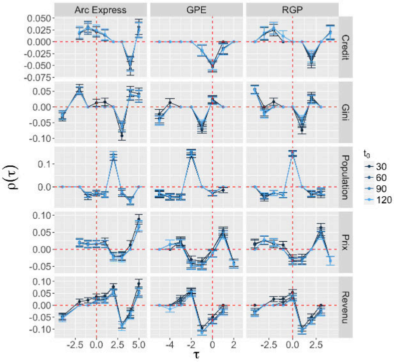


Synthetic data: auto-regressive process with lag 2, cross terms parametrized by random $a_1, a_2 \in -0.1, 0.1$.

Application on model of [Raimbault et al., 2014]







Anticipated effects on the new infrastructure on real estate prices

Modeling contributions

Macroscopic scale:

- Interaction models between cities including transportation networks
  $\rightarrow$ *Evidence of network effects; exploration of interaction regimes*

Modeling contributions

Macroscopic scale:

- Interaction models between cities including transportation networks
  $\rightarrow$ *Evidence of network effects; exploration of interaction regimes*

Mesoscopic scale:

- Morphogenesis model coupling urban form and network
  $\rightarrow$ *Complementarity of multiple processes; calibration at the first and second order*
- Exploration of an extended LUTI model including transportation governance

Which ontology to include more complex functional properties in mesoscopic morphogenesis models?

$\rightarrow$ Territorial systems as the strong coupling between territories and (potential and realized) networks [Dupuy, 1987].

$\rightarrow$ Networks convey functional notions of centralities and accessibility, among others; have furthermore proper topological properties.

A Morphogenesis Model of co-evolution

$\rightarrow$ Coupled grid population distribution and vector transportation network, following the core of [Raimbault et al., 2014]

$\rightarrow$ Local morphological and functional variables determine a patch-value, driving new population attribution through preferential attachment; combined to population diffusion (reaction-diffusion processes studied before)

$\rightarrow$ Network growth is also driven by morphological, functional and local network measures, following diverse heuristics corresponding to different processes (multi-modeling)

Local variables and network properties induce feedback on both, thus a strong coupling capturing the ***co-evolution***

Raimbault, J. (2019). An urban morphogenesis model capturing interactions between networks and territories. In The Mathematics of Urban Morphology (pp. 383-409). Birkhäuser, Cham.

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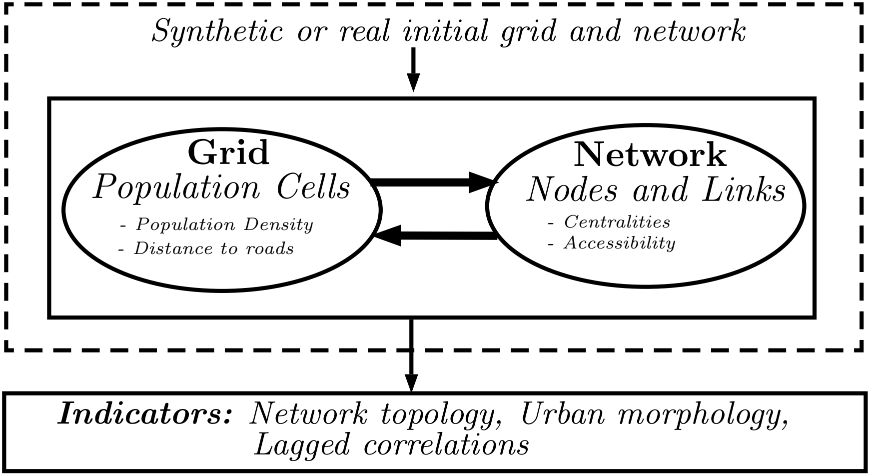
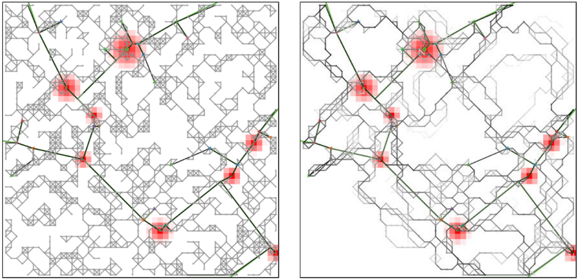
Model: Specification



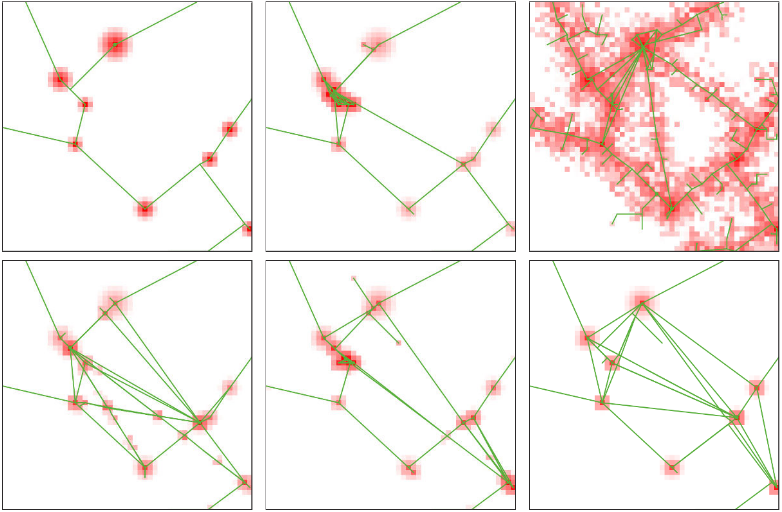
At fixed time steps :

1. Add new nodes preferentially to new population and connect them
2. Variable heuristic for new links, among: nothing, random, gravity-based deterministic breakdown, gravity-based random breakdown (from [Schmitt, 2014]), cost-benefits (from [Louf et al., 2013]), biological network generation (based on [Tero et al., 2010])



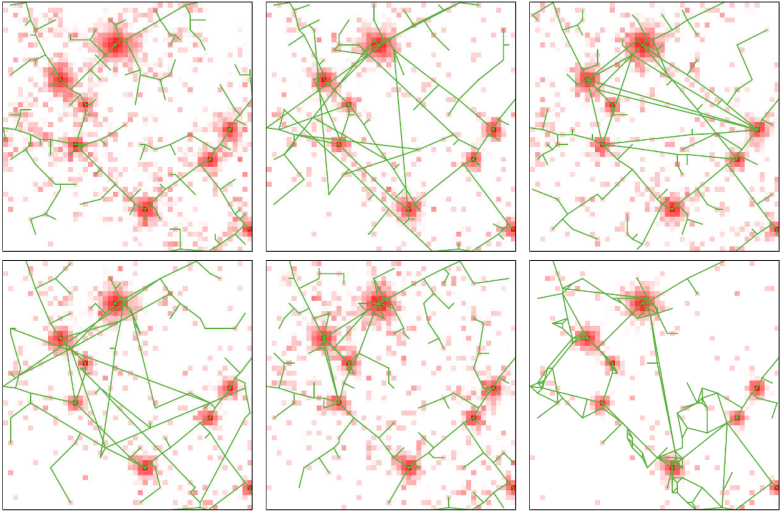
Intermediate stage for biological network generation

Generated Urban Shapes: Urban Form



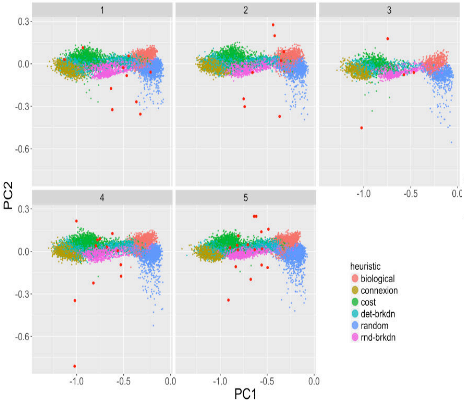
In order: setup; accessibility driven; road distance driven; betweenness driven; closeness driven; population driven.

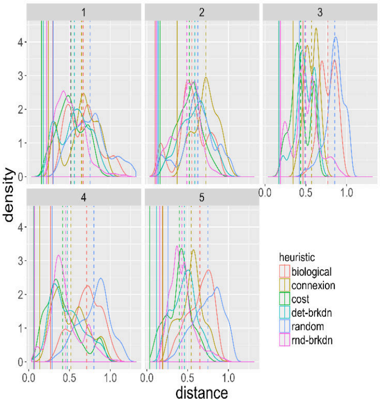
Generated Urban Shapes: Network



In order: connection; random; deterministic breakdown; random breakdown; cost-driven; biological.

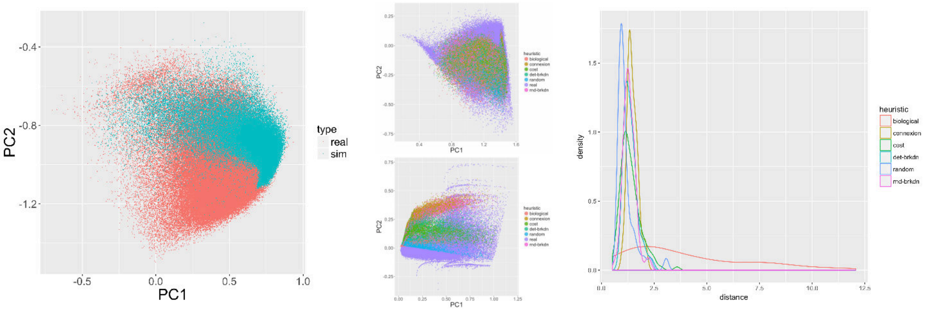
Comparison of feasible space for network indicators with fixed density





(Left) Feasible spaces by morphological class and network heuristic; (Right) Distribution of distances to topologies of real networks

Calibration (model explored with OpenMole [Reuillon et al., 2013], $\sim 10^6$ model runs) at the first order on morphological and topological objectives, and on correlations matrices.

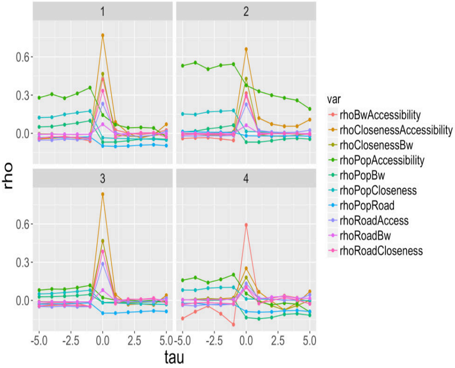


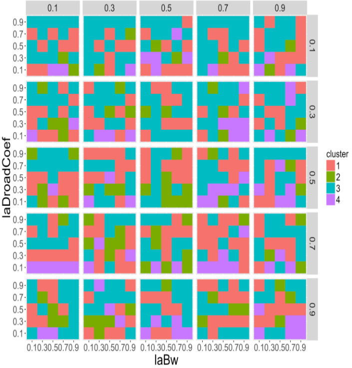
(Left) Full indicator space; (Middle) Morphological and Topology, by network heuristic; (Right) Distance distribution for cumulated distance for indicators and correlations.

Results: Causality Regimes

Unsupervised learning on lagged correlations between local variables unveils a diversity of causality regimes

→ Link between *co-evolution regime* and morphogenetic properties of the urban system





(Left) Lagged correlation profiles of cluster centers; (Right) Distribution of regimes across parameter space

Discussion

Implications

$\rightarrow$ This rather simple model reproduces most of existing urban forms in Europe for both population distribution and road network: which intrinsic dimension to the urban system and its morphological aspect ?

$\rightarrow$ Ability to reproduce static correlations and a variety of dynamical lagged correlation regimes suggests that the model captures some of the processes of co-evolution

Developments

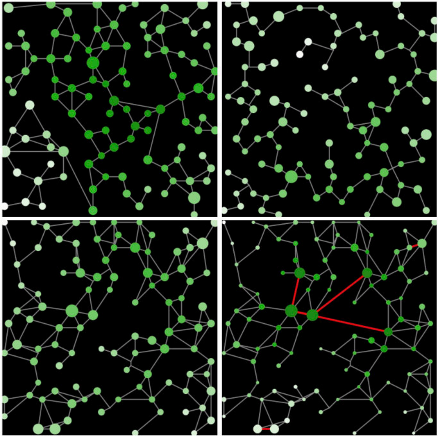
$\rightarrow$ Towards a dynamical calibration? Need for dynamical data

$\rightarrow$ Investigate the link between spatial non-stationarity and non-ergodicity through simulation by the model

$\rightarrow$ Compare network generation in a “fair” way (correcting for additional parameters, open question for models of simulation)

Co-evolution of cities and networks

Exploration of co-evolution regimes for the SimpopNet model



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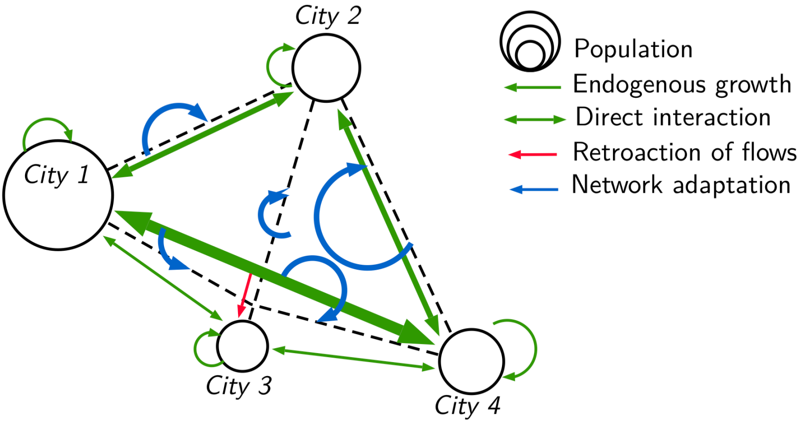

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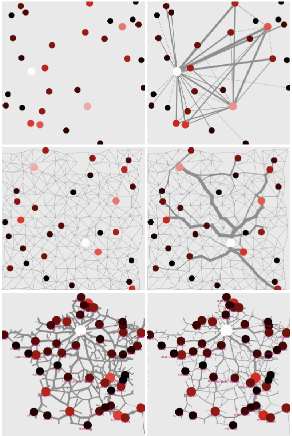

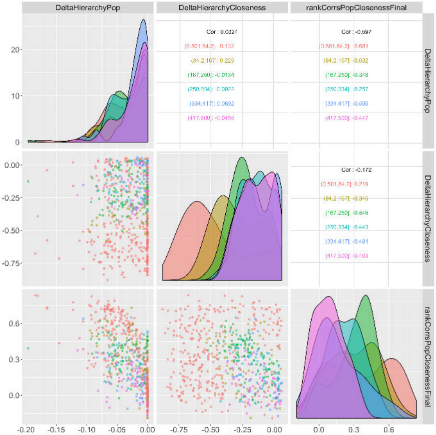

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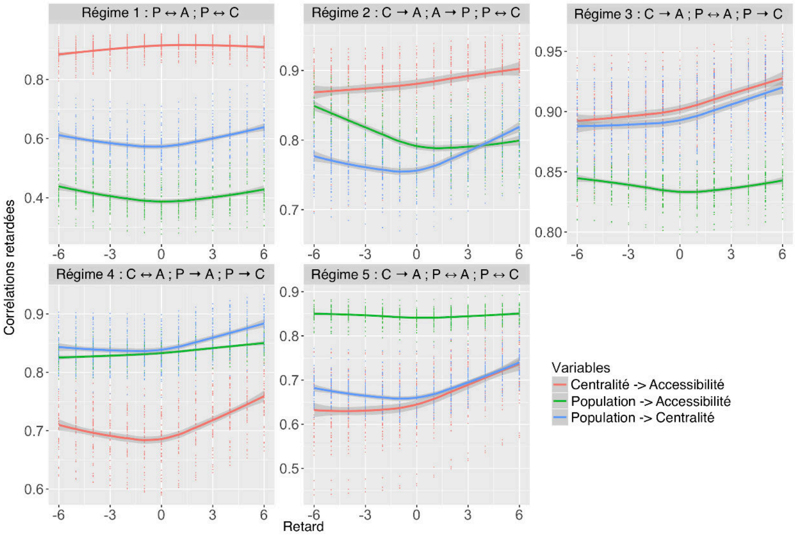
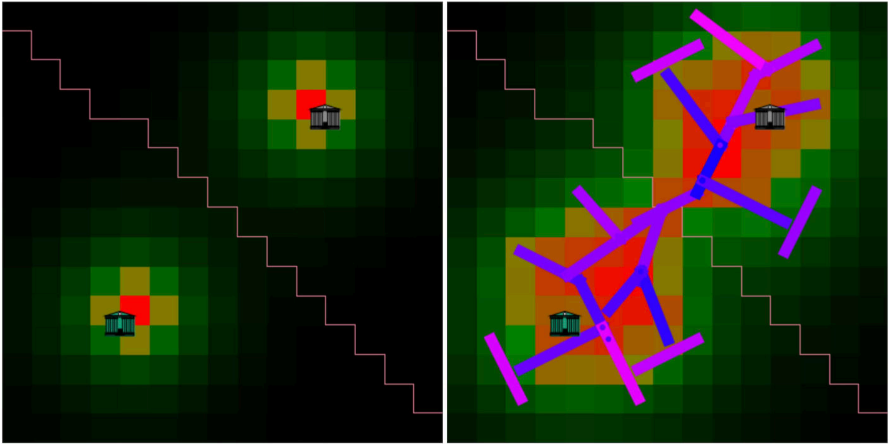
Co-evolution regimes



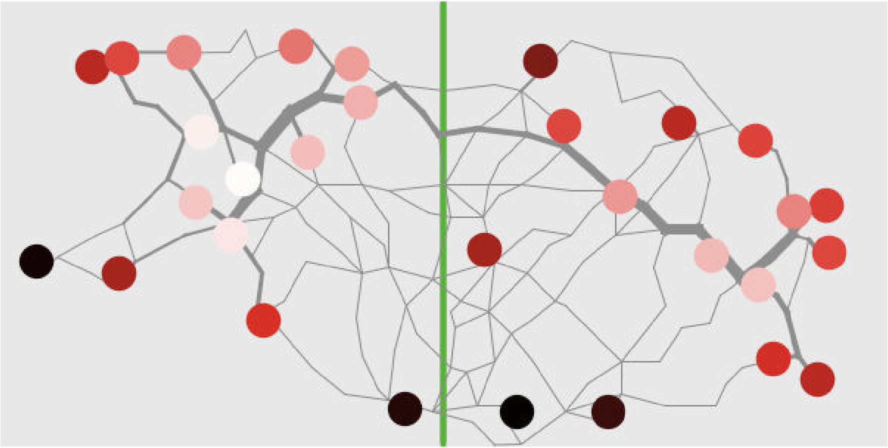
Multiple co-evolution regimes unveiled for synthetic configurations

The LUTECIA model includes transportation governance for network growth [Le Néchet and Raimbault, 2015]



Towards more complex models

Including multinational transportation governance into the macroscopic co-evolution model



[Presentation yesterday at Conference on Complex Systems 2020]

Towards multi-scale models

Crucial aspect of processes at multiple scales and feedback between these [Pumain, 2008]; need to be taken into account to build sustainable territorial policies [Rozenblat and Pumain, 2018]

$\rightarrow$ Empirical analysis of contradictory sustainability indicators on endogenous European mega-city regions [Raimbault, 2019c]

$\rightarrow$ A parsimonious multi-scalar urban growth model coupling spatial interactions at the macroscopic scale with reaction-diffusion models for urban form at the mesoscopic scale in [Raimbault, 2019a]

$\rightarrow$ Include physical transportation network in macroscopic co-evolution models [Raimbault, 2020b]

Conclusion

Urban evolution and co-evolution as a powerful paradigm to model, understand, sustainably manage urban systems

Open repositories for models `https://github.com/JusteRaimbault/CityNetwork` `https://github.com/JusteRaimbault/UrbanEvolution`

Acknowledgments: *European Grid Infrastructure*; UKCRIC DAFNI; Urban Dynamics Lab Grant EPSRC EP/M023583/1

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