

Urban Morphogenesis and the co-evolution of Transportation Networks and Territories

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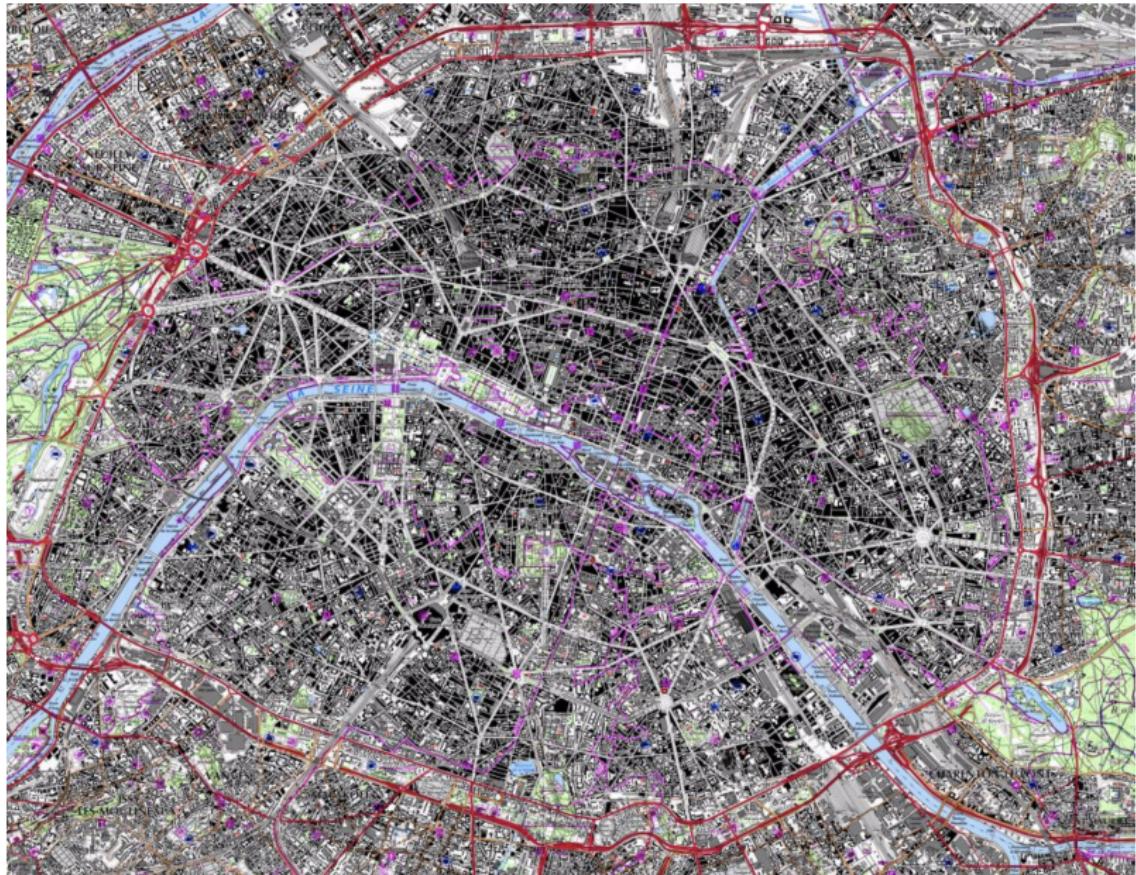
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Complex processes of Urban Morphogenesis



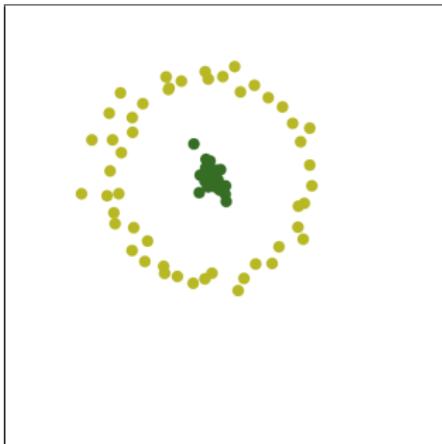
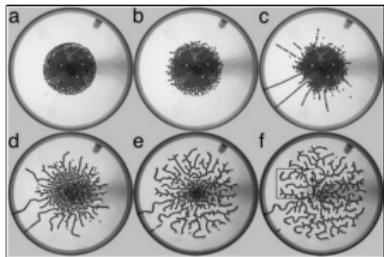
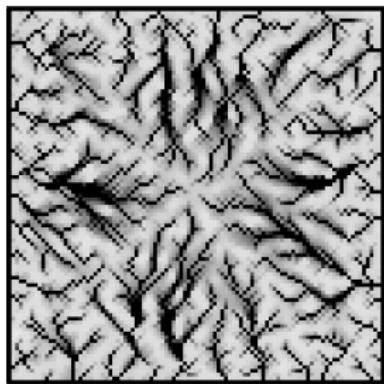
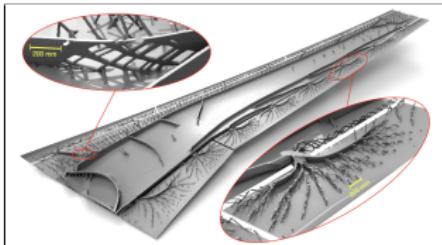
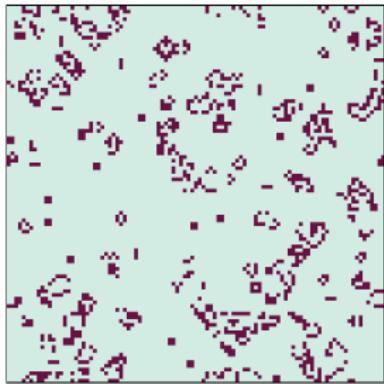
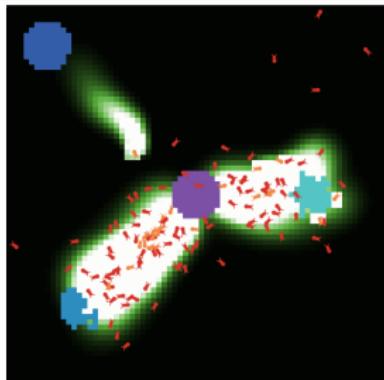
Source: Geoportal

Complex processes of Urban Morphogenesis



Source: Geoportail

What is Morphogenesis ?



Sources (in order by column). Ants, Erosion, Game of Life: NetLogo Library ; Arbotron [Jun and Hübler, 2005]; Industrial design [Aage et al., 2017]; Swarm chemistry [Sayama, 2007]

Defining Morphogenesis

Construction of an interdisciplinary definition in [Antelope et al., 2016]

Imbricated notions:

Self-organization ⊂ Morphogenesis ⊂ Autopoiesis ⊂ Life

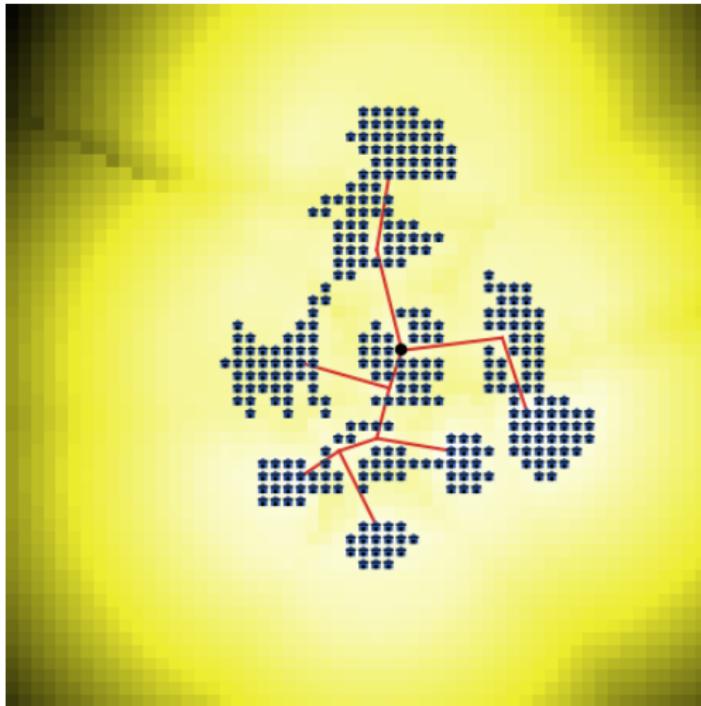
Properties:

- Architecture links form and function
- Emergence strength [Bedau, 2002] diminishing with depth, whereas bifurcations increase [Thom, 1974]

Morphogenesis : *Emergence of the form and the function in a strongly coupled manner, producing an emergent architecture [Doursat et al., 2012]*

Modeling Urban Morphogenesis

Which models for Urban Morphogenesis ?



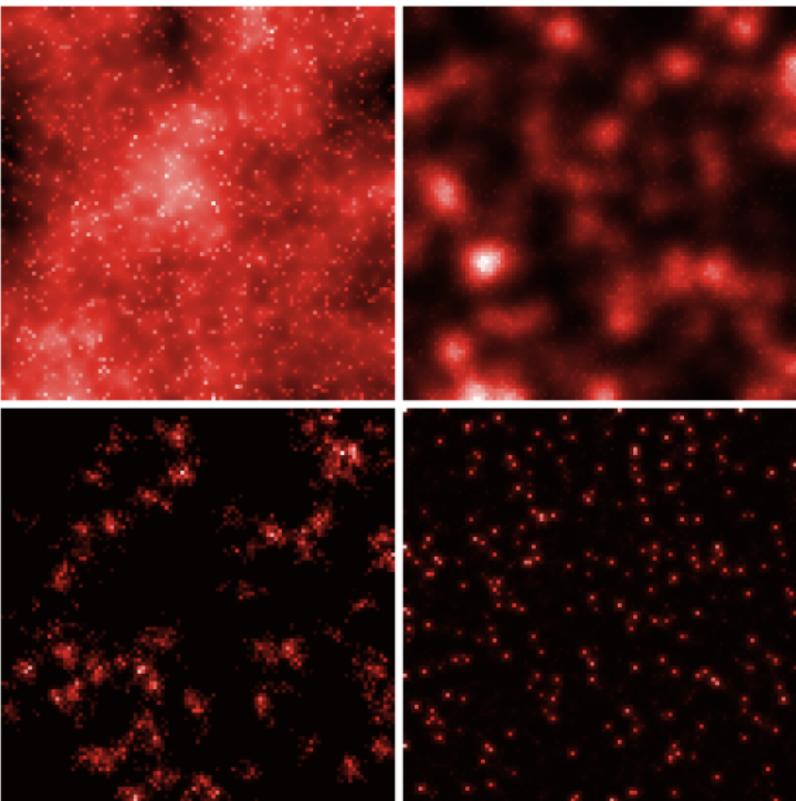
Example: a basic hybrid model based on elementary processes [Raimbault et al., 2014]

A simple Reaction-diffusion model

Model Formalization

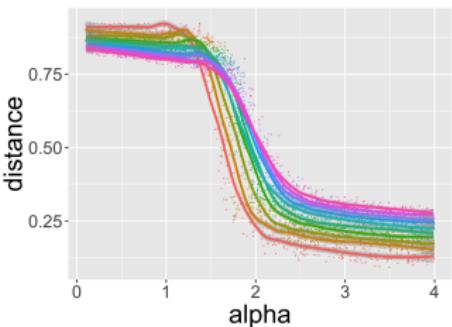
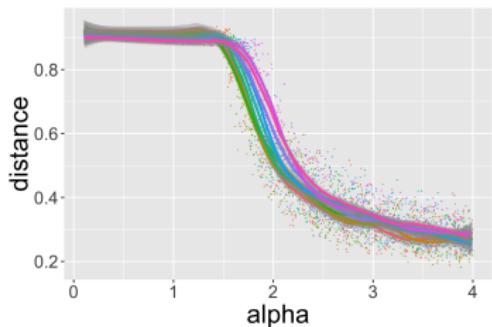
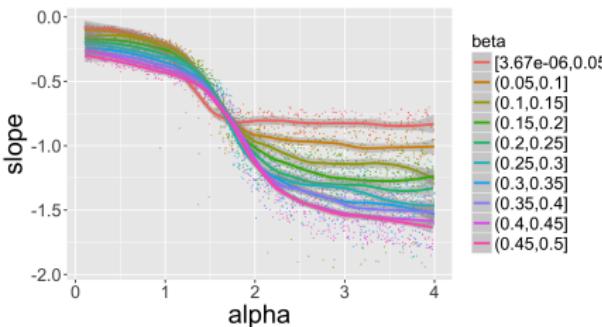
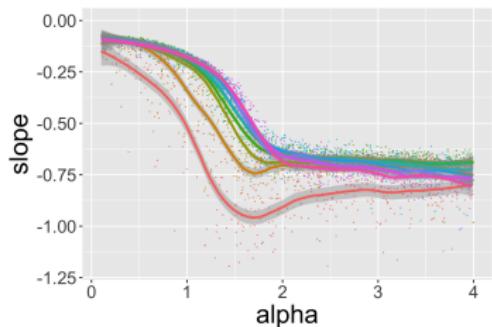
- Grid world with cell populations $(P_i(t))_{1 \leq i \leq N^2}$.
- At each time step:
 - ① Population growth with exogenous rate N_G , attributed independently to a cell following a preferential attachment of strength α
 - ② Population is diffused n_d times with strength β
- Stopping criterion: fixed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

Generating Population Distributions



Examples of generated territorial shapes

Model behavior



Phase transitions of indicators unveiled by exploration of the parameter space (80000 parameter points, 10 repetitions each)

Path-dependence and frozen accidents

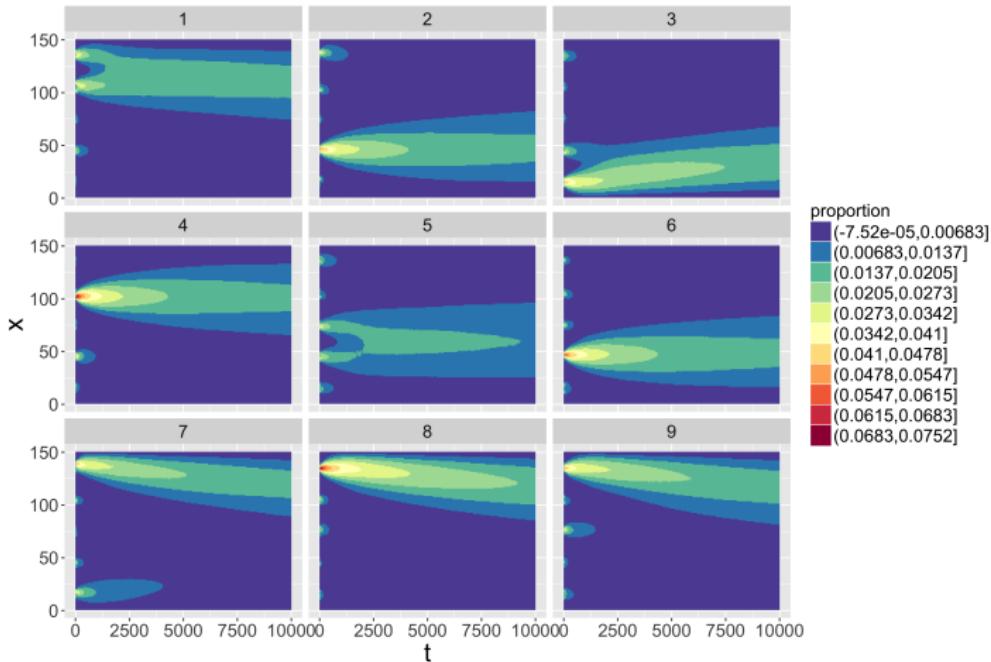
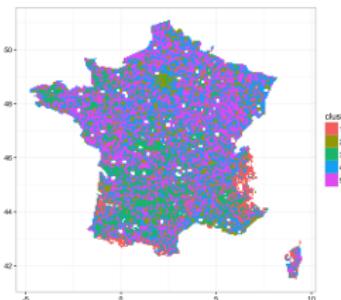
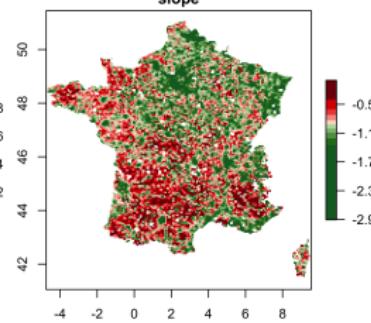
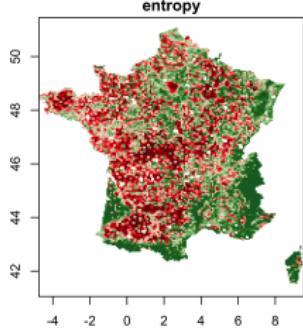
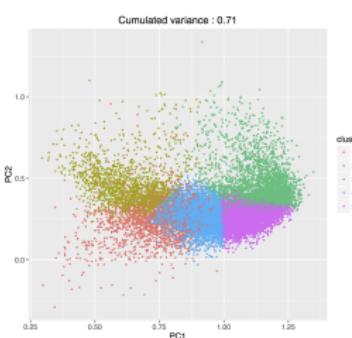
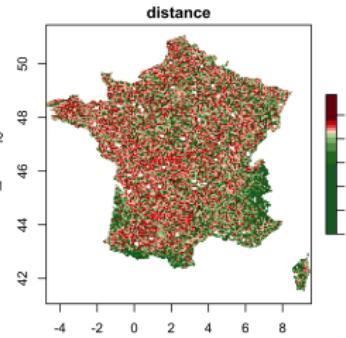
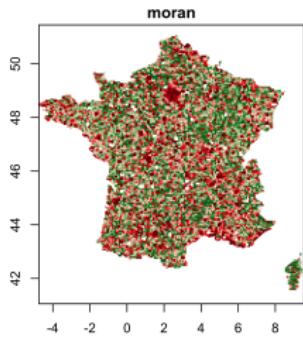


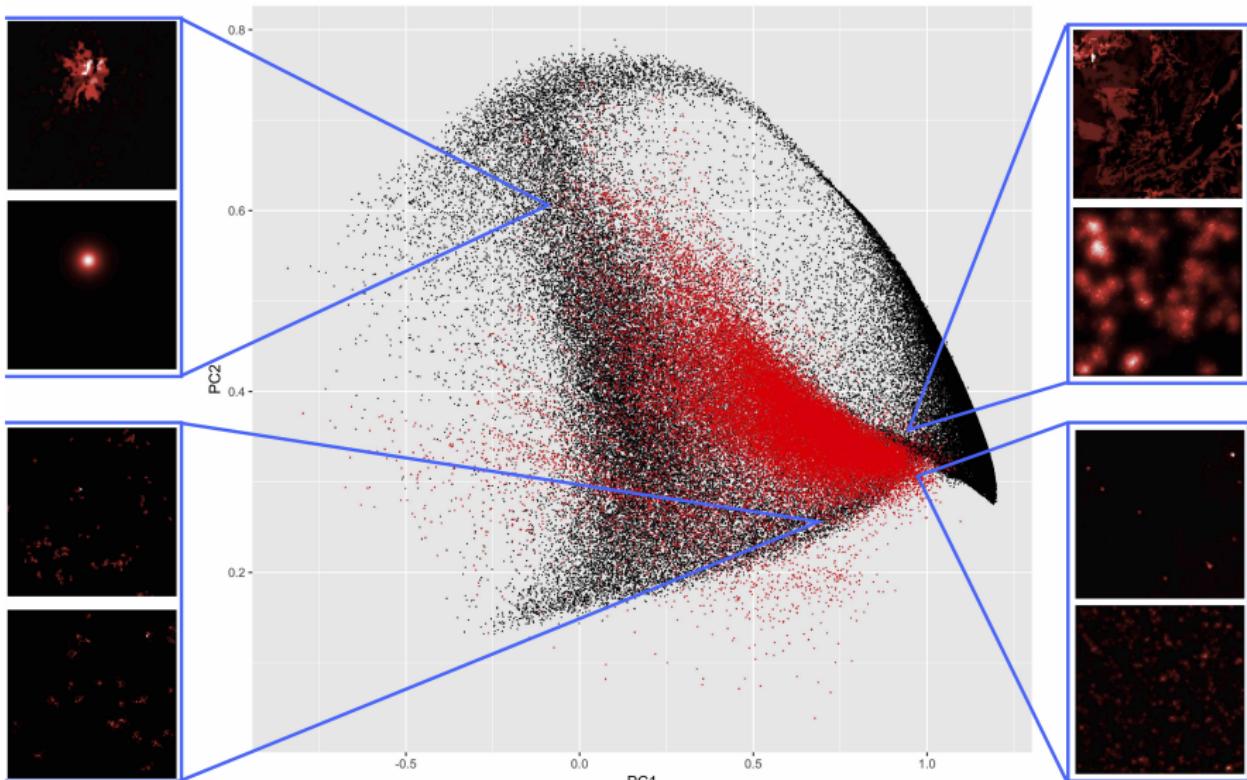
Illustration of path-dependence in a simplified one-dimensional version of the model: cell trajectories in time for 9 independent repetitions from the same initial configuration.

Empirical Data for Calibration



Computation of morphological indicators on real data for Europe (shown here on France), morphological classification.

Model Calibration



Brute force calibration by exploring the parameter space. Reproduction of most existing configuration in the morphological sense (here in principal plan).

Including more complex processes ?

Interactions between Networks and Territories

Complex co-evolutive processes between Territories and Transportation Networks



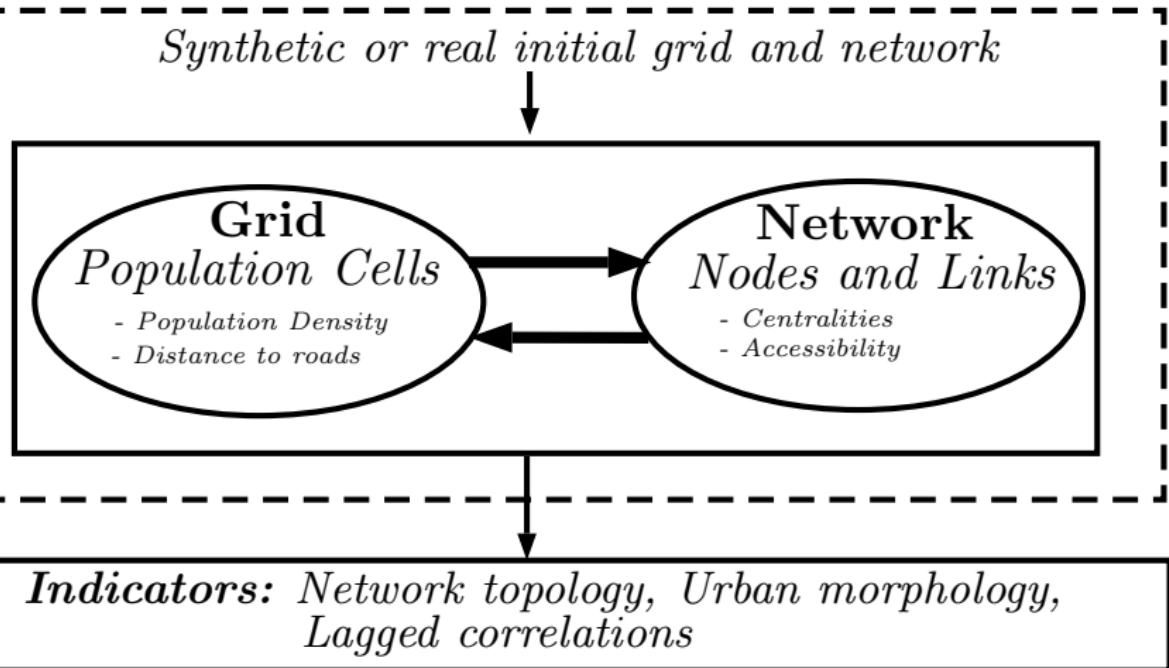
Expanding HSR network in China and ambiguous effects (Source : fieldwork survey)

A Morphogenesis Model of co-evolution

- Coupled grid population distribution and vector transportation network, following the core of [Raimbault et al., 2014]
- Local morphological and functional variables determine a patch-value, driving new population attribution through preferential attachment ; combined to population diffusion (aggregation-diffusion processes studied in [?])
- 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***

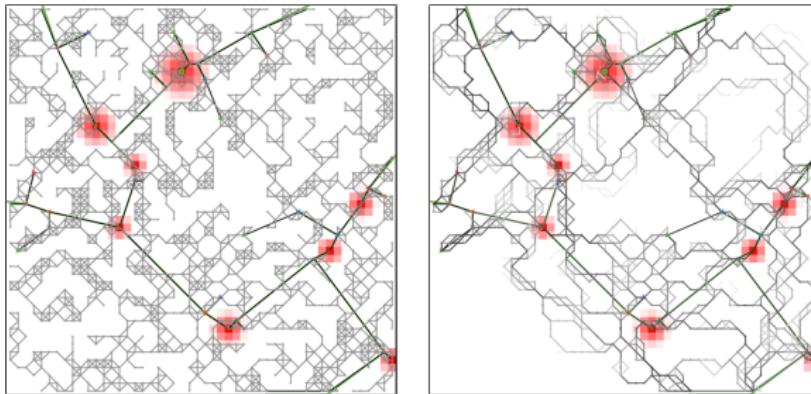
Model : Specification



Network Generation

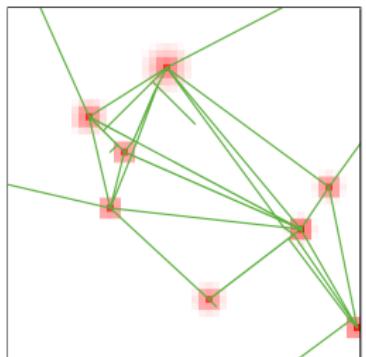
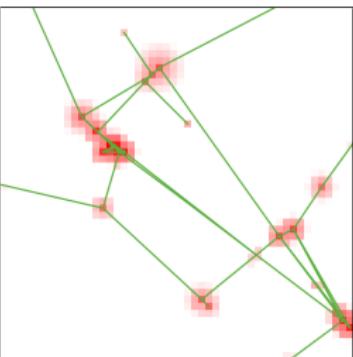
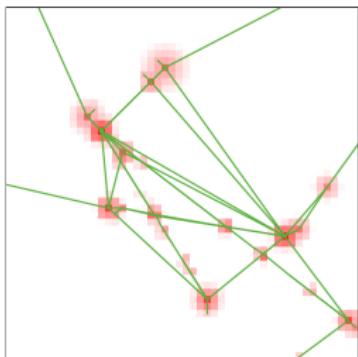
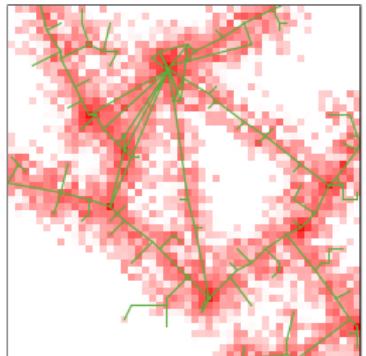
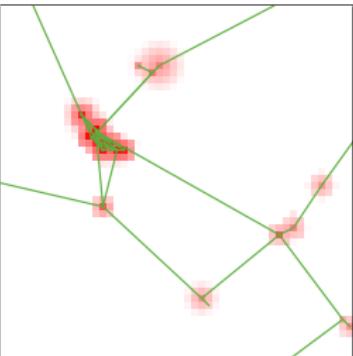
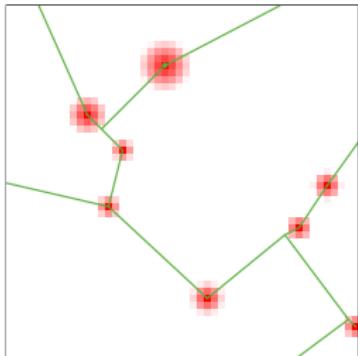
At fixed time steps :

- 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])



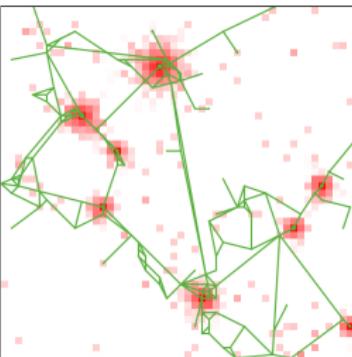
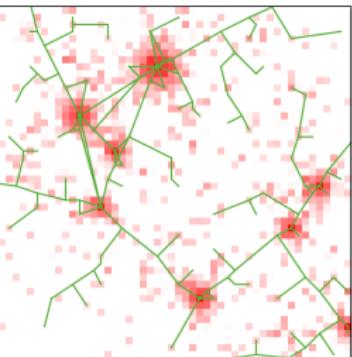
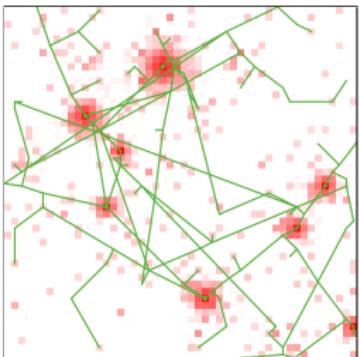
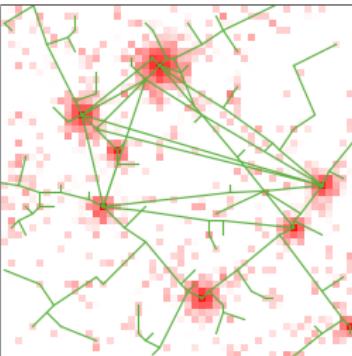
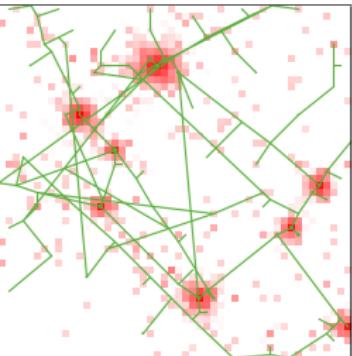
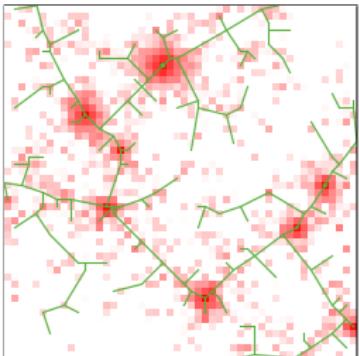
Intermediate stage for biological network generation

Generated Urban Shapes: Urban Form



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

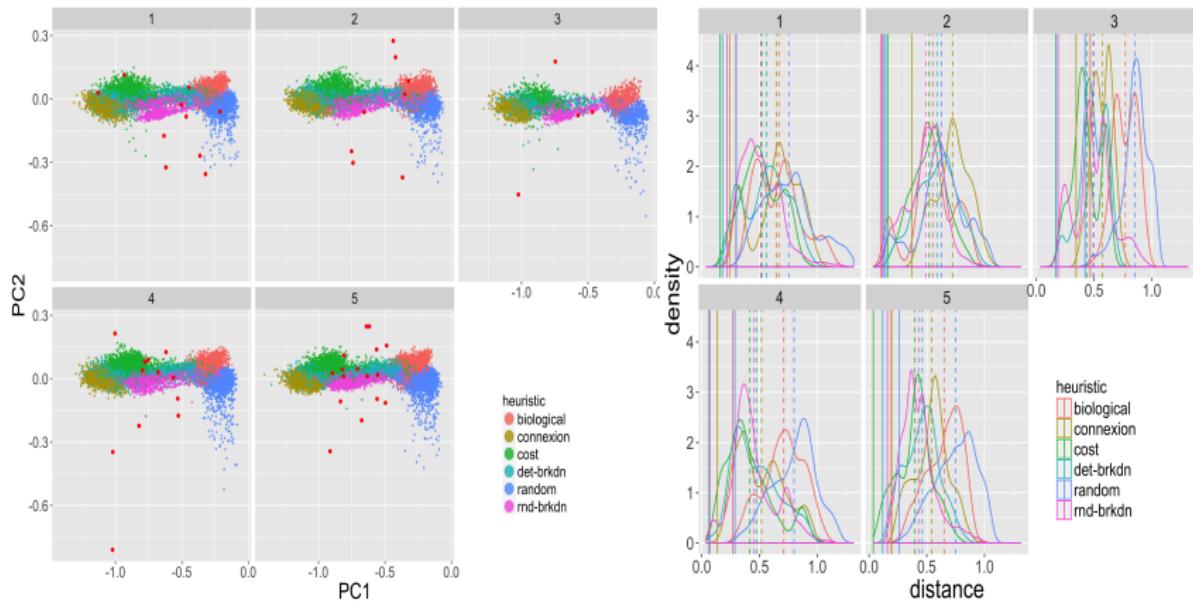
Generated Urban Shapes: Network



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

Results : Network Heuristics

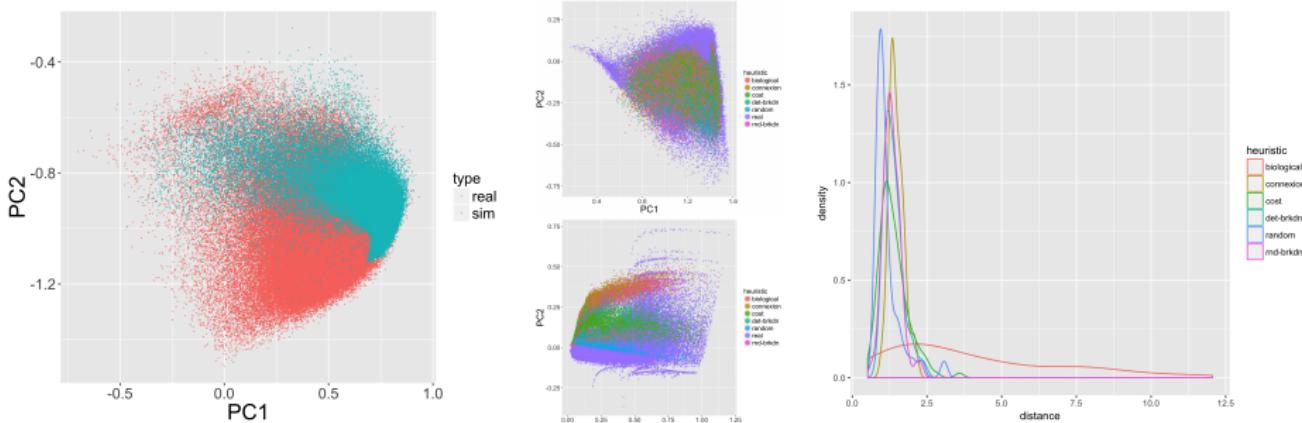
Comparison of feasible space for network indicators with fixed density



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

Results : Calibration

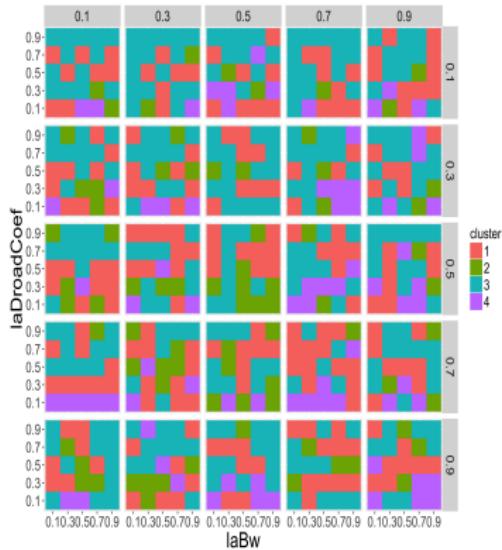
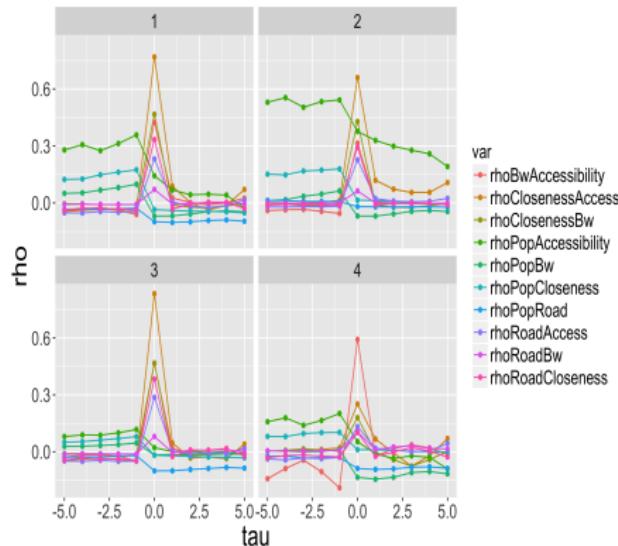
Calibration (model explored with OpenMole [Reuillon et al., 2013], $\sim 10^6$ model runs) at the first order on morphological and topological objectives, and on correlations matrices.



(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



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

Discussion

Conclusion

Reserve Slides

Morphogenesis concepts

- **Morphogenesis and Self-Organisation** : when does a system exhibit an architecture ? Insights from Morphogenetic Engineering [?]. Architecture : the relation between the form and the function ?
- **Scales, Units and Boundaries** From local interactions to global information flow (Holland's *signal and boundaries* [Holland, 2012]: morphogenesis as the development of Complex Adaptive Systems ?)
- **Symmetry and Bifurcations** : on quantitative becoming qualitative. René Thom's *theory of catastrophes* [Thom, 1974]
- **Life and Death** : link with autopoiesis and cognition [Bourgine and Stewart, 2004] ; co-evolution of subsystems as an alternative definition ? In psychology, attractors of the mind.

Catastrophe Theory

Modeling Urban Morphogenesis

- [Makse et al., 1998] correlated growth;
- [Murcio et al., 2015] multi-scale migration and percolation;
- [Bonin et al., 2012] qualitative differentiation of urban function;
- [Achibet et al., 2014] procedural model at the micro-scale

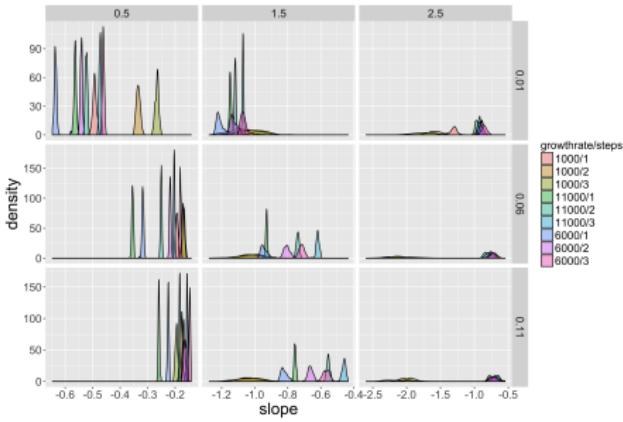
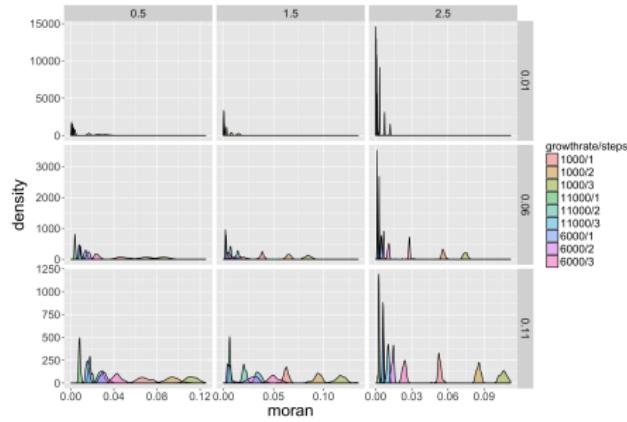
Model classification : PDE

The one-dimensional model verifies the PDE :

$$\delta t \cdot \frac{\partial p}{\partial t} = \frac{N_G \cdot p^\alpha}{P_\alpha(t)} + \frac{\alpha \beta (\alpha - 1) \delta x^2}{2} \cdot \frac{N_G \cdot p^{\alpha-2}}{P_\alpha(t)} \cdot \left(\frac{\partial p}{\partial x} \right)^2 + \frac{\beta \delta x^2}{2} \cdot \frac{\partial^2 p}{\partial x^2} \cdot \left[1 + \alpha \right] \quad (1)$$

Model behavior : Convergence

Large number of repetitions show good convergence properties



Defining co-evolution

No clear definition of co-evolution in the literature : [Bretagnolle, 2009] distinguishes “reciprocal adaptation” where a sense of causality can clearly be identified, from co-evolutive regimes

[?] identifies multiple causality regimes in a simple strongly coupled growth model → to be put in perspective with a theoretical definition of co-evolution based on the conjunction of Morphogenesis and the Evolutive Urban Theory, summarised by [Raimbault, 2017]

Modeling Co-evolution

[Baptiste, 2010] system dynamics with evolving capacities; [Wu et al., 2017] population diffusion and network growth;
[Blumenfeld-Lieberthal and Portugali, 2010] and [Schmitt, 2014] : random potential breakdown for network growth.

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