Modeling the Co-evolution of Urban Form and Transportation Networks

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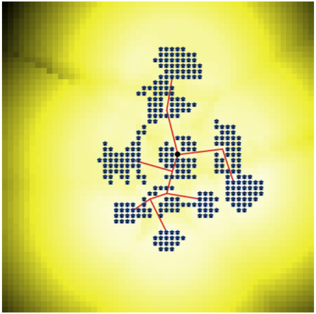
Complex processes of Urban Morphogenesis

Source: Google maps

Modeling Urban Morphogenesis



Source:
[Raimbault et al., 2014]

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

→ Co-evolution of Transportation Networks and Urban Settlements plays a specific role in real Urban Morphogenetic processes

Research Objective : Study a morphogenetic model at an intermediate scale, based on the co-evolution between a transportation network and population distribution.

Model : Rationale

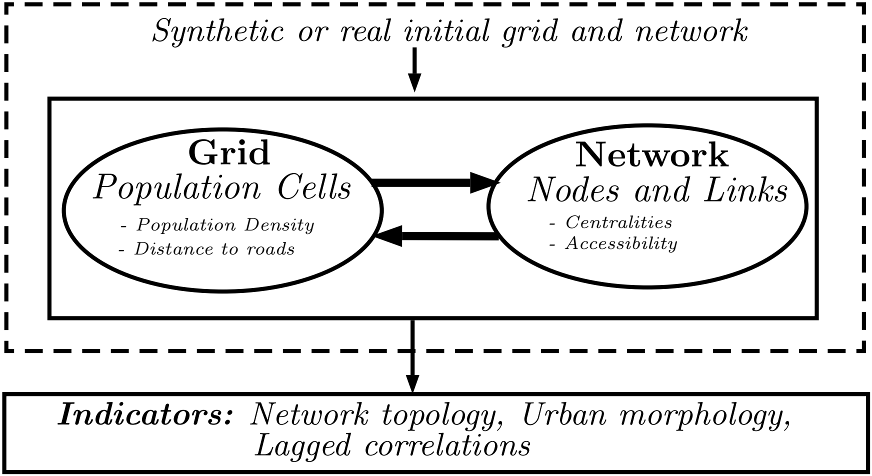
→ Coupled grid population distribution and vector transportation network, following the core of [Raimbault et al., 2014]

→ 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 [Raimbault, 2017])

→ 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***

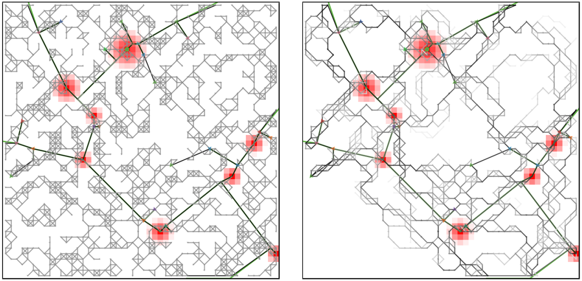
Model : Specification



Network Generation

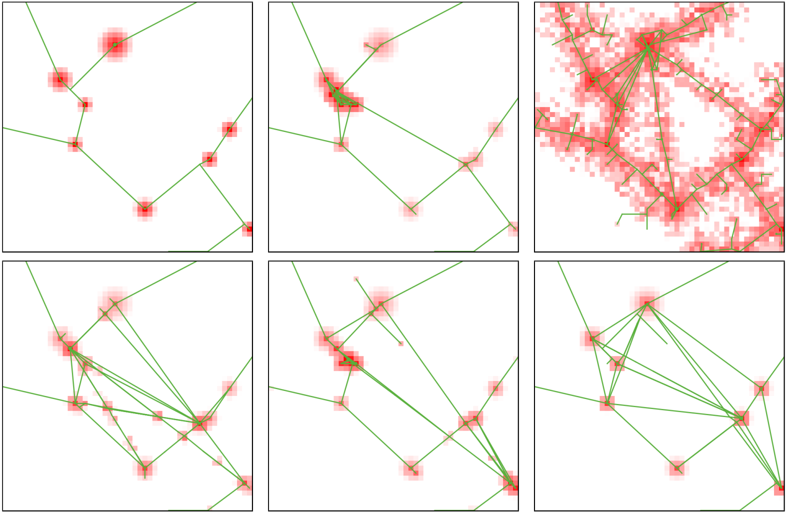
At fixed time steps :

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])



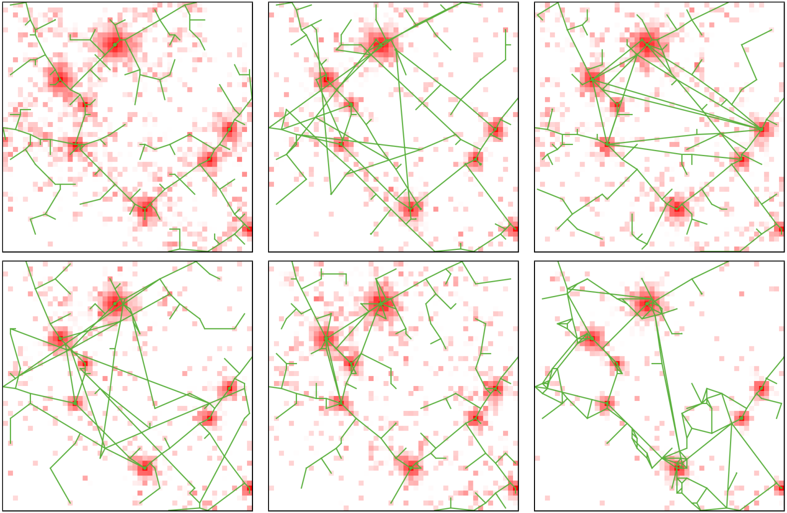
Intermediate stage for biological network generation

Generated Urban Shapes: Urban Form



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

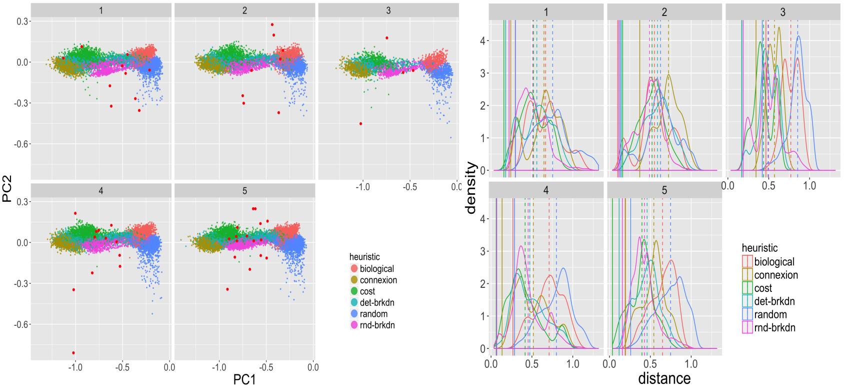
Generated Urban Shapes: Network



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

Results : Network Heuristics

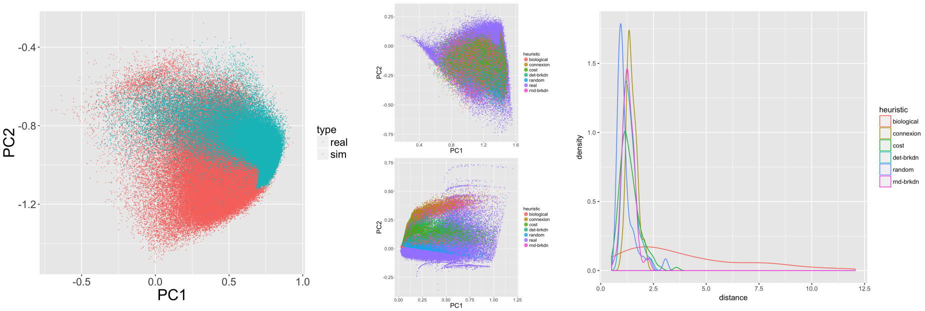
Comparison of feasible space for network indicators with fixed density



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

Results : Calibration

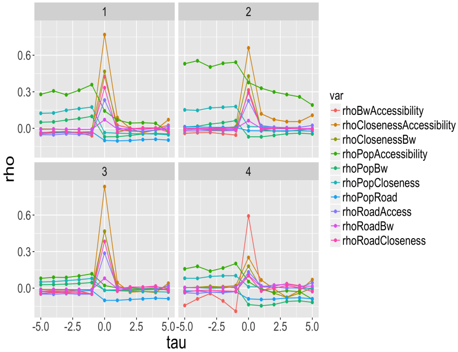
Calibration (model explored with OpenMole [Reuillon et al., 2013], $\sim 10^6$ model runs) at the first order on morphological and topological objectives, and on correlations matrices.

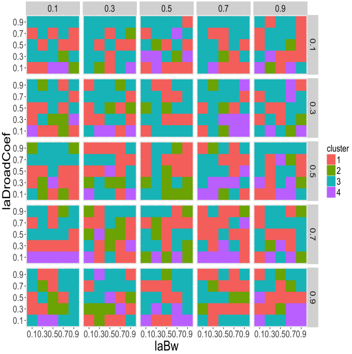


(Left) Full indicator space; (Middle) Morphological and Topology, by network heuristic; (Right) Distance distribution for cumulated distance for indicators and correlations.

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

Implications

→ 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 ?

→ 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

→ Towards a dynamical calibration, despite the sparsity of dynamical data

→ Investigate the link between spatial non-stationarity and non-ergodicity through simulation by the model

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

Conclusion

→ A novel model of urban morphogenesis at the mesoscopic scale systematically explored : need for more coupling and comparison of models.

→ At the macro scale of the system of cities ? Need for multi-scale models.

→ With more refined urban characteristics and other dimensions ? Need for more interdisciplinarity.

- Code, data and results available at
`https://github.com/JusteRaimbault/CityNetwork`

Reserve slides

Reserve Slides

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

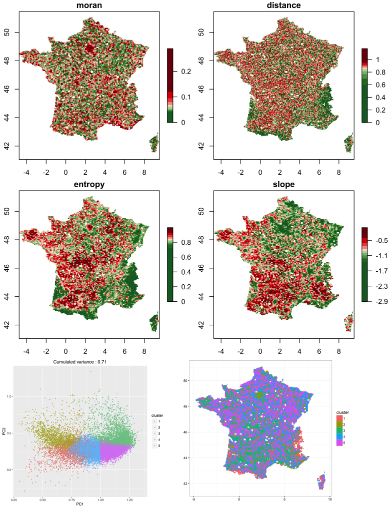
[Raimbault, 2017b] identifies multiple causality regimes in a simple strongly coupled growth model → to be put in perspective with a theoretical definition of co-evolution based on the conjunction of Morphogenesis and the Evolutive Urban Theory, summarised by [Raimbault, 2017a]

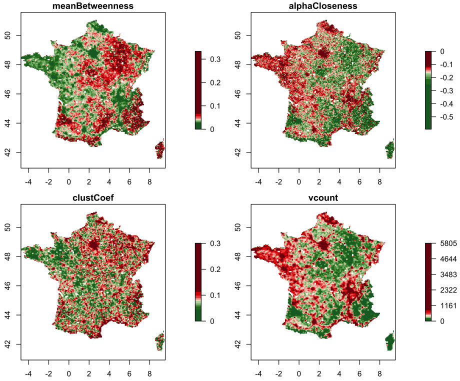
Modeling Urban Morphogenesis and Co-evolution

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

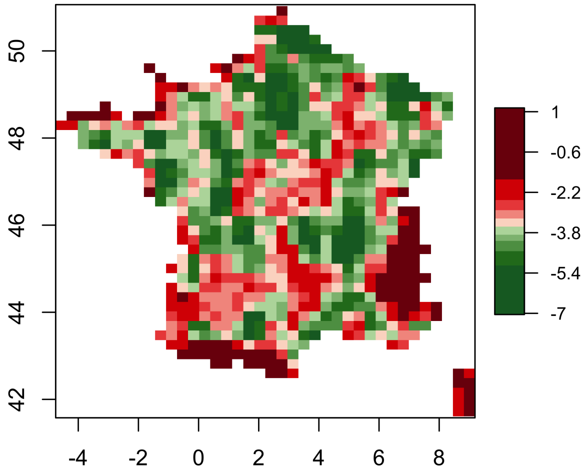
Co-evolution : [Baptiste, 2010] system dynamics with evolving capacities; [Wu et al., 2017] population diffusion and network growth; [Blumenfeld-Lieberthal and Portugali, 2010] and [Schmitt, 2014] : random potential breakdown for network growth.

Real Data : indicators





Real Data : correlations



Indicators

Urban morphology measured by:

- Spatial autocorrelation (Moran Index)
- Average distance
- Entropy
- Hierarchy (OLS slope for rank-size)

Network Topology measured by:

- Betweenness and Closeness centralities: average and hierarchy
- Accessibility (weighted closeness)
- Efficiency (network pace relative to euclidian distance)
- Mean path length, diameter

Model specification

Patch utility given by $U_i = \sum_k w_k \cdot \tilde{x}_k$ with $\tilde{x}_k$ normalized local variables among population, betweenness and closeness centrality, distance to roads, accessibility ; aggregation done with probability $(U_i / \sum_k U_k)^\alpha$; diffusion among neighbors n_d times with strength β

Network Generation :
Adding a fixed number n_N of new nodes : for patches such that $d_r < d_0$, probability to receive a node is

$$p = P/P_{max} \cdot (d_M - d)/d_M \cdot \exp\left(-((d_r - d_0)/\sigma_r)^2\right)$$

Nodes connected the shortest way to existing network.

General model parameters :

- Patch utility weights w_k
- General network generation parameters: growth time steps t_N, maximal additional links

Deterministic breakdown Network generation

1. Gravity potential given by

$$V_{ij}(d) = \left[(1-k_h) + k_h \cdot \left(\frac{P_i P_j}{P^2}\right)^{\gamma}\right] \cdot \exp\left(-\frac{d}{r_g(1+d/d_0)}\right)$$

2. $k \cdot N_L$ links are selected with lowest $V_{ij}(d_N)/V_{ij}(d_{ij})$, among which N_L links with highest (lest costly) are realized
3. Network is planarized

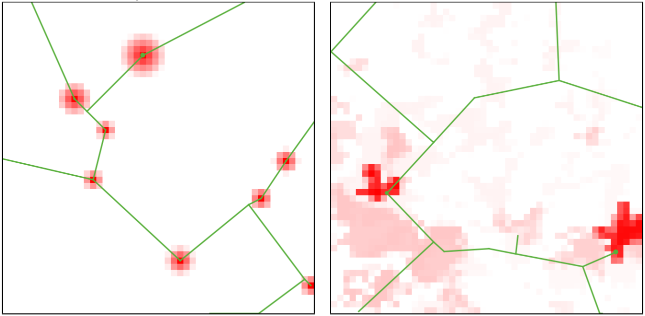
Biological Network generation

Adding new links with biological heuristic:

1. Create network of potential new links, with existing network and randomly sampled diagonal lattice
2. Iterate for k increasing ($k \in \{1, 2, 4\}$ in practice) :
   - Using population distribution, iterate $k \cdot n_b$ times the slime mould model to compute new link capacities
   - Delete links with capacity under θ_d
   - Keep the largest connected component
3. Planarize and simplify final network

Model setup

Synthetic setup: rank-sized monocentric cities, simple connection with bord nodes to avoid bord effects
Real setup: Population density raster at 500m resolution (European Union, from Eurostat)

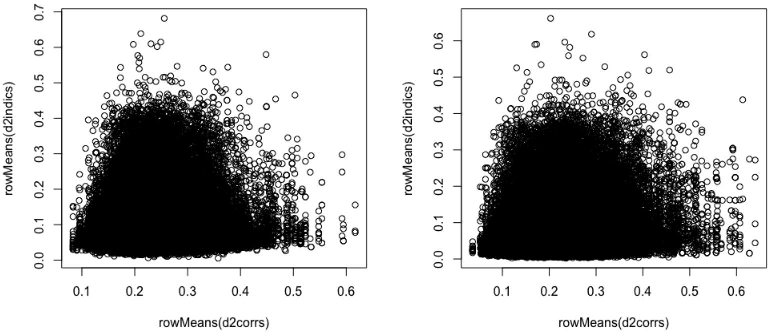


Stopping conditions: fixed final time; fixed total population; fixed network size.

Calibration Method

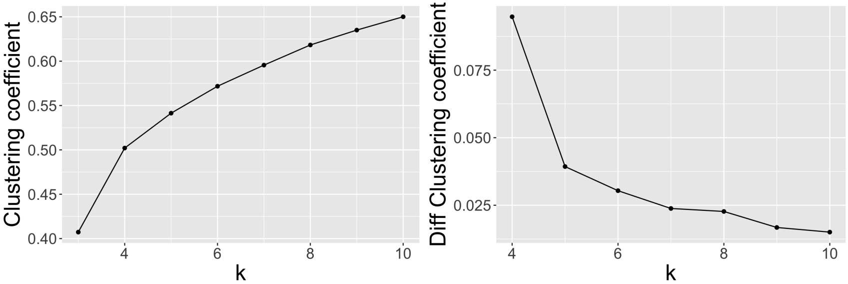
- Brute force exploration of a LHS sampling, 10 repetitions of the model for each parameter point.
- For each simulated point, closest in indicator space (euclidian distance for normalized indicators) among real points are selected.
- Among these, point with lowest distance to correlation matrix are taken.

Calibration : optimal points



Pareto plots of distance to indicators and distance to correlation matrices, for a given simulated configuration and all real points.

Causality regimes: clustering



Clustering coefficient (left) and its derivative (right) as a function of number of clusters

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