Modeling Urban Morphogenesis

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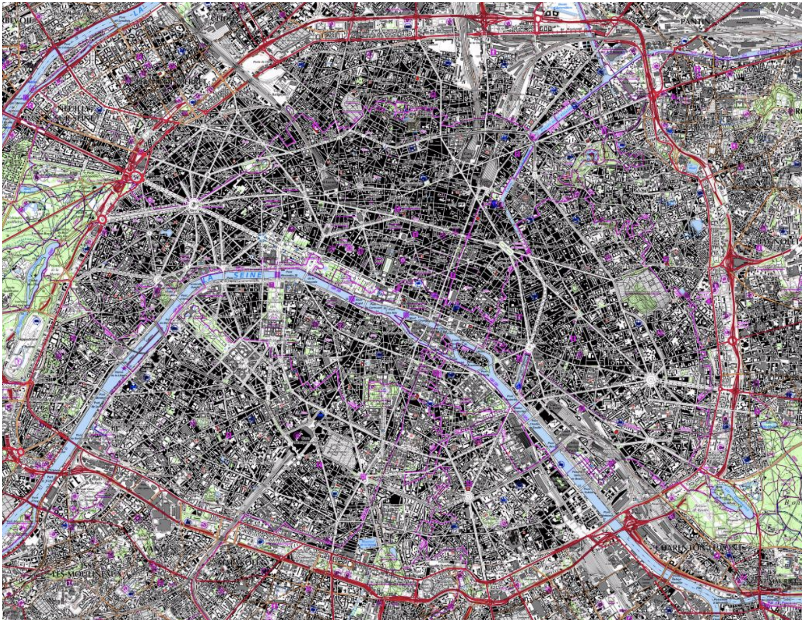
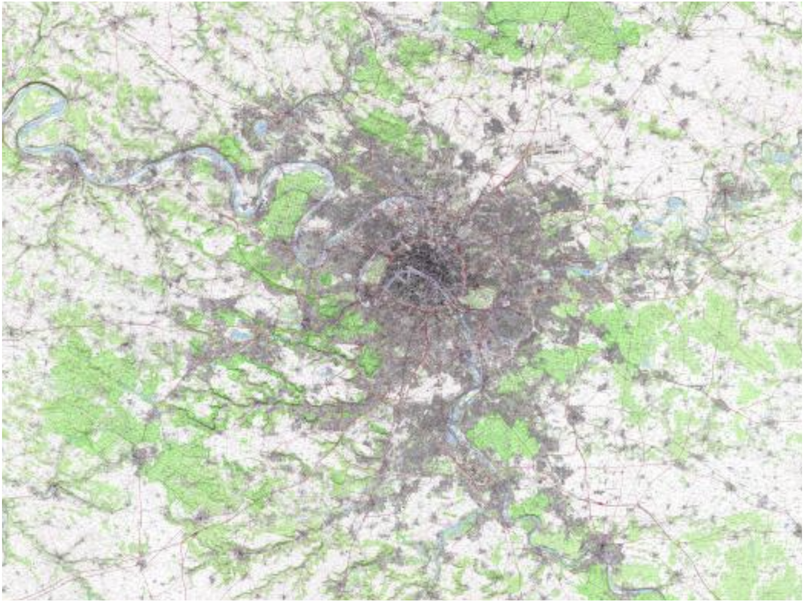
Complex processes of Urban Morphogenesis



Source: Geoportail

Complex processes of Urban Morphogenesis



Source: Geoportail

What is Morphogenesis ?

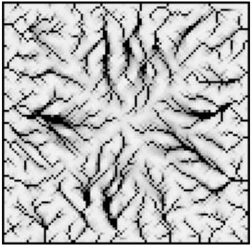
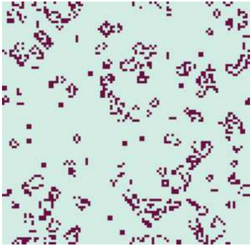
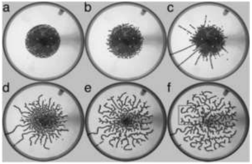
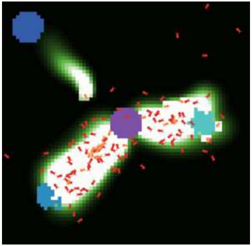
Morphogenesis (*Oxford dictionary*)

1. *Biology* : The origin and development of morphological characteristics
2. *Geology* : The formation of landforms or other structures.

History of the notion

→ Started significantly with embryology around 1930 [Abercrombie, 1977]
→ Turing's 1952 paper [Turing, 1952], linked to the development of Cybernetics
→ first use in 1871, large peak in usage between 1907-1909, increase until 1990, decrease until today. *Scientific fashion ?*

What is Morphogenesis ? Examples

	Physical	Biological	Engineereed
Non Functional			
Functional			

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]

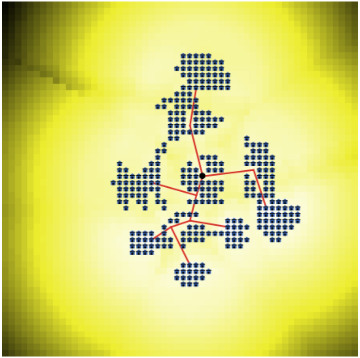
Meta-epistemological framework of imbricated notions:
Self-organization $\supsetneq$ Morphogenesis $\supsetneq$ Autopoiesis $\supsetneq$ Life

Properties:

- Architecture links form and function
- Emergence strength [Bedau, 2002] increases with notion depth, as bifurcations [Thom, 1974]

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

Which models for Urban Morphogenesis ?



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

→*At the crossroad between Urban Simulation and Artificial Life, few models try to integrate and explain the link between Urban Form and Function*

→*Importance of parcimonious, stylized models: modeling as a tool to understand processes*

Research Objective : Explore simple models to capture morphogenesis based on abstract representation of urban processes; test their ability to reproduce existing urban systems.

A simple Reaction-diffusion model

$\rightarrow$ Crucial role of the interplay between concentration forces and dispersion forces [Fujita and Thisse, 1996] in keeping Urban Systems at the border of chaos

$\rightarrow$ Potentiality of aggregation mechanisms (such as Simon model) to produce power laws [Sheridan Dodds et al., 2016]

$\rightarrow$ Link with Reaction-diffusion approaches in Morphogenesis [Turing, 1952]

$\rightarrow$ Extension of a DLA-type model introduced by [Batty, 1991], with simple abstract processes of population aggregation and diffusion

Model Formalization

$\rightarrow$ Grid world with cell populations $(P_i(t))_{1 \leq i \leq N^2}$.

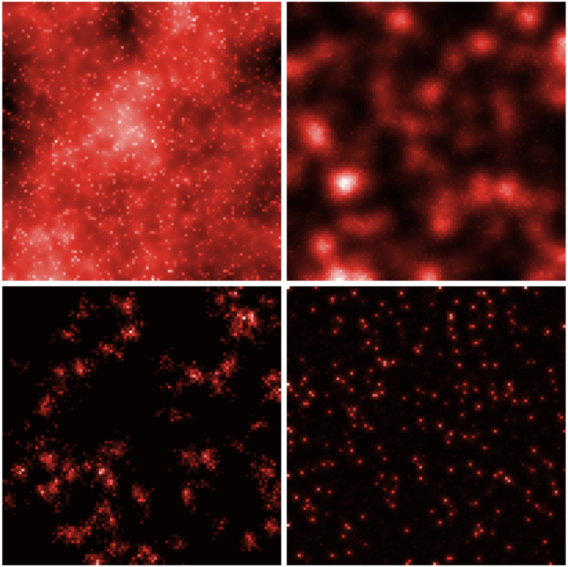
$\rightarrow$ At each time step:

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

$\rightarrow$ Stopping criterion: fixed maximal population P_m.

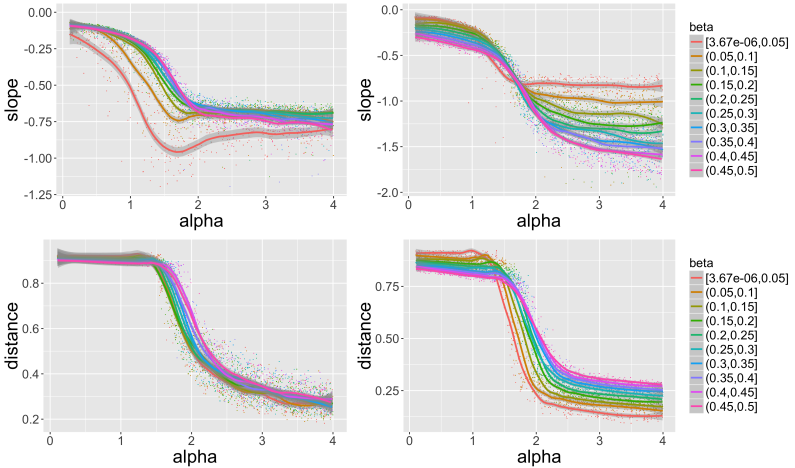
$\rightarrow$ Output measured by morphological indicators: Moran index, average distance, rank-size hierarchy, entropy.

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

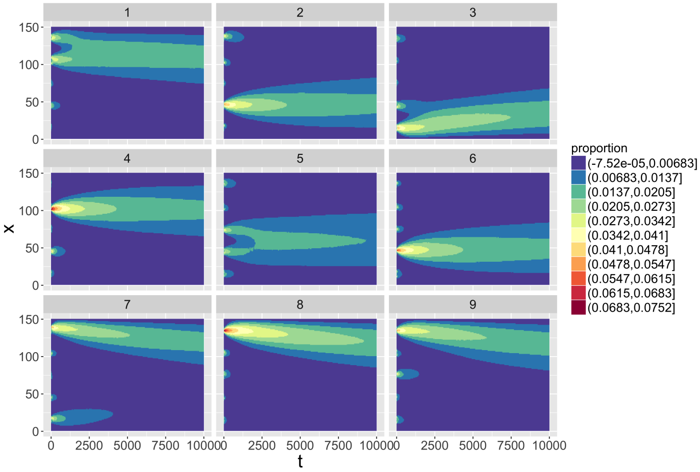
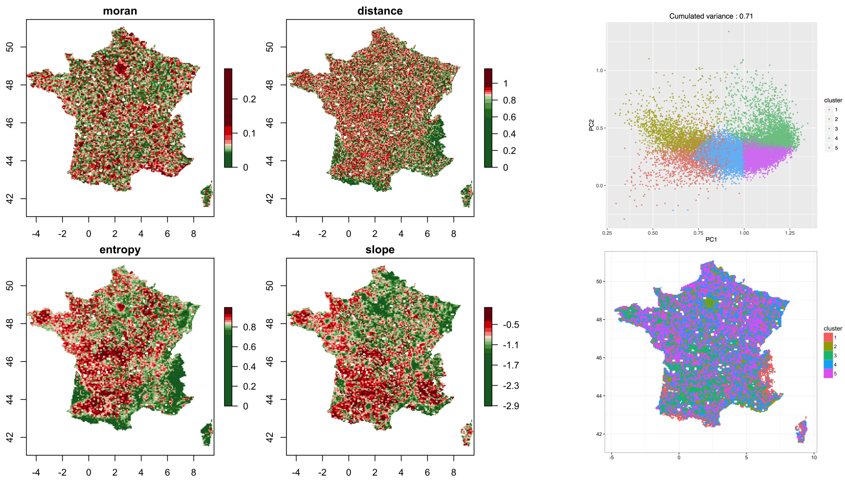


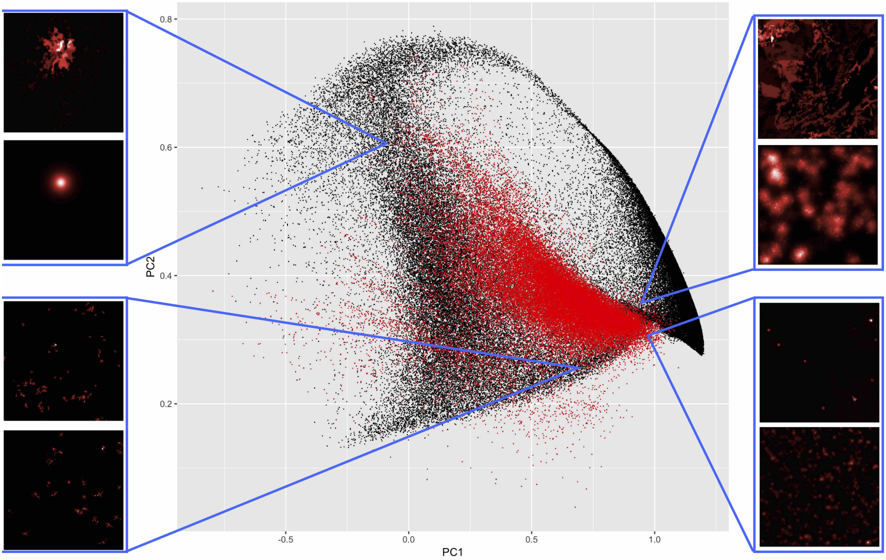
Illustration of path-dependence in a simplified one-dimensional version of the model: cell trajectories in time for 9 independent repetitions from the same initial configuration.

Empirical Data for Calibration



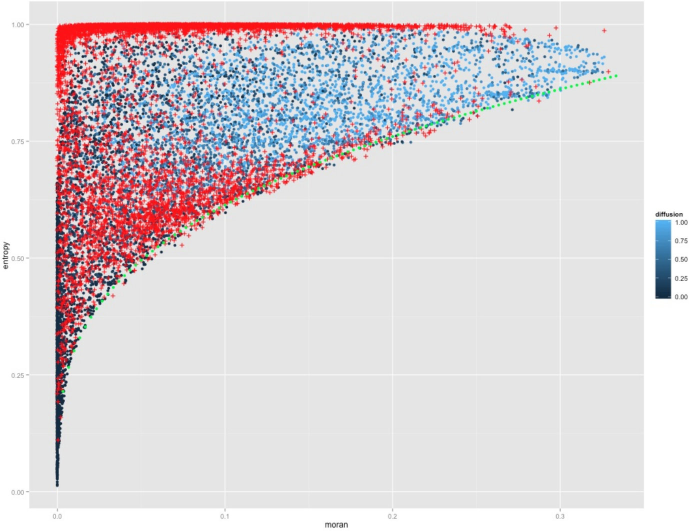
Computation of morphological indicators on population density data for Europe (shown here on France), morphological classification.

Model Calibration



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

Model Targeted Exploration



Potentialities of targeted model explorations: here feasible space using Pattern Space Exploration algorithm [Chérel et al., 2015].

Including more complex processes ?

Which ontology to include more complex functional properties ?

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

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

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

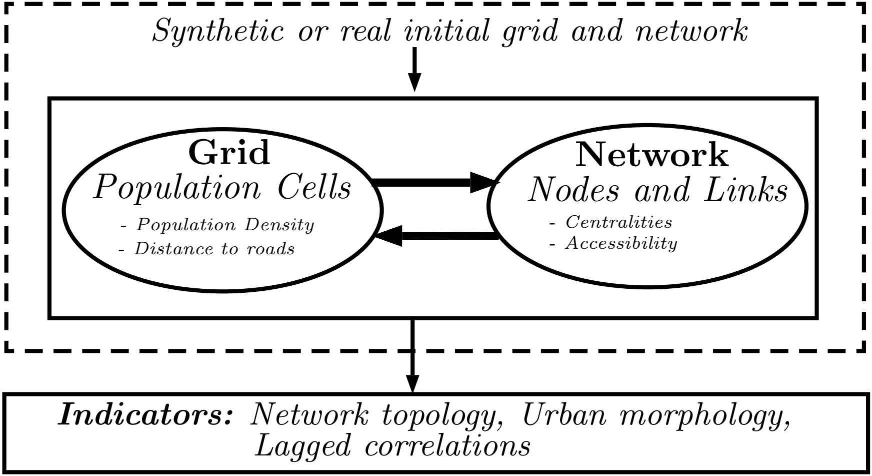
$\rightarrow$ Coupled grid population distribution and vector transportation network, following the core of [Raimbault et al., 2014]

$\rightarrow$ 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***

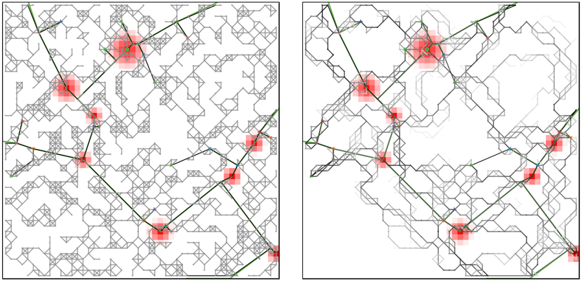
Model : Specification



Network Generation

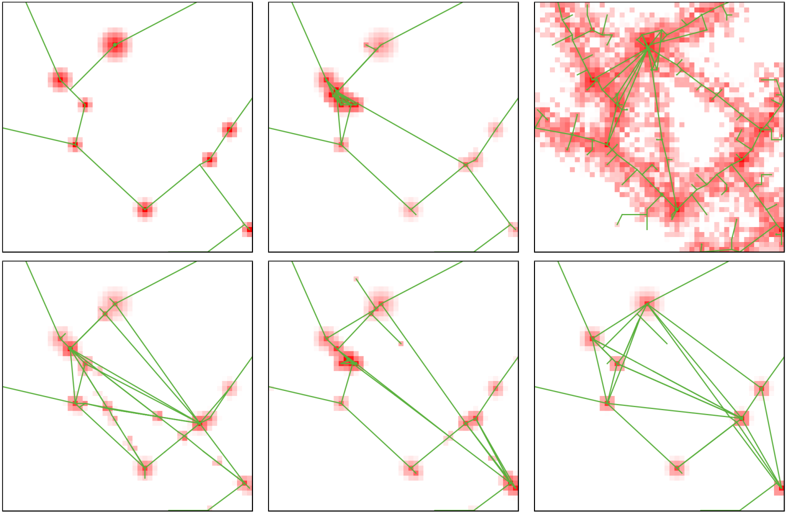
At fixed time steps :

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])



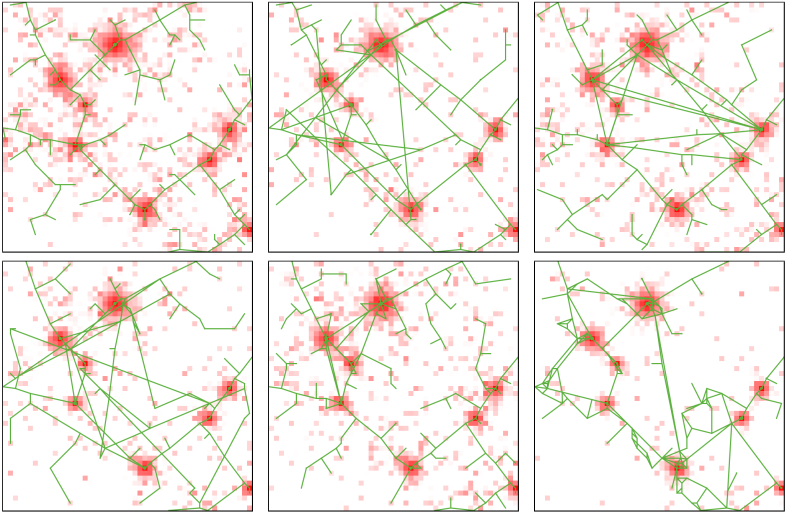
Intermediate stage for biological network generation

Generated Urban Shapes: Urban Form



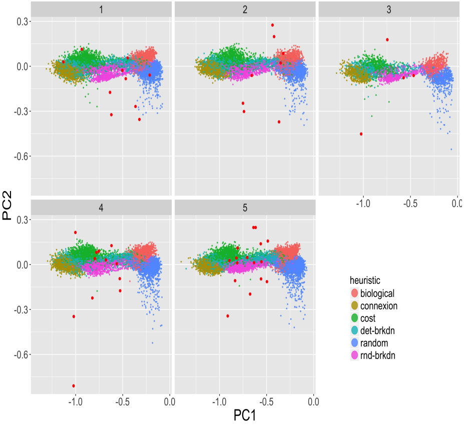
In order: setup; accessibility driven; road distance driven; betweenness driven; closeness driven; population driven.

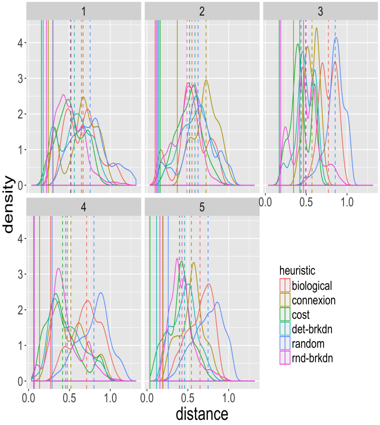
Generated Urban Shapes: Network



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

Comparison of feasible space for network indicators with fixed density

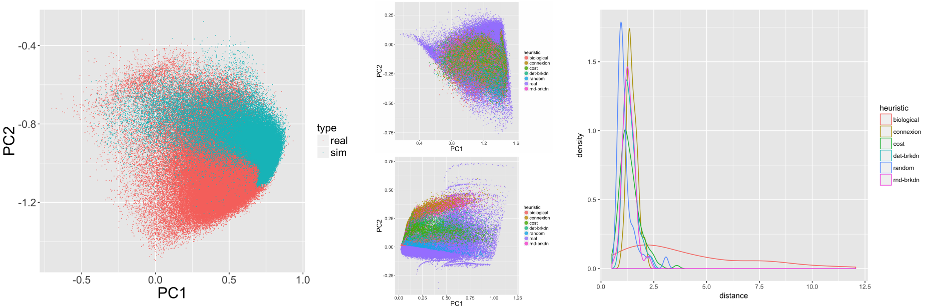




(Left) Feasible spaces by morphological class and network heuristic; (Right) Distribution of distances to topologies of real networks

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.

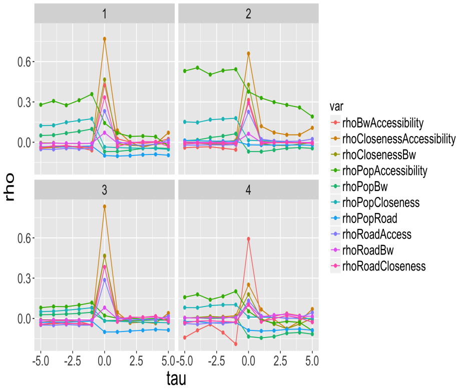


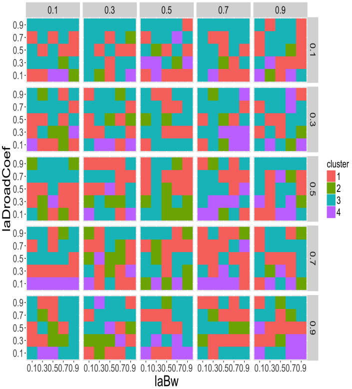
(Left) Full indicator space; (Middle) Morphological and Topology, by network heuristic; (Right) Distance distribution for cumulated distance for indicators and correlations.

Results : Causality Regimes

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

→ 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

→ 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 ? Need of dynamical data

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

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

Conclusion

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

$\rightarrow$ At the macro scale of the system of cities ? **Need for multi-scale models.**

$\rightarrow$ With more refined urban characteristics and other dimensions ? **Need for more interdisciplinarity.**

- Code, data and results available at `https://github.com/JusteRaimbault/CityNetwork`
- Paper on arXiv at `https://arxiv.org/abs/1708.06743`
- Acknowledgments : We thank the *European Grid Infrastructure* and its *National Grid Initiatives* (*France-Grilles* in particular) to give the technical support and the infrastructure.

Reserve Slides

Morphogenesis Overview

[Bourgine and Lesne, 2010] : interdisciplinary workshop on morphogenesis

→ *To what extent the notion is indeed transdisciplinary, i.e. are there common definitions across disciplines ? What are the concepts shared or the divergence ?*

- Biology
  - External phenotype morphogenesis (ant colony) [Minter et al., 2012]
  - Symbiosis of species [Chapman and Margulis, 1998]
  - Botany [Lord, 1981]
- **Social Sciences** : Archeology [Renfrew, 1978]
- **Epistemology** : [Gilbert, 2003]
- **Artificial Intelligence** : From self-assembly to Morphogenetic Engineering [Doursat et al., 2013]. Synthetic Biology ?
- **Geomorphology** : dunes formation [Douady and Hersen, 2011]
- **Physics** : Arbotrons playing Tetris ?
- etc. . .

Morphogenesis concepts

- **Morphogenesis and Self-Organisation** : when does a system exhibit an architecture ? Insights from Morphogenetic Engineering [Doursat 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

A system is viewed as its internal state X_w, where $w \in W$ is a control parameter.

Catastrophe set $K \subset W$ is where the system endures phase transition.

Thom classified possible topologies for K depending on the dimension of W.

Modeling Urban Morphogenesis

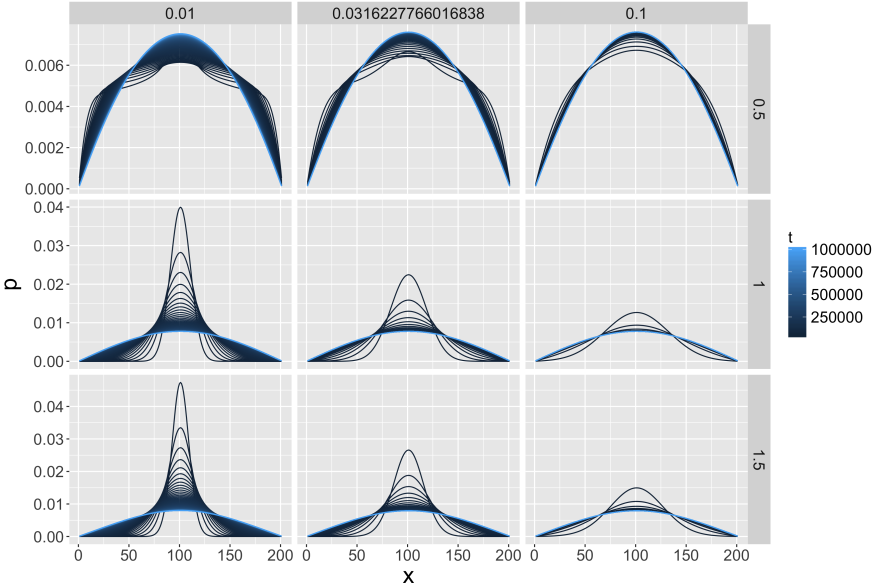
[Makse et al., 1998] correlated growth;
[Murcio et al., 2015] multi-scale migration and percolation;
[Bonin et al., 2012] qualitative differentiation of urban function;
[Achibet et al., 2014] procedural model at the micro-scale

Model classification : PDE

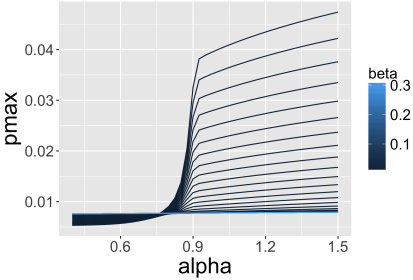
The one-dimensional model verifies the PDE :

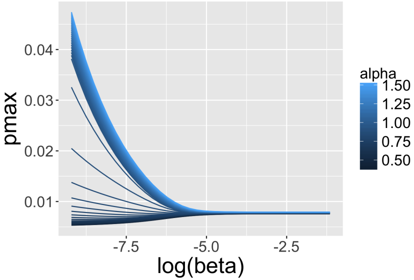
$$\delta t \cdot \frac{\partial p}{\partial t} = \frac{N_G \cdot p^{\alpha}}{P_{\alpha}(t)} + \frac{\alpha\beta(\alpha-1)\delta x^2}{2} \cdot \frac{N_G \cdot p^{\alpha-2}}{P_{\alpha}(t)} \cdot \left(\frac{\partial p}{\partial x}\right)^2 + \frac{\beta \delta x^2}{2} \cdot \frac{\partial^2 p}{\partial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

Stationary behavior of 1D model



Stationary behavior of 1D model





Morphological indicators

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

$$\mathscr{E} = \sum_{i=1}^{M} \frac{P_i}{P} \cdot \ln \frac{P_i}{P} \qquad (2)$$

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

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

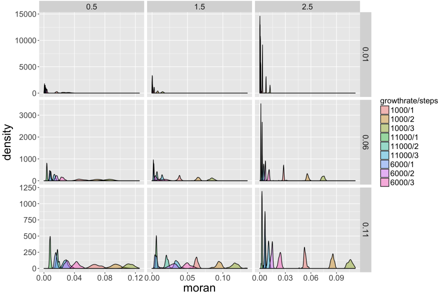
4. Mean distance between individuals

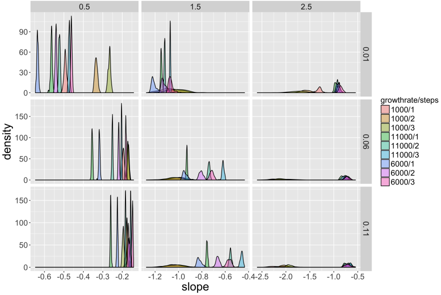
$$\bar{d} = \frac{1}{d_M} \cdot \sum_{i<j} \frac{P_i P_j}{P^2} \cdot d_{ij}$$

   where d_M is a normalisation constant

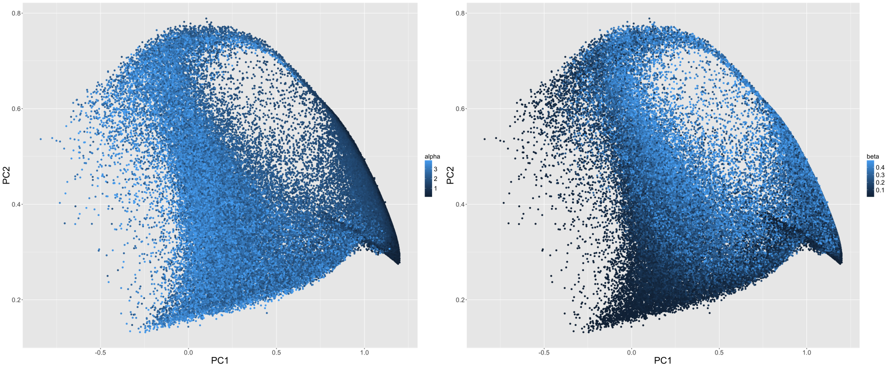
Model behavior : Convergence

Large number of repetitions show good convergence properties





Model behavior



Empirical indicators computation

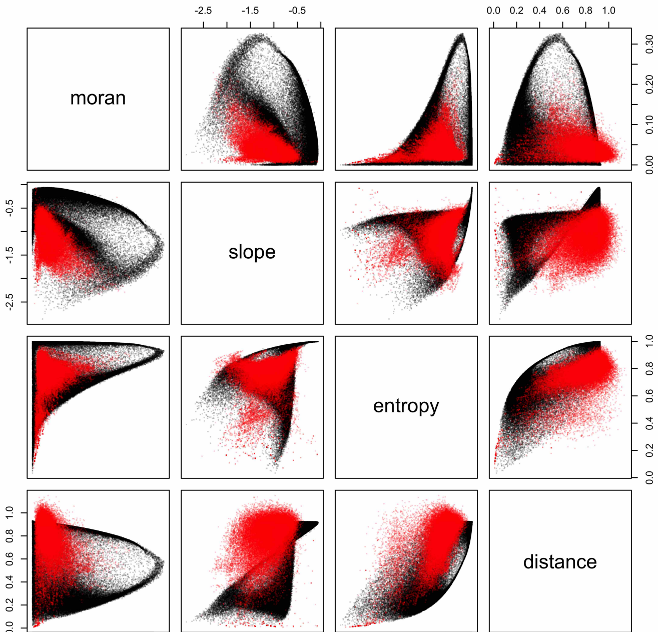
$\rightarrow$ Eurostat population density raster (100m, simplified at 500m resolution)

$\rightarrow$ Overlapping (10km offset) squares of 50km side : equivalent to smoothing, removes window shape effect. Not very sensitive to window size (tested with 30km and 100km)

$\rightarrow$ Indicators computed using Fast Fourier Transform Convolution

$\rightarrow$ Classification using repeated k-means ; number of clusters taken at transition in clustering coefficient.

Model calibration: all indicators



Defining co-evolution

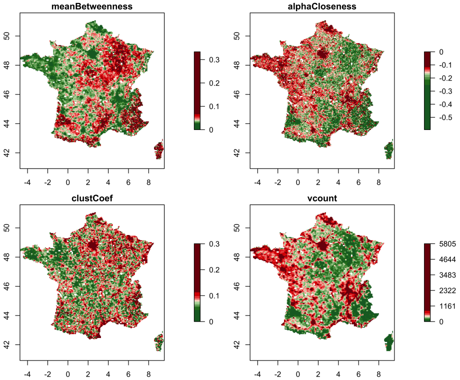
No clear definition of co-evolution in the literature : [Bretagnolle, 2009] distinguishes "reciprocal adaptation" where a sense of causality can clearly be identified, from co-evolutive regimes

Identification of 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]

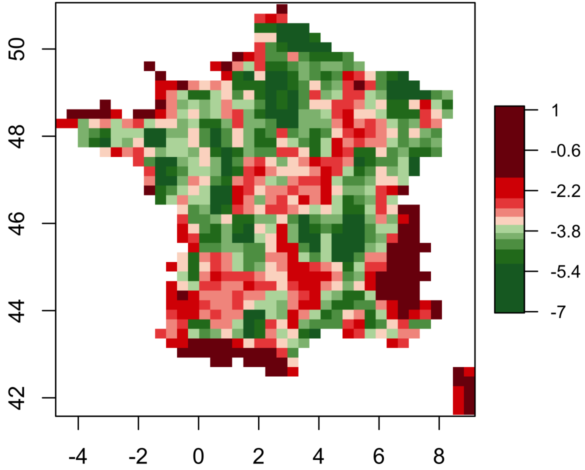
Modeling Co-evolution

[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.
[Barthélemy and Flammini, 2009] geometrical network growth model making network topology co-evolve with vertex density

Empirical Data : network indicators



Empirical Data : correlations



Network Indicators

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

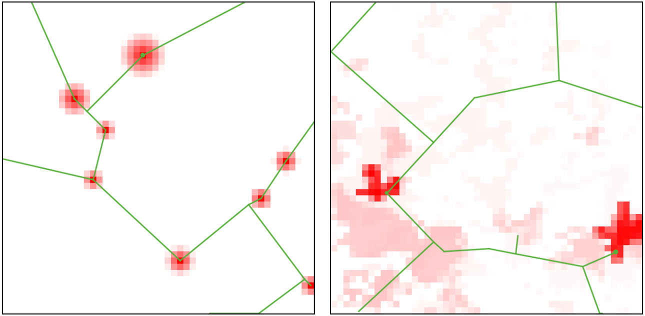
Adding new links with biological heuristic:

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)

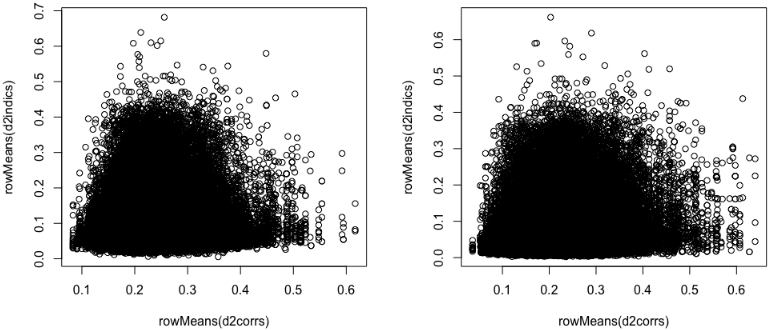


Stopping conditions: fixed final time; fixed total population; fixed network size.

Calibration Method

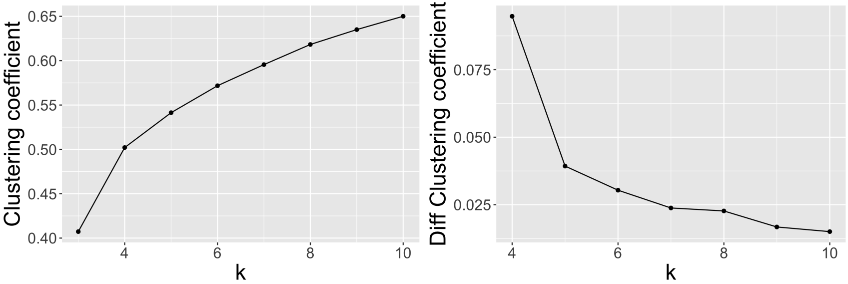
- Brute force exploration of a LHS sampling, 10 repetitions of the model for each parameter point.
- For each simulated point, closest in indicator space (euclidian distance for normalized indicators) among real points are selected.
- Among these, point with lowest distance to correlation matrix are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

Calibration : optimal points



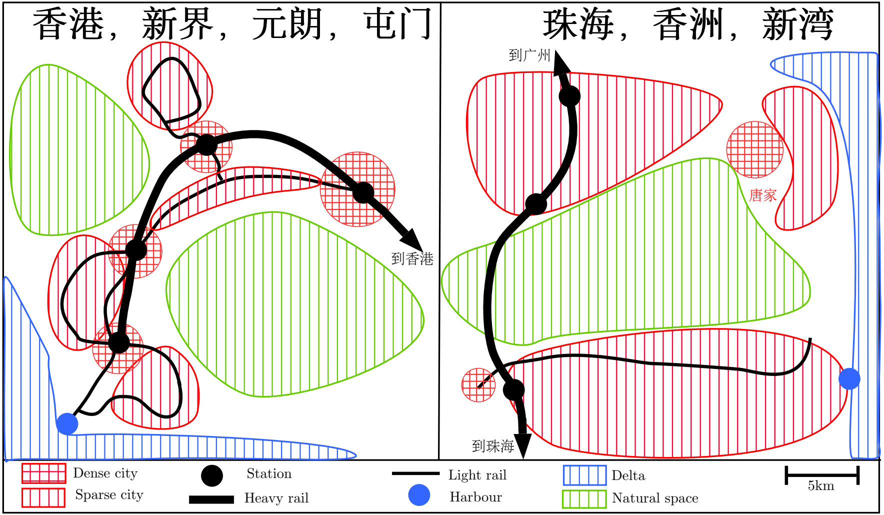
Pareto plots of distance to indicators and distance to correlation matrices, for a given simulated configuration and all real points.

Causality regimes: clustering

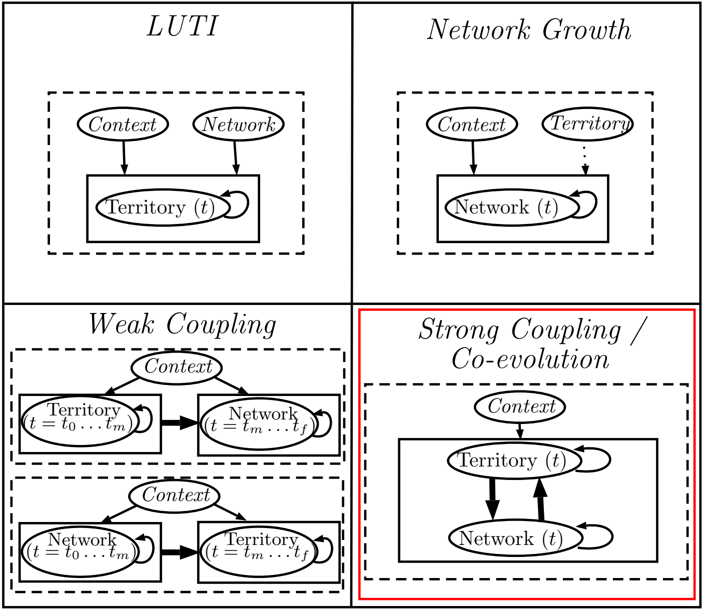


Clustering coefficient (left) and its derivative (right) as a function of number of clusters

Implementations of TOD



Co-evolution Models



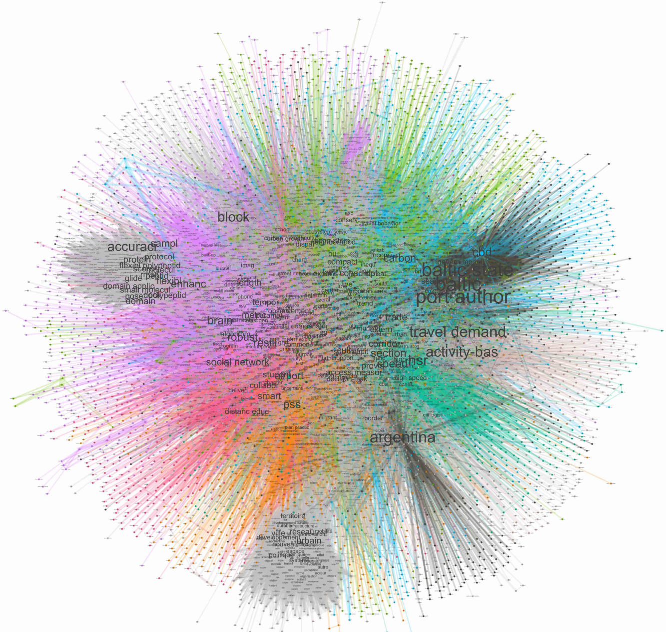
Citation Network

Citation Network Properties

For the core (hence full) subnetwork :

- Size $V = 3510$, Mean degree $\bar{d} = 2.53$ and density $\gamma = 0.0013$, weakly connected.
- 13 communities, directed modularity [Nicosia et al., 2009] 0.66 (null model gives 0.0005 ± 0.0051 on $N = 100$ bootstraps)
- Content : LUTI (18%), Urban and Transportation Geography (16%), Infrastructure Planning (12%), TOD (6%), Spatial Networks (17%), Accessibility studies (18%)

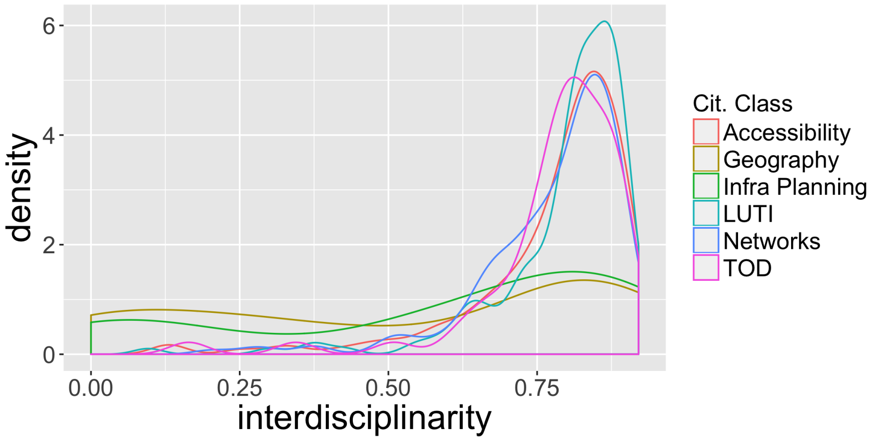
Semantic Network



Semantic communities

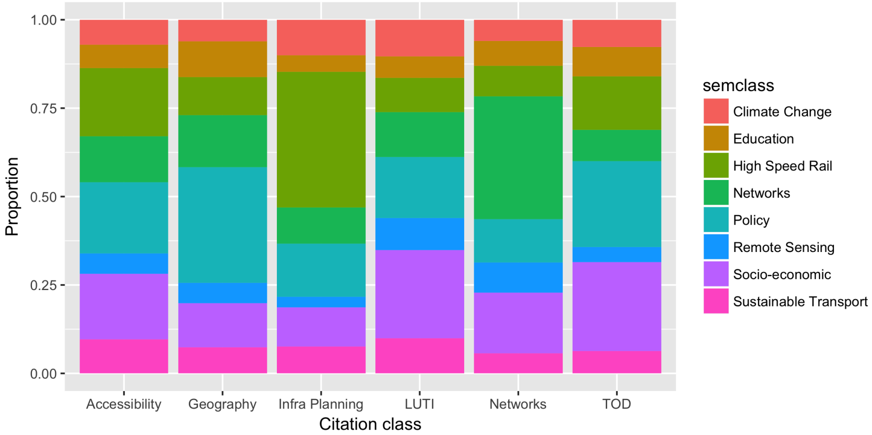
Name	Size	Weight	Keywords
Networks	820	13.57%	social network, spatial network, res
Policy	700	11.8%	actor, decision-mak, societi
Socio-economic	793	11.6%	neighborhood, incom, live
High Speed Rail	476	7.14%	high-spe, corridor, hsr
French Geography	210	6.08%	système, développement, territoire
Education	374	5.43%	school, student, collabor
Climate Change	411	5.42%	mitig, carbon, consumpt
Remote Sensing	405	4.65%	classif, detect, cover
Sustainable Transport	370	4.38%	sustain urban, travel demand, activi
Traffic	368	4.23%	traffic congest, cbd, capit
Maritime Networks	402	4.2%	govern model, seaport, port author
Environment	289	3.79%	ecosystem servic, regul, settlement
Accessibility	260	3.23%	access measur, transport access, urb
Agent-based Modeling	192	3.18%	agent-bas, spread, heterogen
Transportation planning	192	3.18%	transport project, option, cba
Mobility Data Mining	168	2.49%	human mobil, movement, mobil phone
Health Geography	196	2.49%	healthcar, inequ, exclus
Freight and Logistics	239	2.06%	freight transport, citi logist, moda
Measuring	166	1.0%	score, sampl, metric

Interdisciplinarity patterns



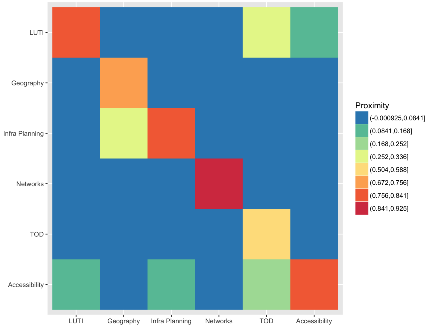
Distribution of interdisciplinarities

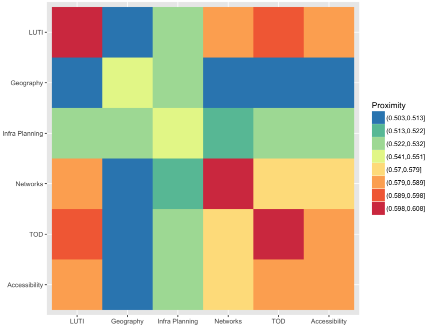
Interdisciplinarity patterns



Semantic composition of citation communities

Community Proximities





Proximities between citation communities (Left) and semantic communities (Right)

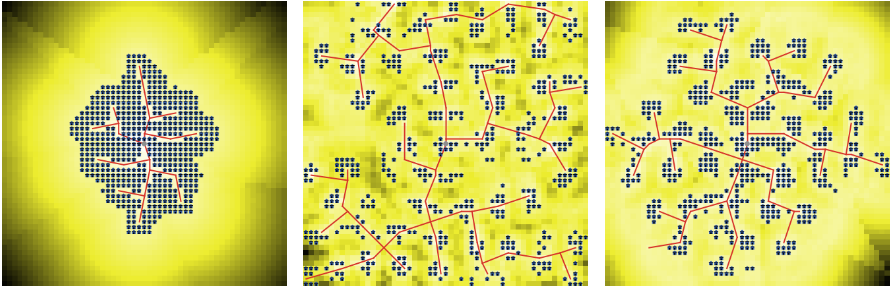
Causality Regimes Method: Formalization

Correlation estimator $\hat{\rho}$ applying in time, space and repetitions, i.e. $\hat{\rho}\left[X, Y\right] = \hat{\mathbb{E}}_{i,t,k}\left[XY\right] - \hat{\mathbb{E}}_{i,t,k}\left[X\right]\hat{\mathbb{E}}_{i,t,k}\left[Y\right]$

Lagged Correlation

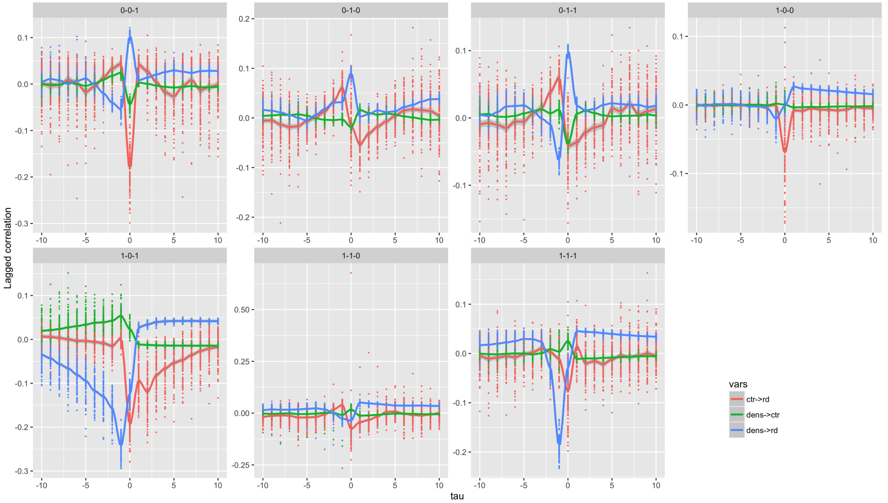
$$\rho_{\tau}\left[X_{j_1}, X_{j_2}\right] = \hat{\rho}\left[x^{(k)}_{i,j_1,t-\tau}, x^{(k)}_{i,j_2,t}\right] \quad (3)$$

Validation: Synthetic Data



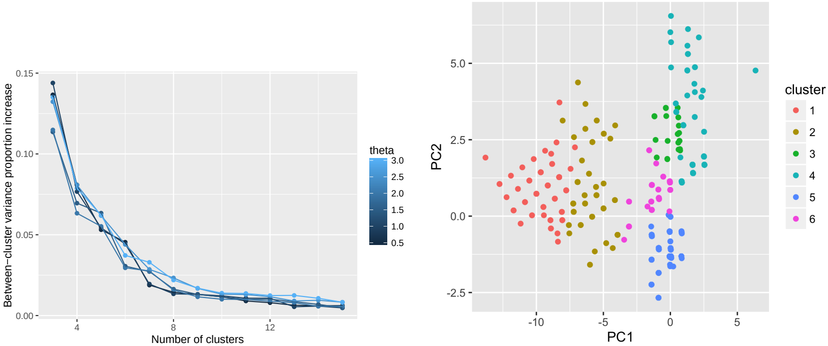
Synthetic urban configurations generated by an hybrid morphogenesis model from [Raimbault et al., 2014]

Profiles of lagged correlations



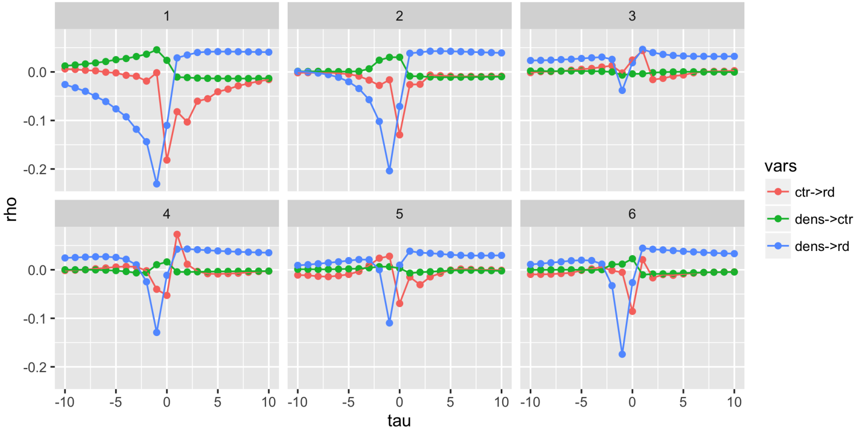
Values of ρ_τ for all couples of three explicative variables (density, distance to center, distance to roads), for 8 extreme parameter points

Unveiling Endogenous causality regimes



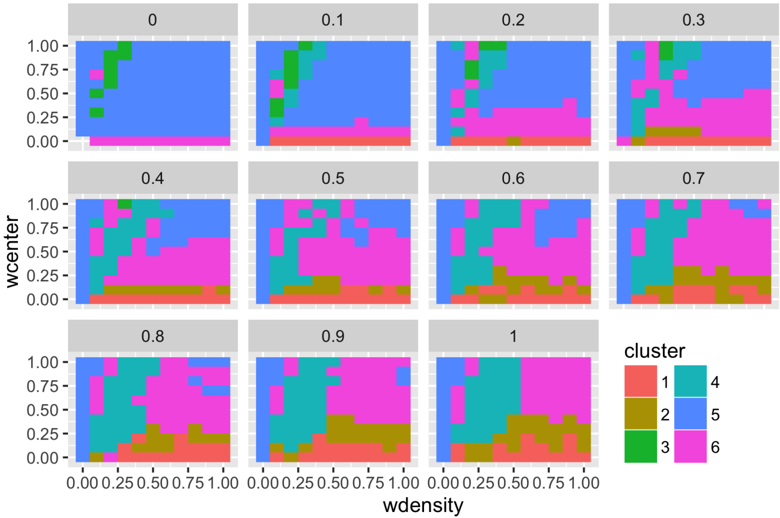
Unsupervised classification (robust k-means) on τ_{min}, τ_{max} features: (Left) Derivative of clustering coefficient for number of clusters k; (Right) PCA visualisation of classification for "optimal" k

Consistence and interpretation of regimes



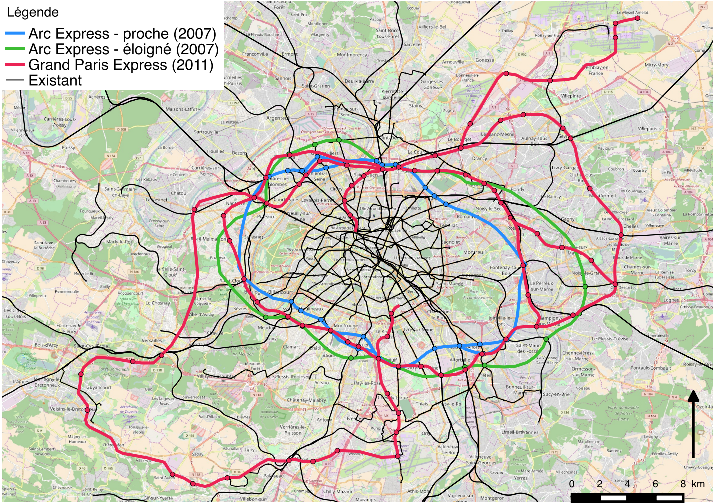
Values of cluster centers in terms of ρ_τ

Consistence and interpretation of regimes



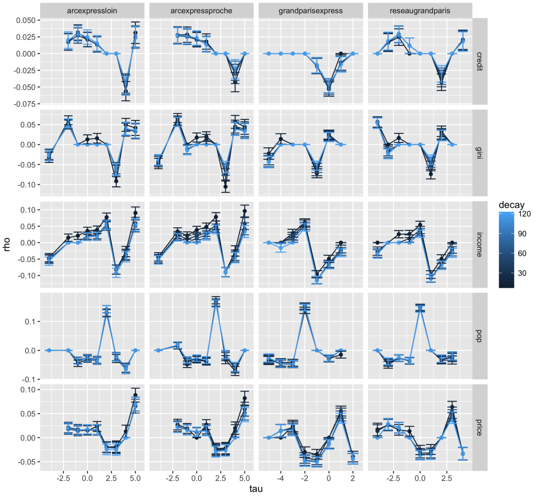
Position of clusters in the parameter space w_i

Application: Case study



Successive projects for the Grand Paris new transportation infrastructure

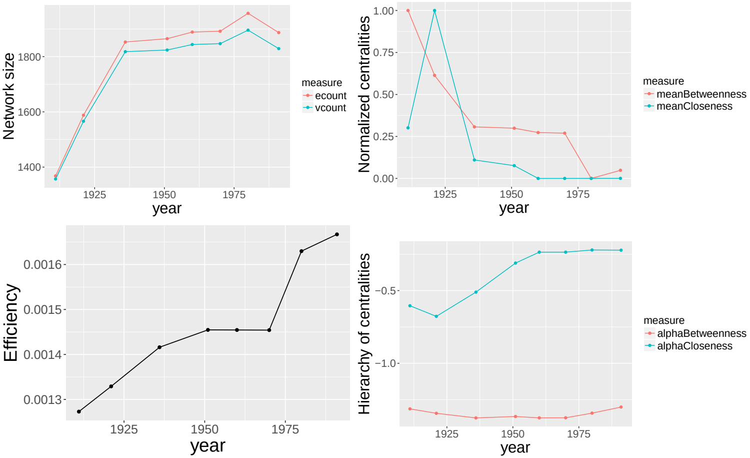
Application: Results



Values of ρ_τ for the different projects (columns) and different variables (rows), with accessibility differentials

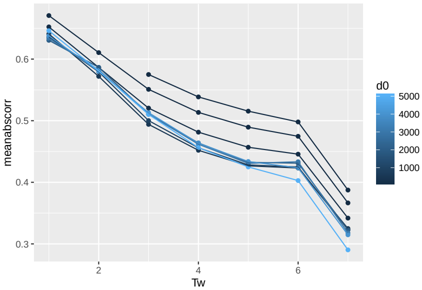
Application to South Africa: Network Analysis

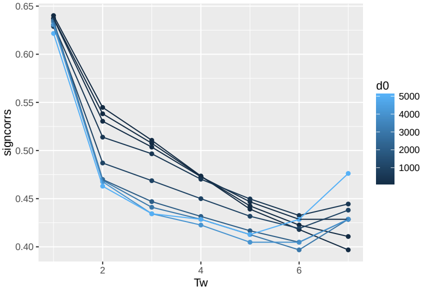
Evolution of Network measures : anomalous trend rupture in centralities



Stationarity scales

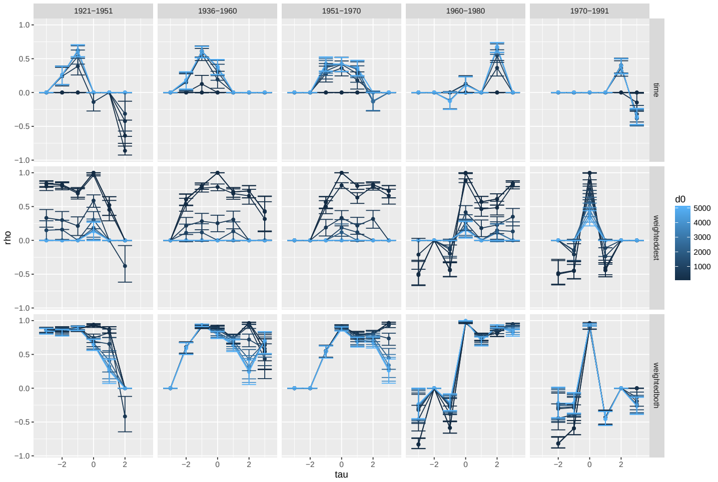
Optimal estimation time window and spatial range for accessibility





Causality Patterns

Clear inversion of the sense of Granger causality suggests a structural segregation effect of the apartheid laws



Macroscopic Interaction Model Rationale

Rationale : extend an interaction model for system of cities by including physical network as an additional carrier of spatial interactions (see [Raimbault, 2016] for developed theoretical context)

$\rightarrow$ Work under Gibrat independence assumptions, i.e. $\text{Cov}[P_i(t), P_j(t)] = 0$. 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 $\vec{\mu}(t+1) = f(\vec{\mu}(t))$

Macroscopic Model Formulation

Let $\vec{\mu}(t) = \mathbb{E}\left[\vec{P}(t)\right]$ cities population and (d_{ij}) distance matrix

Model specified by

$$f(\vec{\mu}) = r_0 \cdot \mathbf{Id} \cdot \vec{\mu} + \mathbf{G} \cdot \mathbf{1} + \mathbf{N}$$

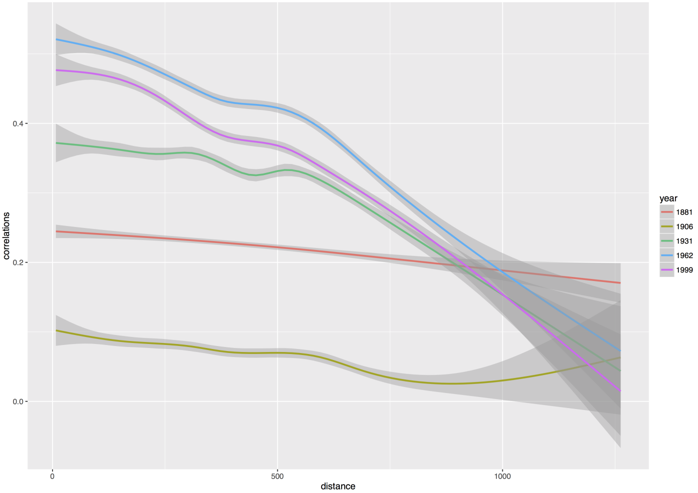
with

- $G_{ij} = w_G \cdot \frac{V_{ij}}{<V_{ij}>}$ 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 $\alpha_0 \simeq 3)$

Data : stylized facts

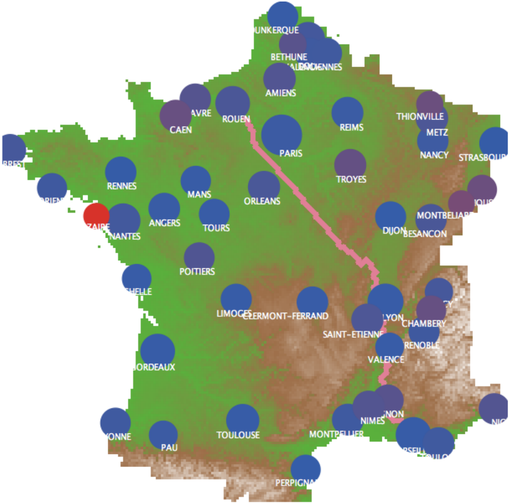
Population data for French-cities (Pumain-INED database : 1831-1999)

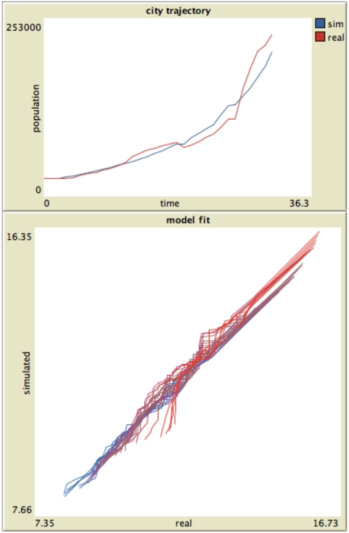
Non-stationarity of log-returns correlations function of distance



Geographic abstract network

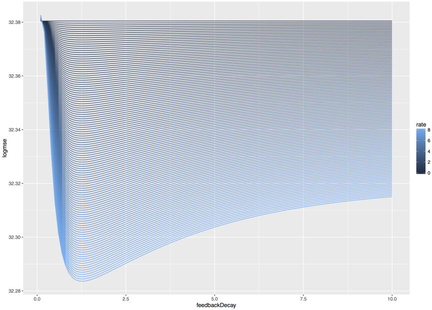
Physical transportation network abstracted through a geographical shortest path network

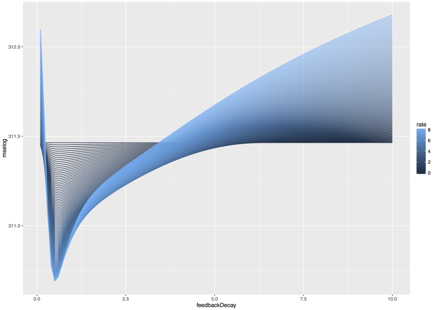




Results : model exploration

Evidence of physical network effects : fit improve through feedback at fixed gravity

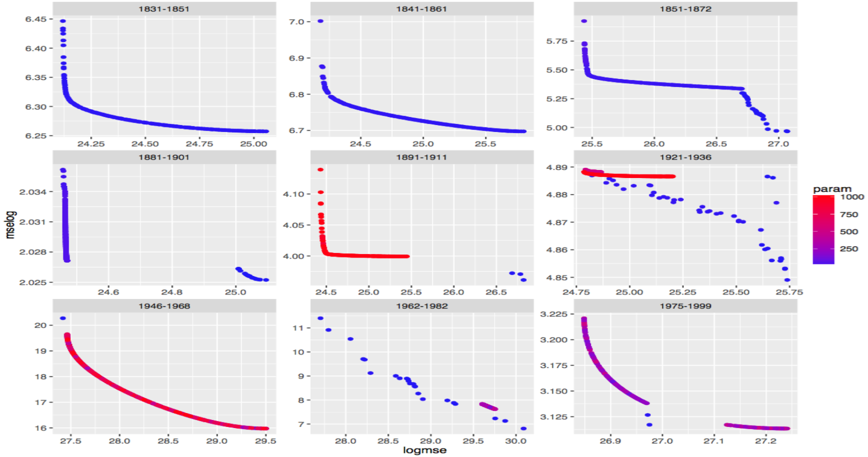




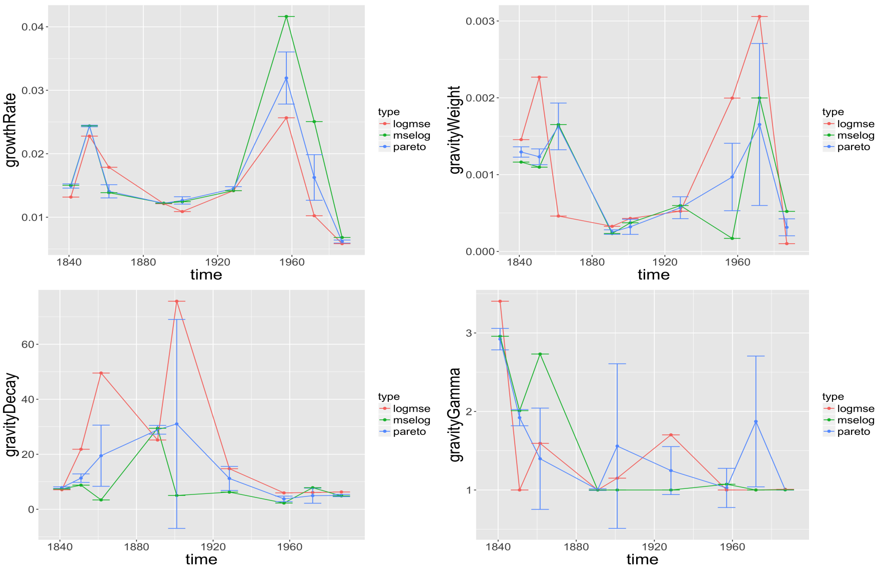
Results : model calibration

Model calibration using GA on computation grid, with software `OpenMole` [Reuillon et al., 2013]

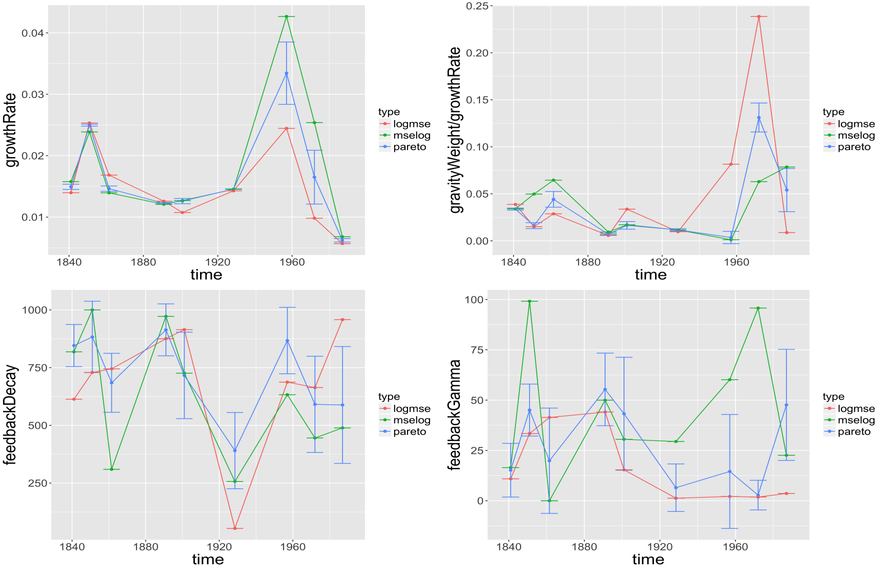
Pareto front for full model calibration, objectives MSE and MSE on logs



Results : non-stationary gravity model calibration



Results : non-stationary full model calibration



Not clear nor well theorized how to deal with overfitting in models of simulation. **Intuitive idea :** Approximate gain of information by approaching models of simulation by statistical models.

Let $M_k^* = M_k\left[\alpha_k^*\right]$ computational models heuristically fitted to the same dataset. With $S_k \simeq M_k^*$, we suppose that $\Delta D_{KL}\left(M_k^*, M_{k'}^*\right) \simeq \Delta D_{KL}\left(S_k, S_{k'}\right)$ if fits of S_k are negligible compared to fit difference between computational models and models have same parameter number.

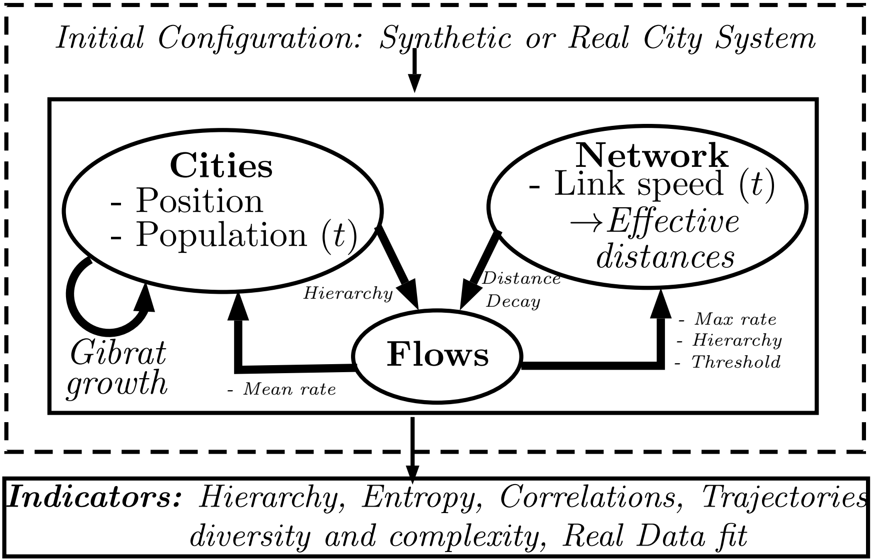
Application M_1 : gravity only model with $(r_0 = 0.0133, w_G = 1.28e-4, \gamma_G = 3.82, d_G = 4e12)$; M_2 : full model with $(r_0 = 0.0128, w_G = 1.30e-4, \gamma_G = 3.80, d_G = 8.4e14, w_N = 0.603, \gamma_N = 1.148, d_N = 7.474)$

Empirical AIC values

Table: Empirical AIC results.

Modèle Statistique	$M^{(1)}$	$M^{(2)}$	ΔAIC	ΔBIC
Polynomial	0.01438	0.01415	19.59	3.65
Log-polynomial	0.01565	0.01435	125.37	109.43
Polynomial Généralisé	0.01415	0.01399	11.70	-4.23

Generic Model



Model Formalization : Network Growth

Given the flow ϕ in a link, its effective distance is updated following

1. For the thresholded case

$$d(t+1) = d(t) \cdot \left(1 + g_{max} \cdot \left[\frac{1 - \left(\frac{\phi}{\phi_0}\right)^{\gamma_s}}{1 + \left(\frac{\phi}{\phi_0}\right)^{\gamma_s}}\right]\right)$$

2. For the full growth case

$$d(t+1) = d(t) \cdot \left(1 + g_{max} \cdot \left[\frac{\phi}{\max \phi}\right]^{\gamma_s}\right)$$

where γ_s is a hierarchy parameter, ϕ_0 a threshold parameter and g_{max} the maximal growth rate easily adjustable to realistic values by computing $(1 + g_{max})^{t_f}$

Model Formalization : Indicators

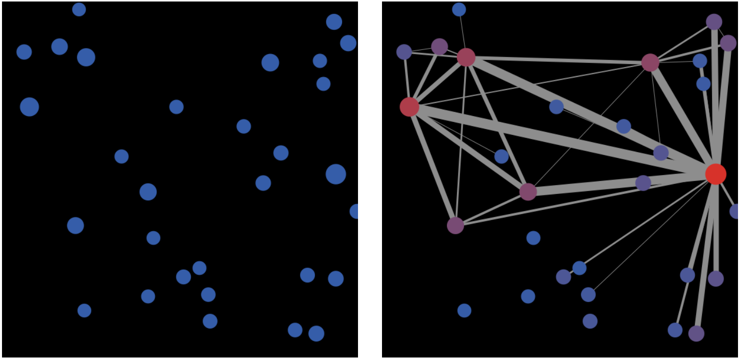
- Hierarchy, Entropy, Summary statistics in time
- Initial-final rank correlation (changes in the hierarchy) for variable X : $\rho\left[X_i(t=0), X_i(t=t_f)\right]$
- Trajectory diversity for variable X : with $\tilde{X}_i(t) \in [0;1]$ rescaled trajectories,

$$\frac{2}{N \cdot (N-1)} \sum_{i<j} \left(\frac{1}{T} \int_t \left(\tilde{X}_i(t) - \tilde{X}_j(t) \right)^2 \right)^{\frac{1}{2}}$$

- Average trajectory complexity (number of inflexion points)
- Pearson correlations conditionally to distance $\hat{\rho}_d\left[(X(\vec{x}_1, Y(\vec{x}_2)) \| ||\vec{x}_1 - \vec{x}_2|| \sim d\right]$
- Lagged return correlations $\hat{\rho}_\tau\left[\Delta X(t), \Delta Y(t-\tau)\right]$ (Granger causality)

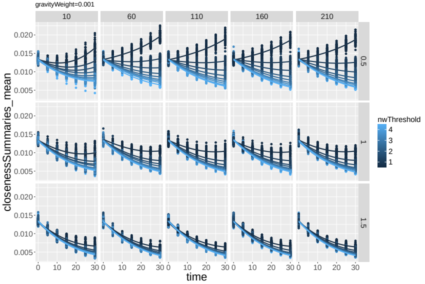
Model Specification : Abstract Network

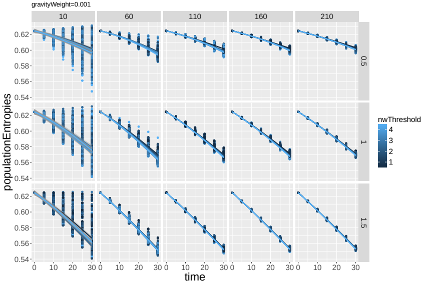
Complete virtual network between cities, initialized with euclidian distances ; thresholded reinforcement of speeds as a function of flows.

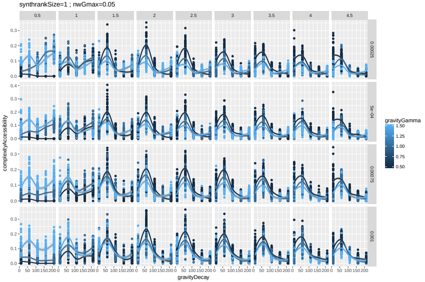


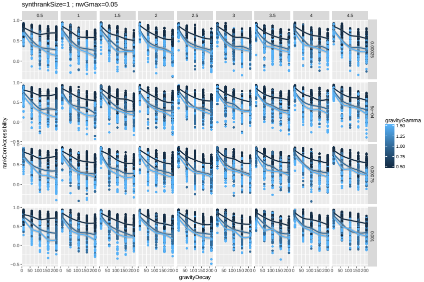
Exemple of run ($t_f = 30$). Level of red gives overall growth and link width flows.

Model Behavior

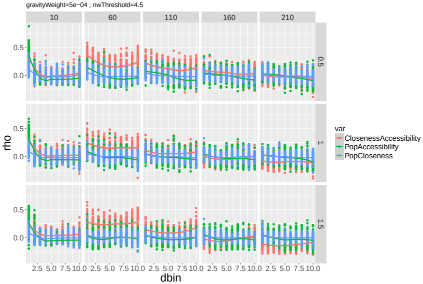


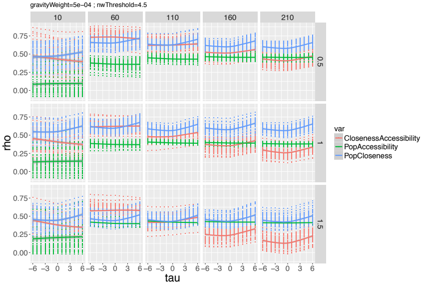




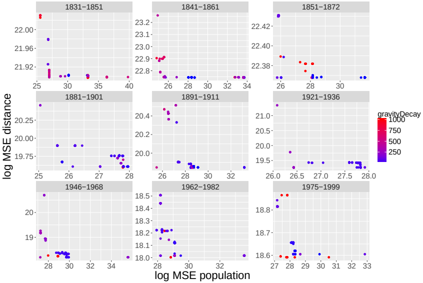


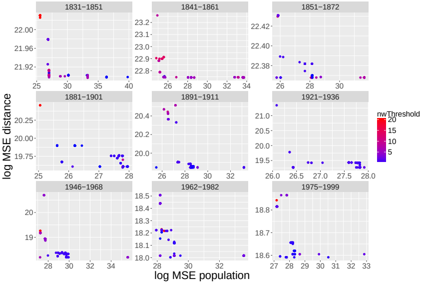
Correlation Patterns



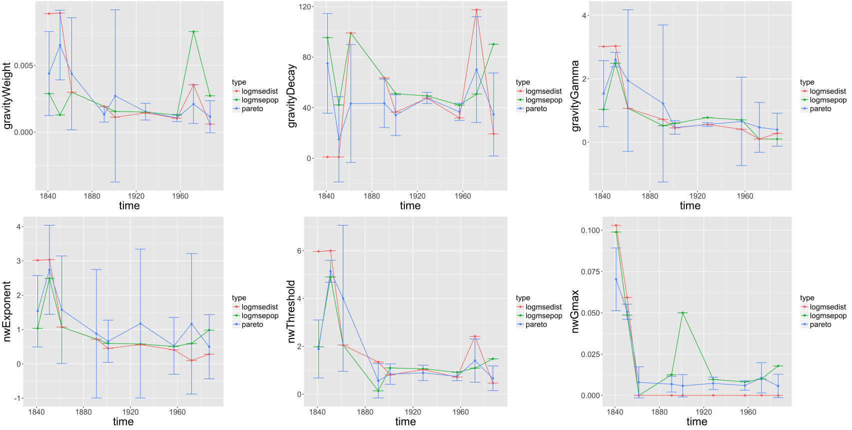


Calibration



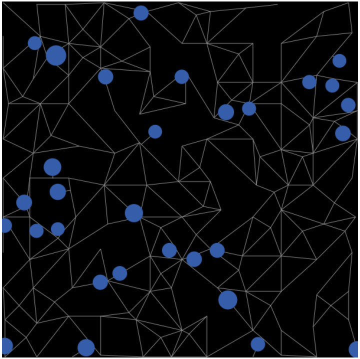


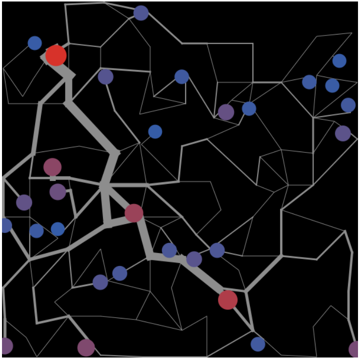
Calibration: Parameters



Model Specification: Physical Network

Physical initial network with uniform speeds ; reinforcement of speeds as a function of flows.





→ *Emergence of a hierarchical transportation network. Full behavior still to be explored.*

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