

Modeling Urban Morphogenesis: towards an integration of territories and networks

J. Raimbault^{1,2,*}

`juste.raimbault@parisgeo.cnrs.fr`

¹UMR CNRS 8504 Géographie-cités

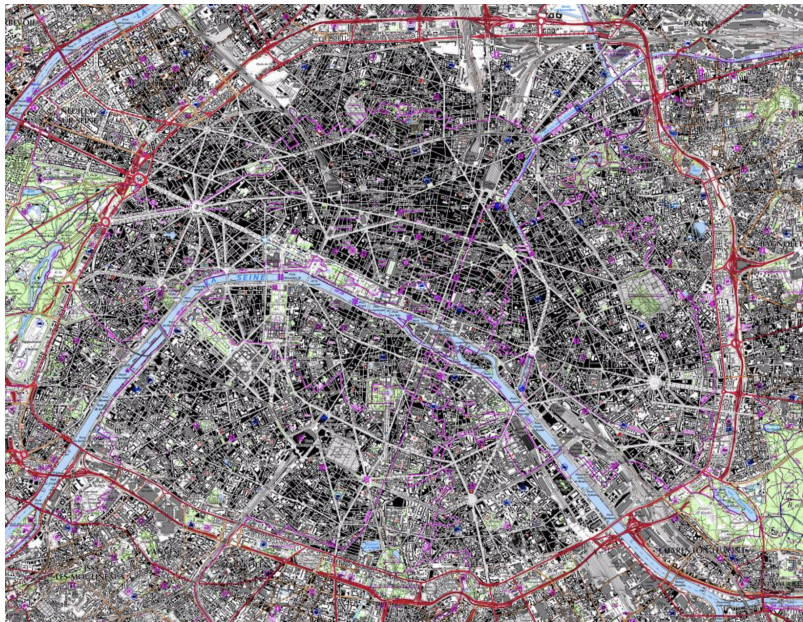
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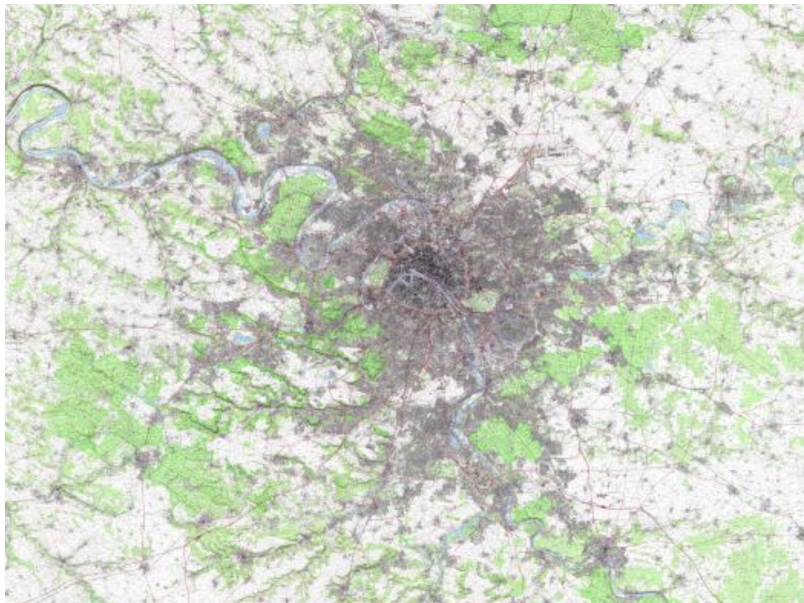
December 14th 2017

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

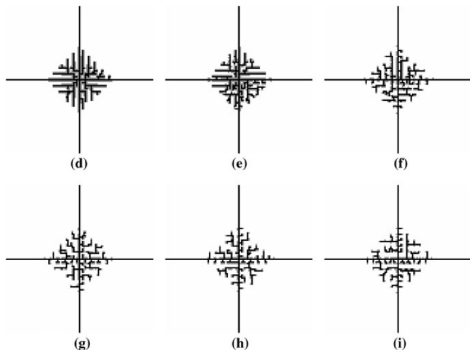
→ first use in 1871, large peak in usage between 1907-1909, increase until 1990, decrease until today. *Scientific fashion* ?

Modeling Urban Morphogenesis

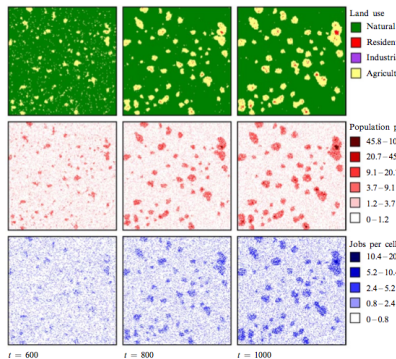
More or less explicit use of the concept of Morphogenesis in Urban Simulation, depending on the scale and the approach.

- [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
- [Caruso et al., 2011] micro-economic model of sprawl
- [Bonin and Hubert, 2014] urban economics morphogenesis, only work to explicitly mention the morphogen

Examples



(a) Microeconomic model of sprawl,
[Caruso et al., 2011]



(b) Land use simulations,
[van Vliet et al., 2012]

Which models for Urban Morphogenesis ?

The relation between the form and the function is a crucial feature in Urban Morphogenesis models.

→ *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 or to optimize new systems from scratch

Different models of Urban Morphogenesis

Four different models with different ontologies and coupling ontologies

Network

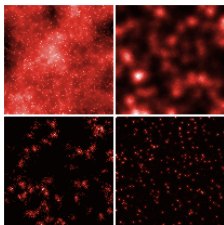
Density

Co-evolution



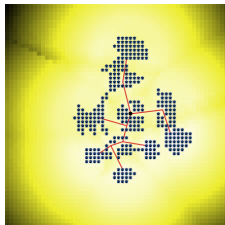
*Self-organizing
network*

Optimisation



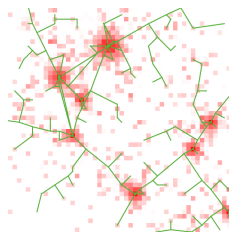
*Reaction-diffusion
density-based model*

Explication



Basic hybrid model
[Raimbault et al., 2014]

Optimisation



Co-evolution model

Explication

Network morphogenesis model

Model studied by [Tero et al., 2010a] : exploration and reinforcement by a slime mould searching for ressources

Settings :

- Initial homogeneous network of tubes ij of length L_{ij} , variable diameter D_{ij} , carrying a flow Q_{ij} .
- Nodes i with a pressure p_i .
- N nodes are origin/destination points : randomly at each step one becomes source $p_{i_+} = l_0$ and one other sink $p_{i_-} = -l_0$

At each iteration :

- 1 Determination of flows with Kirchoff's law (electrostatic analogy) :
Ohm's law $Q_{ij} = \frac{D_{ij}}{L_{ij}} \cdot (p_i - p_j)$ and conservation of flows
 $\sum_{j \rightarrow i} Q_{ij} = 0, \sum_{j \rightarrow i_{\pm}} Q_{i_{\pm}j} = \pm I_0$
- 2 Evolution of diameters (γ reinforcement parameter) by

$$\frac{dD_{ij}}{dt} = \frac{|Q_{ij}|^{\gamma}}{1 + |Q_{ij}|^{\gamma}} - D_{ij}$$

→ Extraction of the final network after convergence given a threshold parameter for diameters

→ Multi-scale model : diameters are constant during an iteration to obtain equilibrium flows

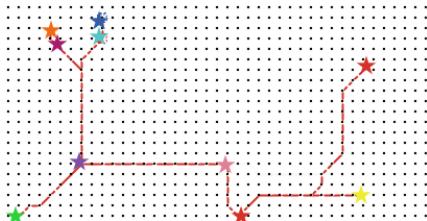
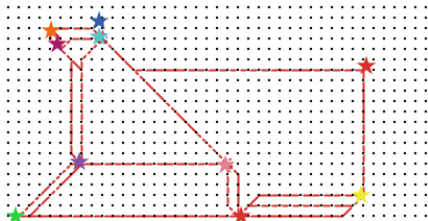
Behavior of the model evaluated with performance indicators for generated network (V_f, E_f) , that are contradictory objectives :

- Construction costs $c = \sum_{ij \in E_f} D_{ij}(t_f)$
- Average performance [Banos and Genre-Grandpierre, 2012]

$$v = \frac{1}{|V_f|^2} \sum_{i,j \in V_f} \frac{d_{i \rightarrow j}}{\|\vec{i} - \vec{j}\|}$$

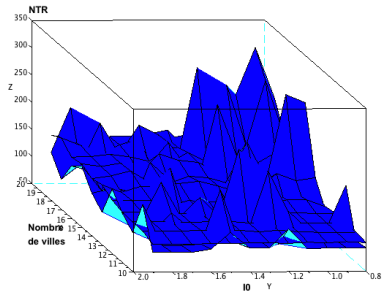
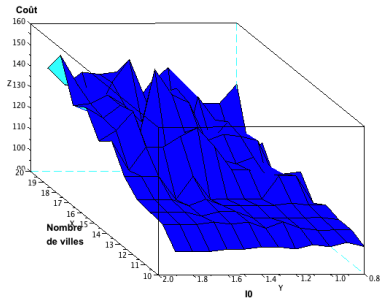
- Robustness (*Network Trip Robustness* index [Sullivan et al., 2010])

Example of networks



Sensitivity of network topology to reinforcement coefficient γ . Left : $\gamma \sim 1$, robust network. Right : $\gamma \gg 1$, arborescent network.

Sensitivity analysis

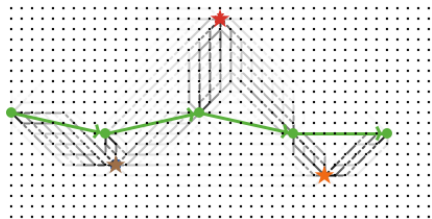
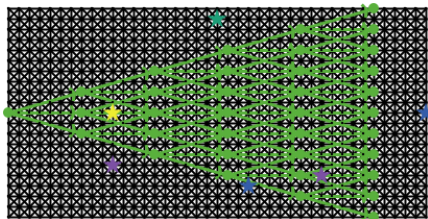


Sensitivity of indicators to parameters (N, I_0).

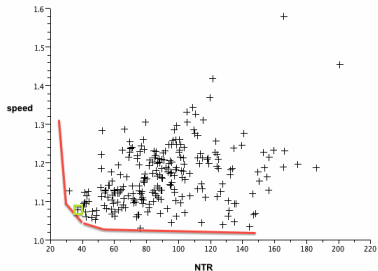
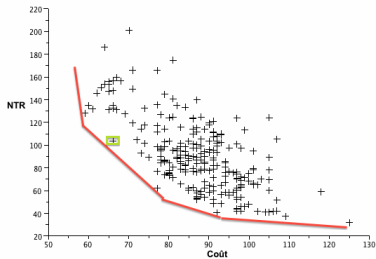
Application : Optimal transportation Corridor

Abstract application : *Given a distribution of nodes to serve (sinks), what is the optimal corridor for an infrastructure at a larger scale (train or metro) for which stations are sources, in the sense of the multi-objective optimality of the local self-organized network ?*

→ Heuristic exploration of an arborescent set of potential infrastructures

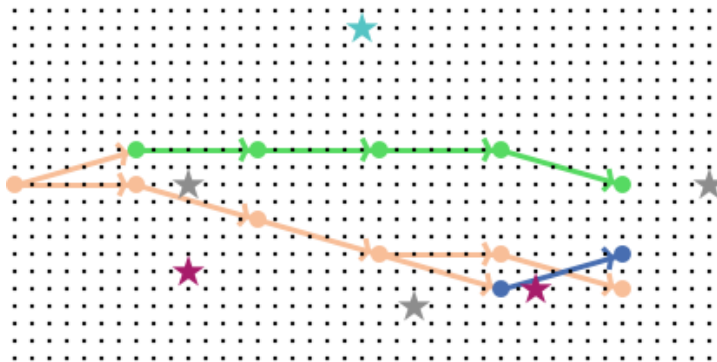


Pareto Optimisation



Pareto optimisation : projection of explored configurations in indicator space to obtain the Pareto front.

Pareto Optimisation

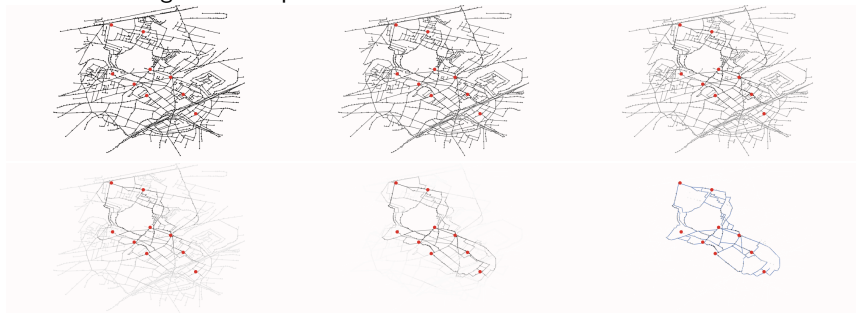


Configurations corresponding to three optimal points.

Application : Optimal Network Design

→ Mission of prospective for Romainville city : itinerary of an intra-urban shuttle with imposed stops.

→ NP-hard problem similar to a Travelling Salesman Problem, but multi-objective (cost, speed, robustness). The bottom-up network generation applied on the initial street network gives a compromise solution.



Progressive convergence of the network towards an optimal network connecting the fixed points (in red), starting from the initial street network.

A simple Reaction-diffusion model for population density

Model based on population only ?

- Crucial role of the interplay between concentration forces and dispersion forces [Fujita and Thisse, 1996] in keeping Urban Systems at the border of chaos
- Potentiality of aggregation mechanisms (such as Simon model) to produce power laws [Sheridan Dodds et al., 2016]
- Link with Reaction-diffusion approaches in Morphogenesis [Turing, 1952]
- Extension of a DLA-type model introduced by [Batty, 1991], with simple abstract processes of population aggregation and diffusion

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

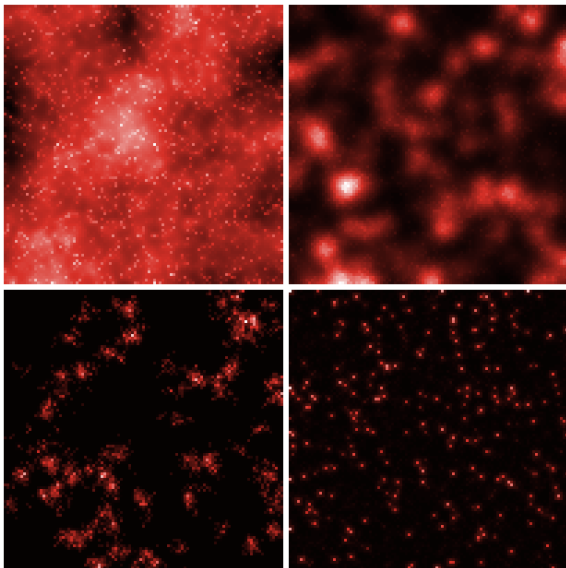
→ At each time step:

- 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 .

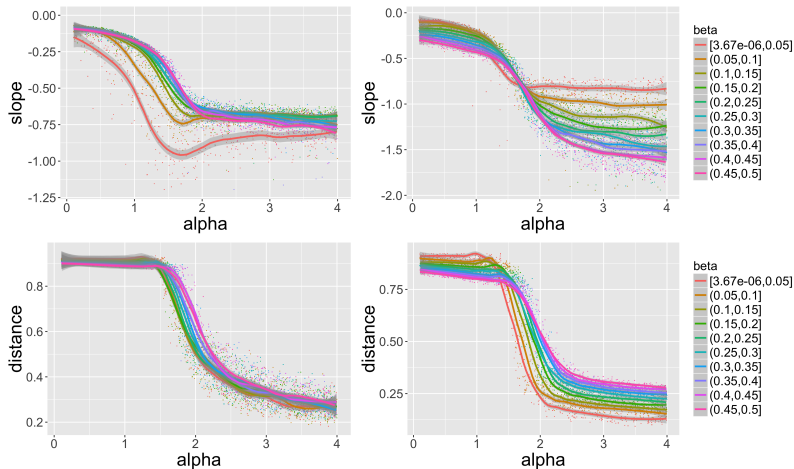
→ Output measured by morphological indicators: Moran index, average distance, rank-size hierarchy, entropy.

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

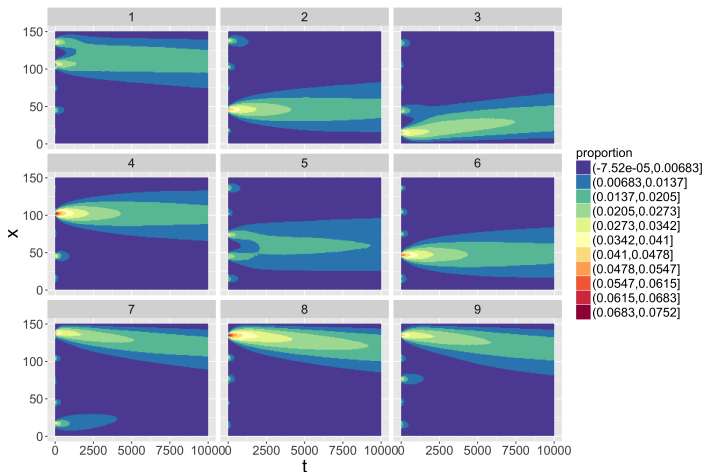
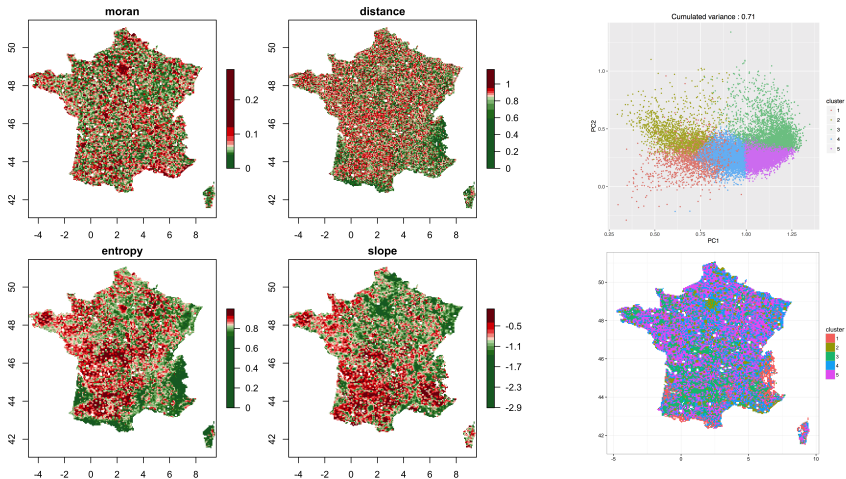


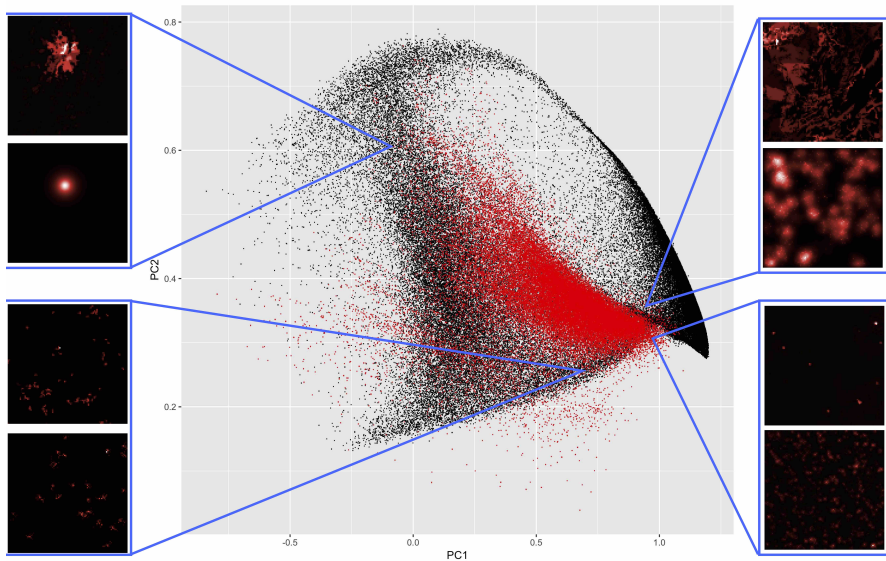
Illustration of path-dependence in a simplified one-dimensional version of the model: cell trajectories in time for 9 independent repetitions from the same initial configuration.

Empirical Data for Calibration



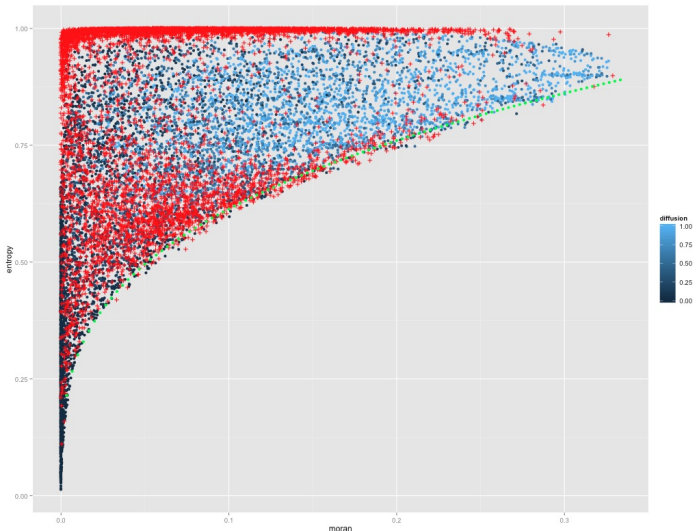
Computation of morphological indicators on population density data for Europe (shown here on France), morphological classification.

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 basic hybrid model

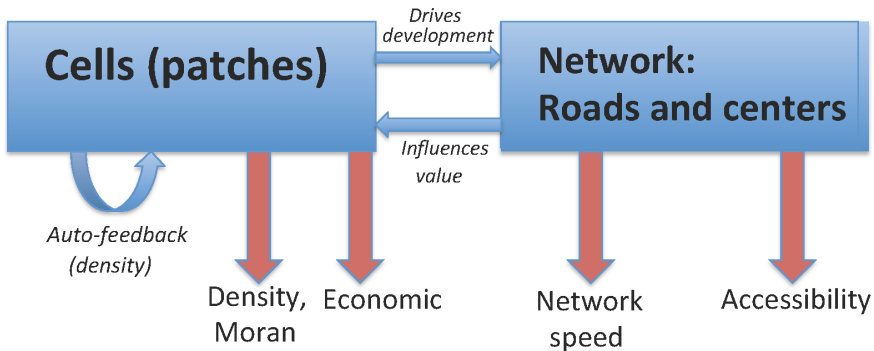
→ How to take into account relations between transportation network and city shape ? Proposition of modeling transportation network coupled with a Cellular Automaton in [Moreno et al., 2007], [Moreno et al., 2009].

→ Generalisation and extension, from morphological to functional properties of the urban environment: Cellular Automaton coupled with an evolving network.

Model description : settings and agents

- Fixed agents: cells in a square lattice $(L_{i,j})_{1 \leq i,j \leq N}$, occupied or not (function $\delta(i,j,t) \in \{0,1\}$)
- Evolving euclidian network $G(t) = (V(t), E(t))$, including fixed city centers $C_0 \subset V(0)$ for each an activity $a \in \{1, \dots, a_{max}\}$ is defined (functional properties of the urban scape).
- Heterogeneous explicative variables $(d_k)_{1 \leq k \leq K}$ defined on cells, with associated weights $(\alpha_k)_{1 \leq k \leq K}$ (main parameters of the model), that are:
 - d_1 the density around the cell (in a fixed radius r)
 - d_2 the distance to the nearest road
 - d_3 the distance to the nearest town center through the network
 - $d_4(i,j,t) = \left(\frac{1}{a_{max}} \sum_{a=1}^{a_{max}} d_3(i,j,t;a)^{p_4} \right)^{1/p_4}$: integrated accessibility of activities

Model workflow



At each time step:

- Sprawling of occupied urban structure. The best N cells according to the value $v(i, j, t) = \frac{1}{\sum_k \alpha_k} \sum_{k=1}^K \alpha_k \frac{d_{k,\max}(t) - d_k(i, j, t)}{d_{k,\max}(t) - d_{k,\min}(t)}$ are built.
- Adaptation of the network: when a new cell is built, if $d_2 > \theta_2$, the cell is connected to the network by a new perpendicular road.

Objective Morphological indicators

- Integrated local density

$$D(t) = \left(\frac{1}{\sum_{i,j} \delta(i,j,t)} \sum_{\substack{i,j=1 \\ \delta(i,j,t) \neq 0}}^N d_1(i,j,t)^{p_D} \right)^{1/p_D}$$

- Moran index (“polycentric” character of a distribution of populated cells, [Tsai, 2005, Le Néchet and Aguilera, 2011]): world decomposed in a grid of size M ($1 \ll M \ll N$), $(P_i)_{1 \leq i \leq M}$ are populations in each part of the grid, then

$$I(t) = \frac{M^2}{\sum_{\mu \neq \nu} 1/d_{\mu\nu}} \frac{\sum_{\mu \neq \nu} (P_\mu - \bar{P})(P_\nu - \bar{P})/d_{\mu\nu}}{\sum_{\mu=1}^{M^2} (P_\mu - \bar{P})^2}$$

Performance indicators

- Network speed ([Banos and Genre-Grandpierre, 2012])

$$S(t) = \left(\frac{1}{\sum_{i,j} \delta(i,j,t)} \sum_{\substack{i,j=1 \\ \delta(i,j,t) \neq 0}}^N \left(\frac{d_3(i,j,t)}{e_3(i,j,t)} \right)^{p_S} \right)^{1/p_S} \quad \text{with } e_3(i,j,t)$$

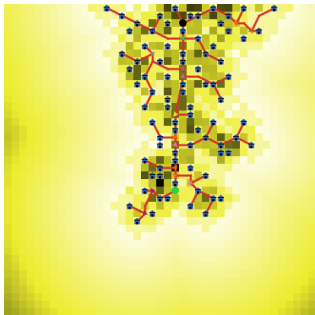
euclidian distance to nearest center

- Normalized functional accessibility

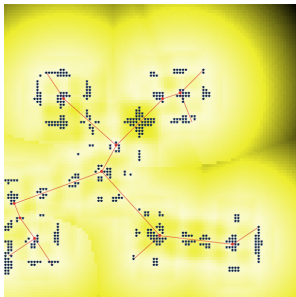
$$A(t) = \left(\frac{1}{\sum_{i,j} \delta(i,j,t)} \sum_{\substack{i,j=1 \\ \delta(i,j,t) \neq 0}}^N \left(\frac{d_4(i,j,t)}{d_{4,\max}(t)} \right)^{p_A} \right)^{1/p_A}$$

- Socio-economic segregation potential: run on the generated configuration of an economic residential ABM dynamics ([Schelling, 1969], [Benenson, 1998]), which is strongly sensitive to spatial structure according to [Banos, 2012], calculation of the final spatialized segregation index E .

Examples of generated shapes



(a) "A city can be a tree",
[Alexander, 1964]

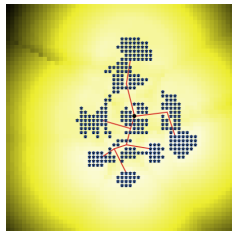
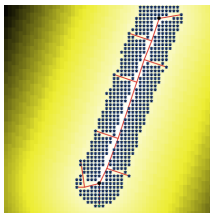
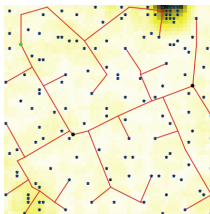
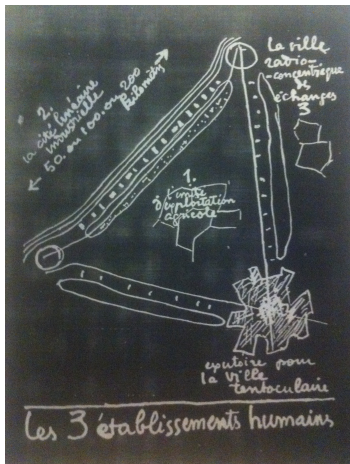


(b) Intermediate shape



(c) One center, no density

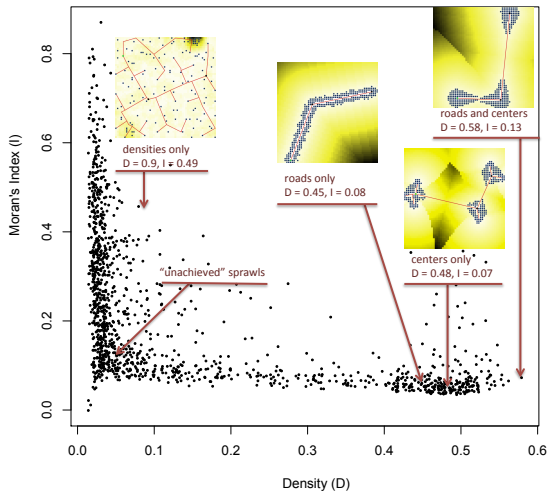
Typology of structures



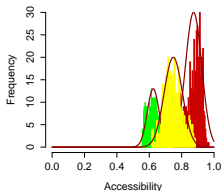
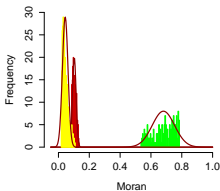
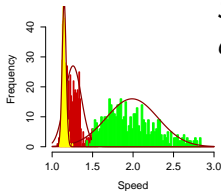
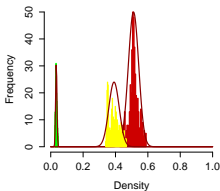
Parallel between Le Corbusier's typology of "human settlements" and some generated structures

Morphological classification

Morphological classification



Projection in the morphological plane of indicators; classification of some structures.

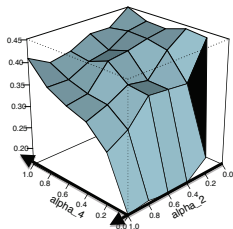


Statistical distributions of outputs for different points in parameter space.

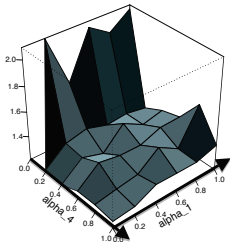
- Statistical study of the behavior of the model: is the output sensitive to initial spatial configurations?
- Internal robustness of the model
- Number of repetitions needed : $n = (2\sigma \cdot 1.96 / 0.05)^2 \simeq 60$ repetitions for 95% confidence interval of width 0.05

Exploration of the parameter space

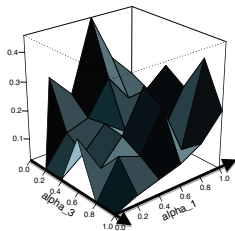
Density



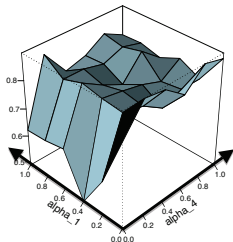
Speed



Moran Index



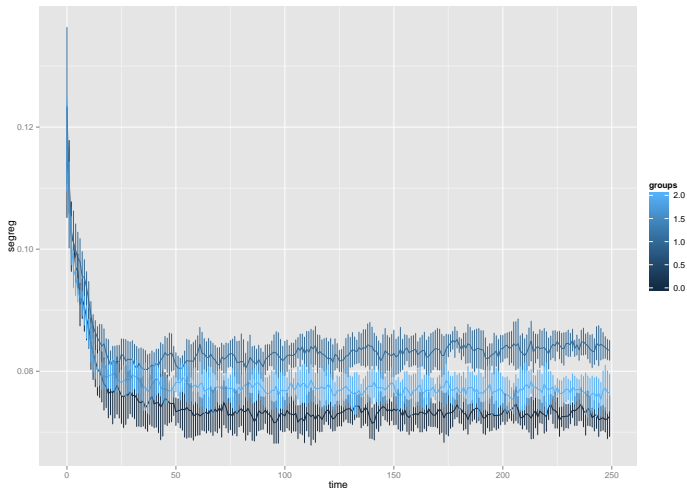
Accessibility



Sample surface plots of the evaluation functions.

- Finer exploration of the (α_k) parameter space: 4D-grid of step 0.2, what gives 1295 points.
- Expected results regarding speed and density.
- Emergent behavior: local competition between agents does not lead to the most efficient structure.

Economic ABM

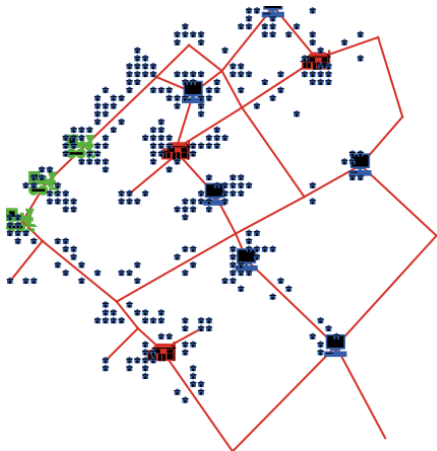


Time series of segregation index during a run of the economic ABM for different configurations.

Practical application: method

- Fixing the spatial initial structure and the parameters, optimize on the possible distribution of activities among centers. Choice of parameters is crucial.
- Importation of real GIS data: centers correspond to centroids of zones in a district, initial network to main roads. Some centers have fixed activity (stations), other can be 2 different ones (residential or tertiary).
- Exploration of all possible configurations (possible here, $2^8 = 256$ configurations), Pareto-plot of economic performance and accessibility.

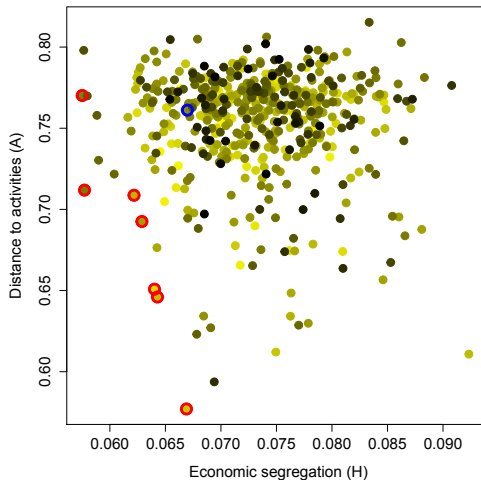
Practical application



Practical application. Optimizing the distribution of activities over urban centers.

Application : Pareto optimization

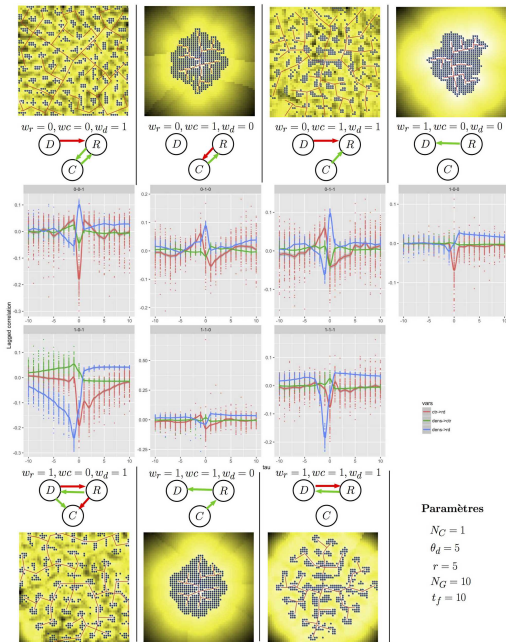
Pareto plot of configurations



Scatterplot of all configurations in the (H, A) morphological plane.

Real situation in blue, Pareto front in red. Color gradient follows level of heterogeneity from low (black) to high (yellow). It suggests the performance of functional heterogeneity, often recommended by planners today.

Causality regimes between network and density variables

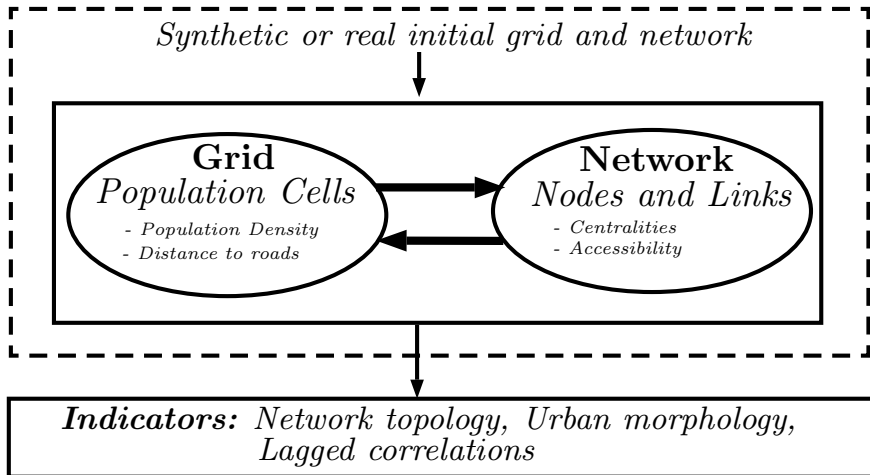


Profiles of lagged correlations unveil diverse interaction networks between variables : towards a definition of causality regimes, including co-evolution in some cases.

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 (reaction-diffusion processes studied before)
- Network growth is also driven by morphological, functional and local network measures, following diverse heuristics corresponding to different processes (multi-modeling)

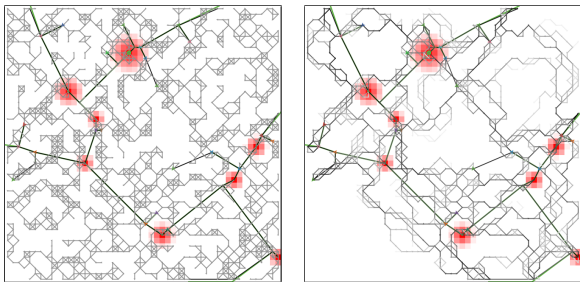
*Local variables and network properties induce feedback on both, thus a strong coupling capturing the **co-evolution***



Network Generation

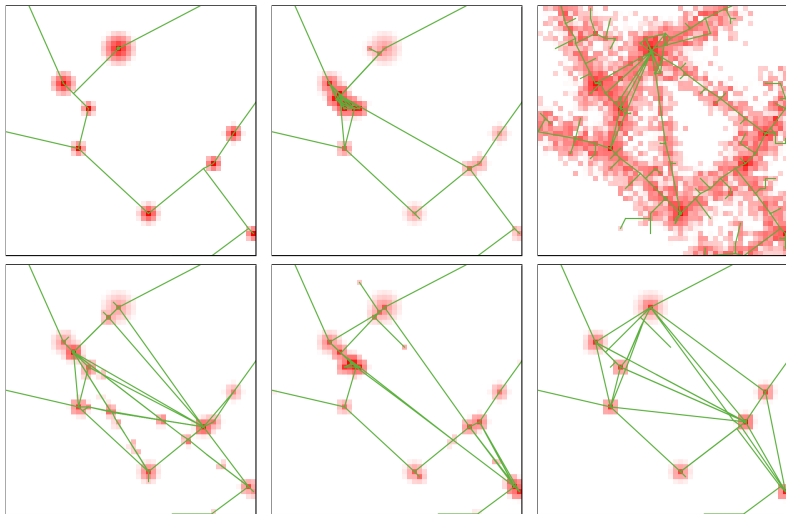
At fixed time steps :

- 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., 2010b])



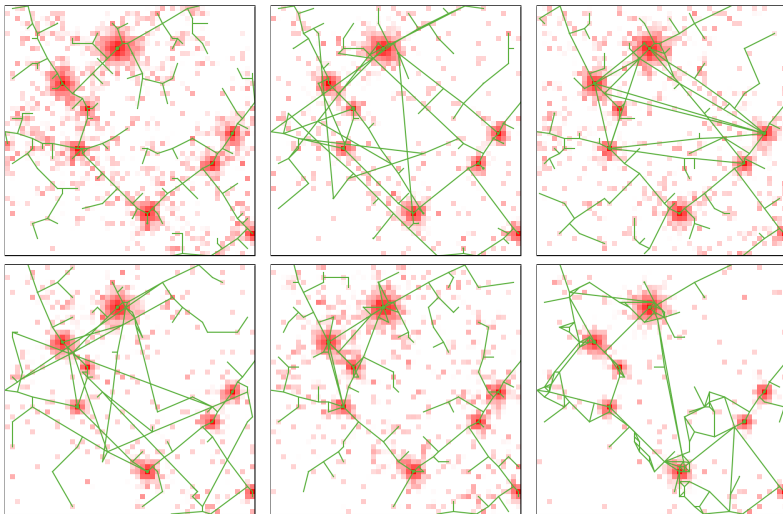
Intermediate stage for biological network generation

Generated Urban Shapes: Urban Form



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

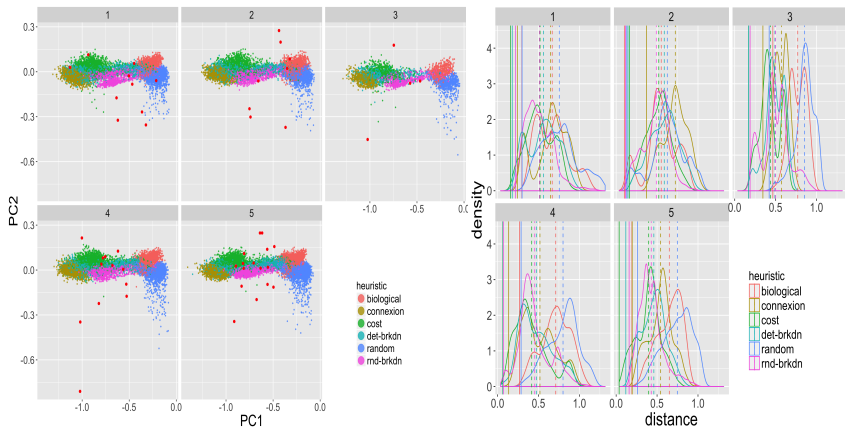
Generated Urban Shapes: Network



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

Results : Network Heuristics

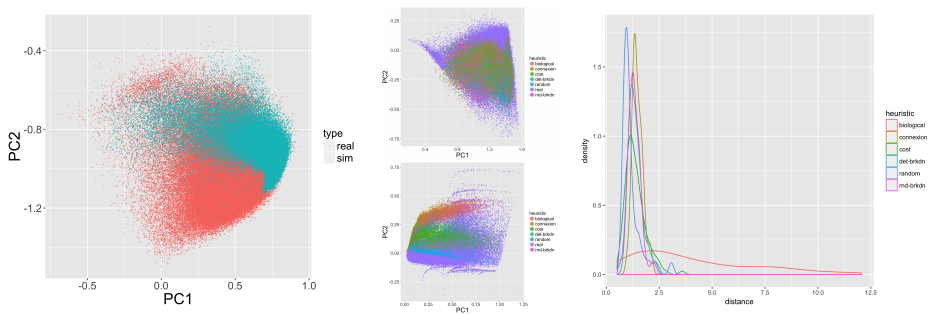
Comparison of feasible space for network indicators with fixed density



(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.

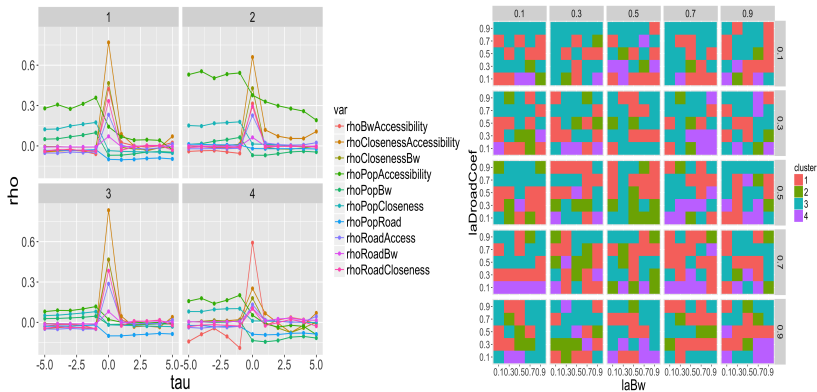


(Left) Full indicator space; (Middle) Morphological and Topology, by network heuristic; (Right) Distance distribution for cumulated distance for indicators and correlations.

Results : Causality Regimes

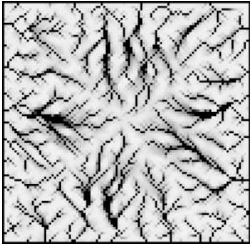
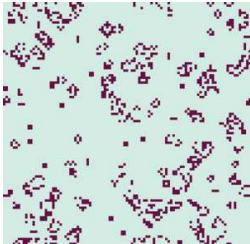
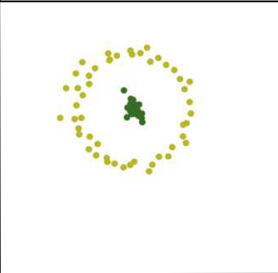
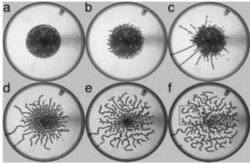
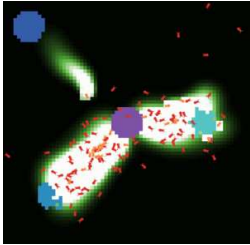

Unsupervised learning on lagged correlations between local variables unveils a diversity of causality regimes

→ 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

What is Morphogenesis ? Examples

| | Physical | Biological | Engineered |
|----------------|---|---|--|
| 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]

Proposition of an Interdisciplinary Definition of 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]*

Implications

(*Optimisation*) → Morphogenesis models (in the sense of strong links between form and function) are an appropriate tool to find optimal urban designs.

(*Explication*) → Simple model reproducing observed urban forms for both population distribution and road network : which intrinsic dimension to the urban system and its morphological aspect ?

Developments

- Towards dynamical calibrations ? Need of dynamical data
- Investigate the link between spatial non-stationarity and non-ergodicity through simulation by the model
- Compare network generation models in a “fair” way (correcting for additional parameters, open question for models of simulation)

Conclusion

- Several urban morphogenesis at the mesoscopic scale 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.**

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Open repository (code, data and results) at

<https://github.com/JusteRaimbault/CityNetwork>

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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 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.

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

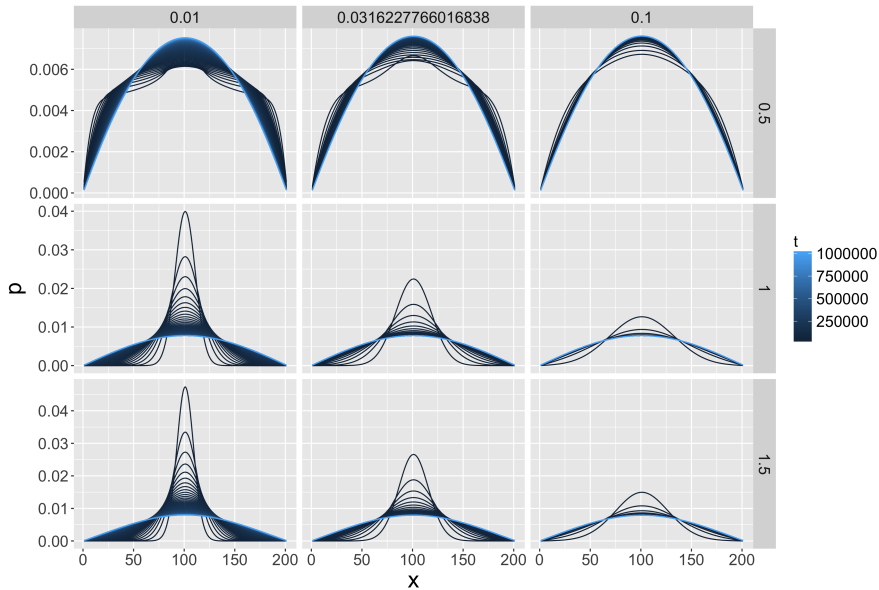
Catastrophe set $K \subset W$ is where the system endures phase transition.

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

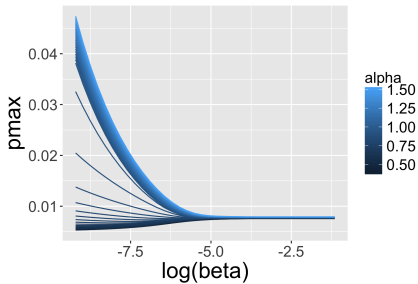
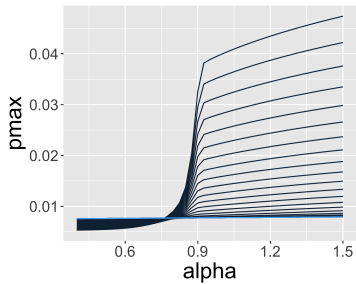
The one-dimensional model verifies the PDE :

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

Stationary behavior of 1D model



Stationary behavior of 1D model



Morphological indicators

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

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

$\mathcal{E} = 0$ means that all the population is in one cell whereas $\mathcal{E} = 0$ means that the population is uniformly distributed.

- 3 Spatial-autocorrelation given by Moran index, with simple spatial weights given by $w_{ij} = 1/d_{ij}$

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

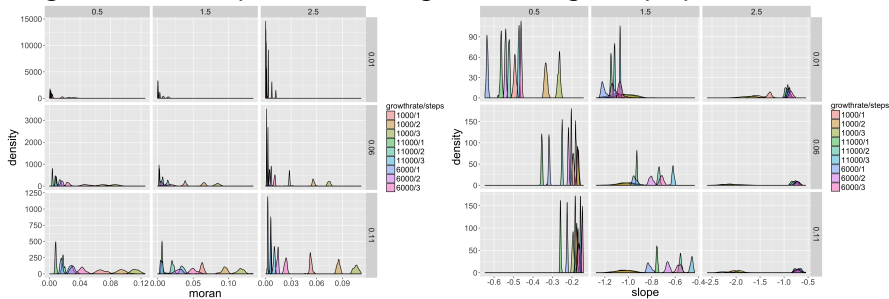
- 4 Mean distance between individuals

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

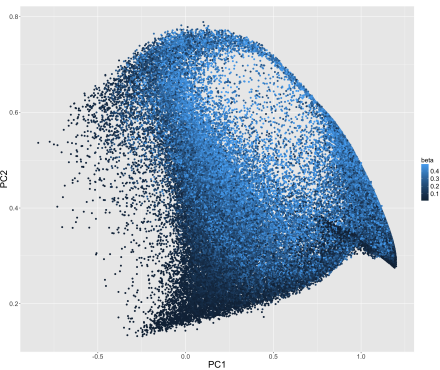
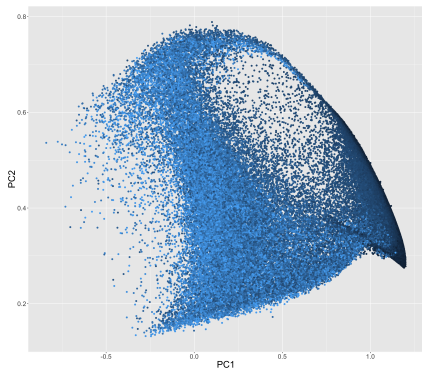
where d_M is a normalisation constant

Model behavior : Convergence

Large number of repetitions show good convergence properties



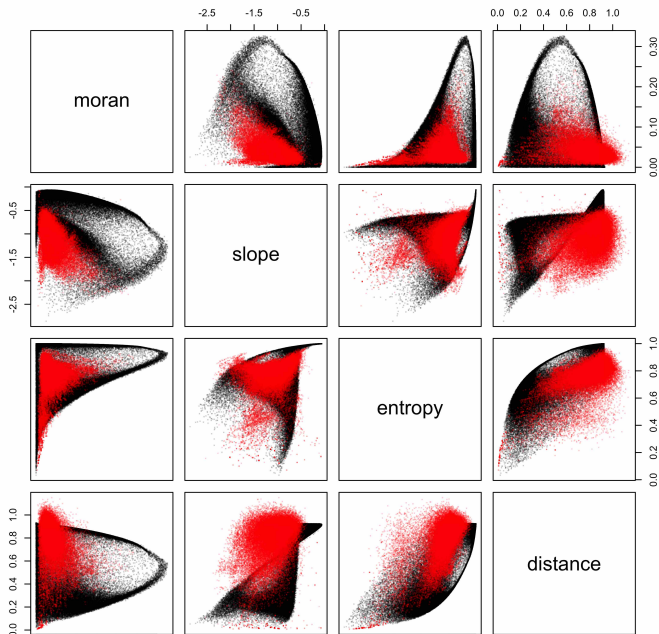
Model behavior



Empirical indicators computation

- Eurostat population density raster (100m, simplified at 500m resolution)
- 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)
- Indicators computed using Fast Fourier Transform Convolution
- 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]

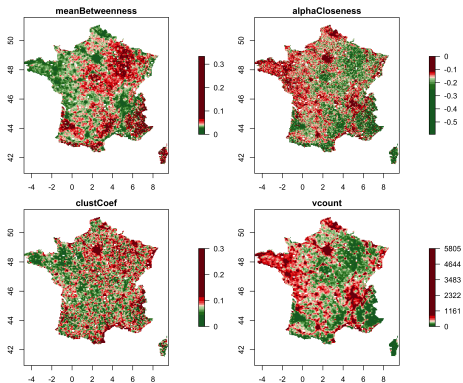
[Baptiste, 2010] system dynamics with evolving capacities

[Wu et al., 2017] population diffusion and network growth

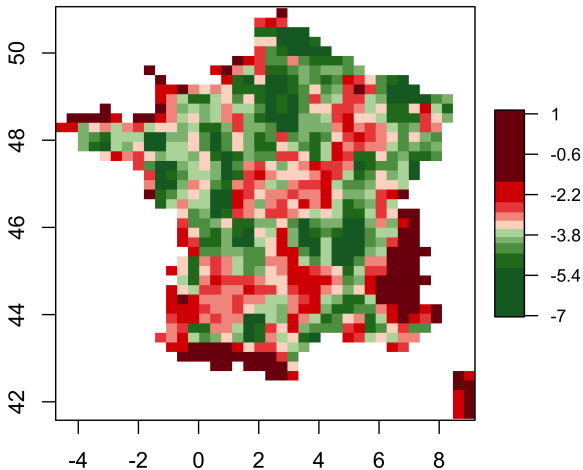
[Blumenfeld-Lieberthal and Portugali, 2010] and [Schmitt, 2014] : random potential breakdown for network growth.

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

Empirical Data : network indicators



Empirical Data : correlations



Network 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 (least costly) are realized
- 3 Network is planarized

Biological Network generation

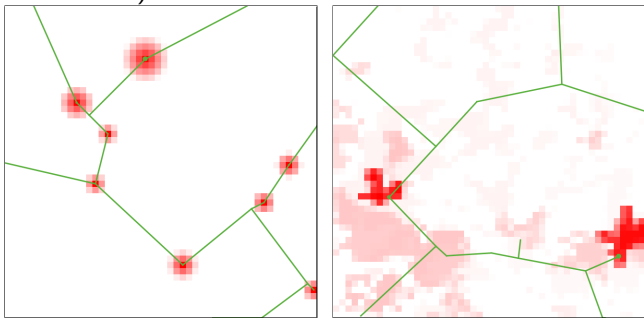
Adding new links with biological heuristic:

- 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 border nodes to avoid border effects

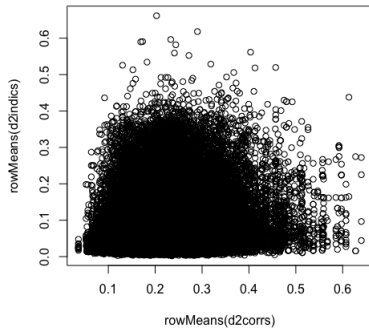
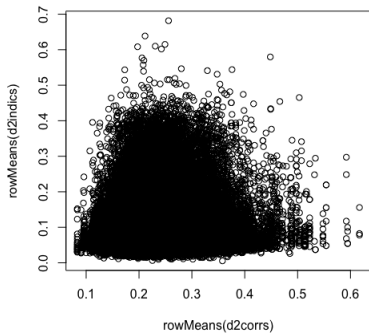
Real setup: Population density raster at 500m resolution (European Union, from Eurostat)



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

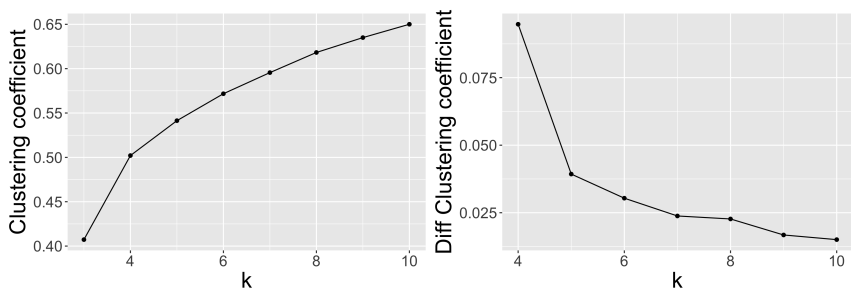
- Brute force exploration of a LHS sampling, 10 repetitions of the model for each parameter point.
- For each simulated point, closest in indicator space (euclidian distance for normalized indicators) among real points are selected.
- Among these, point with lowest distance to correlation matrix are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

Calibration : optimal points



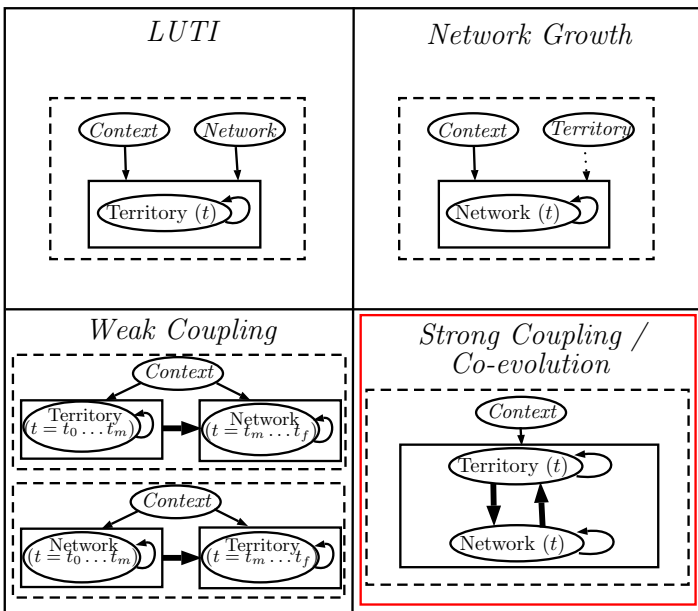
Pareto plots of distance to indicators and distance to correlation matrices, for a given simulated configuration and all real points.





Causality regimes: clustering






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

Co-evolution Models



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