Modeling Urban Morphogenesis: towards an integration of territories and networks

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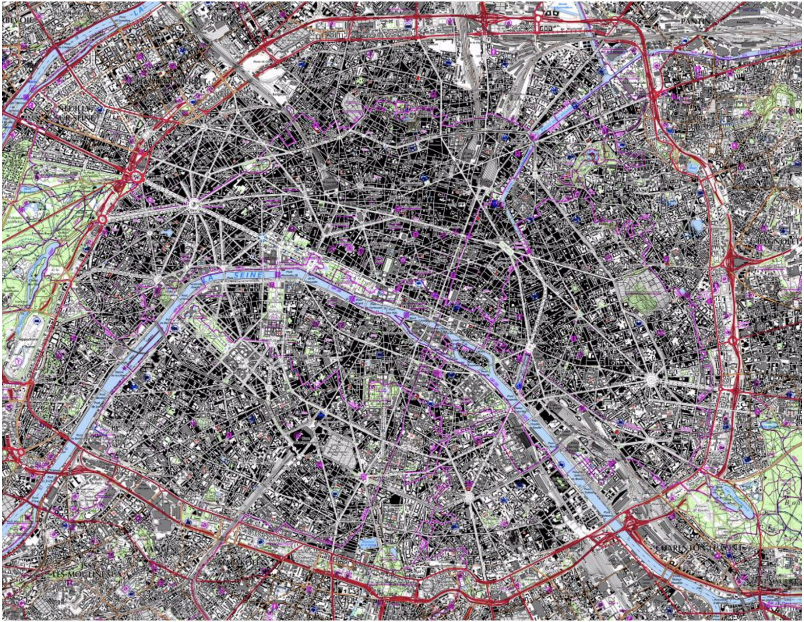
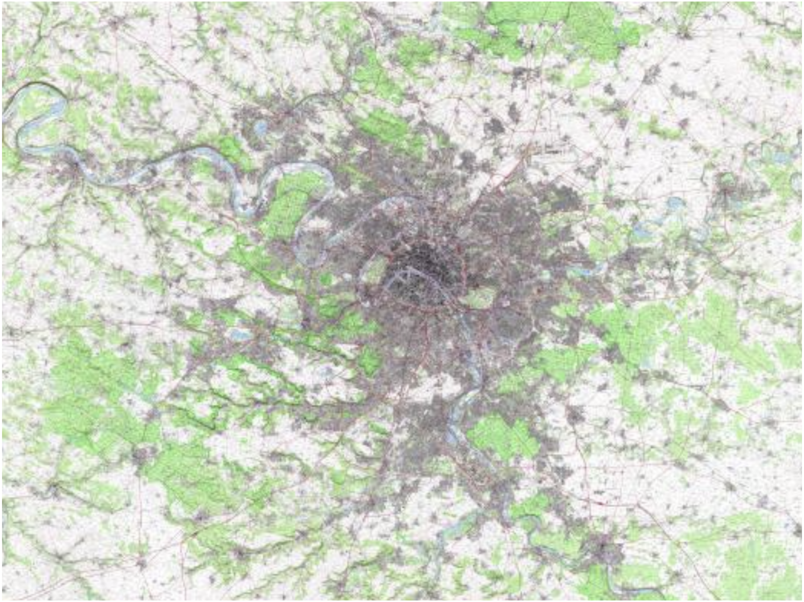
Complex processes of Urban Morphogenesis



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

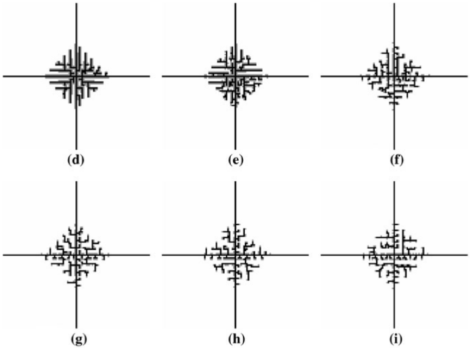
→ first use in 1871, large peak in usage between 1907-1909, increase until 1990, decrease until today. *Scientific fashion ?*

Modeling Urban Morphogenesis

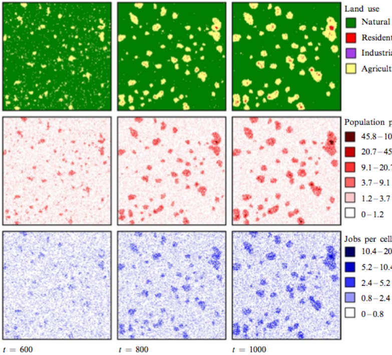
More or less explicit use of the concept of Morphogenesis in Urban Simulation, depending on the scale and the approach.

- [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*

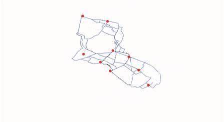
→*Importance of parcimonious, stylized models: modeling as a tool to understand processes*

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

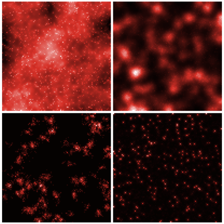
Network



Self-organizing network

Optimisation

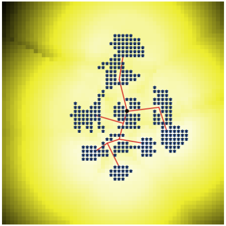
Density



Reaction-diffusion density-based model

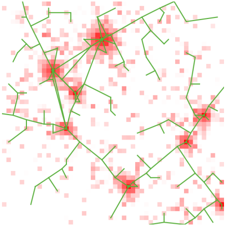
Explication

Co-evolution



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 $p_{i_+} = I_0$ and one other sink $p_{i_-} = -I_0$

Network evolution

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 $\sum_{j \to i} Q_{ij} = 0, \sum_{j \to i_\pm} Q_{i_\pm j} = \pm I_0$
2. Evolution of diameters (γ reinforcement parameter) by

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

$\rightarrow$ Extraction of the final network after convergence given a threshold parameter for diameters

$\rightarrow$ Multi-scale model : diameters are constant during an iteration to obtain equilibrium flows

Indicators

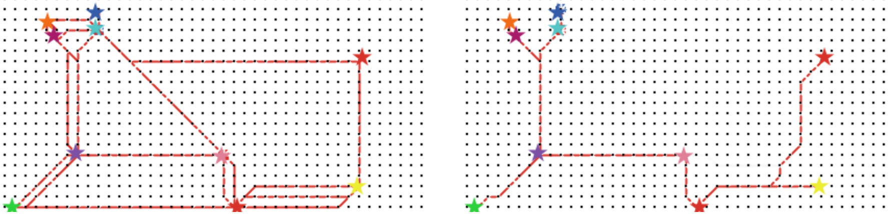
Behavior of the model evaluated with performance indicators for generated network (V_f, E_f), that are contradictory objectives :

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

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

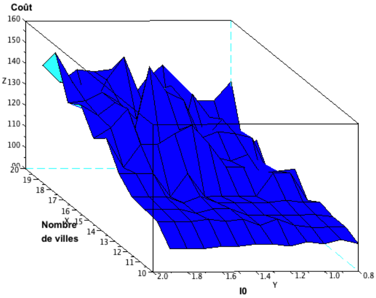
- Robustness (*Network Trip Robustness* index [Sullivan et al., 2010])

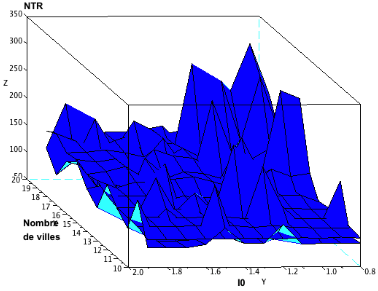
Example of networks



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

Sensitivity analysis



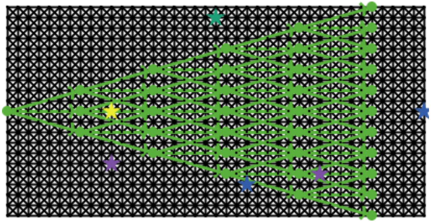


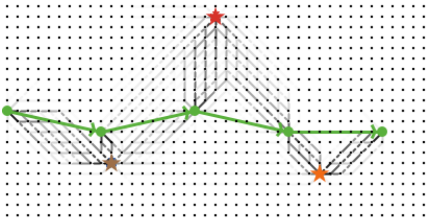
Sensitivity of indicators to parameters (N, I_0).

Application : Optimal transportation Corridor

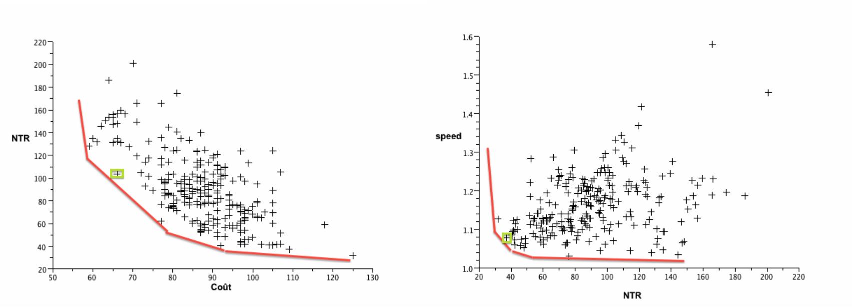
Abstract application : *Given a distribution of nodes to serve (sinks), what is the optimal corridor for an infrastructure at a larger scale (train or metro) for which stations are sources, in the sense of the multi-objective optimality of the local self-organized network ?*

→ Heuristic exploration of an arborescent set of potential infrastructures



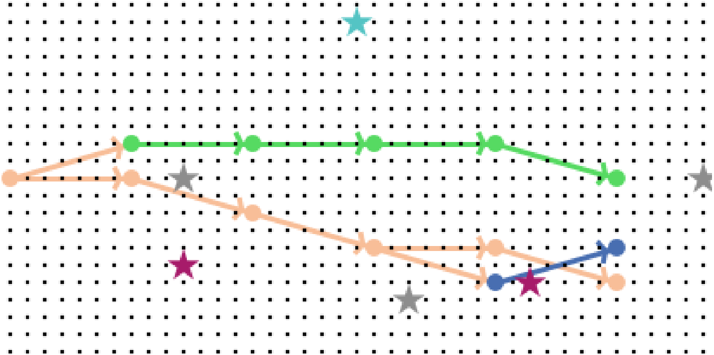


Pareto Optimisation



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

Pareto Optimisation

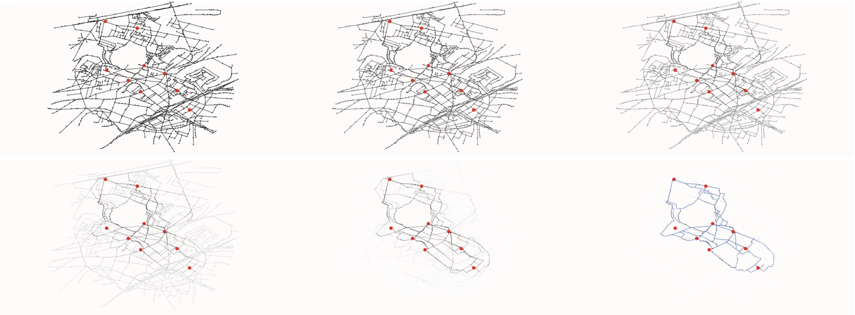


Configurations corresponding to three optimal points.

Application : Optimal Network Design

→ Mission of prospective for Romainville city : itinary 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

Model Formalization

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

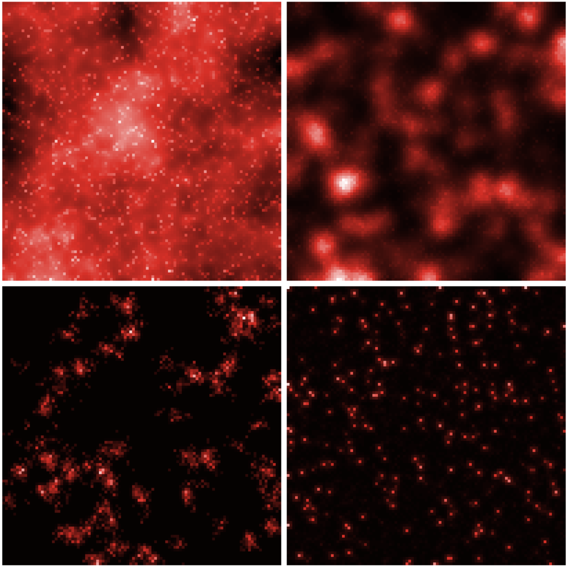
$\rightarrow$ At each time step:

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.

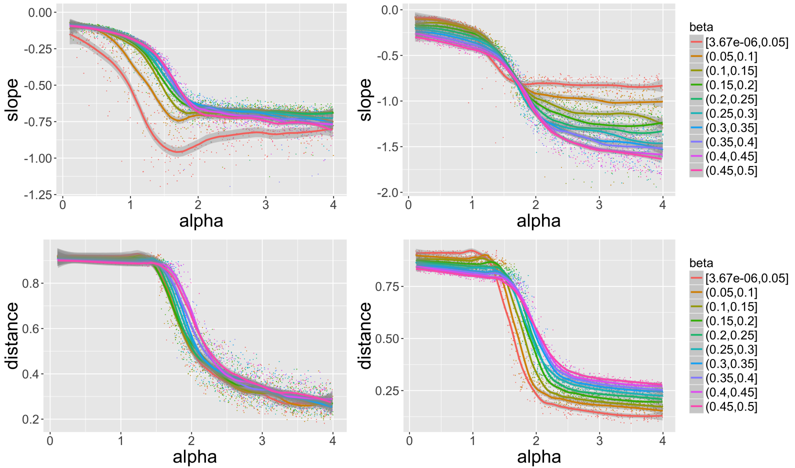
$\rightarrow$ Output measured by morphological indicators: Moran index, average distance, rank-size hierarchy, entropy.

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

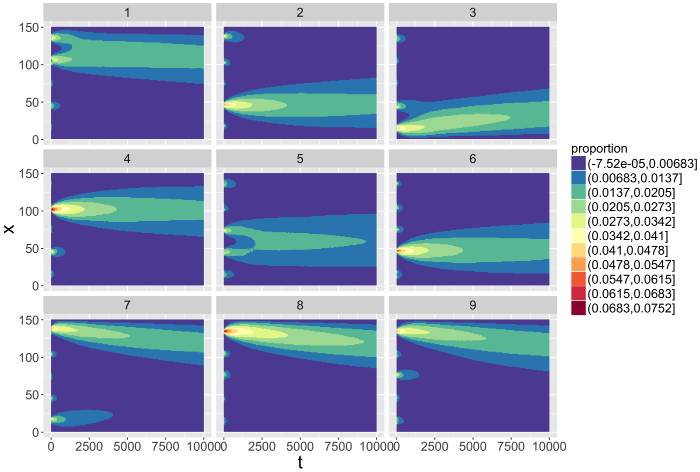
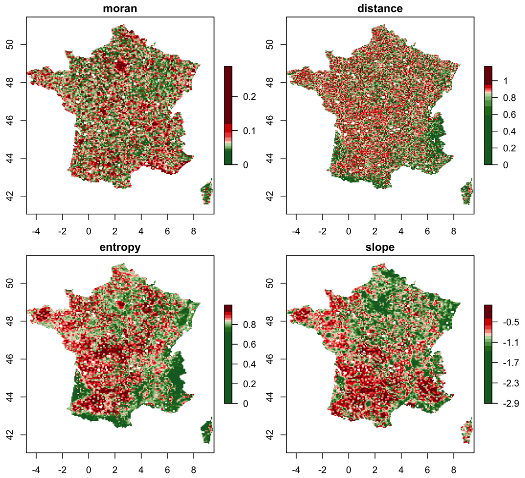
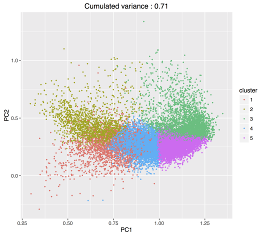
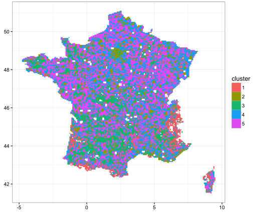


Illustration of path-dependence in a simplified one-dimensional version of the model: cell trajectories in time for 9 independent repetitions from the same initial configuration.

Empirical Data for Calibration

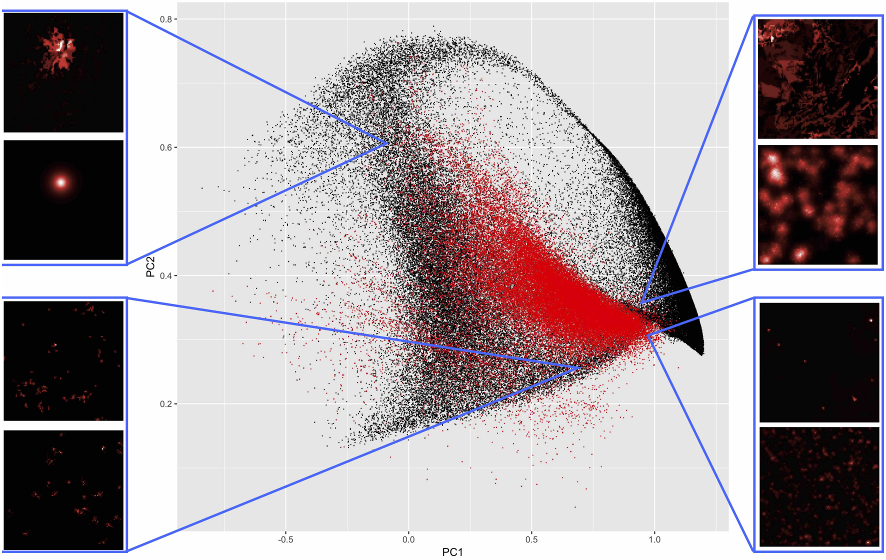






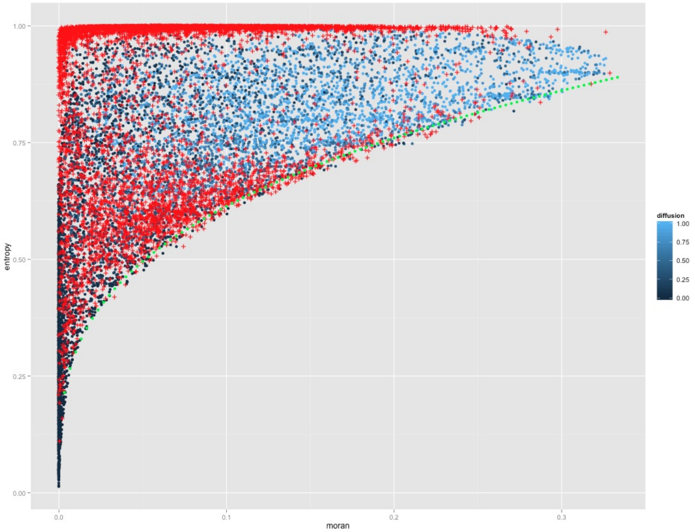
Computation of morphological indicators on population density data for Europe (shown here on France), morphological classification.

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 ?

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

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

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.

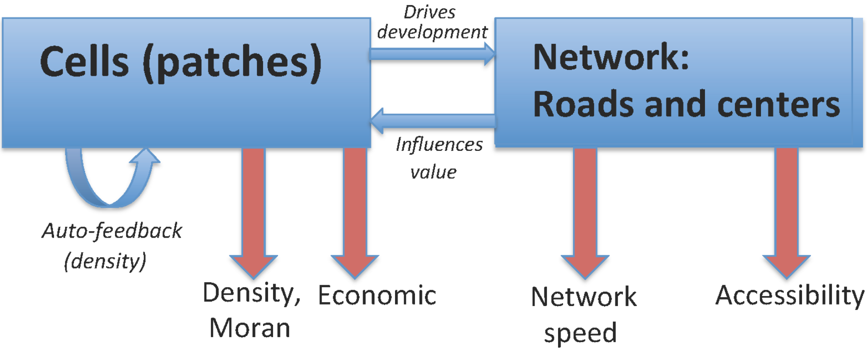
Model description : settings and agents

- 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 $a \in \{1, \ldots, a_{max}\}$ 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
  - $d_4(i,j,t) = \left(\frac{1}{a_{\text{max}}} \sum_{a=1}^{a_{\text{max}}} d_3(i,j,t;a)^{p_4} \right)^{1/p_4}$: integrated accessibility of activities

Model workflow



Evolution rules

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

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

- 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

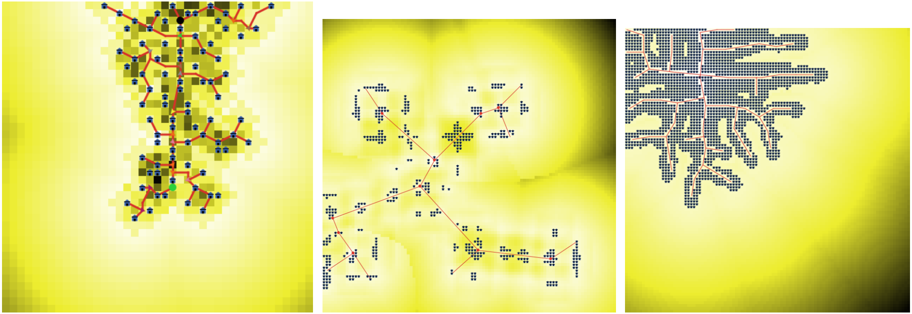
$$I(t) = \frac{M^2}{\sum_{\mu \neq \nu} 1/d_{\mu\nu}} \frac{\sum_{\mu \neq \nu} (P_\mu - \overline{P})(P_\nu - \overline{P})/d_{\mu\nu}}{\sum_{\mu=1}^{M^2} (P_\mu - \overline{P})^2}$$

Evaluation functions

Performance indicators

- Network speed ([Banos and Genre-Grandpierre, 2012])
$$S(t) = \left(\frac{1}{\sum_{i,j} \delta(i,j,t)} \sum_{\substack{i,j=1 \\ \delta(i,j,t) \neq 0}}^{N} \left(\frac{d_3(i,j,t)}{e_3(i,j,t)} \right)^{p_S} \right)^{1/p_S}$$
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

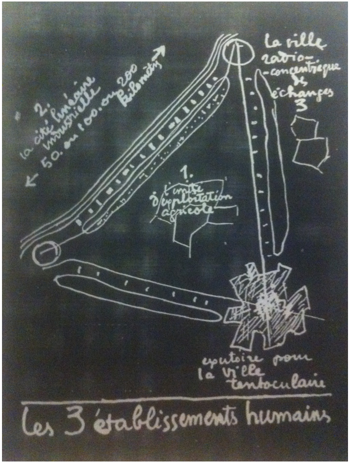


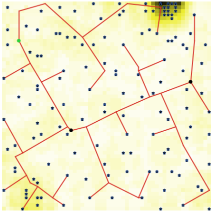
(a) "A city can be a tree", [Alexander, 1964]

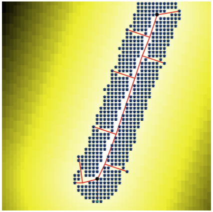
(b) Intermediate shape

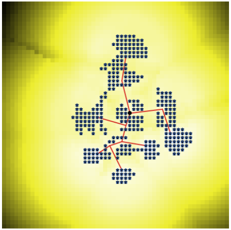
(c) One center, no density

Typology of structures



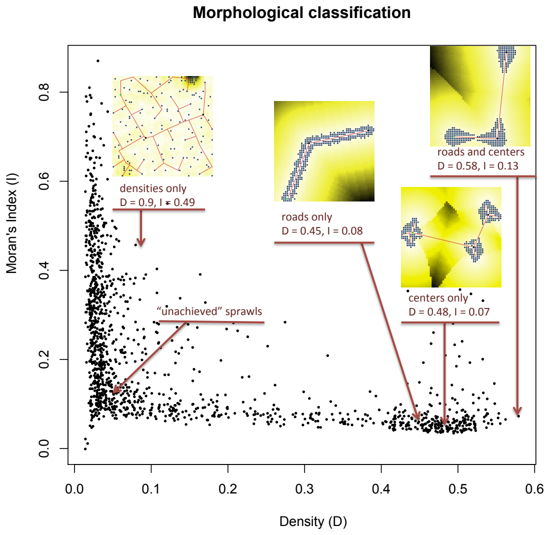






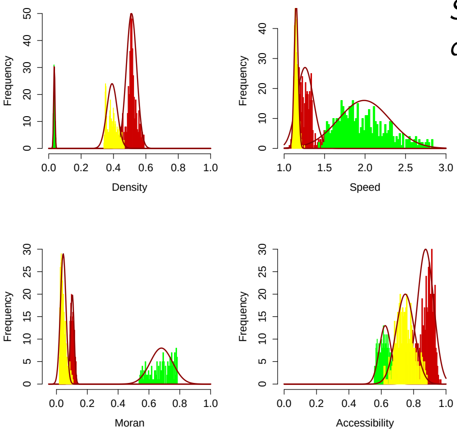
Parallel between Le Corbusier's typology of "human settlements" and some generated structures

Morphological classification



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

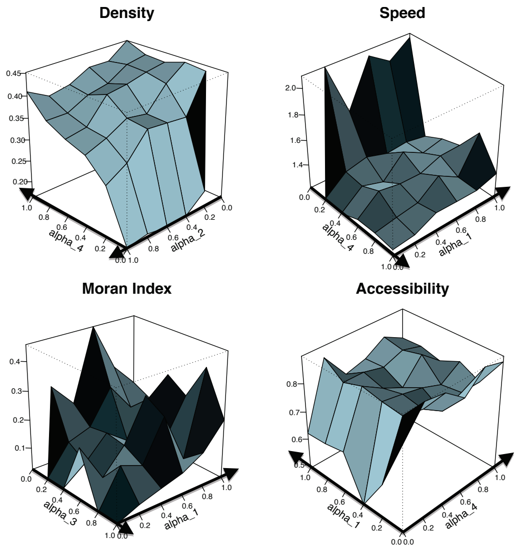
Statistical analysis



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

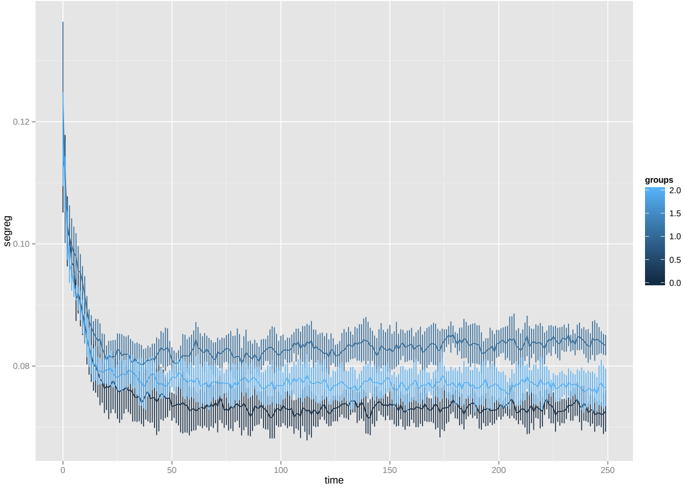
Exploration of the parameter space



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

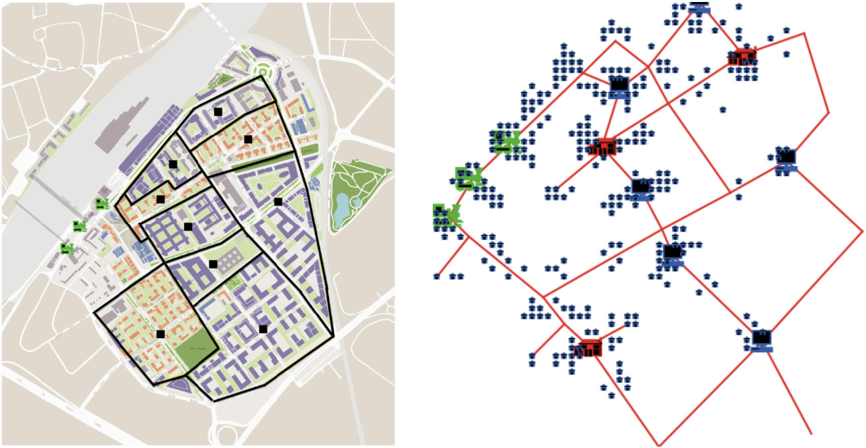


Time series of segregation index during a run of the economic ABM for different configurations.

Practical application: method

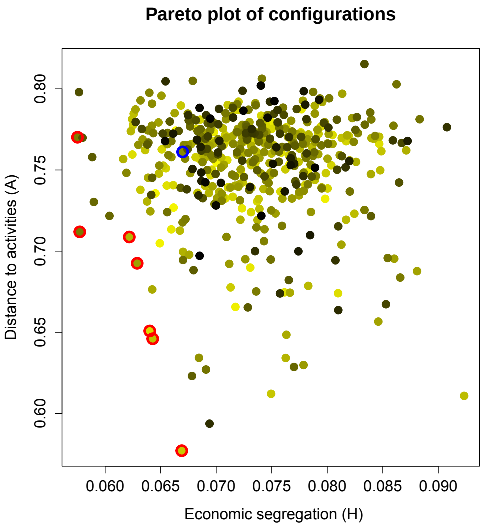
- Fixing the spatial initial structure and the parameters, optimize on the possible distribution of activities among centers. Choice of parameters is crucial.
- Importation of real GIS data: centers correspond to centroids of zones in a district, initial network to main roads. Some centers have fixed 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



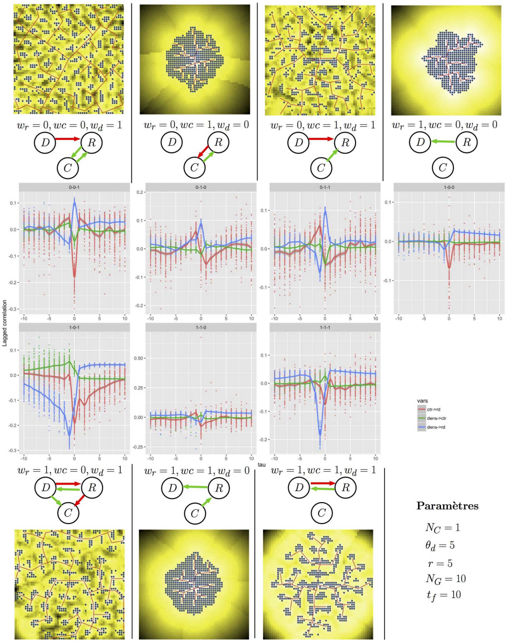
Practical application. Optimizing the distribution of activities over urban centers.

Application : Pareto optimization



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

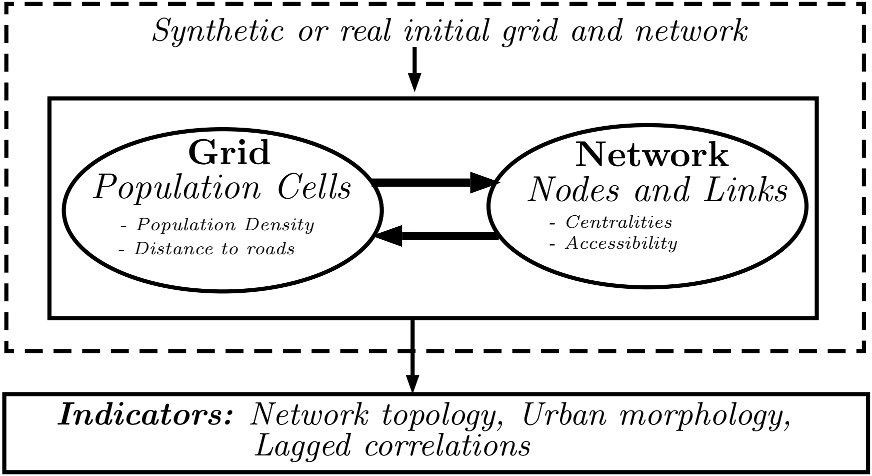
→ Coupled grid population distribution and vector transportation network, following the core of [Raimbault et al., 2014]

→ 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)

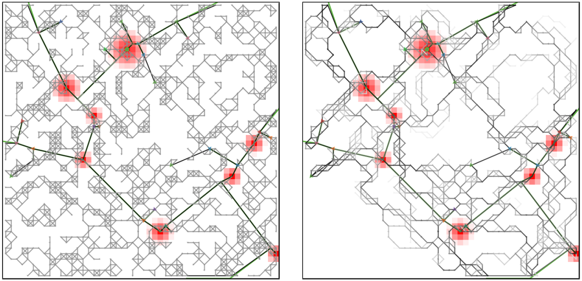
Local variables and network properties induce feedback on both, thus a strong coupling capturing the ***co-evolution***

Model : Specification



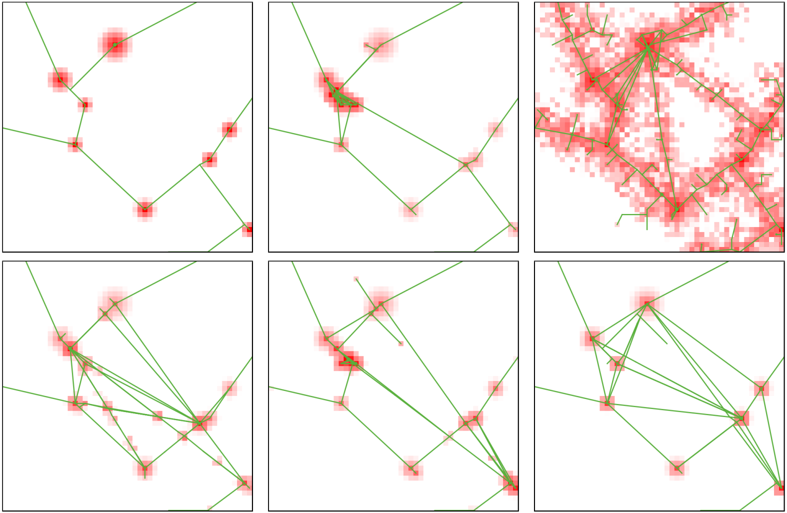
At fixed time steps :

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



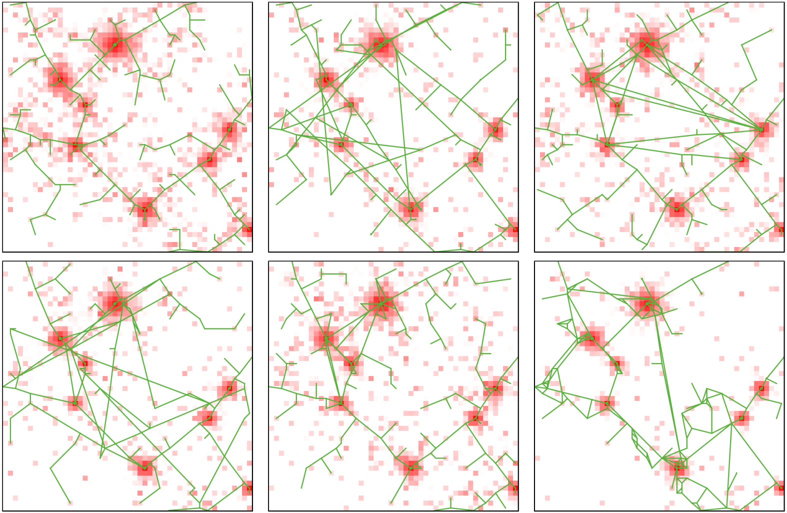
Intermediate stage for biological network generation

Generated Urban Shapes: Urban Form



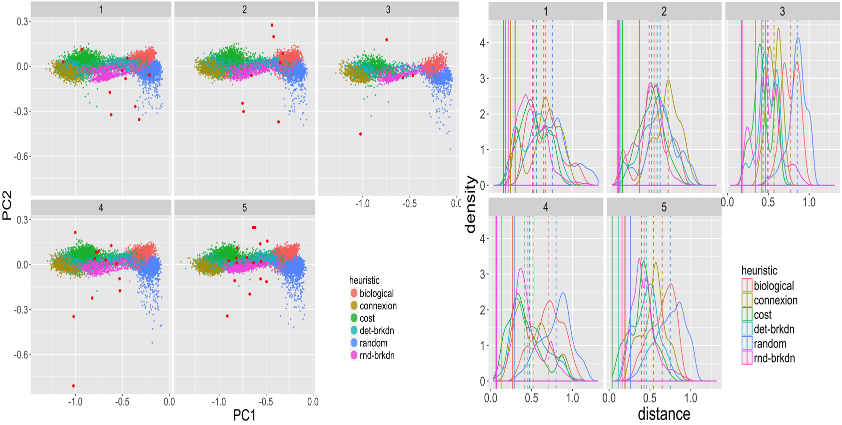
In order: setup; accessibility driven; road distance driven; betweenness driven; closeness driven; population driven.

Generated Urban Shapes: Network



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

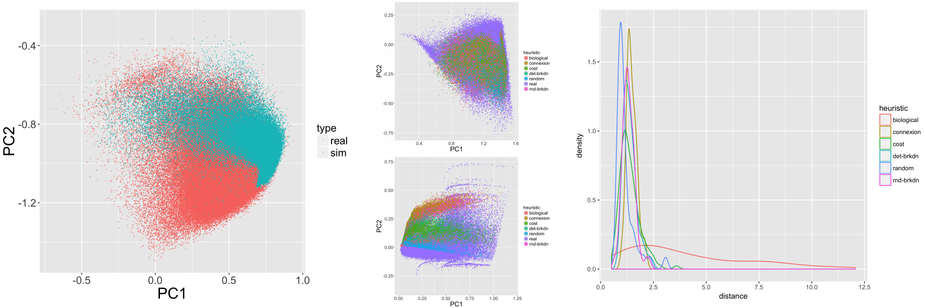
Comparison of feasible space for network indicators with fixed density



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

Results : Calibration

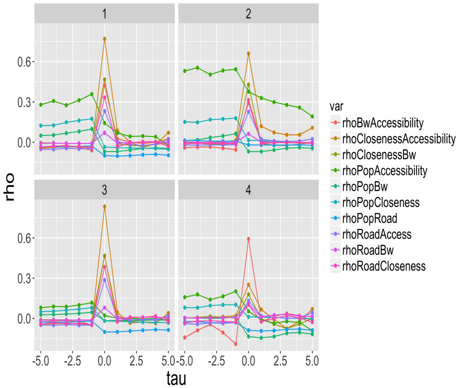
Calibration (model explored with OpenMole [Reuillon et al., 2013], $\sim 10^6$ model runs) at the first order on morphological and topological objectives, and on correlations matrices.

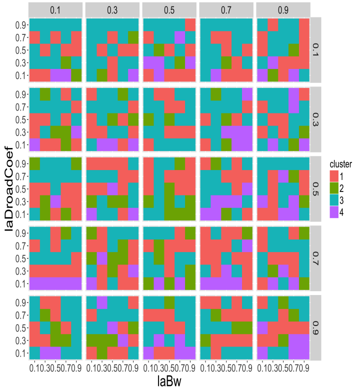


(Left) Full indicator space; (Middle) Morphological and Topology, by network heuristic; (Right) Distance distribution for cumulated distance for indicators and correlations.

Results : Causality Regimes

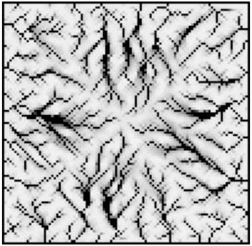
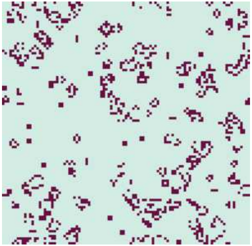
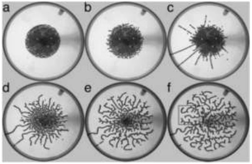
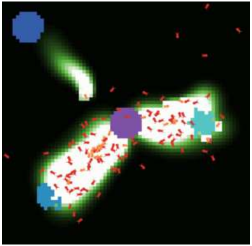
Unsupervised learning on lagged correlations between local variables unveils a diversity of causality regimes
→ Link between *co-evolution regime* and morphogenetic properties of the urban system





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

What is Morphogenesis ? Examples

	Physical	Biological	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]

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]*

Discussion

Implications

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

(*Explication*)$\rightarrow$ 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

$\rightarrow$ Towards dynamical calibrations ? Need of dynamical data

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

$\rightarrow$ 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.**

References

Raimbault, J., Banos, A., & Doursat, R. (2014). A hybrid network/grid model of urban morphogenesis and optimization. Proceedings of 4th ICCSA 2014. arXiv:1612.08552.
Raimbault, J. (2017). Calibration of a Density-based Model of Urban Morphogenesis. arXiv preprint arXiv:1708.06743.

Open repository (code, data and results) at
`https://github.com/JusteRaimbault/CityNetwork`
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.

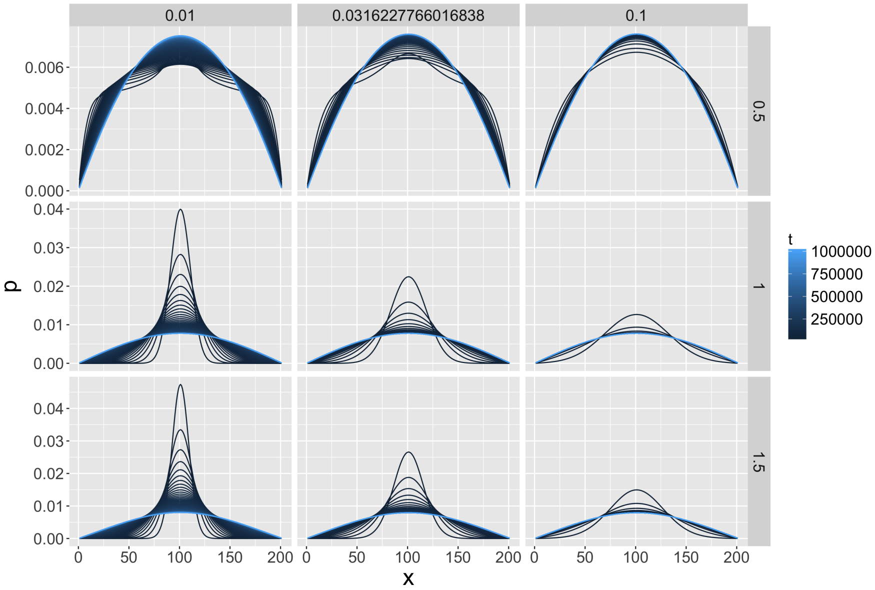
Catastrophe set $K \subset W$ is where the system endures phase transition.

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

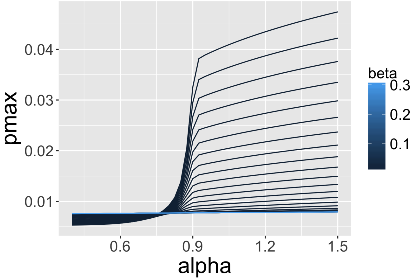
The one-dimensional model verifies the PDE :

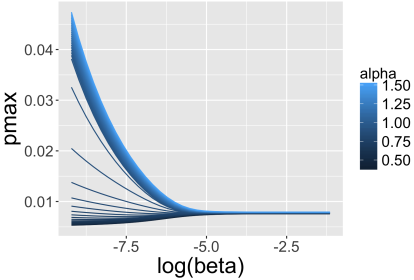
$$\delta t \cdot \frac{\partial p}{\partial t} = \frac{N_G \cdot p^{\alpha}}{P_{\alpha}(t)} + \frac{\alpha\beta(\alpha-1)\delta x^2}{2} \cdot \frac{N_G \cdot p^{\alpha-2}}{P_{\alpha}(t)} \cdot \left(\frac{\partial p}{\partial x}\right)^2 + \frac{\beta\delta x^2}{2} \cdot \frac{\partial^2 p}{\partial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

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 $w_{ij} = 1/d_{ij}$

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

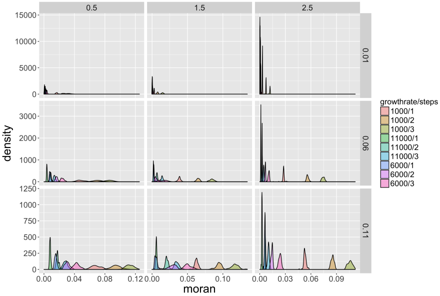
4. Mean distance between individuals

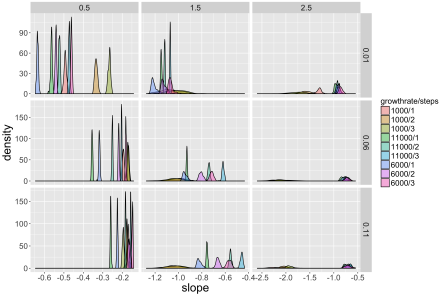
$$\bar{d} = \frac{1}{d_M} \cdot \sum_{i<j} \frac{P_i P_j}{P^2} \cdot d_{ij}$$

   where d_M is a normalisation constant

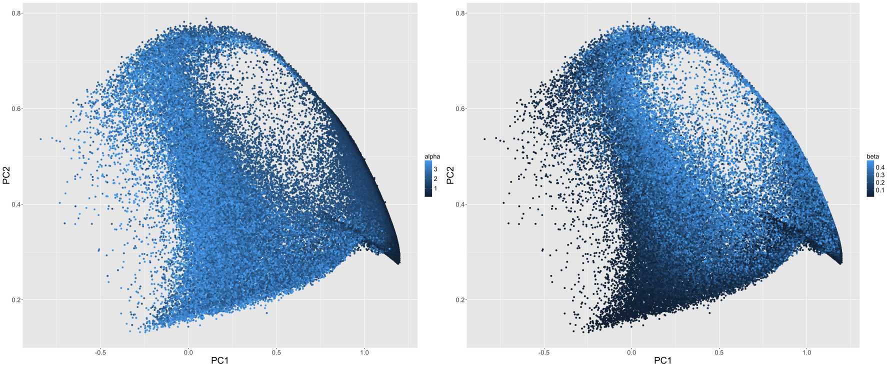
Model behavior : Convergence

Large number of repetitions show good convergence properties





Model behavior



Empirical indicators computation

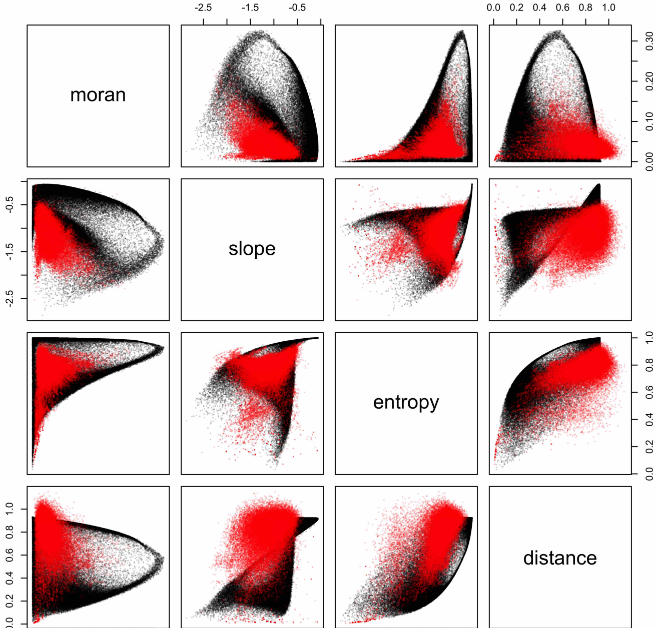
→ Eurostat population density raster (100m, simplified at 500m resolution)

→ 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

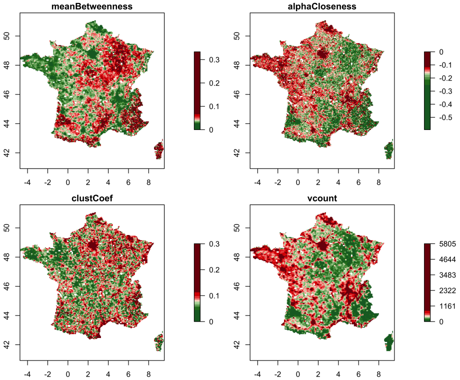
No clear definition of co-evolution in the literature : [Bretagnolle, 2009] distinguishes "reciprocal adaptation" where a sense of causality can clearly be identified, from co-evolutive regimes

Identification of multiple causality regimes in a simple strongly coupled growth model $\rightarrow$ 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]

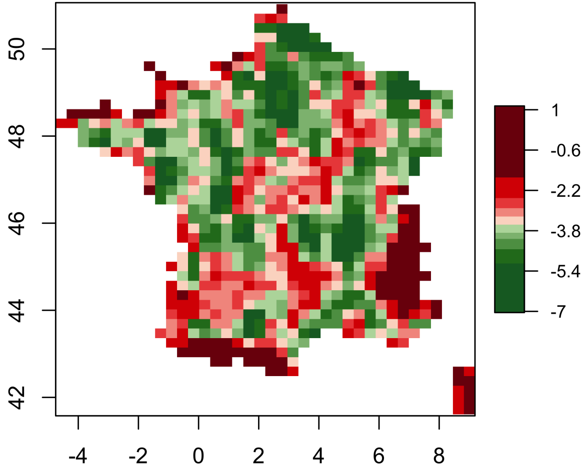
Modeling Co-evolution

[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

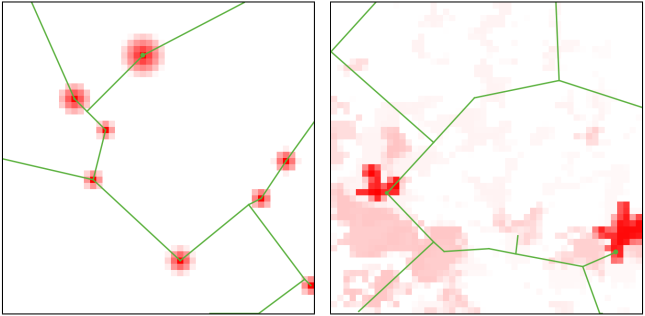
Biological Network generation

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)

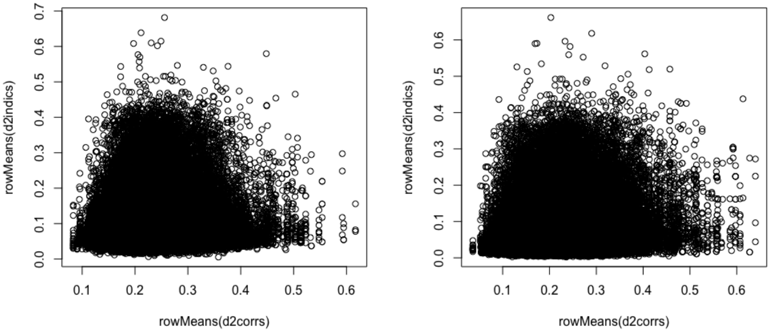


Stopping conditions: fixed final time; fixed total population; fixed network size.

Calibration Method

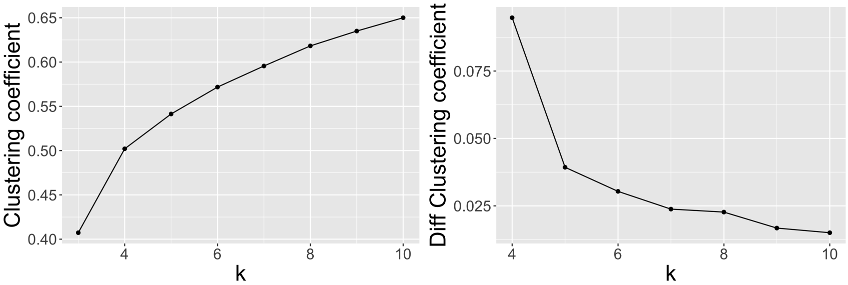
- Brute force exploration of a LHS sampling, 10 repetitions of the model for each parameter point.
- For each simulated point, closest in indicator space (euclidian distance for normalized indicators) among real points are selected.
- Among these, point with lowest distance to correlation matrix are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

Calibration : optimal points



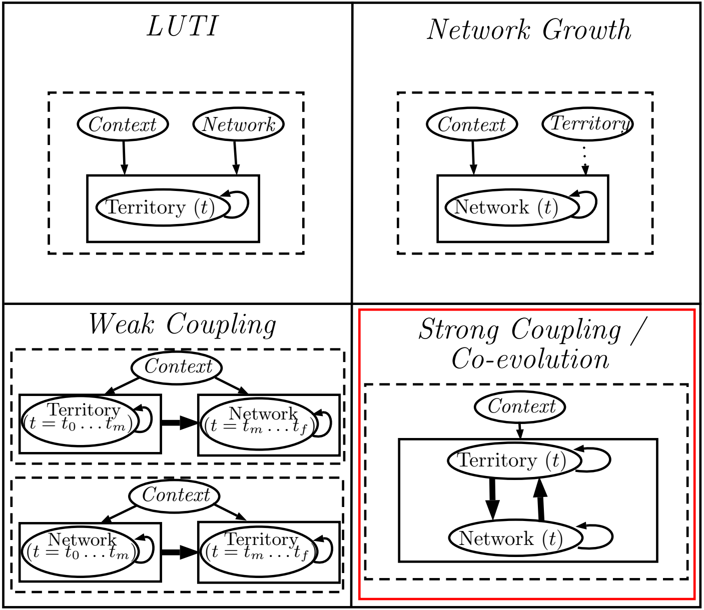
Pareto plots of distance to indicators and distance to correlation matrices, for a given simulated configuration and all real points.

Causality regimes: clustering



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

Co-evolution Models



References I

Aage, N., Andreassen, E., Lazarov, B. S., and Sigmund, O. (2017).
Giga-voxel computational morphogenesis for structural design.
Nature, 550(7674):84–86.

Abercrombie, M. (1977).
Concepts in morphogenesis.
Proceedings of the Royal Society of London B: Biological Sciences, 199(1136):337–344.

Achibet, M., Balev, S., Dutot, A., and Olivier, D. (2014).
A model of road network and buildings extension co-evolution.
Procedia Computer Science, 32:828–833.

Alexander, C. (1964).
A city is not a tree.

Antelope, C., Hubatsch, L., Raimbault, J., and Serna, J. M. (2016).
An interdisciplinary approach to morphogenesis.
Forthcoming in Proceedings of Santa Fe Institute CSSS 2016.

Banos, A. (2012).
Network effects in schelling's model of segregation: new evidences from agent-based simulation.
Environment and Planning B: Planning and Design, 39(2):393–405.

Banos, A. and Genre-Grandpierre, C. (2012).
Towards new metrics for urban road networks: Some preliminary evidence from agent-based simulations.
In *Agent-based models of geographical systems*, pages 627–641. Springer.

References III

Baptiste, H. (2010).
Modeling the evolution of a transport system and its impacts on a french urban system.
Graphs and Networks: Multilevel Modeling, Second Edition, pages 67–89.

Barthélemy, M. and Flammini, A. (2009).
Co-evolution of density and topology in a simple model of city formation.
Networks and spatial economics, 9(3):401–425.

Batty, M. (1991).
Generating urban forms from diffusive growth.
Environment and Planning A, 23(4):511–544.

Bedau, M. (2002).
Downward causation and the autonomy of weak emergence.
Principia: an international journal of epistemology, 6(1):5–50.

References IV

Benenson, I. (1998).
Multi-agent simulations of residential dynamics in the city.
Computers, Environment and Urban Systems, 22(1):25–42.

Blumenfeld-Lieberthal, E. and Portugali, J. (2010).
Network cities: A complexity-network approach to urban dynamics and development.
In *Geospatial Analysis and Modelling of Urban Structure and Dynamics*, pages 77–90. Springer.

Bonin, O. and Hubert, J.-P. (2014).
Modélisation morphogénétique de moyen terme des villes: une schématisation du modèle théorique de ritchot et desmarais dans le cadre du modèle standard de l'économie urbaine.
Revue d'Économie Régionale & Urbaine, (3):471–497.

References V

Bonin, O., Hubert, J.-P., et al. (2012).
Modèle de morphogénèse urbaine: simulation d'espaces qualitativement différenciés dans le cadre du modèle de l'économie urbaine.
In *49è colloque de l'ASRDLF*.

Bourgine, P. and Lesne, A. (2010).
Morphogenesis: origins of patterns and shapes.
Springer Science & Business Media.

Bourgine, P. and Stewart, J. (2004).
Autopoiesis and cognition.
Artificial life, 10(3):327–345.

Bretagnolle, A. (2009).
Villes et réseaux de transport : des interactions dans la longue durée, France, Europe, États-Unis.
Hdr, Université Panthéon-Sorbonne - Paris I.

References VI

Caruso, G., Vuidel, G., Cavailhes, J., Frankhauser, P., Peeters, D., and Thomas, I. (2011).
Morphological similarities between dbm and a microeconomic model of sprawl.
Journal of Geographical Systems, 13:31–48.

Chapman, M. J. and Margulis, L. (1998).
Morphogenesis by symbiogenesis.
International Microbiology, 1(4).

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

Douady, S. and Hersen, P. (2011).
Dunes, the collective behaviour of wind and sand, or: Are dunes living beings?
In *Morphogenesis*, pages 107–118. Springer.

Doursat, R., Sayama, H., and Michel, O. (2012).
Morphogenetic engineering: toward programmable complex systems.
Springer.

Doursat, R., Sayama, H., and Michel, O. (2013).
A review of morphogenetic engineering.
Natural Computing, 12(4):517–535.

Dupuy, G. (1987).
Vers une théorie territoriale des réseaux: une application au transport urbain.
In *Annales de Géographie*, pages 658–679. JSTOR.

Fujita, M. and Thisse, J.-F. (1996).
Economics of agglomeration.
Journal of the Japanese and international economies, 10(4):339–378.

Gilbert, S. F. (2003).
The morphogenesis of evolutionary developmental biology.
International Journal of Developmental Biology, 47(7-8):467.

Holland, J. H. (2012).
Signals and boundaries: Building blocks for complex adaptive systems.
Mit Press, Cambridge, ISBN: 9780262525930.

Jun, J. K. and Hübler, A. H. (2005).
Formation and structure of ramified charge transportation networks in an electromechanical system.
Proceedings of the National Academy of Sciences of the United States of America, 102(3):536–540.

References IX

Le Néchet, F. and Aguilera, A. (2011).
Déterminants spatiaux et sociaux de la mobilité domicile-travail dans 13 aires urbains françaises : une approche par la forme urbaine, à deux échelles géographiques.
In *ASRDLF 2011*, SCHOELCHER, Martinique.
http://asrdlf2011.com/.

Lord, E. M. (1981).
Cleistogamy: a tool for the study of floral morphogenesis, function and evolution.
The Botanical Review, 47(4):421–449.

Louf, R., Jensen, P., and Barthelemy, M. (2013).
Emergence of hierarchy in cost-driven growth of spatial networks.
Proceedings of the National Academy of Sciences, 110(22):8824–8829.

Makse, H. A., Andrade, J. S., Batty, M., Havlin, S., Stanley, H. E., et al. (1998).
Modeling urban growth patterns with correlated percolation.
Physical Review E, 58(6):7054.

Minter, N. J., Franks, N. R., and Brown, K. A. R. (2012).
Morphogenesis of an extended phenotype: four-dimensional ant nest architecture.
Journal of the Royal Society Interface, 9(68):586–595.

Moreno, D., Badariotti, D., and Banos, A. (2009).
Un automate cellulaire pour expérimenter les effets de la proximité dans le processus d'étalement urbain : le modèle raumulus.
Cybergeo : European Journal of Geography.

References XI

Moreno, D., Banos, A., and Badariotti, D. (2007).
Conception d'un automate cellulaire non stationnaire à base de graphe pour modéliser la structure spatiale urbaine: le modèle remus.

Cybergeo: European Journal of Geography.

Murcio, R., Morphet, R., Gershenson, C., and Batty, M. (2015).
Urban transfer entropy across scales.
PLoS ONE, 10(7):e0133780.

Raimbault, J. (2017).
Co-construire modèles, etudes empiriques et théories en géographie théorique et quantitative: le cas des interactions entre réseaux et territoires.
In *Treizièmes Rencontres de ThéoQuant*.

Raimbault, J., Banos, A., and Doursat, R. (2014).
A hybrid network/grid model of urban morphogenesis and optimization.
In *Proceedings of the 4th International Conference on Complex Systems and Applications (ICCSA 2014), June 23-26, 2014, Université de Normandie, Le Havre, France; M. A. Aziz-Alaoui, C. Bertelle, X. Z. Liu, D. Olivier, eds.: pp. 51-60.*

Renfrew, C. (1978).
Trajectory discontinuity and morphogenesis: the implications of catastrophe theory for archaeology.
American Antiquity, pages 203–222.

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

Sayama, H. (2007).
Decentralized control and interactive design methods for large-scale heterogeneous self-organizing swarms.
Advances in Artificial Life, pages 675–684.

Schelling, T. C. (1969).
Models of segregation.
The American Economic Review, 59(2):488–493.

Schmitt, C. (2014).
Modélisation de la dynamique des systèmes de peuplement: de SimpopLocal à SimpopNet.
PhD thesis, Paris 1.

References XIV

Sheridan Dodds, P., Rushing Dewhurst, D., Hazlehurst, F. F., Van Oort, C. M., Mitchell, L., Reagan, A. J., Ryland Williams, J., and Danforth, C. M. (2016).
Simon's fundamental rich-gets-richer model entails a dominant first-mover advantage.
ArXiv e-prints.

Sullivan, J., Novak, D., Aultman-Hall, L., and Scott, D. M. (2010).
Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach.
Transportation Research Part A: Policy and Practice, 44(5):323–336.

Tero, A., Takagi, S., Saigusa, T., Ito, K., Bebber, D. P., Fricker, M. D., Yumiki, K., Kobayashi, R., and Nakagaki, T. (2010a).
Rules for biologically inspired adaptive network design.
Science, 327(5964):439–442.

References XV

Tero, A., Takagi, S., Saigusa, T., Ito, K., Bebber, D. P., Fricker, M. D., Yumiki, K., Kobayashi, R., and Nakagaki, T. (2010b).
Rules for biologically inspired adaptive network design.
Science, 327(5964):439–442.

Thom, R. (1974).
Stabilité structurelle et morphogénèse.
Poetics, 3(2):7–19.

Tsai, Y.-H. (2005).
Quantifying urban form: compactness versus' sprawl'.
Urban studies, 42(1):141–161.

Turing, A. M. (1952).
The chemical basis of morphogenesis.
Philosophical Transactions of the Royal Society of London B: Biological Sciences, 237(641):37–72.

References XVI

van Vliet, J., Hurkens, J., White, R., and van Delden, H. (2012).
An activity-based cellular automaton model to simulate land-use dynamics.
Environment and Planning-Part B, 39(2):198.

Wu, J., Li, R., Ding, R., Li, T., and Sun, H. (2017).
City expansion model based on population diffusion and road growth.
Applied Mathematical Modelling, 43:1–14.