Modeling Network Morphogenesis: a co-evolution approach

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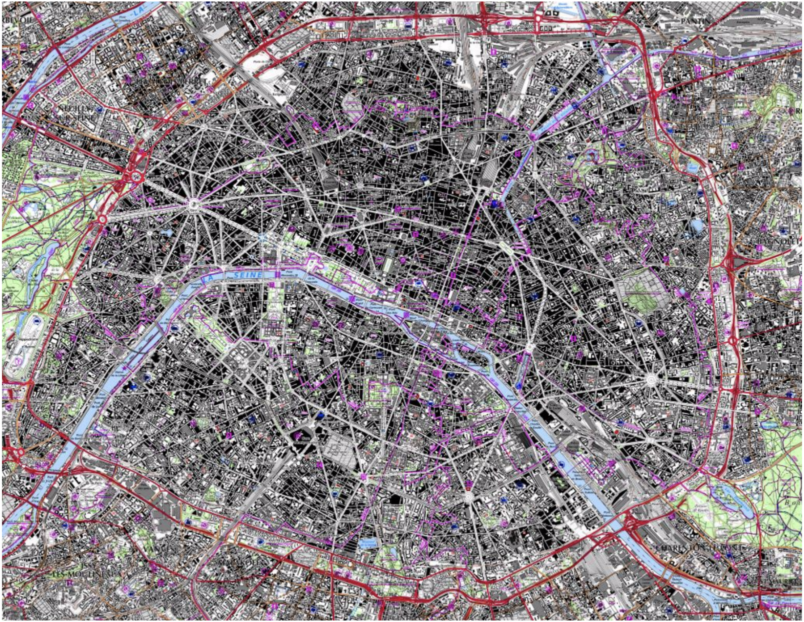
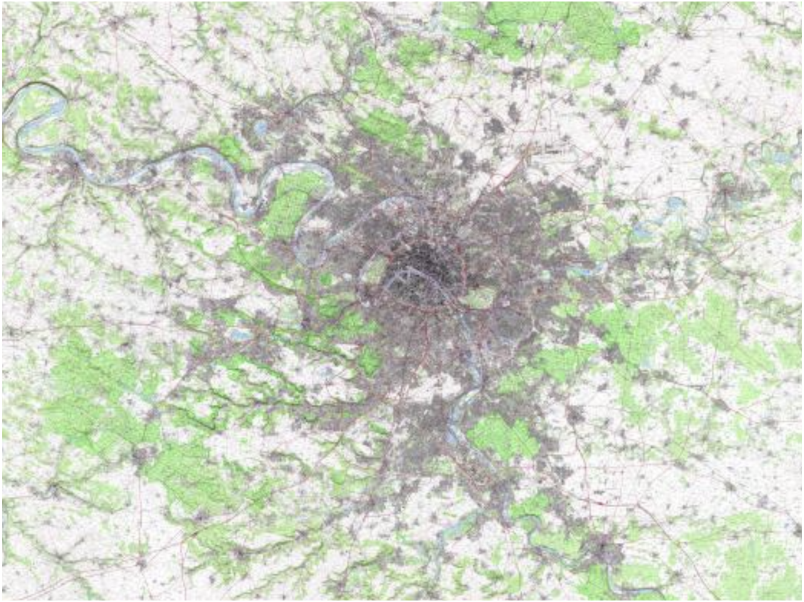
Complex processes of Urban Morphogenesis



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

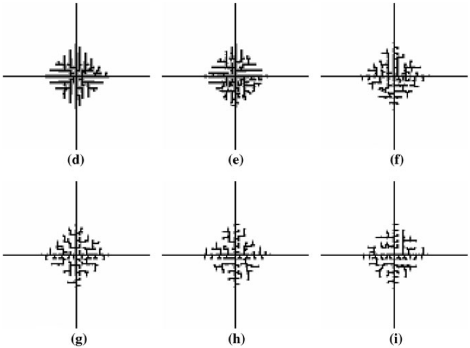
→ first use in 1871, large peak in usage between 1907-1909, increase until 1990, decrease until today. *Scientific fashion ?*

Modeling Urban Morphogenesis

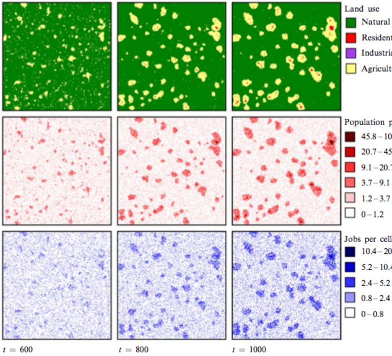
More or less explicit use of the concept of Morphogenesis in Urban Simulation, depending on the scale and the approach.

- [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]

Territorial approach to networks

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

$\rightarrow$ Networks as realized potential transactions (Dupuy's territorial theory of networks [Dupuy, 1987]).

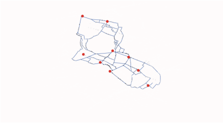
$\rightarrow$ Networks capture functions within co-evolution processes with territories, and the study of network morphogenesis thus informs more generally on urban morphogenesis.

$\rightarrow$ Importance of parcimonious, stylized models: modeling as a tool to understand processes.

Different approaches to Network Morphogenesis

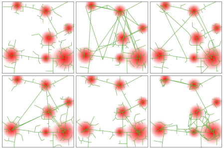
Different models with different ontologies and coupling ontologies

Network | *Co-evolution*



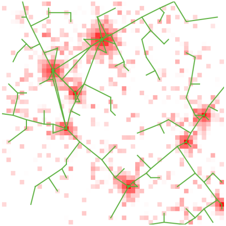
Self-organizing biological network

Optimisation



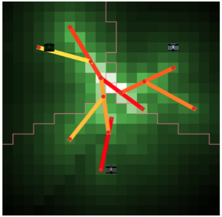
Multi-modeling network growth

Explication



Co-evolution model

Explication



Transportation governance

Explication

Network morphogenesis model

Model studied by [Tero et al., 2010] : 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

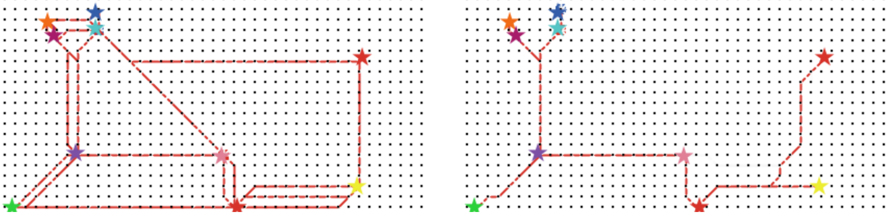
Behavior of the model evaluated with performance indicators for generated network (V_f, E_f), that are contradictory objectives :

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

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

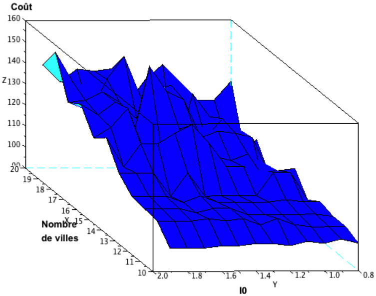
- Robustness (*Network Trip Robustness* index [Sullivan et al., 2010])

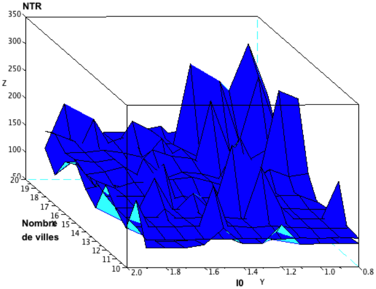
Example of networks



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

Sensitivity analysis



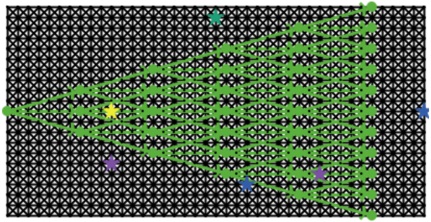


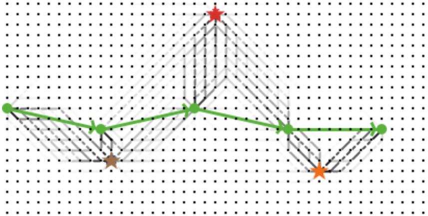
Sensitivity of indicators to parameters (N, I_0).

Application : Optimal transportation Corridor

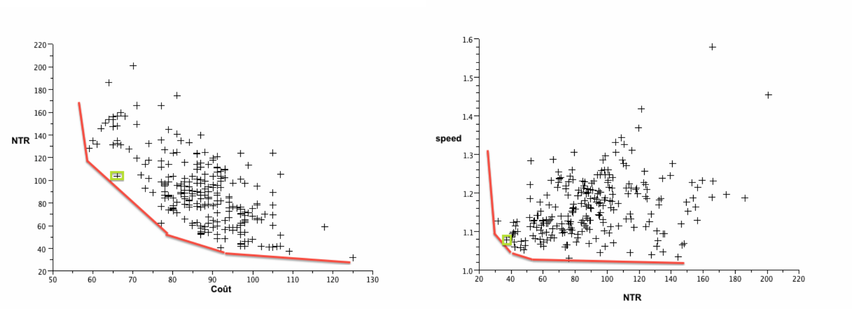
Abstract application : *Given a distribution of nodes to serve (sinks), what is the optimal corridor for an infrastructure at a larger scale (train or metro) for which stations are sources, in the sense of the multi-objective optimality of the local self-organized network ?*

→ Heuristic exploration of an arborescent set of potential infrastructures



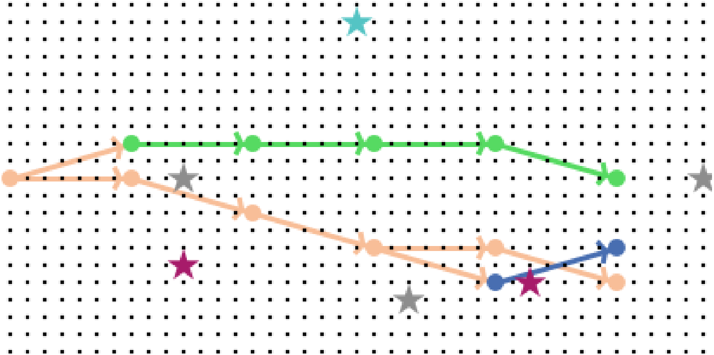


Pareto Optimisation



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

Pareto Optimisation

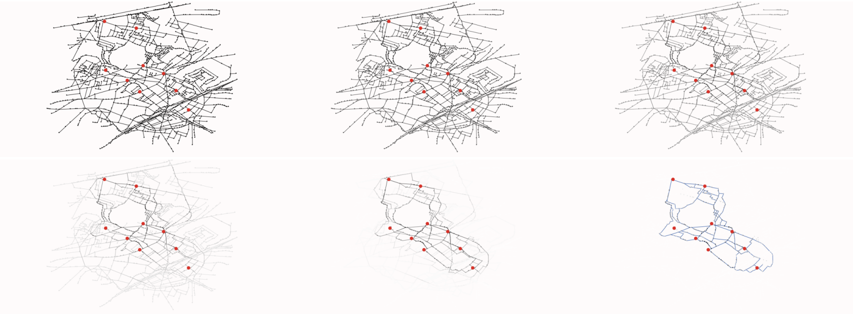


Configurations corresponding to three optimal points.

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.

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

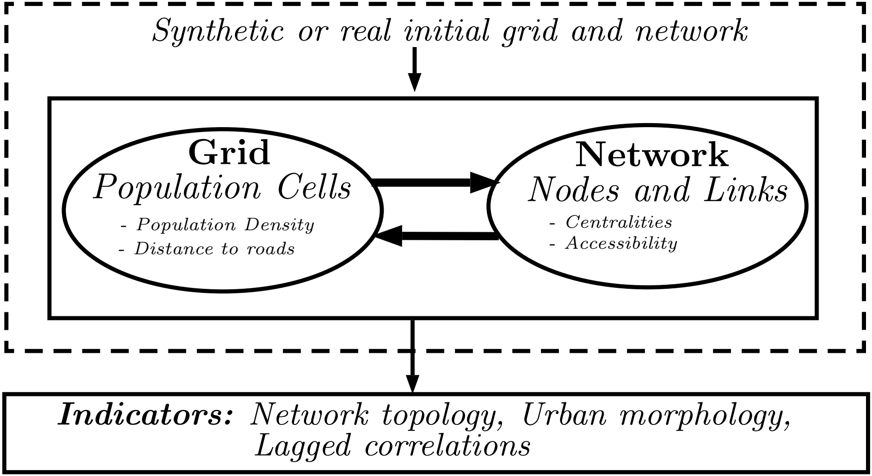
→ Coupled grid population distribution and vector transportation network, following the core of [Raimbault et al., 2014]

→ 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***

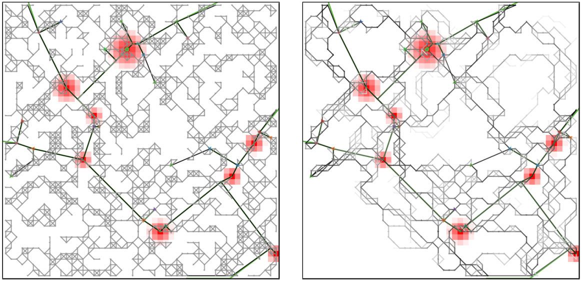
Model : Specification



Network Generation: multi-modeling network growth

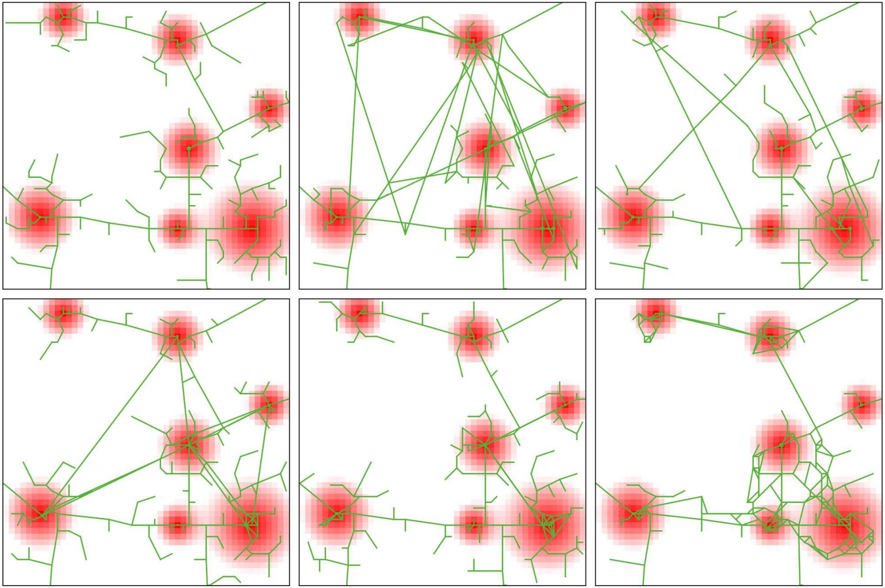
At fixed time steps :

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])



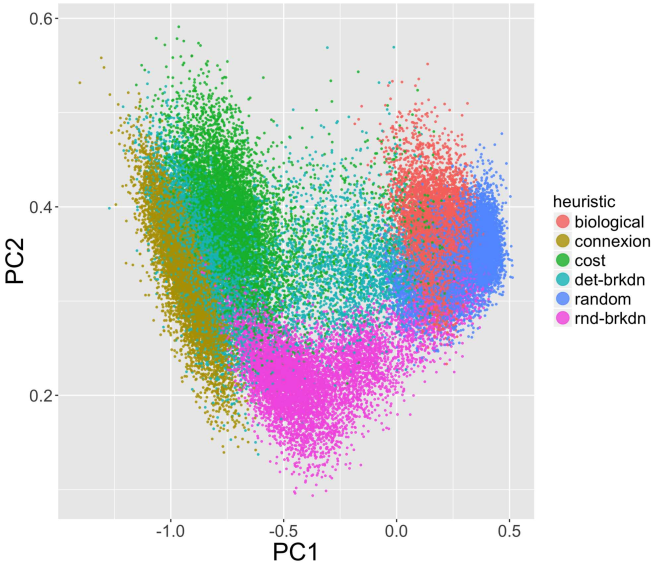
Intermediate stage for biological network generation

Generated Urban Shapes: Network

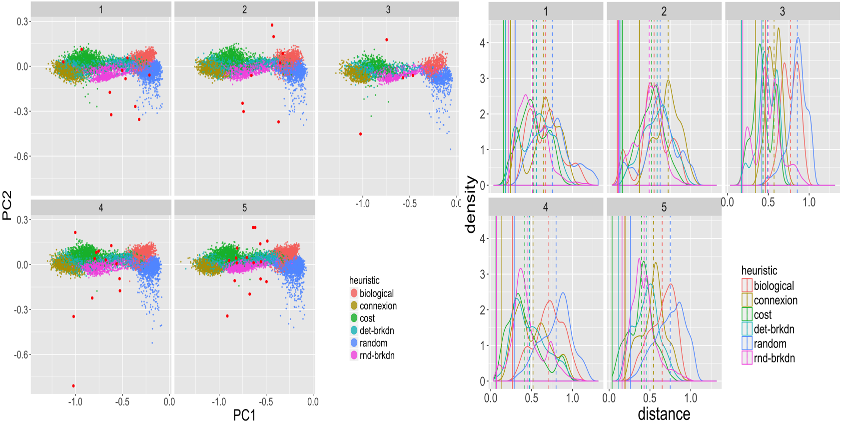


In order: connection; random; deterministic breakdown; random breakdown; cost-driven; biological.

Results : Feasible space of network topologies

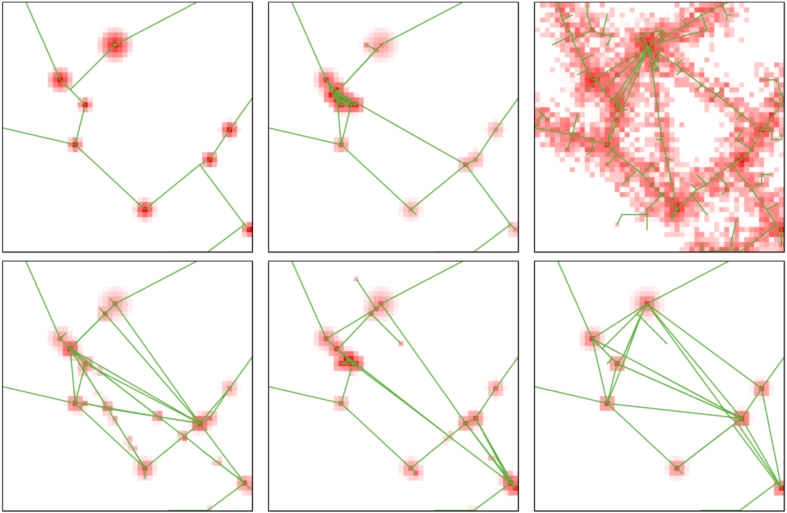


Comparison of feasible space for network indicators with fixed density



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

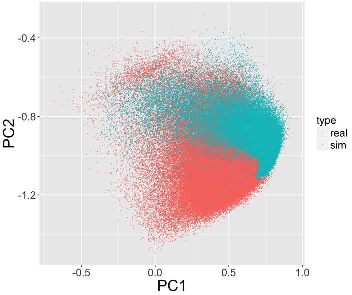
Generated Urban Shapes: Urban Form

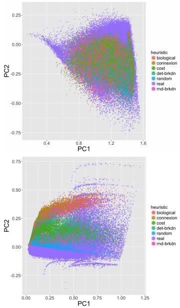


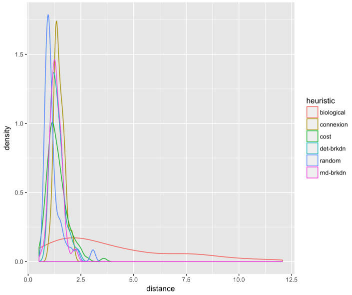
In order: setup; accessibility driven; road distance driven; betweenness driven; closeness driven; population driven.

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.





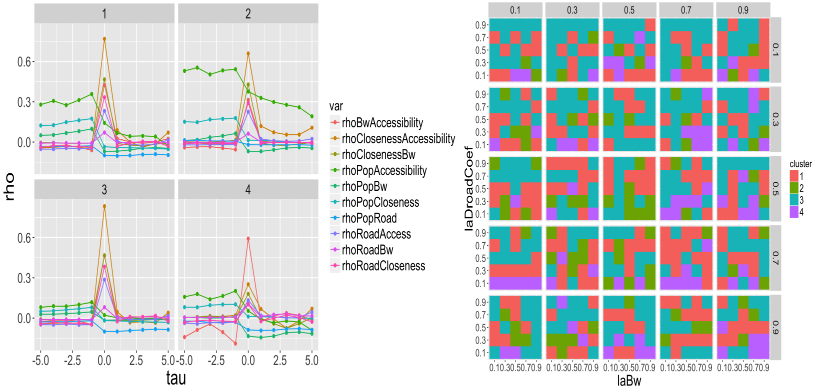


(Left) Full indicator space; (Middle) Morphological and Topology, by network heuristic; (Right) Distance distribution for cumulated distance for indicators and correlations.

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

The LUTECIA Model : Rationale

Towards a more complex approach to network growth rules ? $\rightarrow$ a co-evolution approach including transportation governance

Mega-city Regions [Hall and Pain, 2006] exhibit new qualitative regimes of urban systems ?

$\rightarrow$ A LUTI + infrastructure provision model (LUTECIA)

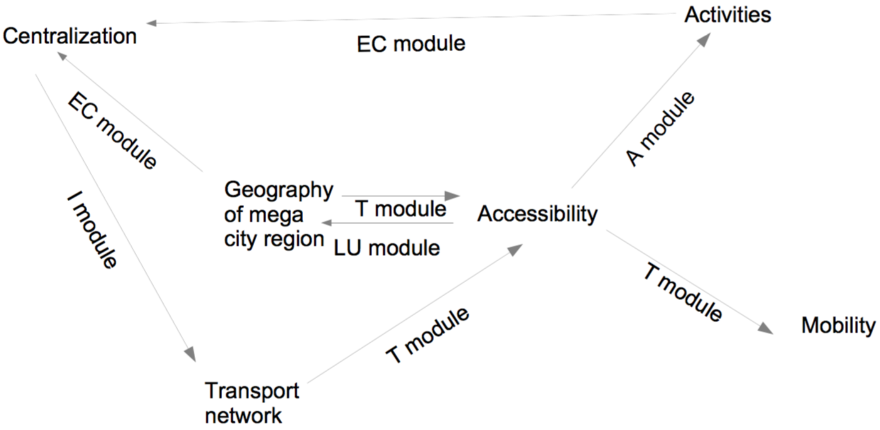
$\rightarrow$ Coevolution transport / urbanism (LUTI model with endogeneous transport infrastructure provision)

$\rightarrow$ Game theory framework to predict emergence of centralized decision within a polycentric region

$\rightarrow$ Importance of accessibility at MCR scale

The LUTECIA Model : Structure

LU : Land Use module ; T : Transport module ; EC : Evaluation of Centralized decision module ; I : Infrastructure provision module ; A : Agglomeration economies module



Governance Modeling

Matrix of actors utilities, depending on respective choices

0 | 1	C	NC
C	$U_i = \kappa \cdot \Delta X_i(Z_C^*) - I - \frac{J}{2}$	$\begin{cases} U_0 = \kappa \cdot \Delta X_0(Z_0^*) - I \\ U_1 = \kappa \cdot \Delta X_1(Z_1^*) - I - \frac{J}{2} \end{cases}$
NC	$\begin{cases} U_0 = \kappa \cdot \Delta X_0(Z_0^*) - I - \frac{J}{2} \\ U_1 = \kappa \cdot \Delta X_1(Z_1^*) - I \end{cases}$	$U_i = \kappa \cdot \Delta X_i(Z_i^*) - I$

Two types of games implemented :

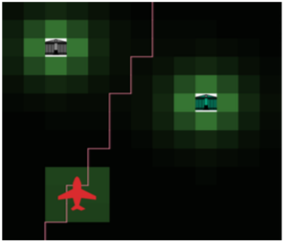
- Mixed Nash equilibrium, where actors compete
- One Rational Discrete Choice equilibrium

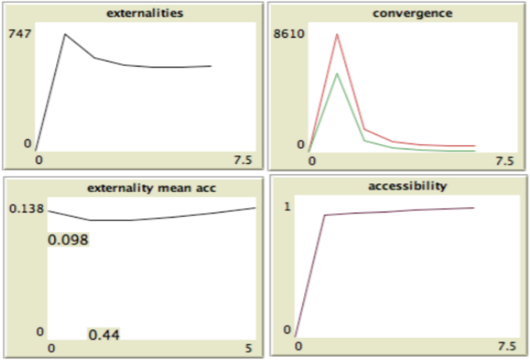
Lutecia model parameters

Sub-model	Parameter	Name
Land-use	λ	Accessibility range
	γ_A	Cobb-Douglas exponents actives
	γ_E	Cobb-Douglas exponents employments
	β	Discrete choices exponent
	α	Relocation rate
Transport	v_G	Network speed
Governance	J	Collaboration cost
	l_r	Infrastructure length

Model Output : Examples

Implementation : Netlogo ; particular treatment for dynamical programming computation of network shortest distances. Exploration with High Performance Computing on grid with `OpenMole` [Reuillon et al., 2013]

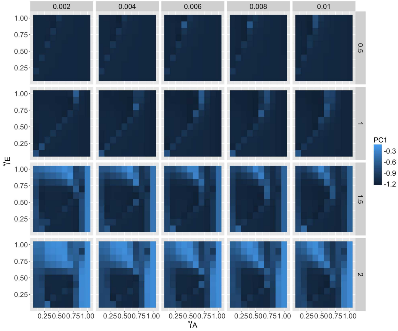


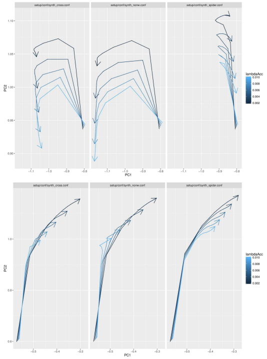


Land-use dynamics

Lessons from systematic exploration of the land-use module:

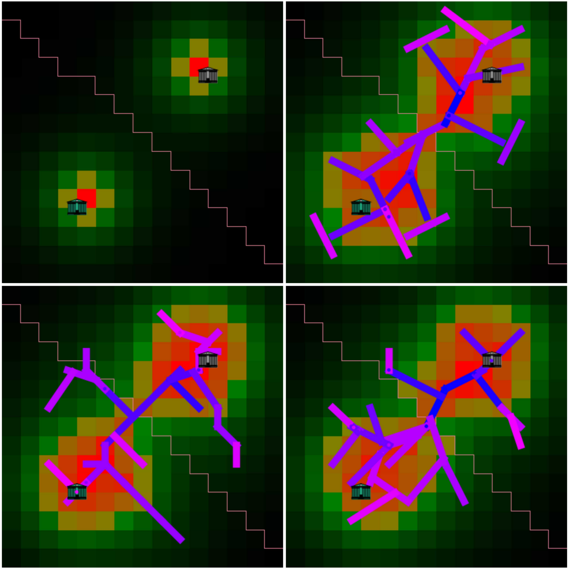
- Large diversity of morphological trajectories in time for varying $\gamma_A, \gamma_E, \lambda, \beta$
- Diversity of final forms obtained
- It is possible to minimize, at fixed $\alpha = 1$, the total quantity of relocalization





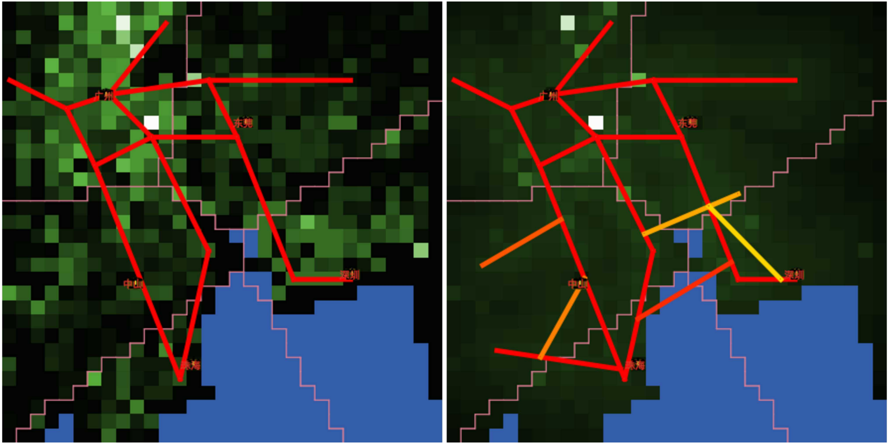
Model Exploration

Influence of governance parameters on network topology



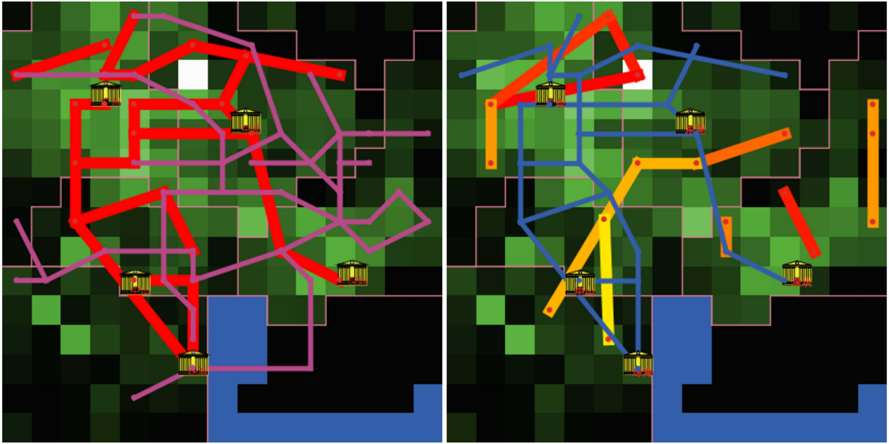
Model Application

Stylized application to the Pear River Delta Mega-city Region



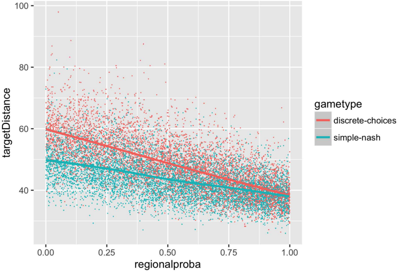
Model Application: target networks

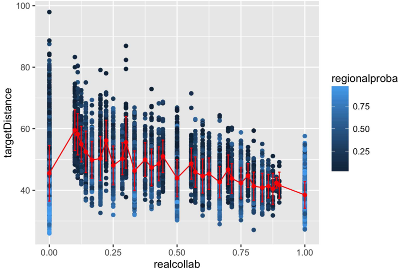
Different calibration setup: current and planned network

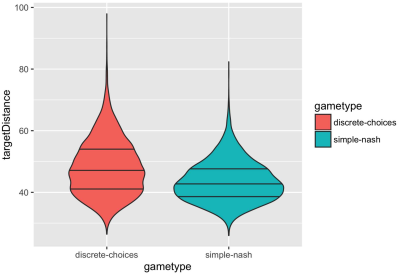


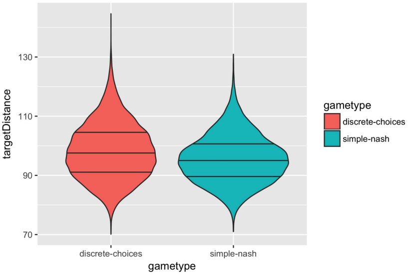
Model Calibration

Calibration on the generated network (fixed land-use)



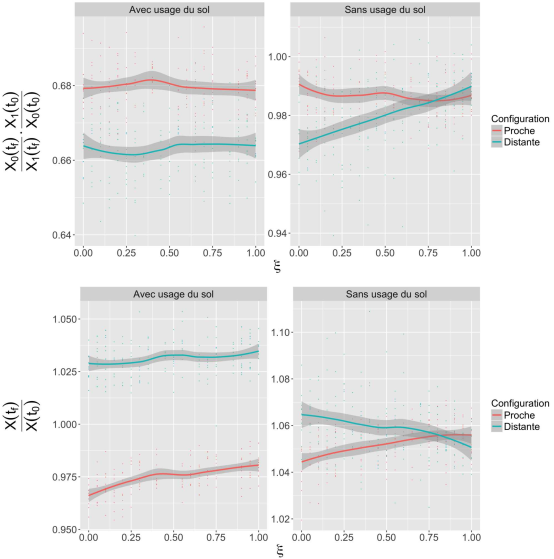






Effects of co-evolution

Unveiling the coupling between urban development and transportation networks



What is Morphogenesis ? Examples

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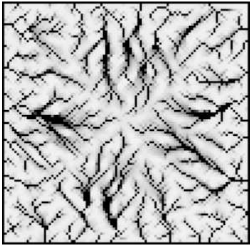
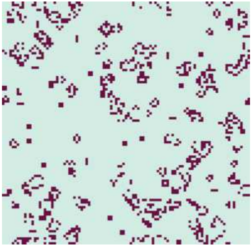
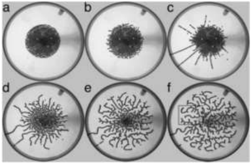
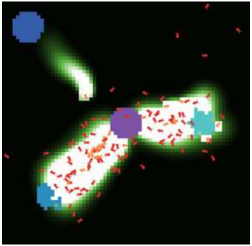
Non Functional			
Functional			

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, 2009]

Interdisciplinary Definition of Morphogenesis

Proposition of an interdisciplinary definition

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, 1972]

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 stylized facts: which intrinsic dimension to the urban system and its morphological aspect are effectively captured?

Developments

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

$\rightarrow$ Investigate the link between spatial non-stationarity and non-ergodicity

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

Conclusion

→ Several morphogenesis models 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.**

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, 1972]
- **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.

Defining co-evolution

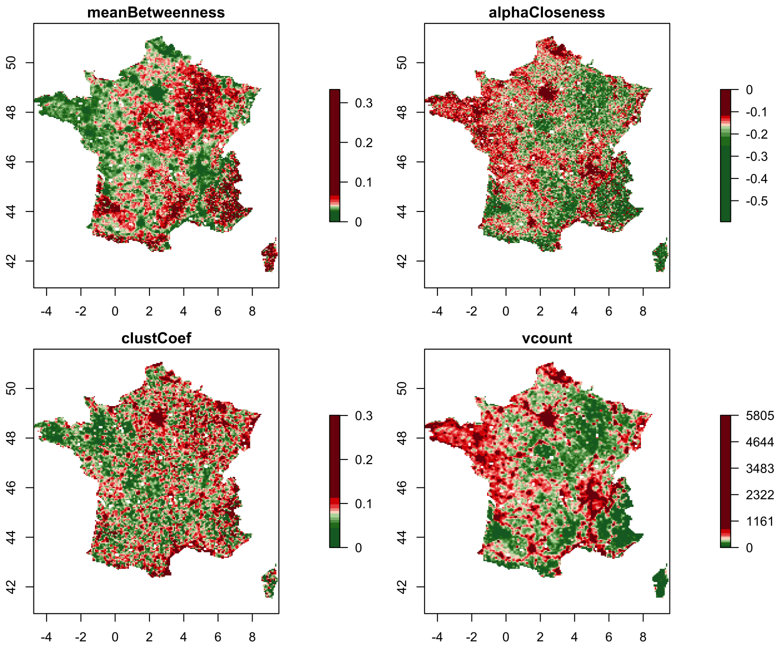
No clear definition of co-evolution in the literature : [Bretagnolle, 2009] distinguishes "reciprocal adaptation" where a sense of causality can clearly be identified, from co-evolutive regimes

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

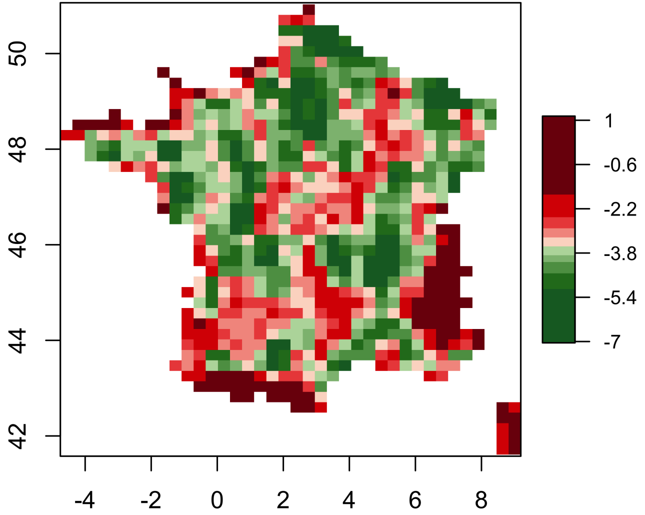
Modeling Co-evolution

[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.
[Barthelemy 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

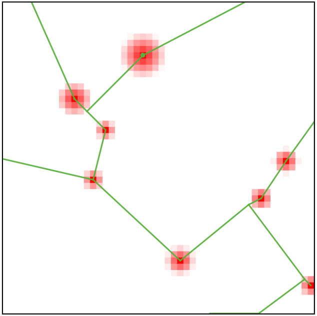
Adding new links with biological heuristic:

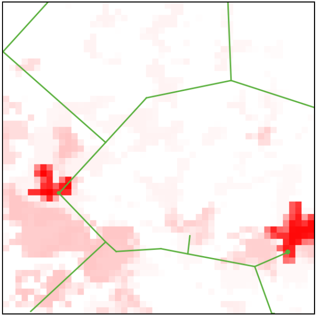
1. Create network of potential new links, with existing network and randomly sampled diagonal lattice
2. Iterate for k increasing ($k \in \{1, 2, 4\}$ in practice) :
   - Using population distribution, iterate $k \cdot n_b$ times the slime mould model to compute new link capacities
   - Delete links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



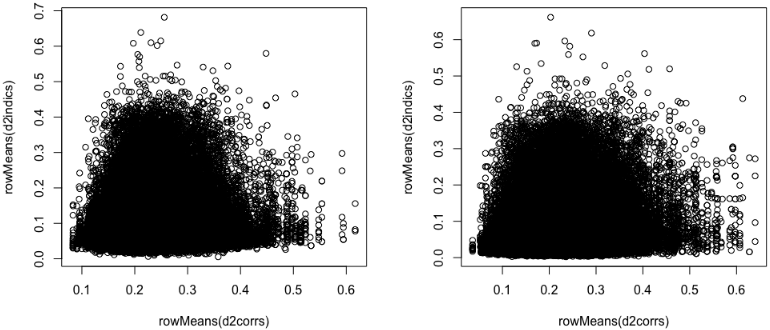


Stopping conditions: fixed final time; fixed total population; fixed network size.

Calibration Method

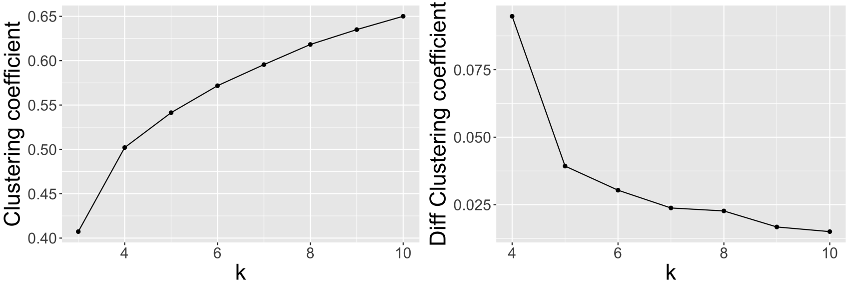
- Brute force exploration of a LHS sampling, 10 repetitions of the model for each parameter point.
- For each simulated point, closest in indicator space (euclidian distance for normalized indicators) among real points are selected.
- Among these, point with lowest distance to correlation matrix are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

Calibration : optimal points



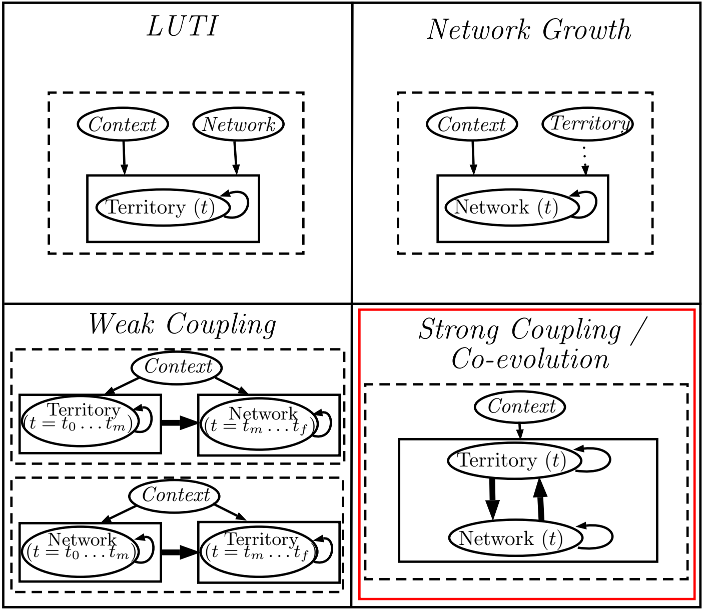
Pareto plots of distance to indicators and distance to correlation matrices, for a given simulated configuration and all real points.

Causality regimes: clustering



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

Co-evolution Models



Governance Game Specification

Mixed Nash equilibrium probability :

$$p_i = \frac{J}{\Delta X_{\bar{i}} Z_C^\star - \Delta X_{\bar{i}} Z_{\bar{i}}^\star}$$

Discrete Choice model :

$$U_i(C) - U_i(NC) = p_{\bar{i}} (\Delta X_i Z_C^\star - \Delta X_i Z_i^\star) - J$$

then

$$p_i = \frac{1}{1 + \exp\left(-\beta_{DC} \cdot \left(\frac{\Delta X_i Z_C^\star - \Delta X_i Z_i^\star}{1+\exp\left(-\beta_{DC}(p_i \cdot (\Delta X_{\bar{i}} Z_C^\star - \Delta X_{\bar{i}} Z_{\bar{i}}^\star) - J)\right)} - J\right)\right)}$$

Lutetia : default parameter values

$A_{max} = E_{max} = 500; r_A = 1; r_E = 0.8; \gamma_E = 0.9; \gamma_A = 0.65; \beta_I = 1.8; \lambda = 0.005; r_0 = 2$
$N_{expl} = 25; I = 0.001; J = 0.0001; \nu = 5; E_{ext}(t_0) = 3E_{max}; t_f = 4$

Lutetia : Land-use Initialization

Initial distribution of Actives and Employments around governance centers at positions $\vec{x}_i$ by

$$A(\vec{x}) = A_{max} \cdot \exp\left(\frac{\|\vec{x} - \vec{x}_i\|}{r_A}\right); E(\vec{x}) = E_{max} \cdot \exp\left(\frac{\|\vec{x} - \vec{x}_i\|}{r_E}\right)$$

Lutetia : Transportation

Transportation module : computation of flows ϕ_{ij} by solving on p_i, q_j by a fixed point method (Furness algorithm), the system of gravital flows

$$\begin{cases} \phi_{ij} = p_i q_j A_i E_j \exp\left(-\lambda_{tr} d_{ij}\right) \\ \sum_k \phi_{kj} = E_j ; \sum_k \phi_{ik} = A_i \\ p_i = \frac{1}{\sum_k q_k E_k \exp\left(-\lambda_{tr} d_{ik}\right)} ; q_j = \frac{1}{\sum_k p_k A_k \exp\left(-\lambda_{tr} d_{kj}\right)} \end{cases}$$

Trajectories then attributed by effective shortest path, and corresponding congestion c obtained (no Wardrop equilibrium).
Speed of network given by BPR function $v(c) = v_0 \left(1 - \frac{c}{\kappa}\right)^{\gamma_c}$. Congestion not used in current studies (infinite capacity κ).

Lutetia : Land-use Evolution

Land-Use module : we assume that residential/employments relocations are at equilibrium at the time scale of a tick, that corresponds to transportation infrastructure evolution time scale which is much larger (Bretagnolle, 2009).
We take a Cobb-douglas function for utilities of actives/employments at a given cell

$$U_i(A) = X_i(A)^{\gamma_A} \cdot F_i(A)^{1-\gamma_A} ; F_i(A) = \frac{1}{A_i E_i}$$

$$U_j(E) = X_j(E)^{\gamma_E} \cdot F_j(E)^{1-\gamma_E} ; F_j(E) = 1$$

where $X_i(A) = A_i \cdot \sum_j E_j \exp(-\lambda \cdot d_{ij})$ and $X_j(E) = E_j \cdot \sum_i A_i \exp(-\lambda \cdot d_{ij})$.
Relocations are then done deterministically following a discrete choice model :

$$A_i(t+1) = \sum_i A_i(t) \cdot \frac{\exp(\beta U_i(A))}{\sum_i \exp(\beta U_i(A))}$$

$$E_j(t+1) = \sum_j E_j(t) \cdot \frac{\exp(\beta U_j(E))}{\sum_j \exp(\beta U_j(E))}$$

Lutetia : Network Distance Computation

Effective distances computation

- Euclidian distance matrix $d(i,j)$ computed analytically
- Network shortest paths between network intersections (rasterized network) updated in a dynamic way (addition of new paths and update/change of old paths if needed when a link is added), correspondance between network patches and closest intersection also updated dynamically ; $O(N_{inters}^3)$
- Weak component clusters and distance between clusters updated ; $O(N_{nw}^2)$
- Network distances between network patches updated, through the heuristic of only minimal connexions between clusters ; $O(N_{nw}^2)$
- Effective distances (taking paces/congestion into account) updated as minimum between euclidian time and $\min_{C,C'} d(i,C) + d_{nw}(p_C(i), p'_C(j)) + d(C',j)$; $O(N_{clusters}^2 \cdot N^2)$ [Approximed with $\min_C$ only in the implementation, consistent within the interaction ranges ~ 5 patches taken in the model].

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.

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 II

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.

Barthelemy, 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.

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

References III

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.

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.

Caruso, G., Vuidel, G., Cavailhès, J., Frankhauser, P., Peeters, D., and Thomas, I. (2011).
Morphological similarities between dbm and a microeconomic model of sprawl.
Journal of geographical systems, 13(1):31–48.

References V

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

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.

References VI

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

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

Hall, P. G. and Pain, K. (2006).
The polycentric metropolis: learning from mega-city regions in Europe.
Routledge.

Holland, J. H. (2012).
Signals and boundaries: Building blocks for complex adaptive systems.
MIT Press.

References VII

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.

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.

References VIII

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.

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

References IX

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)*, pages 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. (2009).
Swarm chemistry.
Artificial life, 15(1):105–114.

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

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. (2010).
Rules for biologically inspired adaptive network design.
Science, 327(5964):439–442.

Thom, R. (1972).
Stabilité structurelle et morphogénèse.
InterÉditions.

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

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.

References XII

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.