Caractérisation et modélisation de la co-évolution des réseaux de transport et des territoires

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Soutenance de Thèse

Institut des Systèmes Complexes

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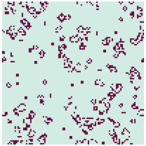
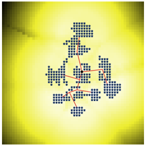
Une approche originale

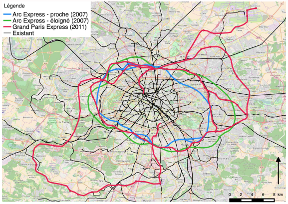
Parcours personnel

- Ingénieur généraliste
- Intérêt pour l'objet ville : expériences en architecture et urbanisme, puis formation aux Ponts et Chaussées
- Une transition progressive vers les sciences humaines et la géographie, tout en gardant un ancrage fort dans les systèmes complexes

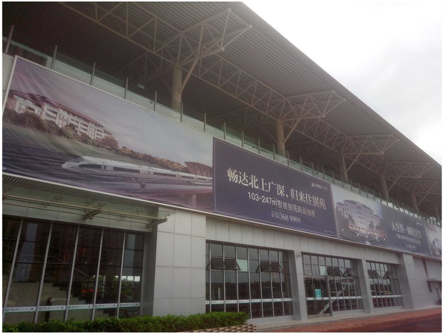
→ *Une articulation théorique et thématique structurante.*







Interactions entre réseaux et territoires



Observation d'interactions entre transport et ville dans le Delta de la Rivière des Perles : promotion de la grande vitesse, développement urbain ciblé autour des gares.

Problématique de la thèse

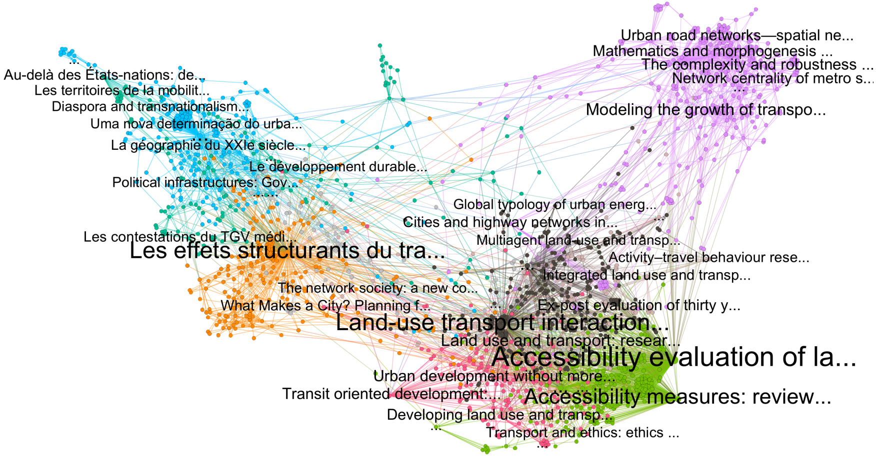
Des dynamiques *co-évolutives* entre réseaux de transport et territories suggérées par de nombreux travaux (Théorie Evolutive des Villes)

Axe 1 : *Proposition d'une définition et d'une méthode de caractérisation empirique des ces dynamiques co-évolutives.*

Connaissance limitée par les seules études empiriques (données pauvres, cas d'étude, temps long, couplage fort): utilisation de la modélisation comme outil de connaissance.

Axe 2 : *Construction de modèles de co-évolution des réseaux de transport et des territoires.*

Vers une modélisation ? Cartographie des disciplines



Multiples points de vue sur les mêmes objets, autant de façons complémentaires de les modéliser.

Entrée théorique : définitions

Objets :

- Villes et territoires lus au prisme de la *Théorie Evolutive des Villes*
- Réseaux de transport comme matérialisation de "projets transactionnels", suivant la *Théorie Territoriale des Réseaux*

Processus :

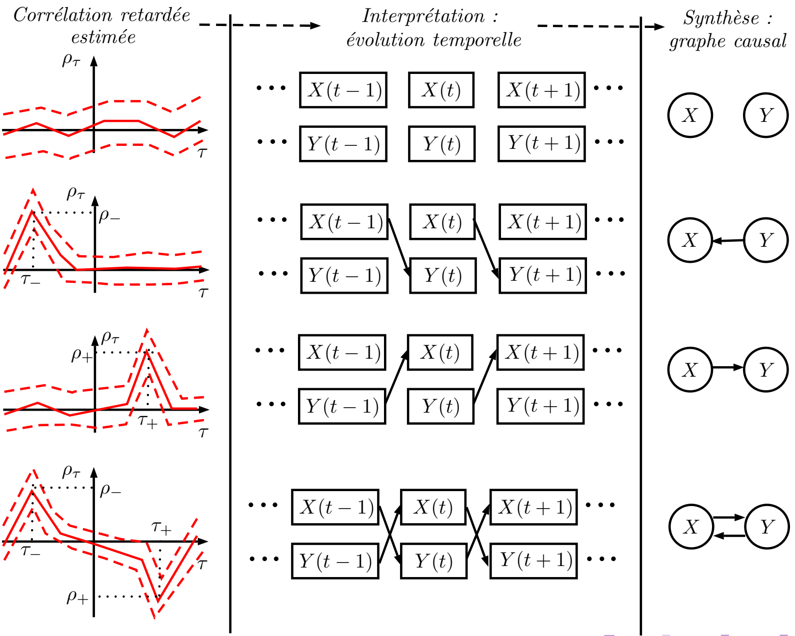
Une définition de la co-évolution à trois niveaux :

1. niveau individuel d'individus donnés
2. niveau statistique des populations d'individus
3. niveau global du système

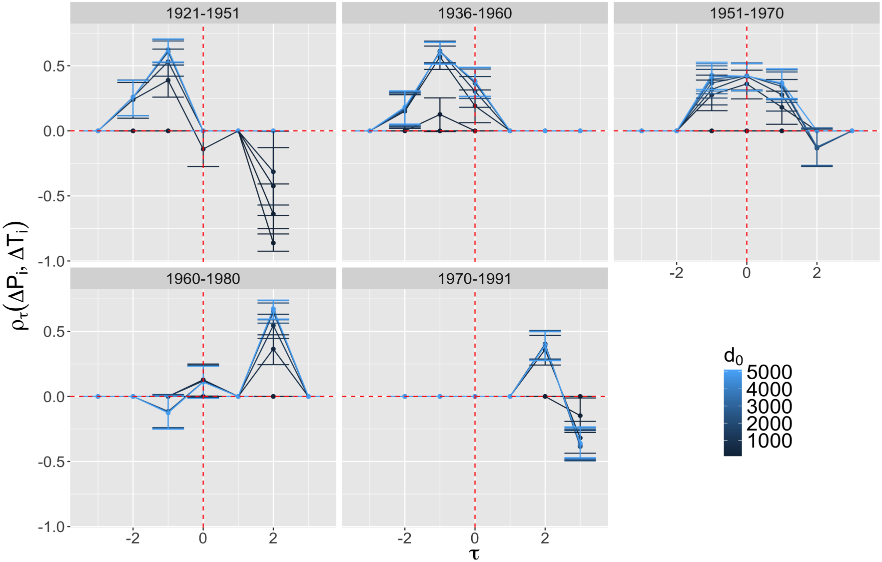
Entrées :

1. Une entrée par la morphogenèse correspond à la notion de niche et l'échelle mésoscopique
2. Une entrée systémique par la théorie évolutive à l'échelle macroscopique

Elaboration d'une méthode de caractérisation

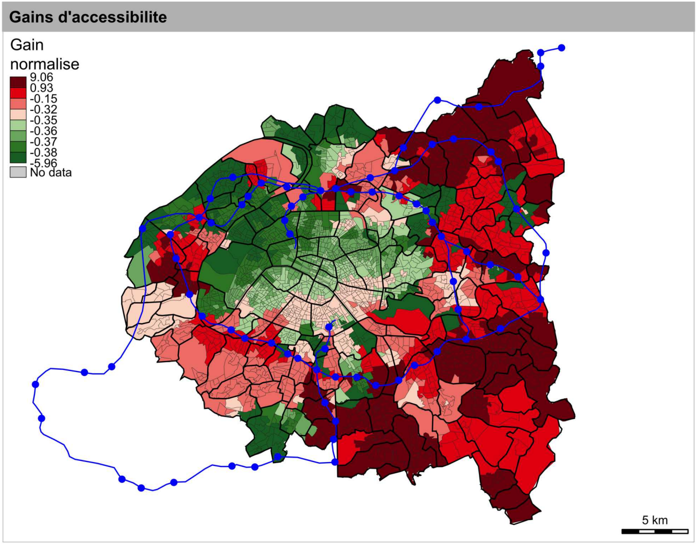


Des observations empiriques contrastées



Inversion du sens de la causalité entre croissance des populations et de l'accessibilité ferroviaire en Afrique du Sud au cours du 20ème siècle

Des observations empiriques contrastées



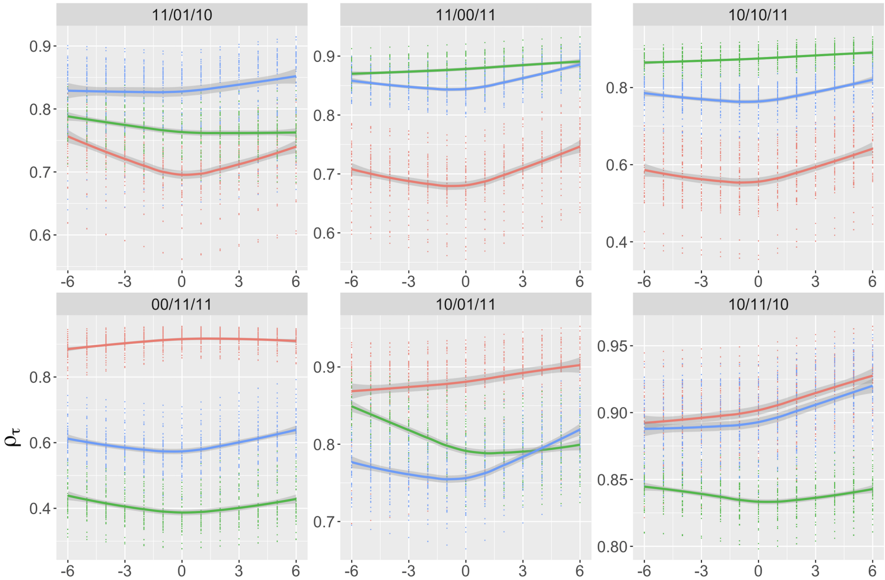
Relations plus complexes dans le cas du gain d'accessibilité permis par le Grand Paris Express et les dynamiques socio-économiques des territoires

Famille de modèles d'interaction dans un système de villes, basés sur les flux entre villes, incluant effets directs des flux, rétroactions par les flux traversés, rétroactions sur la vitesse du réseau.

Application 1 :
Effets de réseau robustes au suraprentissage révélés par le modèle avec réseau statique

Modèle stat.	ΔAIC	ΔBIC
Polynomial	19.6	3.7
Log-polynomial	125.4	109.4
Polynomial-généralisé	11.7	-4.2

Modèles macroscopiques : co-évolution

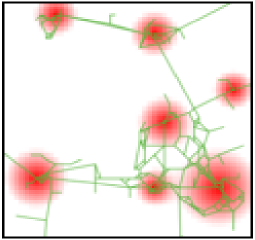


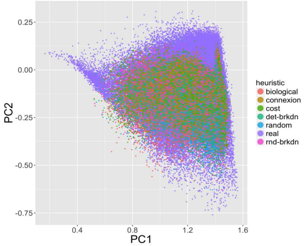
Multiples régimes mis en évidence dans des configurations synthétiques

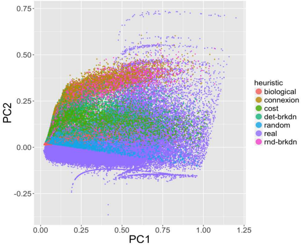
Modèles mésoscopiques

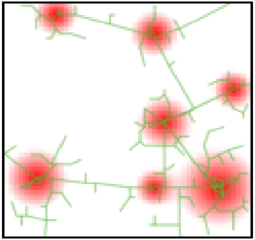
Relation entre forme et fonction (morphogenèse) comme paradigme pour modéliser la co-évolution à l'échelle mésoscopique.

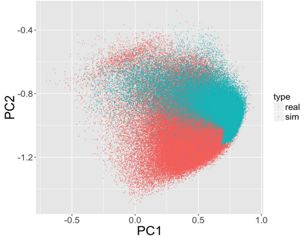
Un modèle par réaction-diffusion et multi-modélisation de la croissance du réseau : complémentarité des heuristiques, calibration sur les formes et leurs corrélations

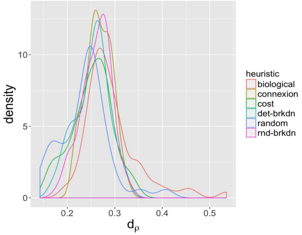




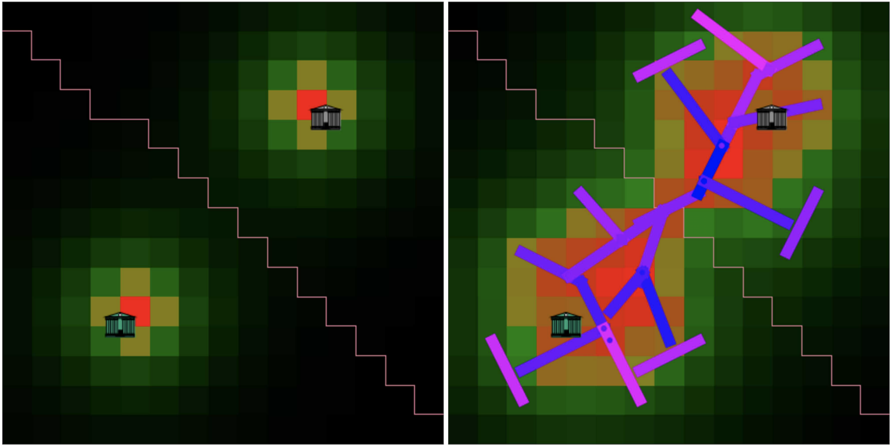




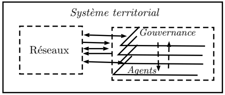




Le modèle Lutecia : vers une prise en compte de la gouvernance pour la croissance des réseaux de transport

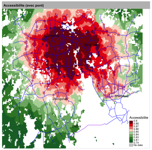


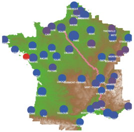
Lecture par les domaines de connaissance

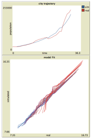


Théorique

Empirique ⟷ Modélisation







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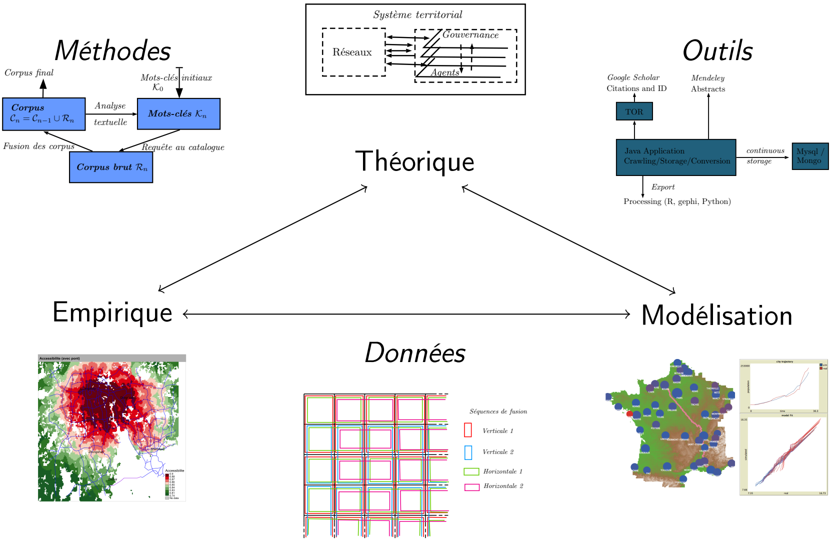
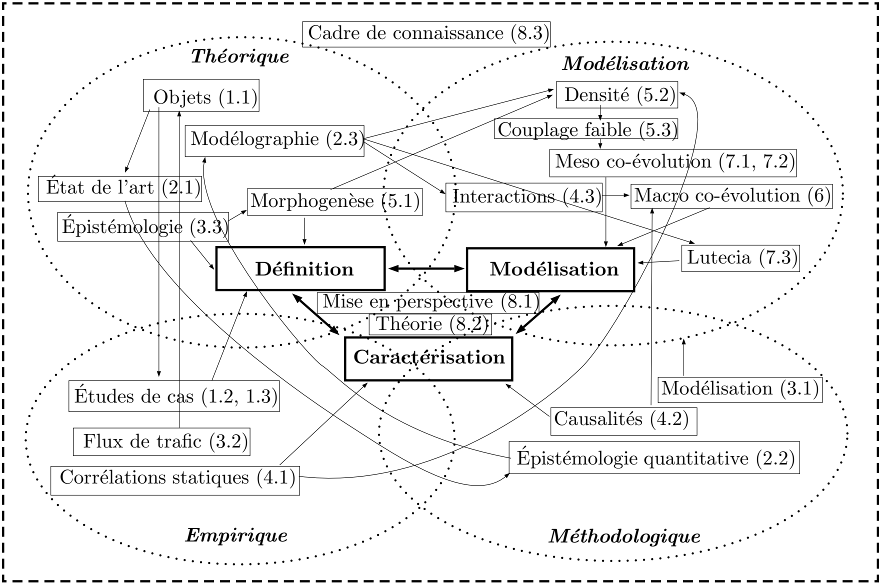
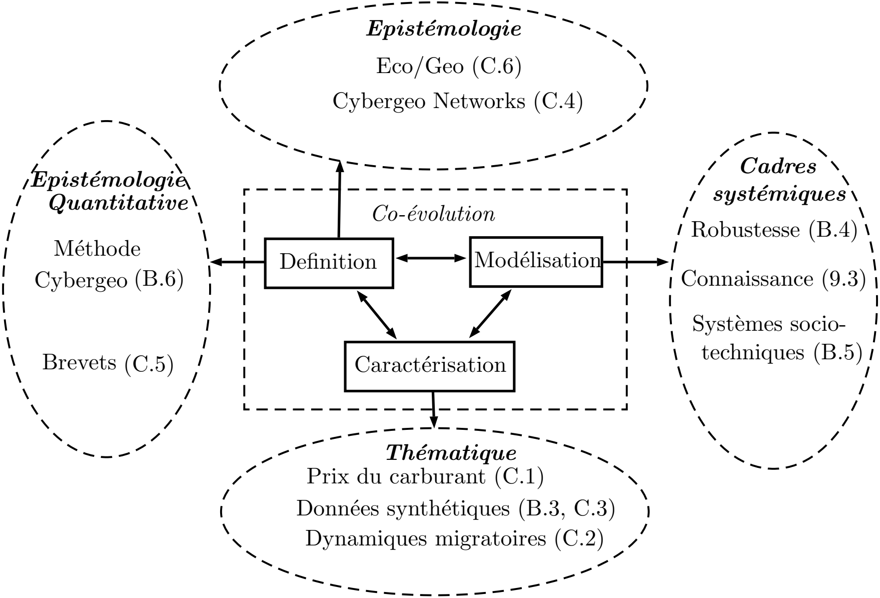


Problématique et plan dans les domaines de connaissance



Mise en perspective



Développements

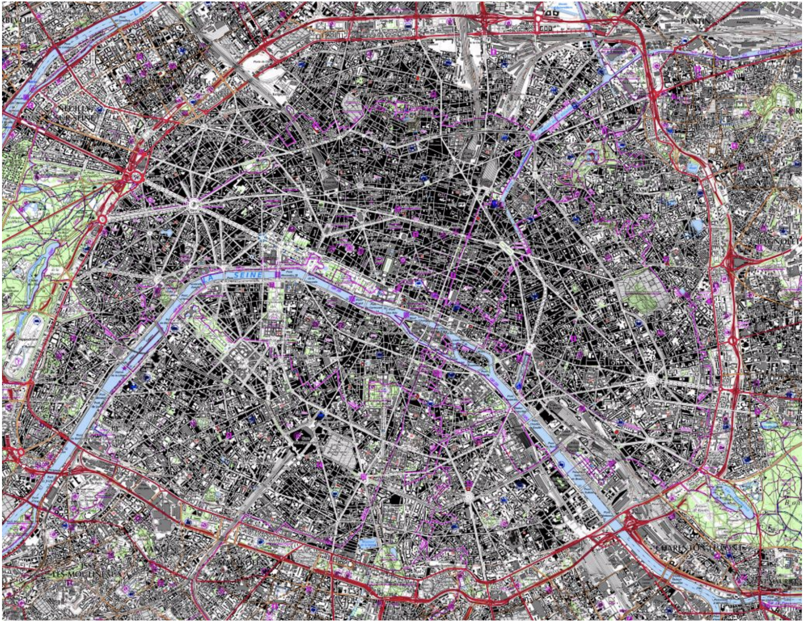
- Adaptation de Lutecia pour le développement de méthodes d'exploration de modèles spatiaux (développement d'OpenMole)
- Multi-modélisation de la co-évolution à l'échelle macroscopique

Perspectives

- *Extension des méthodes d'exploration des modèles de simulation spatiaux :* données spatiales synthétiques, multi-modélisation et surajustement, robustesse des algorithmes génériques à la stochasticité.
- *Vers des théories intégrées des systèmes territoriaux :* modèles multi-échelle et couplage de la théorie évolutive avec le *Scaling*, réflexivité et épistémologie, intelligence artificielle.

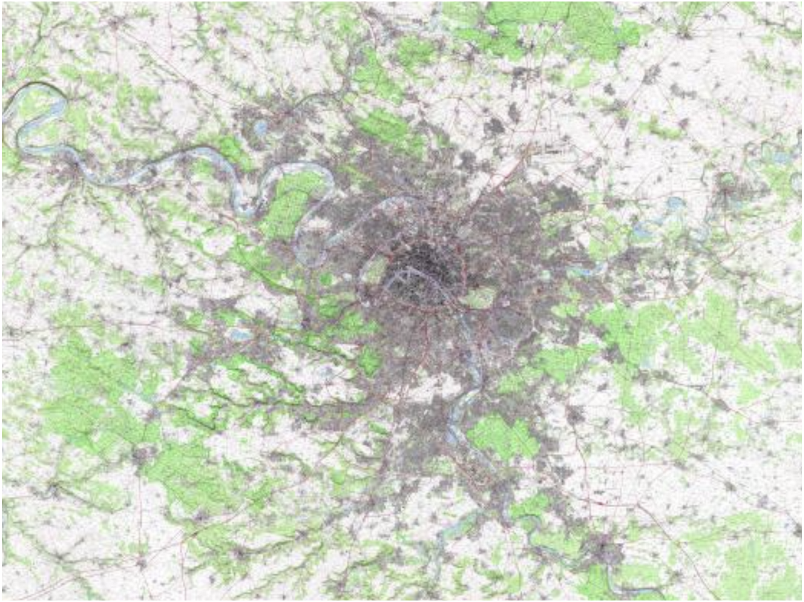
Reserve Slides

Complex processes of Urban Morphogenesis



Source: Geoportail

Complex processes of Urban Morphogenesis



Source: Geoportail

What is Morphogenesis ?

Morphogenesis (*Oxford dictionary*)

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

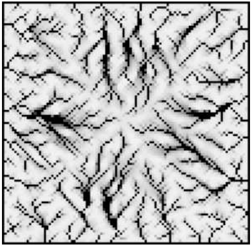
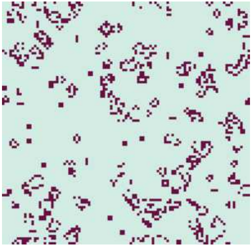
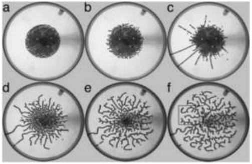
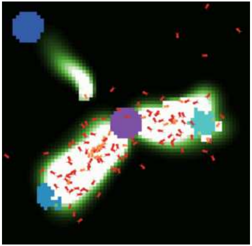
History of the notion

→ Started significantly with embryology around 1930 [Abercrombie, 1977]

→ Turing's 1952 paper [Turing, 1952], linked to the development of Cybernetics

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

What is Morphogenesis ? Examples

	Physical	Biological	Engineereed
Non Functional			
Functional			

Sources (in order by column). Ants, Erosion, Game of Life: NetLogo Library ; Arbotron [Jun and Hübler, 2005]; Industrial design [Aage et al., 2017]; Swarm chemistry [Sayama, 2007]

Defining Morphogenesis

Construction of an interdisciplinary definition :

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]*

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

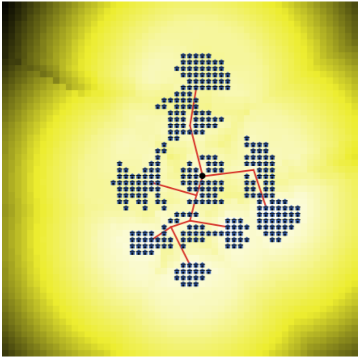
A system is viewed as its internal state X_w, where $w \in W$ is a control parameter.

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

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

[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

Which models for Urban Morphogenesis ?



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

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

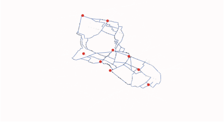
→*Importance of parcimonious, stylized models: modeling as a tool to understand processes*

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

Different approaches to Network Morphogenesis

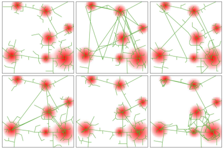
Different models with different ontologies and coupling ontologies

Network | *Co-evolution*



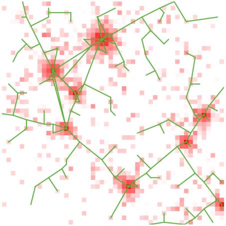
Self-organizing biological network

Optimisation



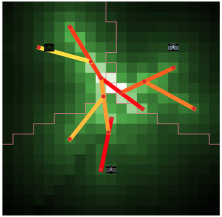
Multi-modeling network growth

Explication



Co-evolution model

Explication



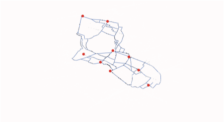
Transportation governance

Explication

Different models of Urban Morphogenesis

Four different models with different ontologies and coupling ontologies

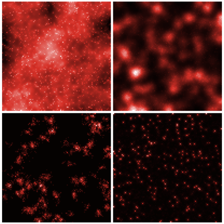
Network



Self-organizing network

Optimisation

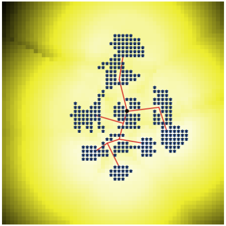
Density



Reaction-diffusion density-based model

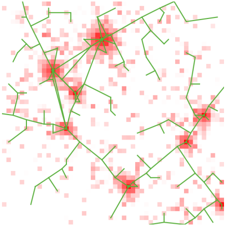
Explication

Co-evolution



Basic hybrid model [Raimbault et al., 2014]

Optimisation



Co-evolution model

Explication

A simple Reaction-diffusion model

→ 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

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

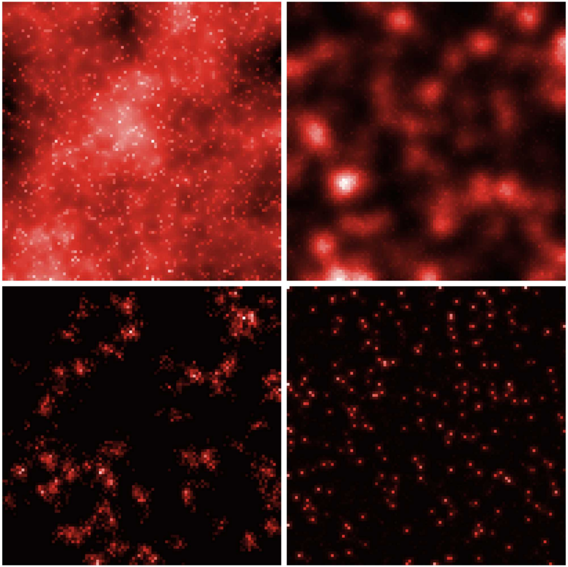
→ At each time step:

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.

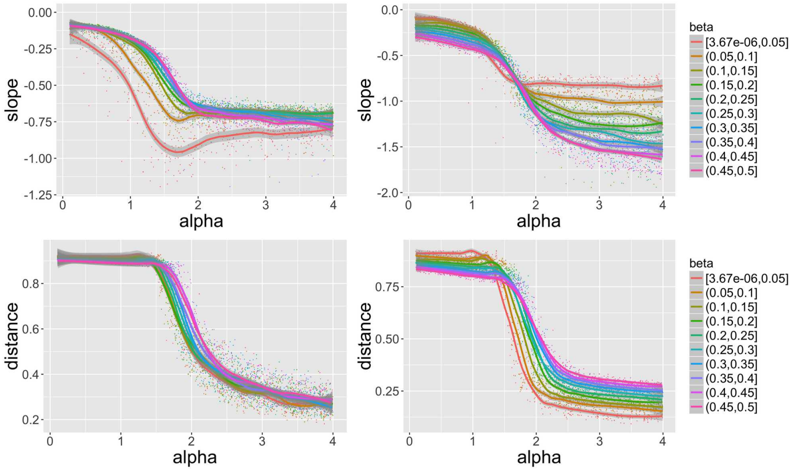
→ Output measured by morphological indicators: Moran index, average distance, rank-size hierarchy, entropy.

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

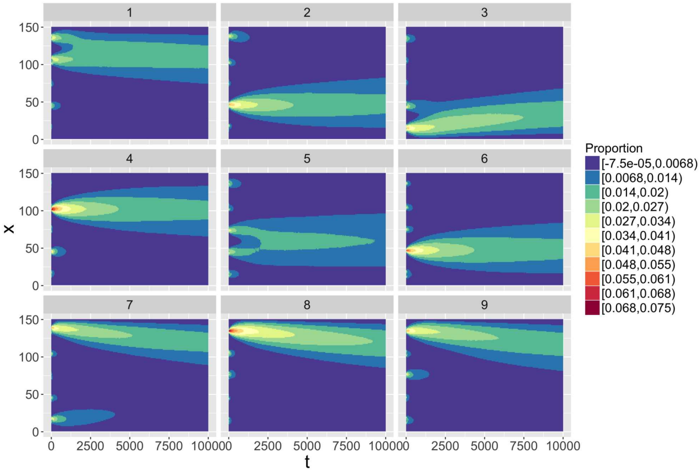
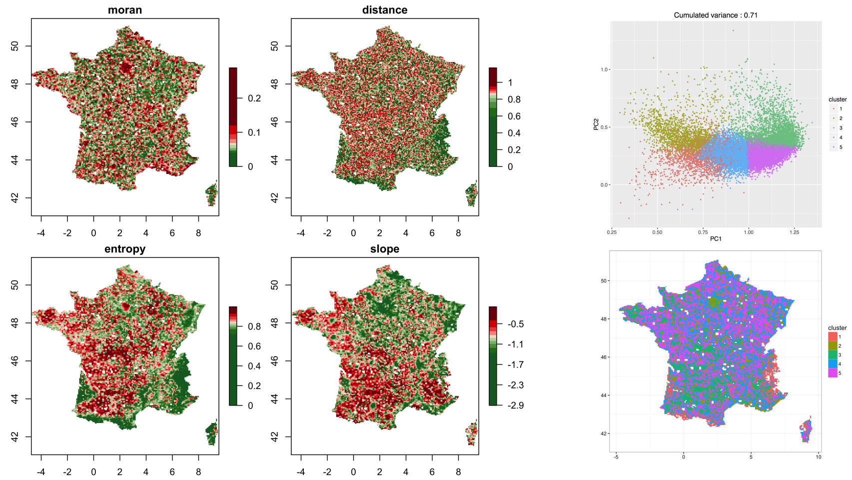


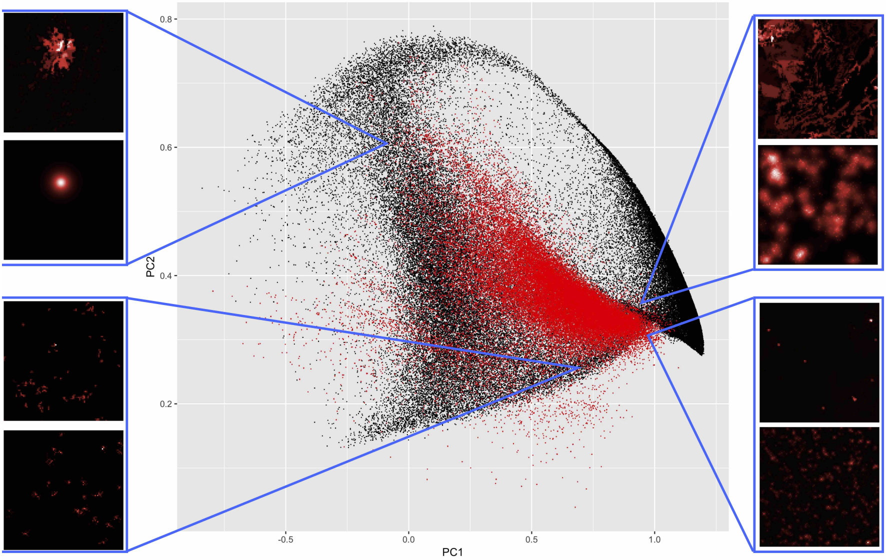
Illustration of path-dependence in a simplified one-dimensional version of the model: cell trajectories in time for 9 independent repetitions from the same initial configuration.

Empirical Data for Calibration



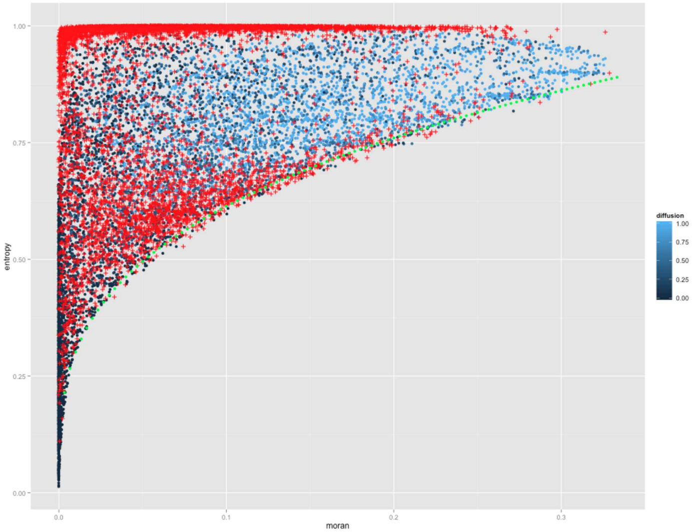
Computation of morphological indicators on population density data for Europe (shown here on France), morphological classification.

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

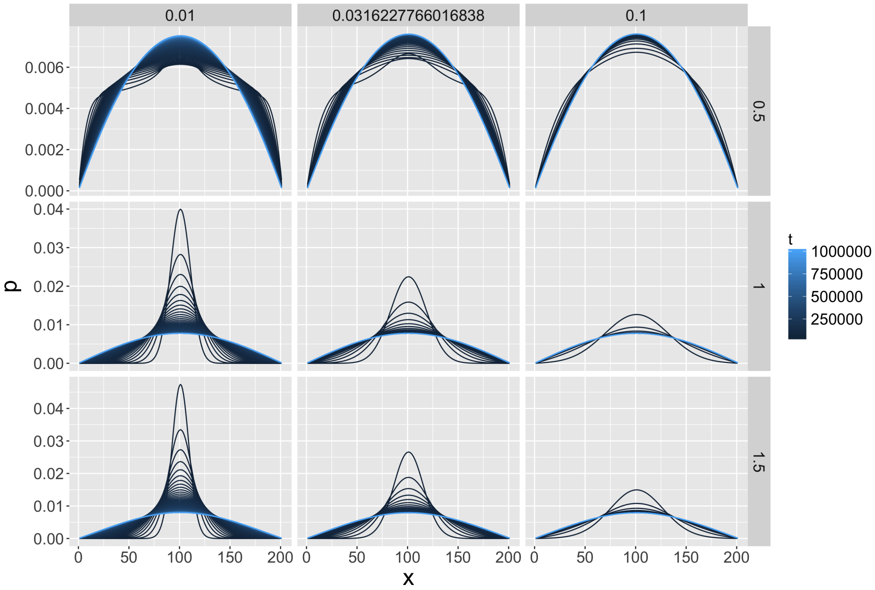


Potentialities of targeted model explorations: here feasible space using Pattern Space Exploration algorithm [Chérel et al., 2015].

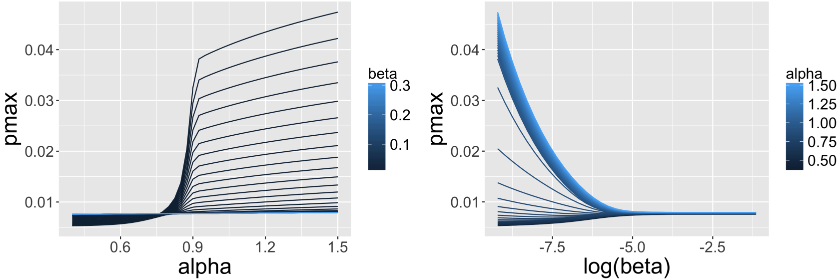
The one-dimensional model verifies the PDE :

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

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:

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

   $\mathscr{E} = 0$ 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 $w_{ij} = 1/d_{ij}$

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

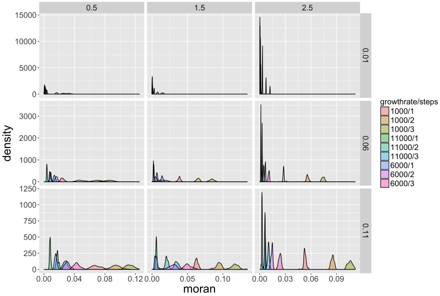
4. Mean distance between individuals

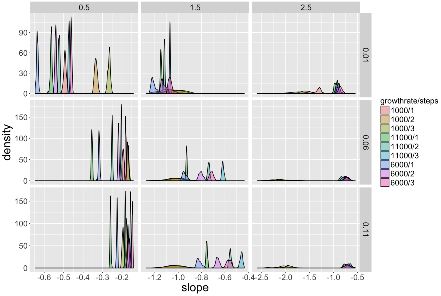
$$\bar{d} = \frac{1}{d_M} \cdot \sum_{i<j} \frac{P_i P_j}{P^2} \cdot d_{ij}$$

   where d_M is a normalisation constant

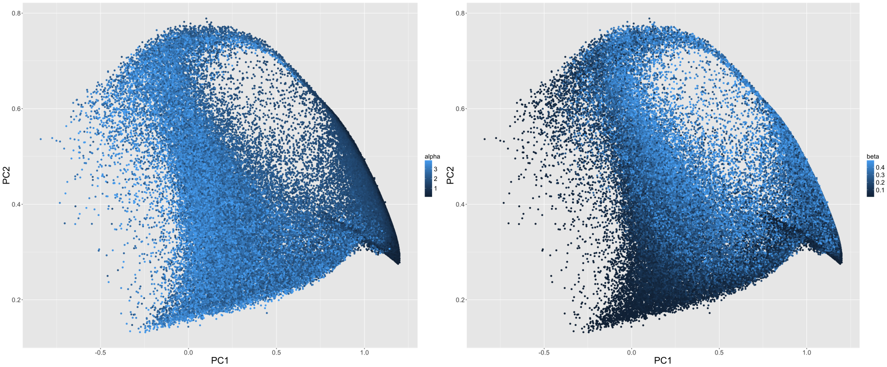
Model behavior : Convergence

Large number of repetitions show good convergence properties





Model behavior



Empirical indicators computation

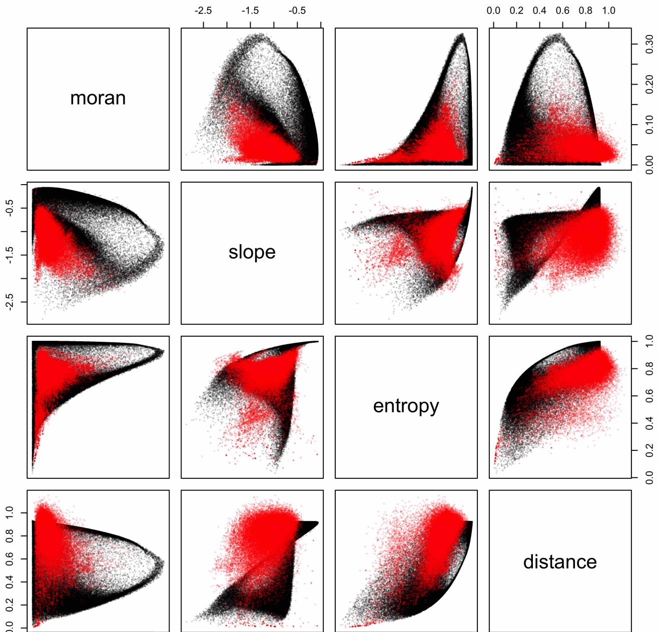
→ Eurostat population density raster (100m, simplified at 500m resolution)

→ 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



Including more complex processes ?

Which ontology to include more complex functional properties ?

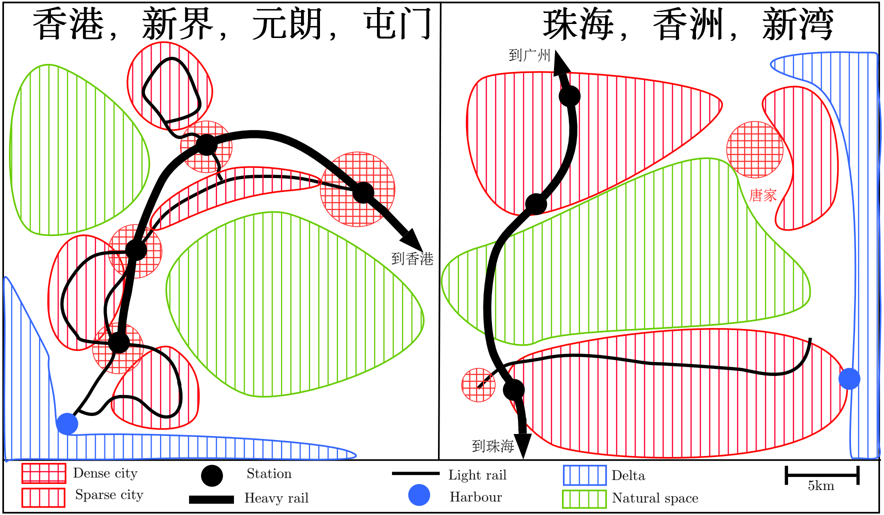
→ Territorial systems as the strong coupling between territories and (potential and realized) networks [Dupuy, 1987].

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

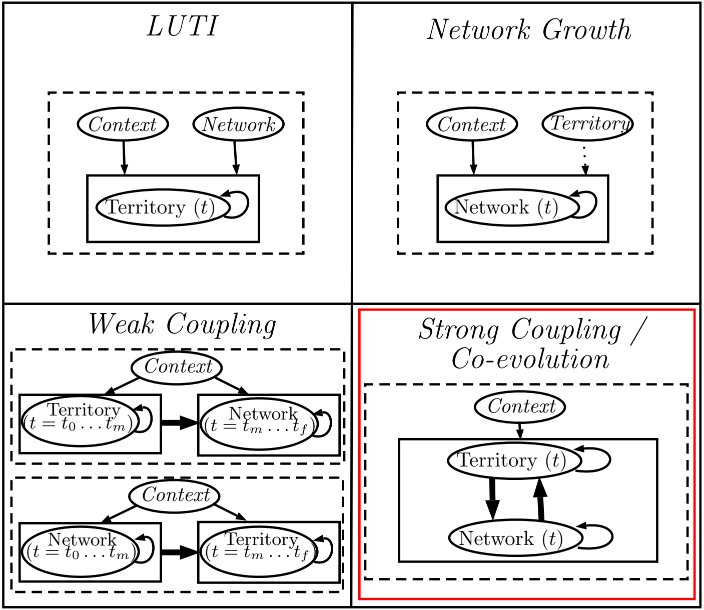
Complex co-evolutive processes between Territories and Transportation Networks

Expanding HSR network in China and ambiguous effects (Source : fieldwork survey)

Implementations of TOD



Co-evolution Models



Defining co-evolution

No clear definition of co-evolution in the literature : [Bretagnolle, 2009a] 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 [?]

Perspective : co-évolution

Proposition d'une définition de la co-évolution, basée sur une revue multi-disciplinaire :

1. Existence de processus évolutifs : transformations des composantes du système territorial aux différentes échelles
2. Trois manifestations de la co-évolution à des niveaux emboités :
   - Entités en relations causales circulaires
   - Population d'entités dans une région géographique, identifiable en pratique par les régimes de causalité
   - Niveau global du système, interdépendance forte
3. Existence de sous-systèmes en relative isolation spatio-temporelle où s'opèrent différentes co-évolutions (lien avec le concept de morphogenèse

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

A Morphogenesis Model of co-evolution

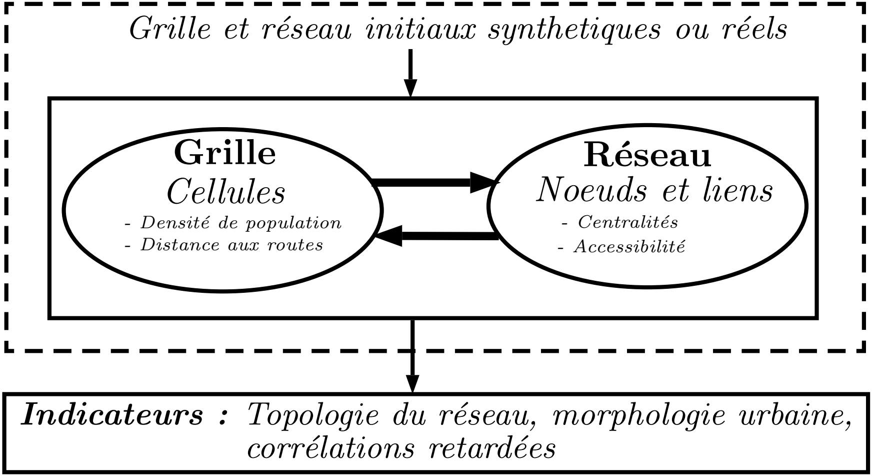
→ Coupled grid population distribution and vector transportation network, following the core of [Raimbault et al., 2014]

→ 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***

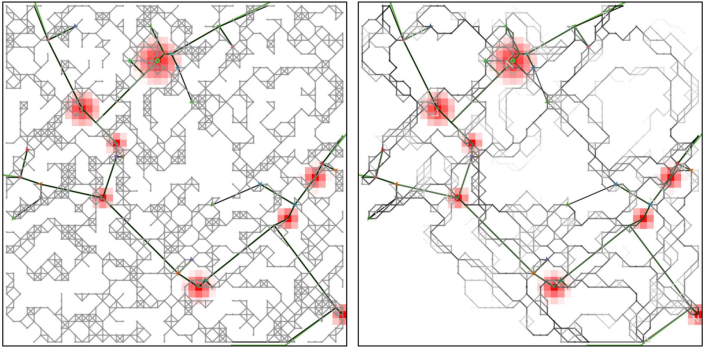
Model : Specification



Network Generation

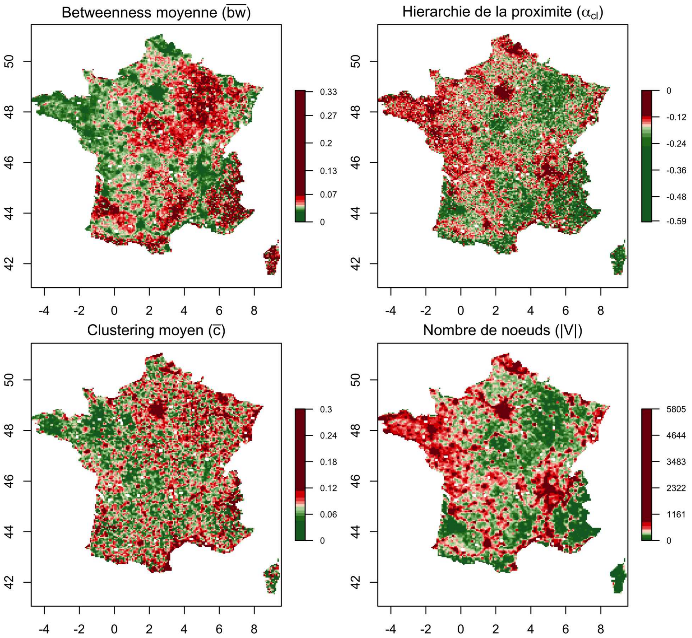
At fixed time steps :

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])

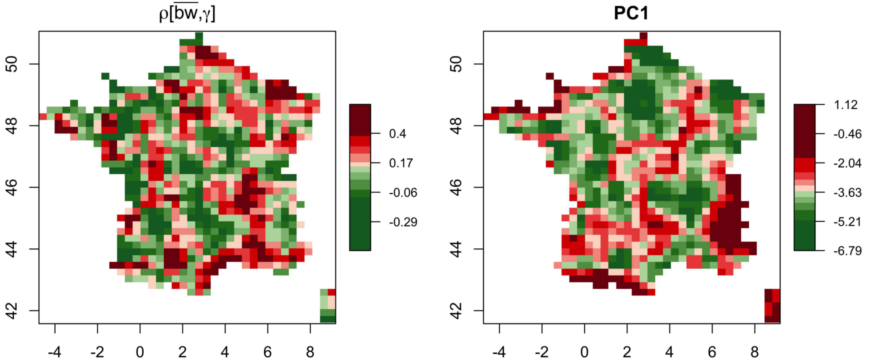


Intermediate stage for biological network generation

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

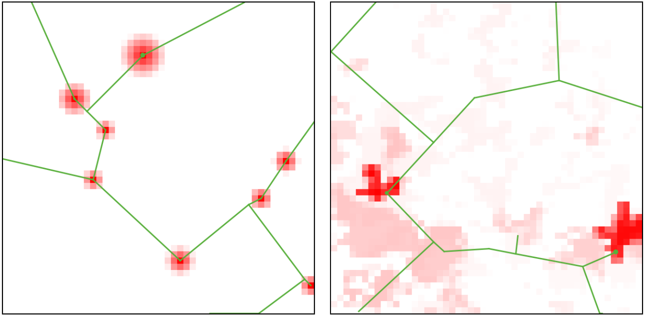
Adding new links with biological heuristic:

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

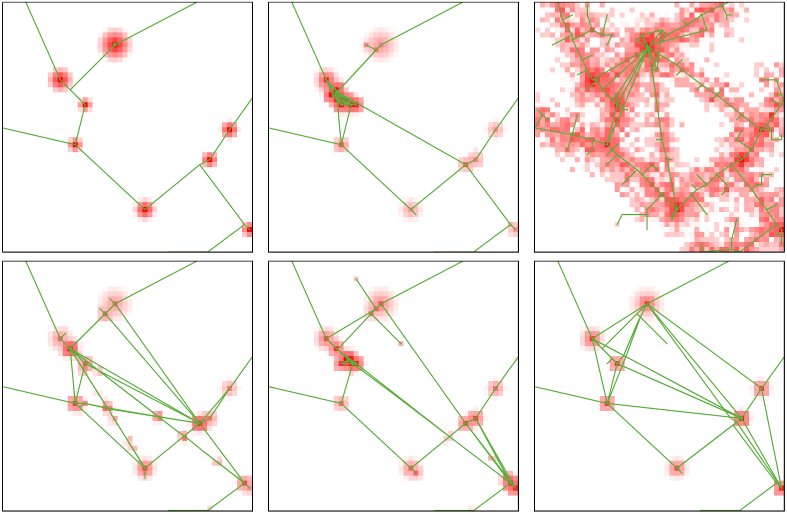
Synthetic setup: rank-sized monocentric cities, simple connection with bord nodes to avoid bord effects

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



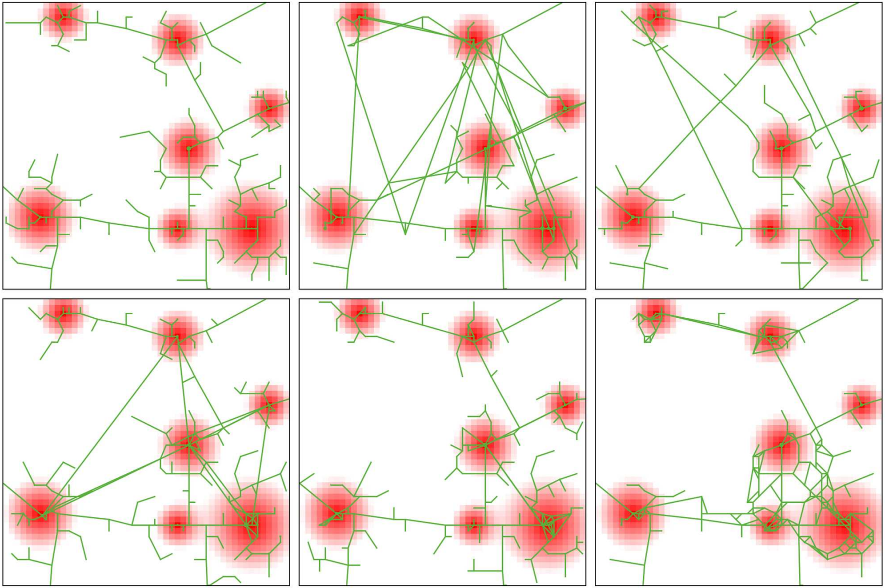
Stopping conditions: fixed final time; fixed total population; fixed network size.

Generated Urban Shapes: Urban Form



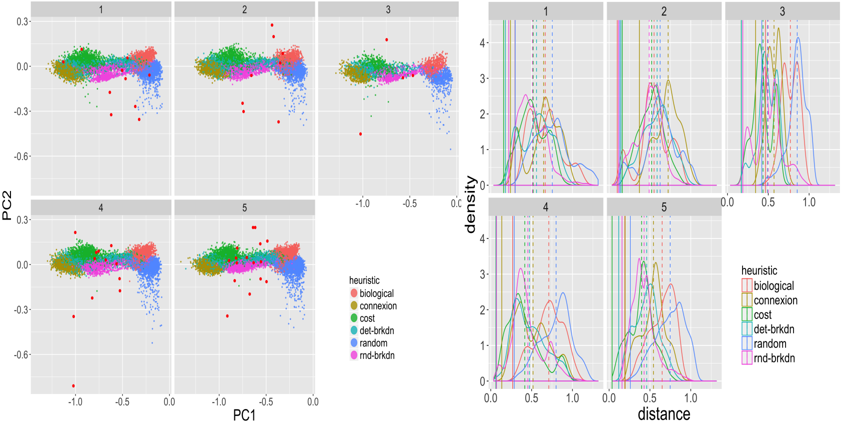
In order: setup; accessibility driven; road distance driven; betweenness driven; closeness driven; population driven.

Generated Urban Shapes: Network



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

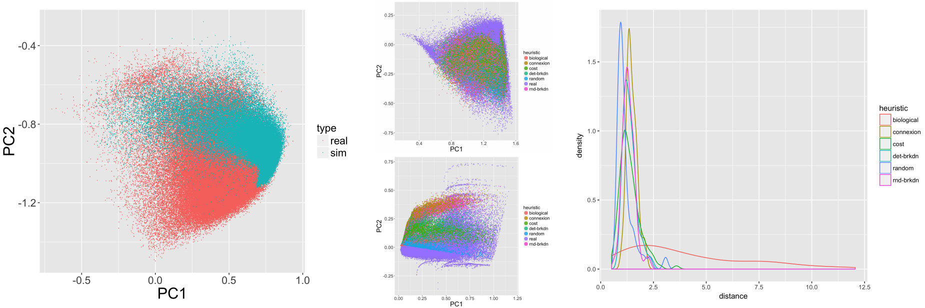
Comparison of feasible space for network indicators with fixed density



(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.

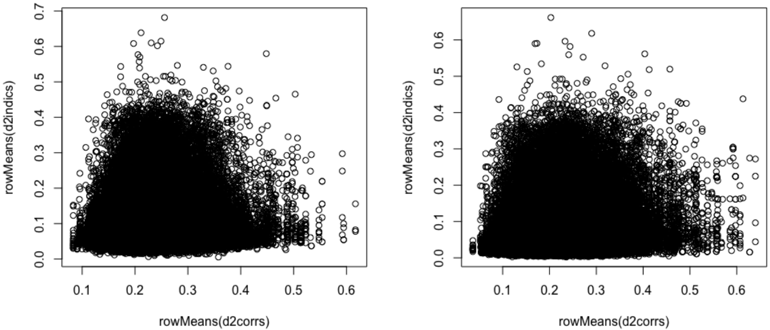


(Left) Full indicator space; (Middle) Morphological and Topology, by network heuristic; (Right) Distance distribution for cumulated distance for indicators and correlations.

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.

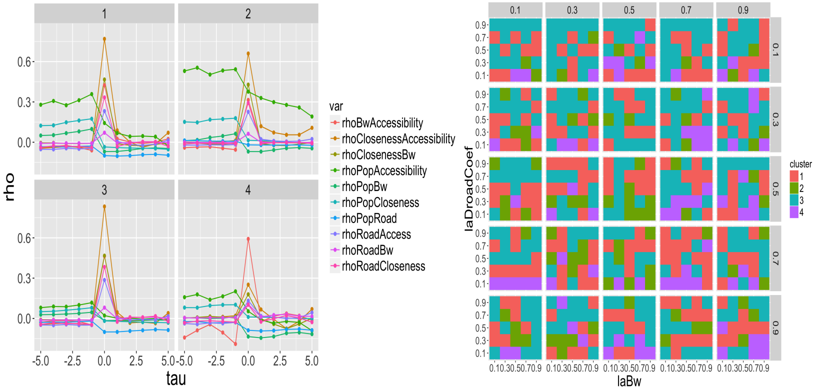
Calibration : optimal points



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

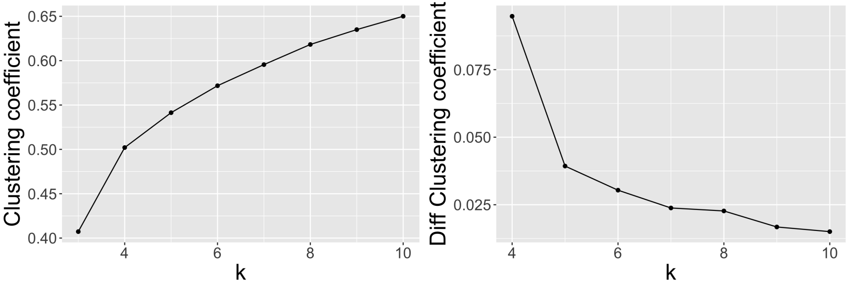
Results : Causality Regimes

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

Causality regimes: clustering



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

Discussion

Implications

→ This rather simple model reproduces most of existing urban forms in Europe for both population distribution and road network : which intrinsic dimension to the urban system and its morphological aspect ?

→ Ability to reproduce static correlations and a variety of dynamical lagged correlation regimes suggests that the model captures some of the processes of co-evolution

Developments

→ Towards a dynamical calibration ? Need of dynamical data

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

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

Slime mold 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

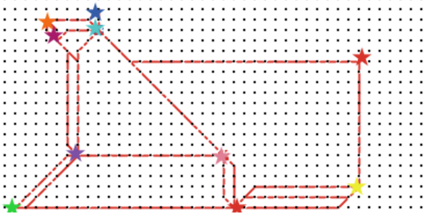
Behavior of the model evaluated with performance indicators for generated network (V_f, E_f), that are contradictory objectives :

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

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

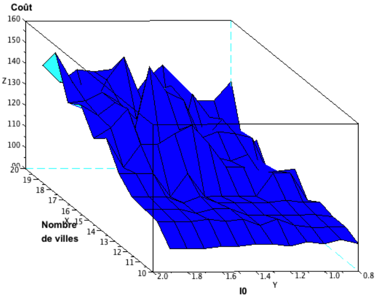
- Robustness (*Network Trip Robustness* index [Sullivan et al., 2010])

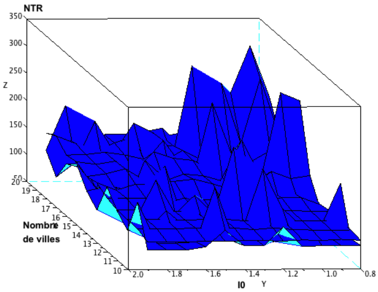
Example of networks



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

Sensitivity analysis



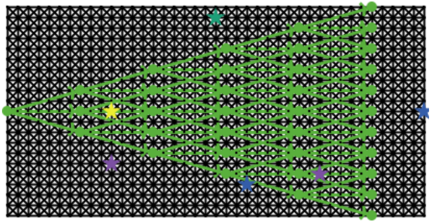


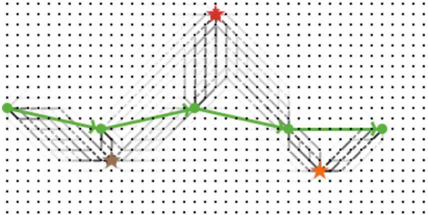
Sensitivity of indicators to parameters (N, I_0).

Application : Optimal transportation Corridor

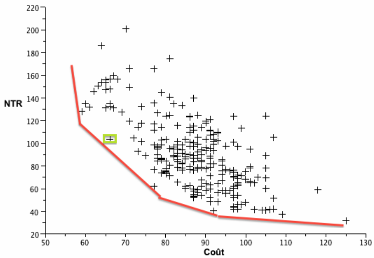
Abstract application : *Given a distribution of nodes to serve (sinks), what is the optimal corridor for an infrastructure at a larger scale (train or metro) for which stations are sources, in the sense of the multi-objective optimality of the local self-organized network ?*

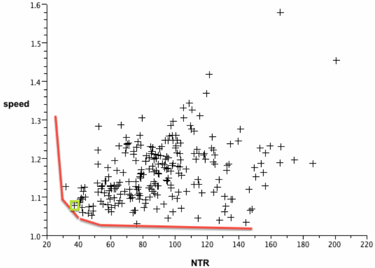
→ Heuristic exploration of an arborescent set of potential infrastructures





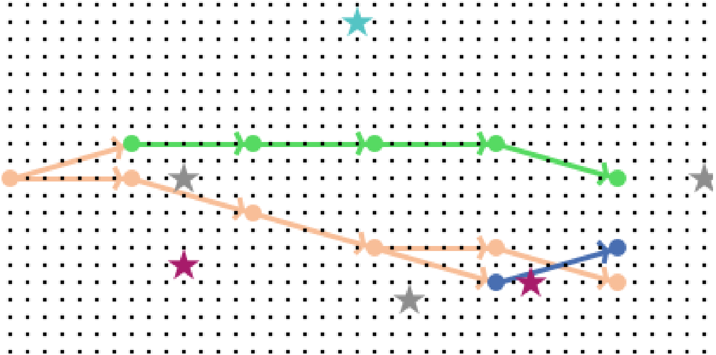
Pareto Optimisation





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

Pareto Optimisation

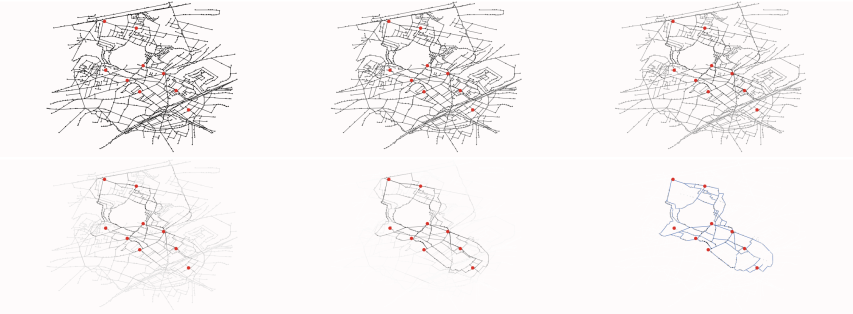


Configurations corresponding to three optimal points.

Application : Optimal Network Design

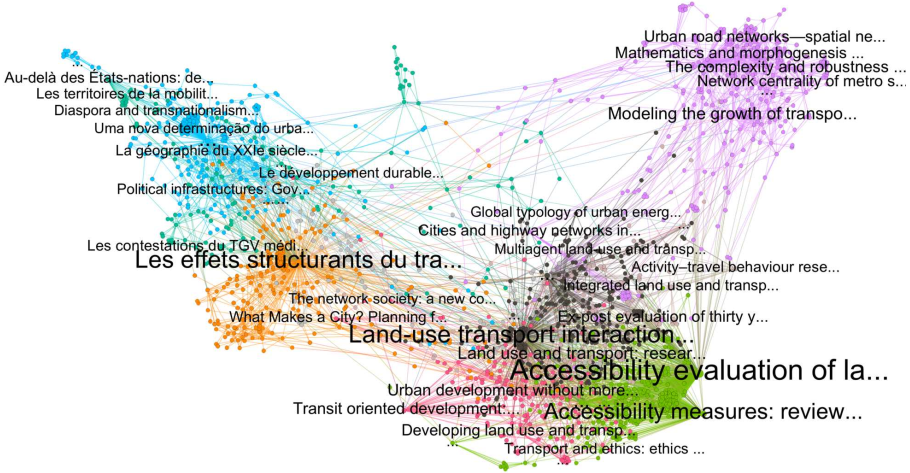
→ Mission of prospective for Romainville city : itinary of an intra-urban shuttle with imposed stops.

→ 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.

Citation Network

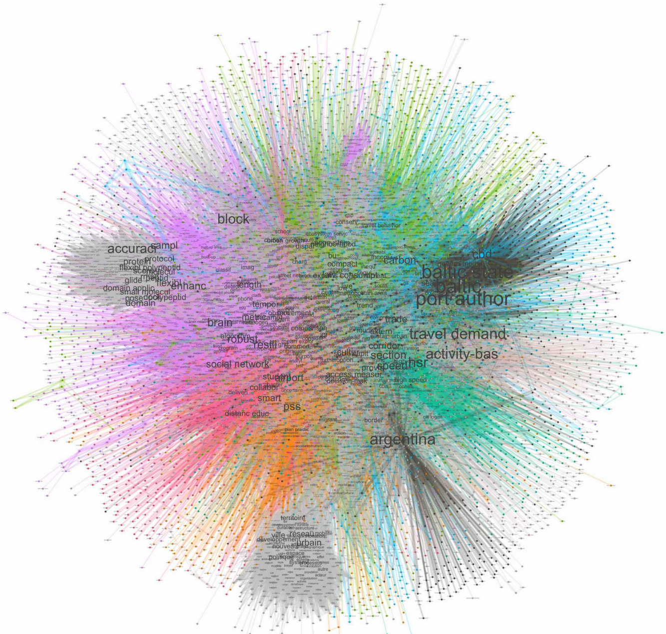


Citation Network Properties

For the core (hence full) subnetwork :

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

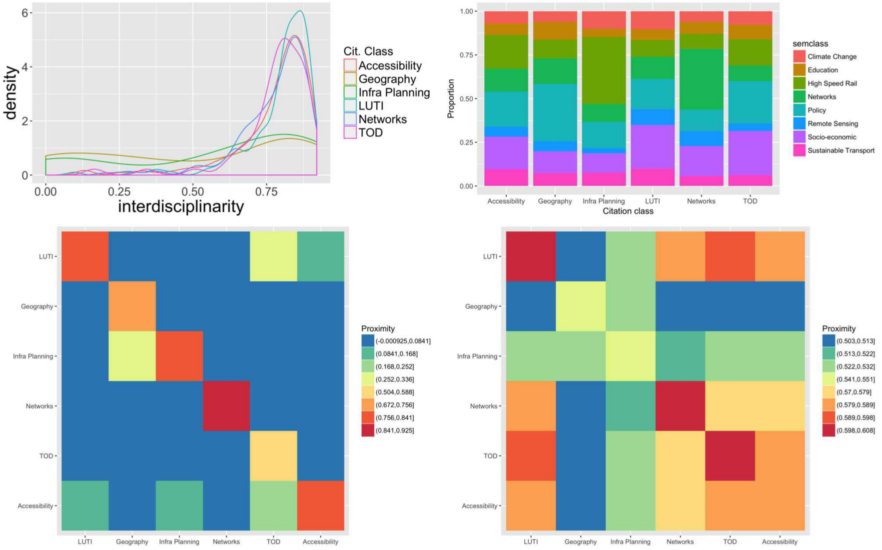
Semantic Network



Semantic communities

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

Interdisciplinarity patterns



Measures of interdisciplinarities

Effet structurants des infrastructures

De [Bonnafous and Plassard, 1974] à [Offner, 1993] : quels effets de structure des infrastructures de transport sur les territoires ?

→ Existence de processus co-évolutifs [Bretagnolle, 2009b]

→ A petite échelle et sur le temps long, existence de dynamiques structurelles des systèmes urbains [Offner et al., 2014]

→ La question des causalités circulaires revient à toutes les échelles (e.g. échelle métropolitaine et mobilité [Cerqueira, 2017]) et dans différents domaines (retombées locales et innovation [Audretsch and Feldman, 1996])

Causalité en Géographie

→ La Géographie classique s'intéressait déjà à des liens causaux dans l'espace [Loi, 1985]

→ [Claval, 1985] : au delà de la causalité réductionniste en analyse systémique

→ La systèmogenèse introduite par [Durand-Dastes, 2003] se concentre sur la dynamique et les dépendances au chemin

→ Vers une approche complexe de la causalité ? [Morin, 1976]

Approches empiriques existantes

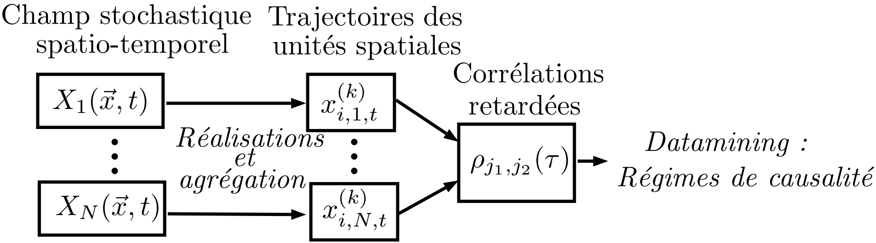
Réseaux de transports et territoires

- Corrélations retardées : [Levinson, 2008] Population et connectivité au réseau à Londres ; [Gargi Chaudhuri and Keith C Clarke, 2015] données historiques en Italie du Nord
- Variables instrumentales : [Duranton and Turner, 2012] Réseau routier et emplois aux Etats-Unis ; [Berger and Enflo, 2017] effet significatif du réseau ferré suédois sur les trajectoires urbaines

Corrélations spatio-temporelles

- Méthode de correspondance pour les flux de trafic [Liu et al., 2011]
- Causalité de Granger généralisée en neurosciences [Ke et al., 2007]
- Corrélations spatio-temporelles en Vision par Ordinateur [Ke et al., 2007]

Aperçu de la méthode



Formalisation de la méthode

Estimateur de corrélation $\hat{\rho}$ s'appliquant dans le temps, l'espace, et les répétitions, i.e. la covariance est estimée par $\hat{\text{Cov}}[X,Y] = \hat{\mathbb{E}}_{i,t,k}[XY] - \hat{\mathbb{E}}_{i,t,k}[X]\hat{\mathbb{E}}_{i,t,k}[Y]$

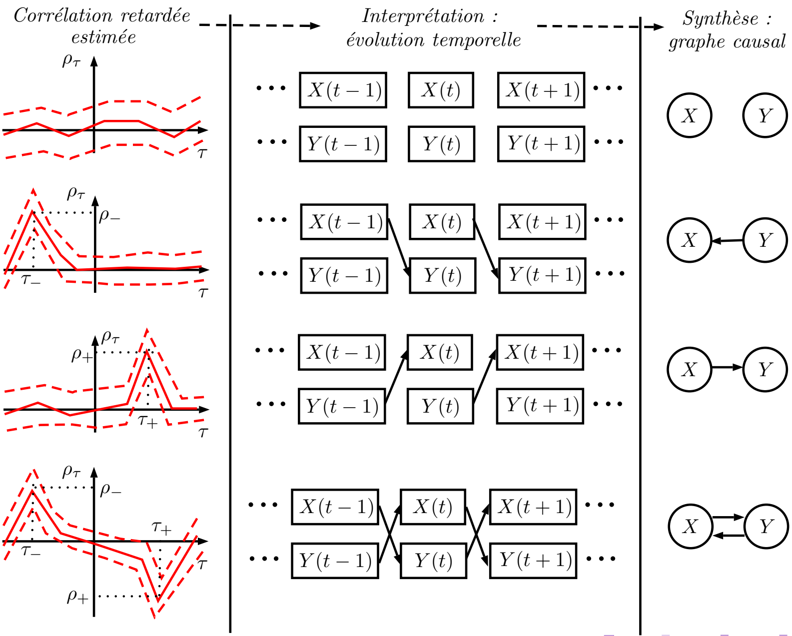
Corrélations retardées définies comme

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

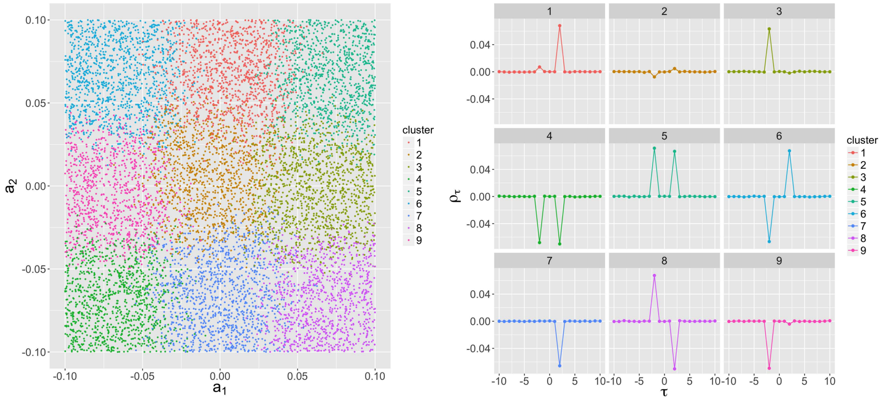
Le motifs de $\text{argmax}_\tau \rho_\tau[X_{j_1}, X_{j_2}]$ ou de $\text{argmin}_\tau \rho_\tau[X_{j_1}, X_{j_2}]$ (en les supposant clairement définis : e.g. significativité statistique, valeur seuil) capture le sens de la causalité entre j_1 et j_2

$\rightarrow$ Datamining sur ρ_τ (possiblement paramétré comme $\rho_\tau^{(\omega)}$) pour explorer les motifs de causalité.

Illustration pour 2 variables

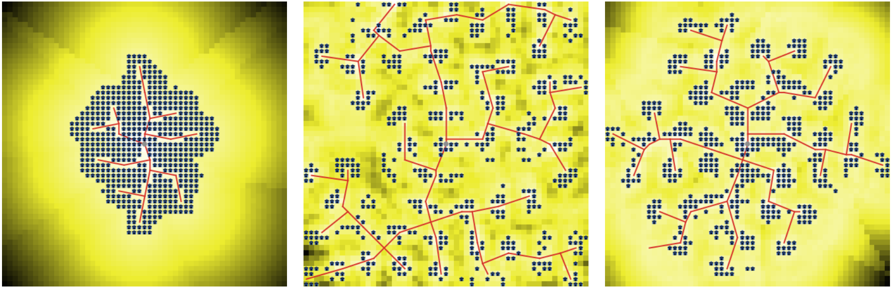


Validation basique



Données synthétiques : processus AR avec retard 2, termes croisés paramétrés par $(a_1, a_2) \in [-0.1, 0.1]$ *aléatoires.*

Validation sur données synthétiques



Configurations urbaines synthétiques générées par un modèle de morphogenèse hybride issu de [Raimbault et al., 2014]

Description du modèle de morphogenèse

- Automate cellulaire: cellules d'une grille carrée $(L_{i,j})_{1\leq i,j\leq N}$, occupées ou non (fonction $\delta(i,j,t)\in\{0,1\}$)

- Réseau vectoriel $G(t)=(V(t),E(t))$ qui évolue, incluant des centres urbains fixes $C_0\subset V(0)$ auxquels des activités $a\in\{1,\ldots,a_{max}\}$ sont attribuées (propriétés fonctionnelles de l'environnement urbain).

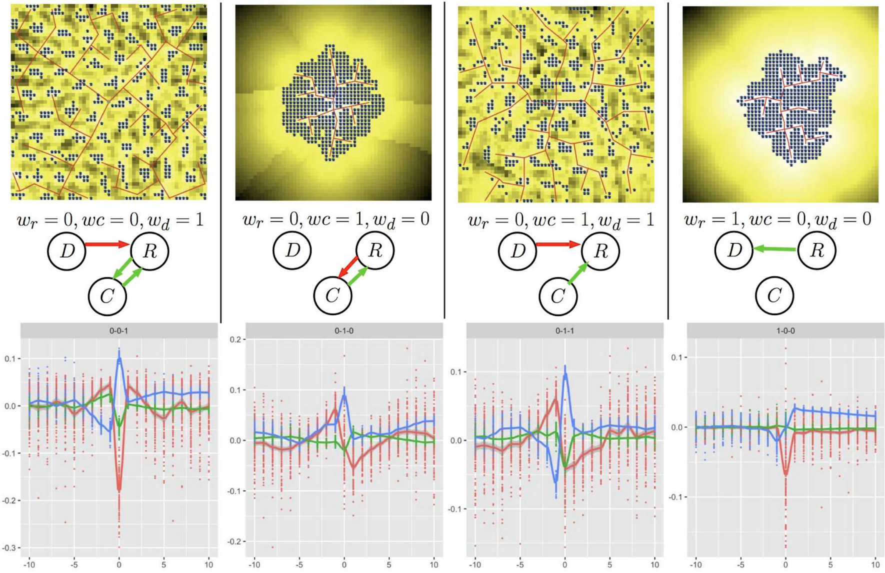
- Variables explicatives $(d_k)_{1\leq k\leq K}$ définies sur les cellules, avec des poids associés $(\alpha_k)_{1\leq k\leq K}$ (paramètres principaux du modèle), qui sont:
  - d_1 densité autour de la cellule (dans un rayon fixé r)
  - d_2 distance à la route la plus proche
  - d_3 distance au centre le plus proche par le réseau
  - $d_4(i,j,t)=\left(\frac{1}{a_{\max}}\sum_{a=1}^{a_{\max}}d_3(i,j,t;a)^{p_4}\right)^{1/p_4}$: accessibilité intégrée aux activités

Règles d'évolution

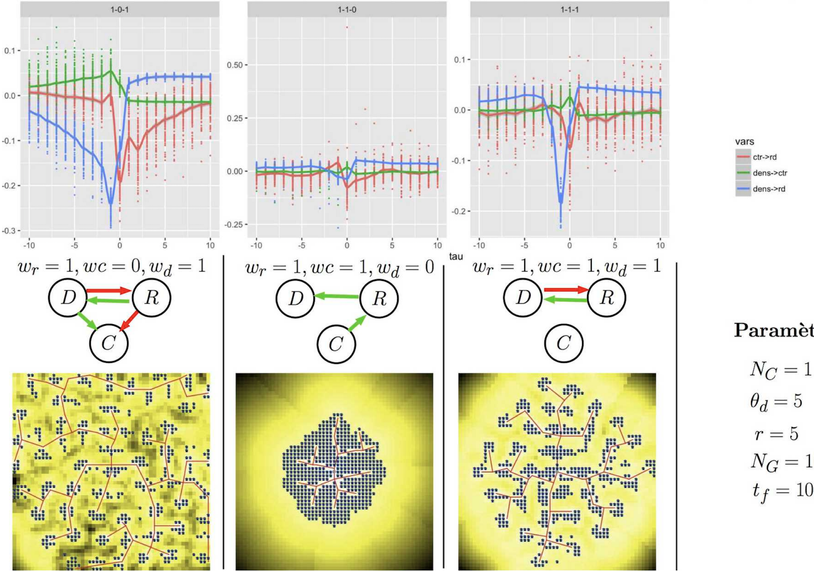
A chaque pas de temps :

- Etalement de la surface occupée : les meilleures N cellules selon la valeur du potentiel $v(i,j,t) = \frac{1}{\sum_k \alpha_k} \sum_{k=1}^{K} \alpha_k \frac{d_{k,\max}(t) - d_k(i,j,t)}{d_{k,\max}(t) - d_{k,\min}(t)}$ sont construites.
- Adaptation du réseau : quand une nouvelle cellule est construite, si $d_2 > \theta_2$, la cellule est connectée au réseau par une route directe.

Profils de corrélations retardées



Profils de corrélations retardées



$w_r = 1, wc = 0, w_d = 1$ | $w_r = 1, wc = 1, w_d = 0$ | $w_r = 1, wc = 1, w_d = 1$

Paramètres

$N_C = 1$

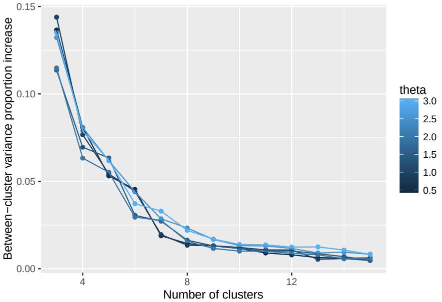
$\theta_d = 5$

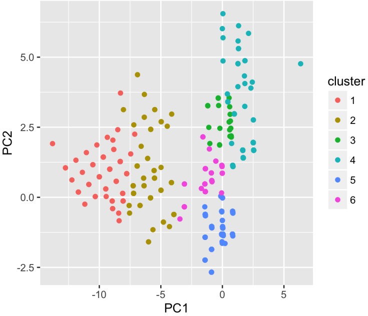
$r = 5$

$N_G = 10$

$t_f = 10$

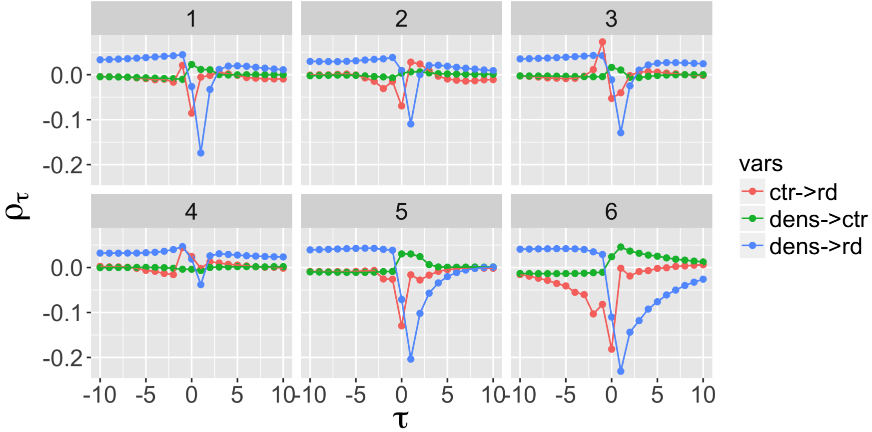
Exploration intensive de l'espace des paramètres du modèle (1000 points de paramètres x 100 répétitions) avec le logiciel OpenMole [Reuillon et al., 2013]





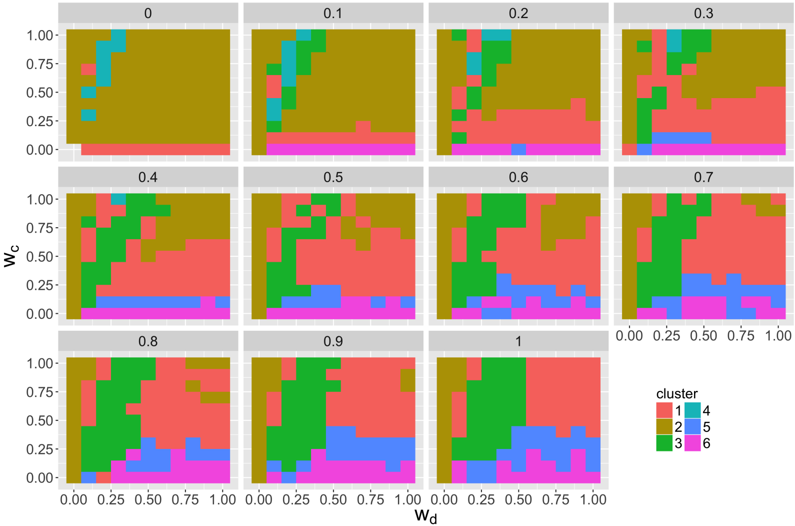
Classification non-supervisée (k-means robustes) sur les caractéristiques τ_{min}, τ_{max} : (Gauche) Dérivée du coefficient de clustering en fonction du nombre de clusters k; (Droite) Visualisation en plan principal pour $k = 6$.

Composition des régimes



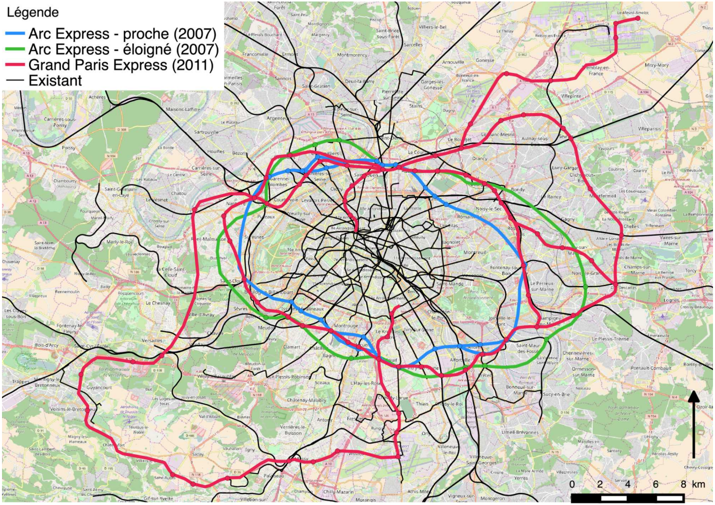
Valeurs des centres des clusters en termes de ρ_τ

Interprétation des régimes



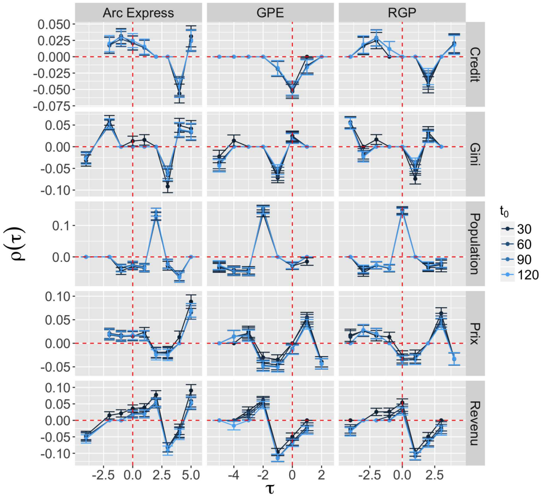
Position des clusters dans l'espace des paramètres w_i

Application: Cas d'étude



Projet de transport successifs pour la nouvelle infrastructure de transport du Grand Paris

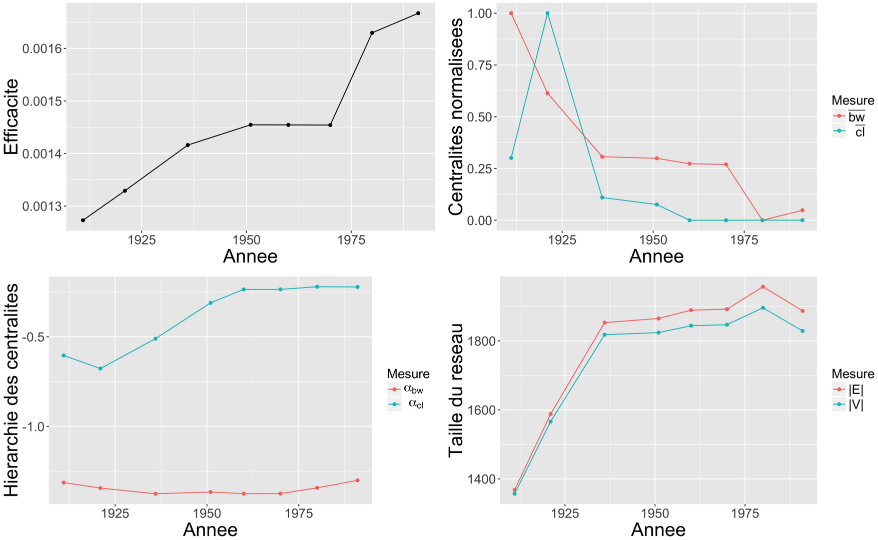
Application: Résultats



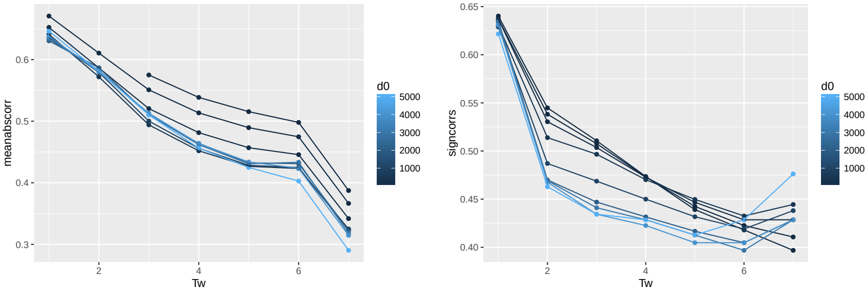
Valeurs de ρ_τ pour les différents projets (colonnes) et les différentes variables (lignes), avec les différentiels d'accessibilité

Application to South Africa: Network Analysis

Evolution of Network measures : anomalous trend rupture in centralities

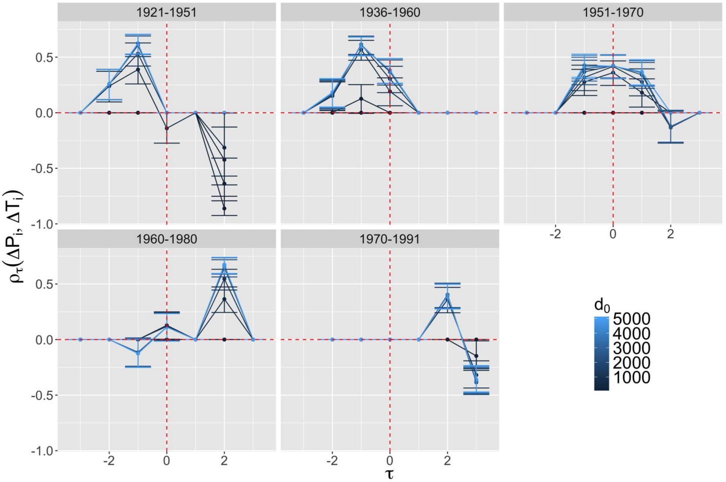


Application à l'Afrique du Sud



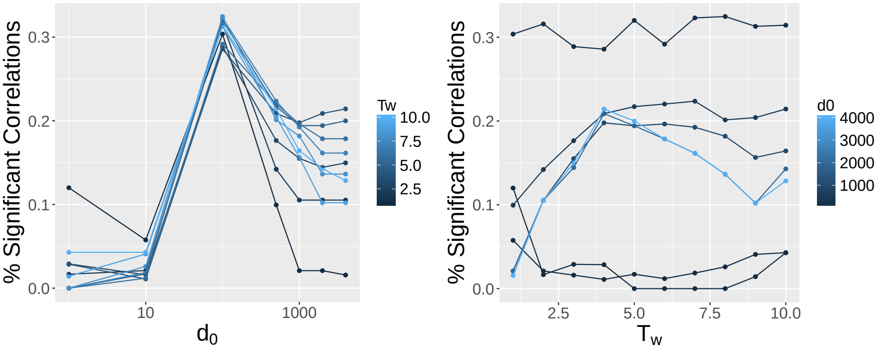
Détermination de la fenêtre temporelle et de la portée spatiale de l'accessibilité

Application à l'Afrique du Sud



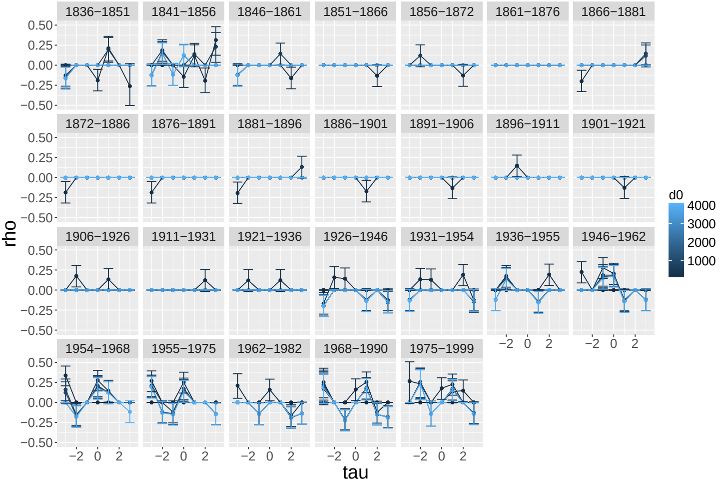
Inversion du sens de la causalité suggère un effet de ségrégation structurelle des politiques d'apartheid

Application à la France



Fenêtre temporelle et portée spatiale optimales (réseau ferré et population sur la période 1830-1999)

Application à la France



Profils de corrélation : pas de signal significatif

Discussion

Implications

→ Motifs de corrélations retardées pour identifier des “effets structurants” dans des systèmes complexes

→ Le concept opérationnel de *Régime de causalité* introduit une nouvelle façon de comprendre la co-évolution dans les modèles de simulation

Développements

→ Caractérisation de la diffusion spatio-temporelle : test de l'hypothèse de la diffusion spatiale de l'innovation dans la Théorie Evolutive des Villes [Pumain, 2010]

→ Echelles optimales pour la stationnarité : lien avec GWR [Brunsdon et al., 1998]

Granger causality test based on VAR processes :

$$X(t) = \sum_{0 \leq \tau \leq \tau_Y} b_\tau Y(t-\tau)$$

If there exists b_τ such that $|b_\tau| > 0$ significantly, then Y Granger-causes X.

We have then $\rho_\tau(Y, X) > 0$.

Macroscopic Interaction Model Rationale

Rationale : extend an interaction model for system of cities by including physical network as an additional carrier of spatial interactions

$\rightarrow$ Work under Gibrat independence assumptions, i.e. $\text{Cov}[P_i(t), P_j(t)] = 0$. If $\vec{P}(t+1) = \mathbf{R} \cdot \vec{P}(t)$ where $\mathbf{R}$ is also independent, then $\mathbb{E}\left[\vec{P}(t+1)\right] = \mathbb{E}[\mathbf{R}] \cdot \mathbb{E}\left[\vec{P}\right](t)$. Consider expectancies only (higher moments computable similarly)

$\rightarrow$ With $\vec{\mu}(t) = \mathbb{E}\left[\vec{P}(t)\right]$, we generalize this approach by taking $\vec{\mu}(t+1) = f(\vec{\mu}(t))$

Macroscopic Model Formulation

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

Model specified by

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

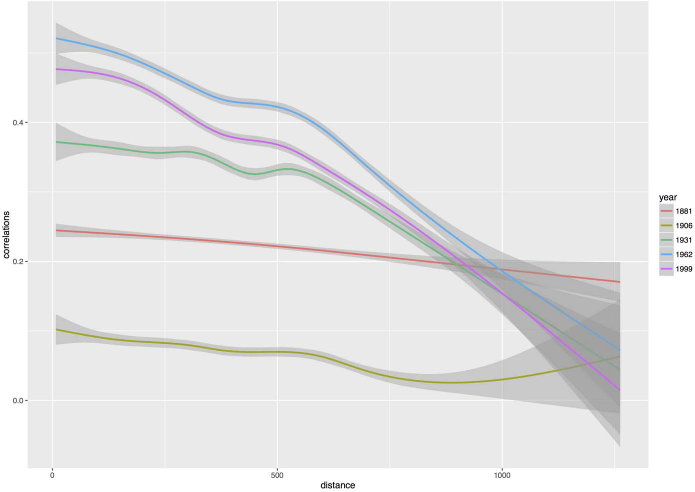
with

- $G_{ij} = w_G \cdot \frac{V_{ij}}{<V_{ij}>}$ and $V_{ij} = \left(\frac{\mu_i \mu_j}{\sum \mu_k{}^2}\right)^{\gamma_G} \exp\left(-d_{ij}/d_G\right)$
- $N_i = w_N \cdot \sum_{kl} \left(\frac{\mu_k \mu_l}{\sum \mu}\right)^{\gamma_N} \exp\left(-d_{kl,i}\right)/d_N$ where $d_{kl,i}$ is distance to shortest path between k, l computed with slope impedance $(Z = (1 + \alpha/\alpha_0)^{n_0}$ with $\alpha_0 \simeq 3)$

Data : stylized facts

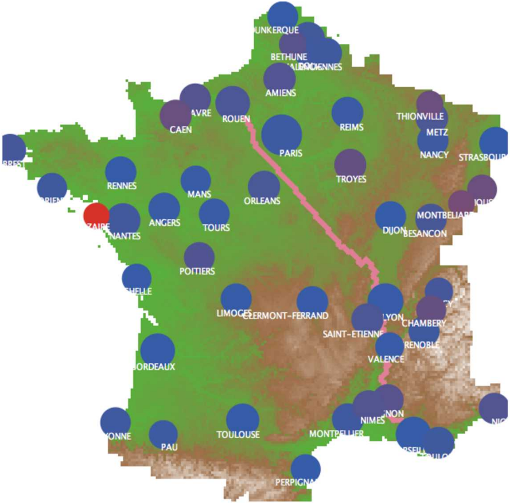
Population data for French-cities (Pumain-INED database : 1831-1999)

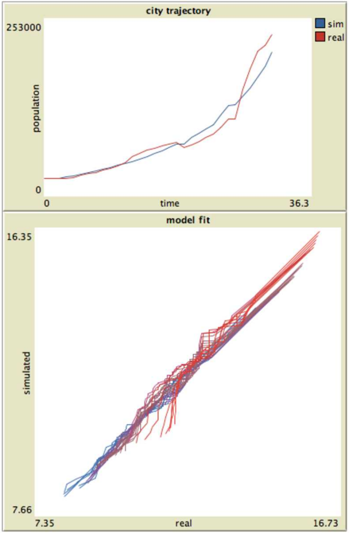
Non-stationarity of log-returns correlations function of distance



Geographic abstract network

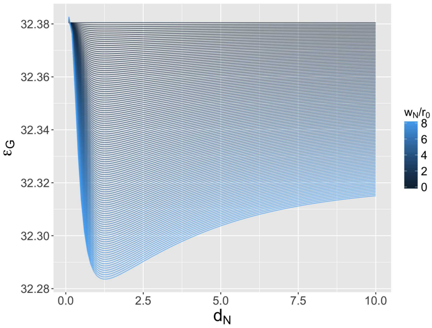
Physical transportation network abstracted through a geographical shortest path network

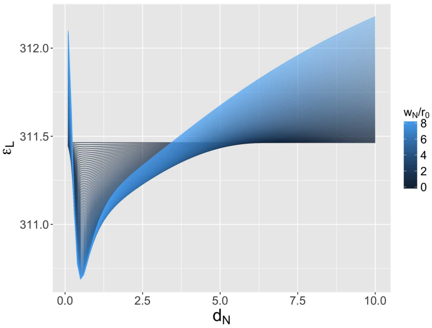




Results : model exploration

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

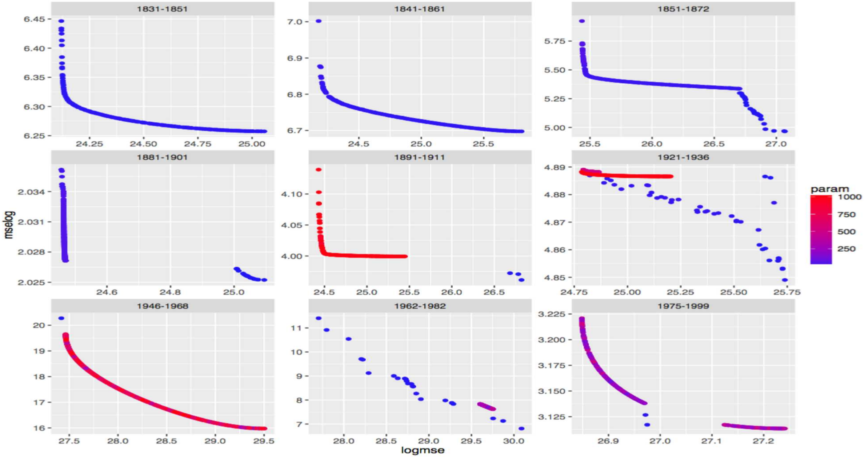




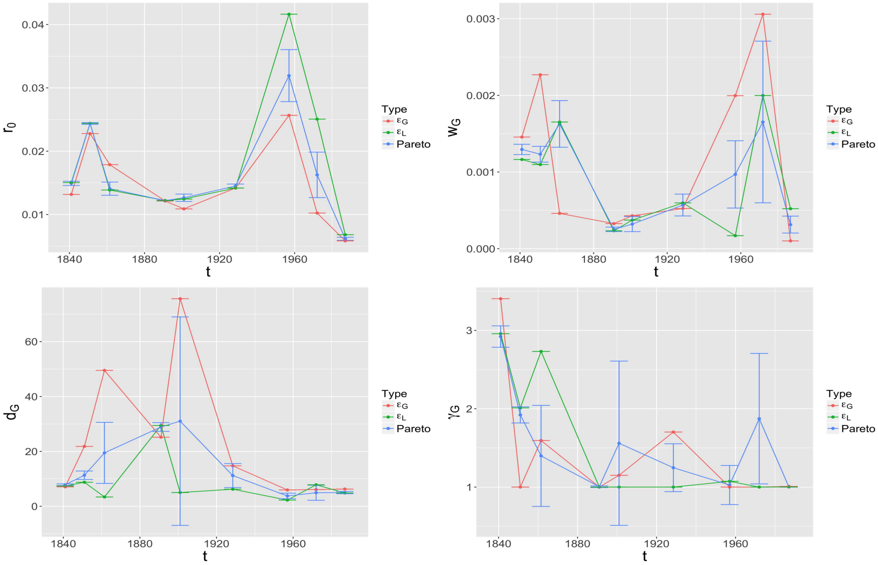
Results : model calibration

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

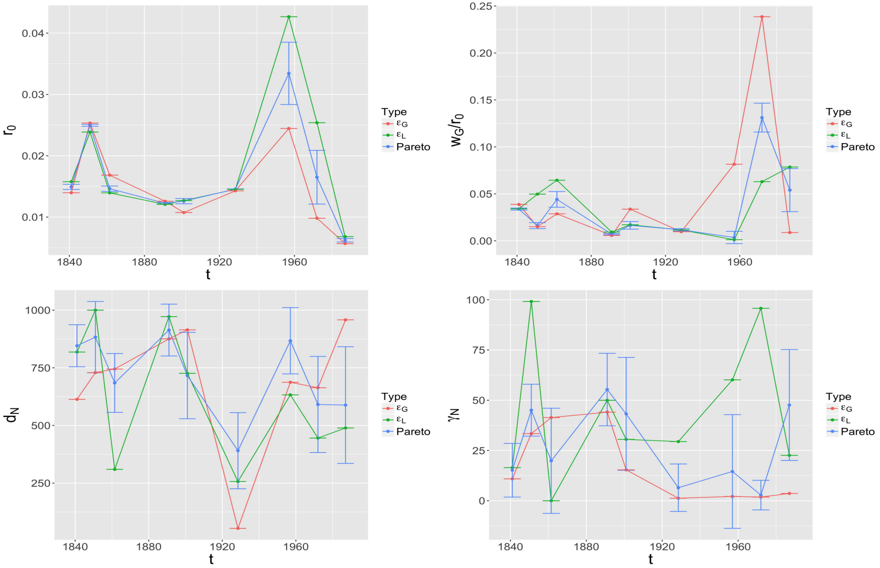
Pareto front for full model calibration, objectives MSE and MSE on logs



Results : non-stationary gravity model calibration



Results : non-stationary full model calibration



Quantifying overfitting : Empirical AIC

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

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

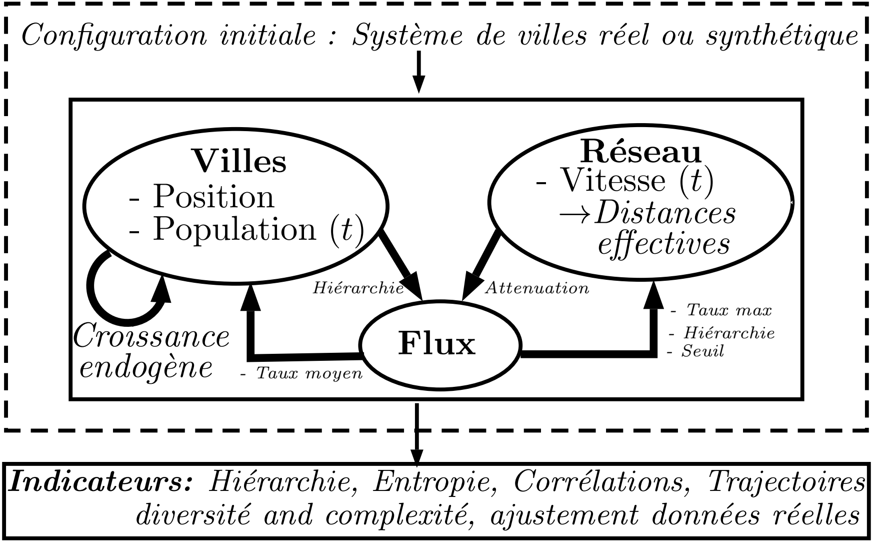
Application M_1 : gravity only model with $(r_0 = 0.0133, w_G = 1.28e-4, \gamma_G = 3.82, d_G = 4e12)$; M_2 : full model with $(r_0 = 0.0128, w_G = 1.30e-4, \gamma_G = 3.80, d_G = 8.4e14, w_N = 0.603, \gamma_N = 1.148, d_N = 7.474)$

Empirical AIC values

Table: Empirical AIC results.

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

Generic Model



Model Formalization : Network Growth

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

1. For the thresholded case

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

2. For the full growth case

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

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

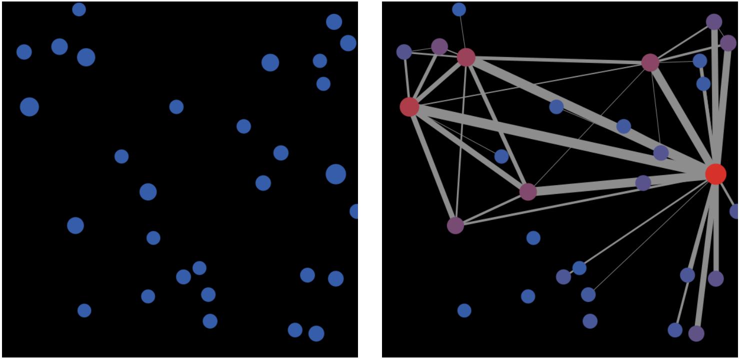
Model Formalization : Indicators

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

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

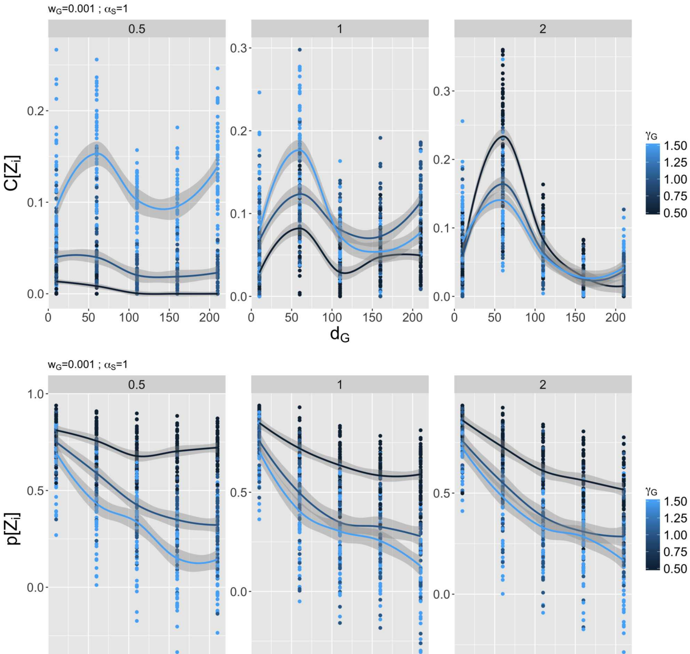
- Average trajectory complexity (number of inflexion points)
- Pearson correlations conditionally to distance $\hat{\rho}_d\left[(X(\vec{x}_1, Y(\vec{x}_2)) \| ||\vec{x}_1 - \vec{x}_2|| \sim d\right]$
- Lagged return correlations $\hat{\rho}_\tau\left[\Delta X(t), \Delta Y(t-\tau)\right]$ (Granger causality)

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

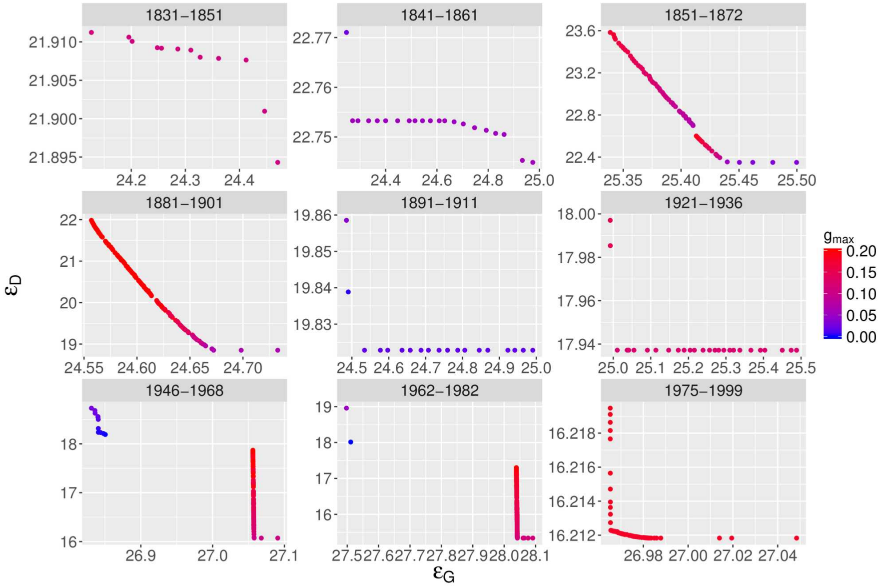


Exemple of run ($t_f = 30$). Level of red gives overall growth and link width flows.

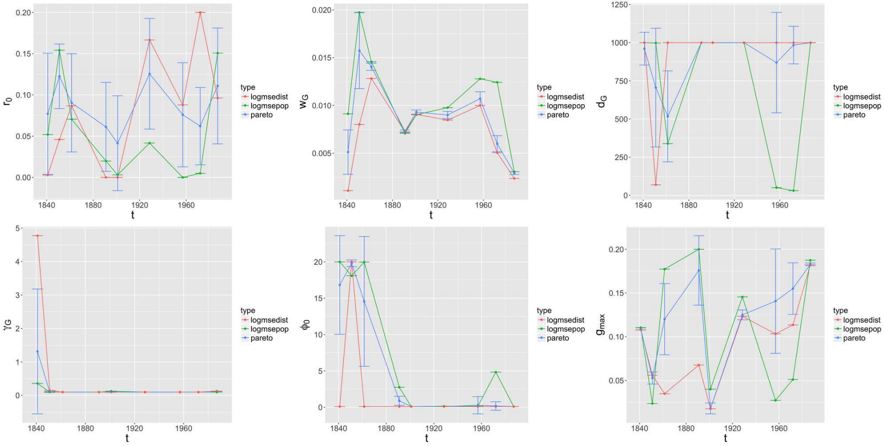
Model Behavior



Calibration

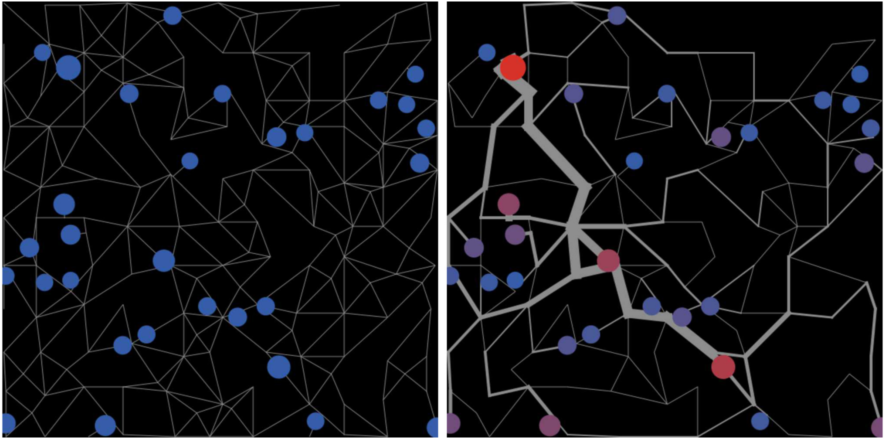


Calibration: Parameters



Model Specification: Physical Network

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



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

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)

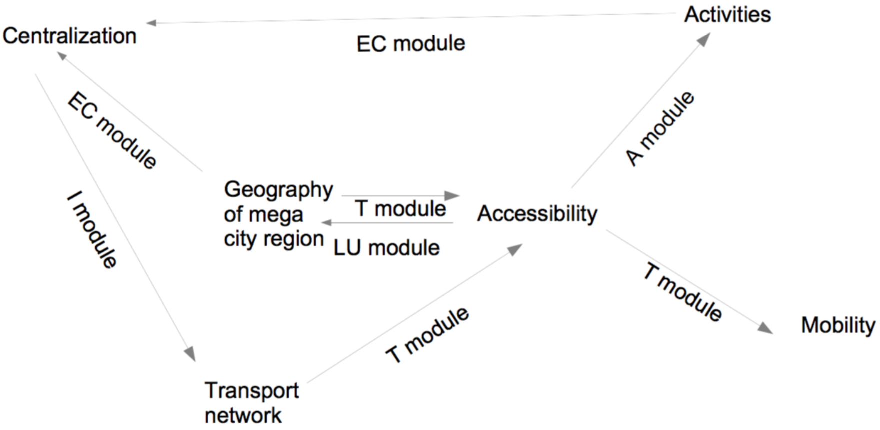
$\rightarrow$ Coevolution transport / urbanism (LUTI model with endogeneous transport infrastructure provision)

$\rightarrow$ 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 :

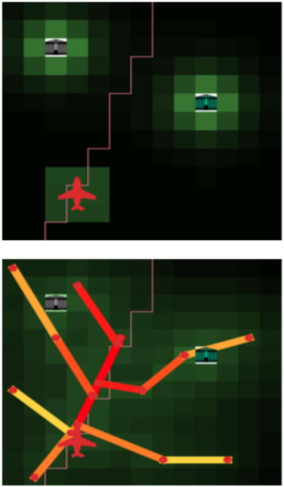
- Mixed Nash equilibrium, where actors compete
- One Rational Discrete Choice equilibrium

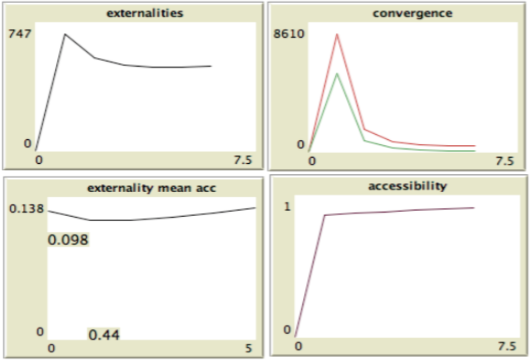
Lutecia model parameters

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]

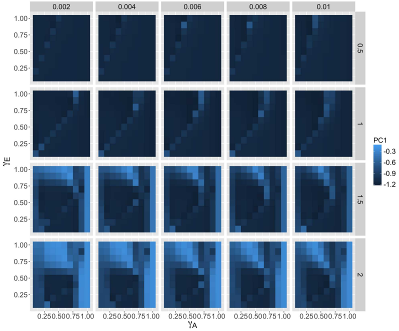


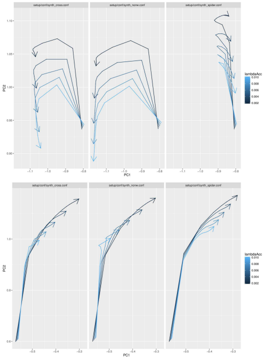


Land-use dynamics

Lessons from systematic exploration of the land-use module:

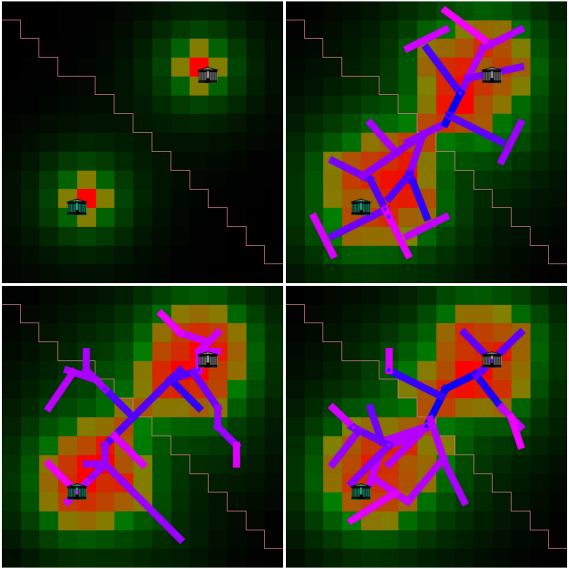
- Large diversity of morphological trajectories in time for varying $\gamma_A, \gamma_E, \lambda, \beta$
- Diversity of final forms obtained
- It is possible to minimize, at fixed $\alpha = 1$, the total quantity of relocalization



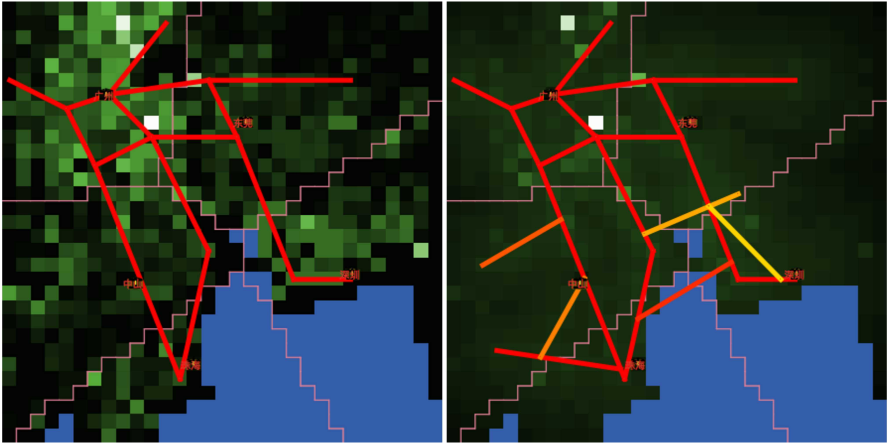


Model Exploration

Influence of governance parameters on network topology

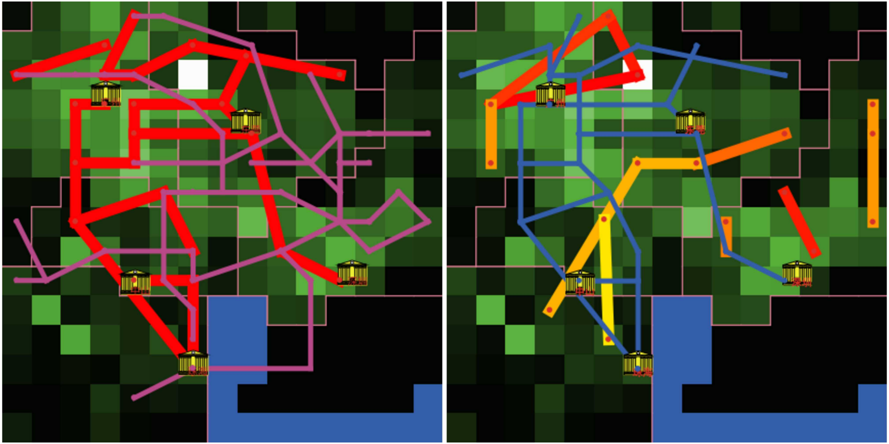


Stylized application to the Pear River Delta Mega-city Region



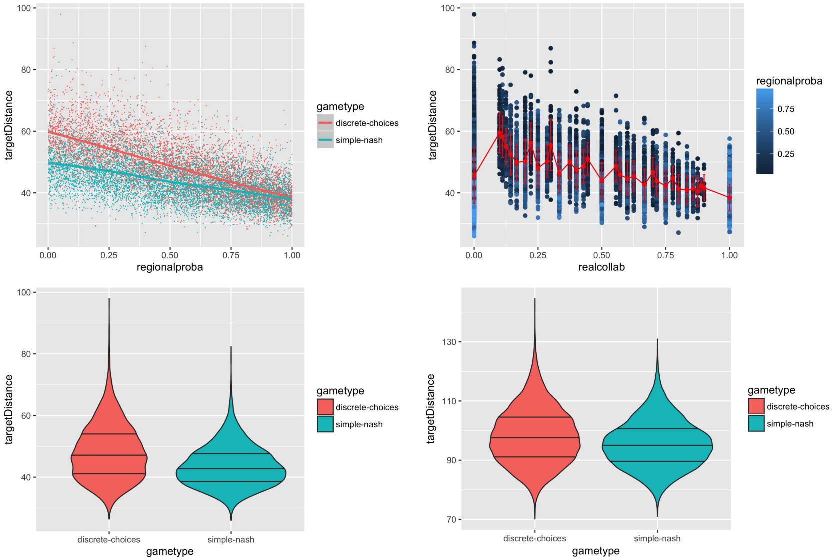
Model Application: target networks

Different calibration setup: current and planned network



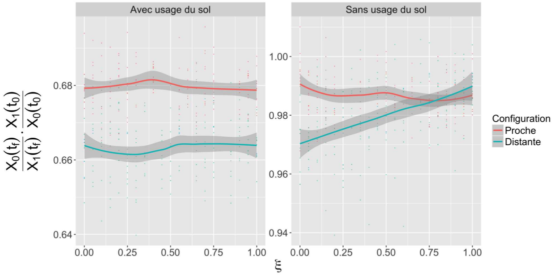
Model Calibration

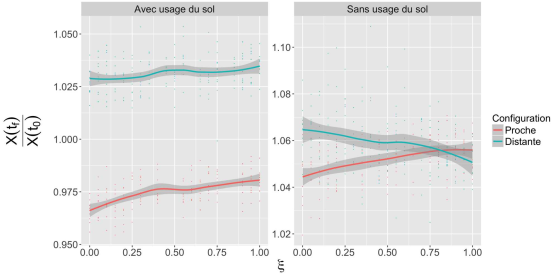
Calibration on the generated network (fixed land-use)



Effects of co-evolution

Unveiling the coupling between urban development and transportation networks





Transportation network model: graph with edges flows and capacity.

Question: How to compute traffic flows from a demand pattern ?
$\rightarrow$ *Traffic assignment problem*

1. Basic solution: shortest path assignment (betweenness centrality)
2. More elaborate: user equilibrium at which no user can improve his travel time, coined by [Wardrop, 1952] (game theory approach: similar to a Nash equilibrium)
   - mathematical existence generally verified (fixed point theorem), unicity more difficult
   - temporal stationarity assumption: flows are assumed to converge on the considered period, generally rush hour

Diverse developments of the SUE:

→ Dynamic Stochastic User Equilibrium [Han, 2003]

→ Restricted Stochastic User Equilibrium [Rasmussen et al., 2015] more realistic in alternatives

→ Boundedly User Equilibrium [Mahmassani and Chang, 1987]

→ Assignment techniques inspired from other fields such as Network Science [Puzis et al., 2013]

Validation and Practical Use

Static User Equilibrium lacks empirical validation in the literature

$\rightarrow$ Some examples such as the behavioral study of user route choices ("Wardrop's first principle") in [Zhu and Levinson, 2010]

However still largely used

$\rightarrow$ in theoretical literature, as for example [Leurent and Boujnah, 2014] : do refinements in the model such as adding parking cruising flows have a sense if the core is not validated ?

$\rightarrow$ in real-world application, such as the MODUS model for Paris Metropolitan area : what are the implications of basing decision-making and traffic management on an unvalidated framework ?

Empirical Investigation of SUE Existence

Research Objective : *Investigate empirically the spatio-temporal stationarity of traffic flows, combining different complementary quantitative approaches*

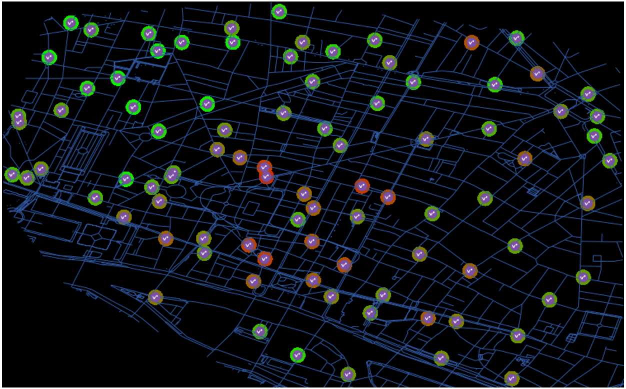
$\rightarrow$ Construction of a real-time dataset for major links of Paris region on 6 month by data crawling

$\rightarrow$ Complementarity of approaches (Complex Systems general paradigm) : Spatio-temporal data visualization, Network analysis, Spatial analysis

Data collection: illustration

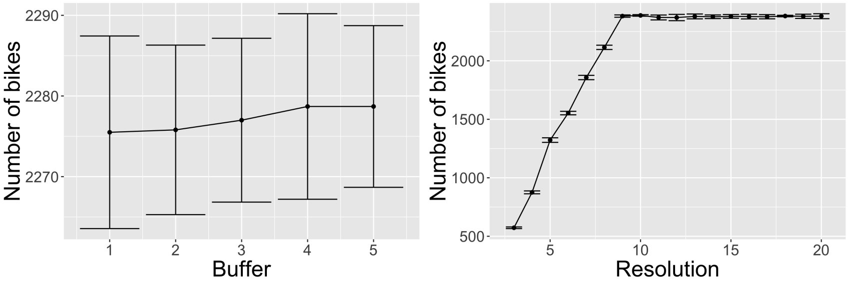
Crawling of semi-open data may be necessary to study territorial systems

Mobility data: status of VLib stations in real time (easy: API) [Raimbault, 2015]



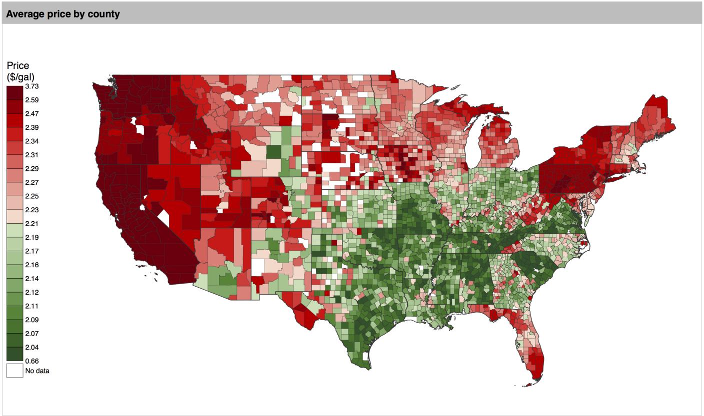
Data collection

More difficult mobility data: dockless bike sharing. Evaluation of an ad-hoc algorithm.



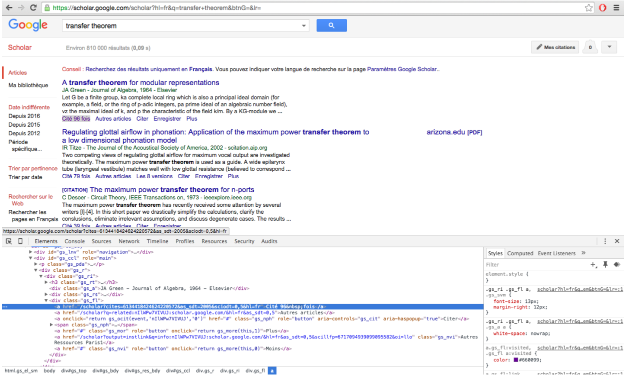
Data collection

Even more difficult: ad-hoc algorithm and large scale data (150000 records every 12 hours). Example of US gaz prices.



Not only for spatial data

Paper citation data: example of a journal not referenced by classical databases



Dataset Construction

Difficulty to find Open Data on Transportation Systems [Bouteiller and Berjoan, 2013]

→ Construction of an open historical travel time dataset for major links in the region of Paris, collecting in real time public traffic data from `www.sytadin.fr`

Data collection : Each two minutes, automated python script

- fetch raw webpage giving traffic information
- parse html code
- store in a `sqlite` database

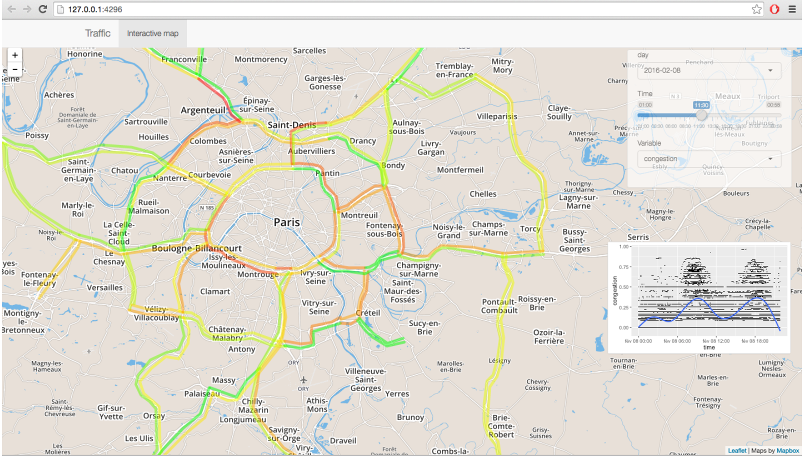
Openly available (CC Licence) at
`http://dx.doi.org/10.7910/DVN/X22ODA`

Data summary: more than 2 years (since Feb. 2016), 2min time granularity, effective travel time for 101 links ($\simeq$ 10km spatial granularity)

Interactive Data Visualization

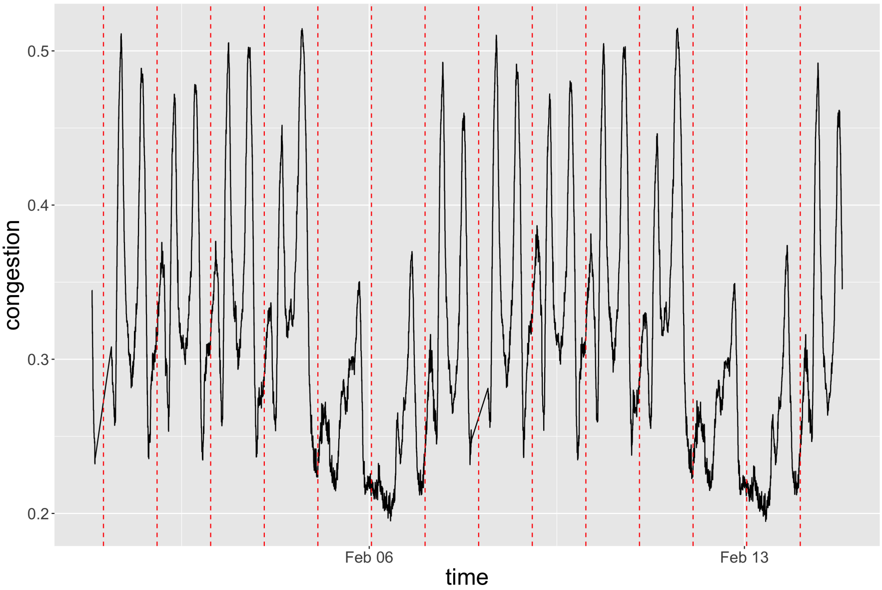
Interactive web-application for spatio-temporal exploration

`http://shiny.parisgeo.cnrs.fr/transportation`



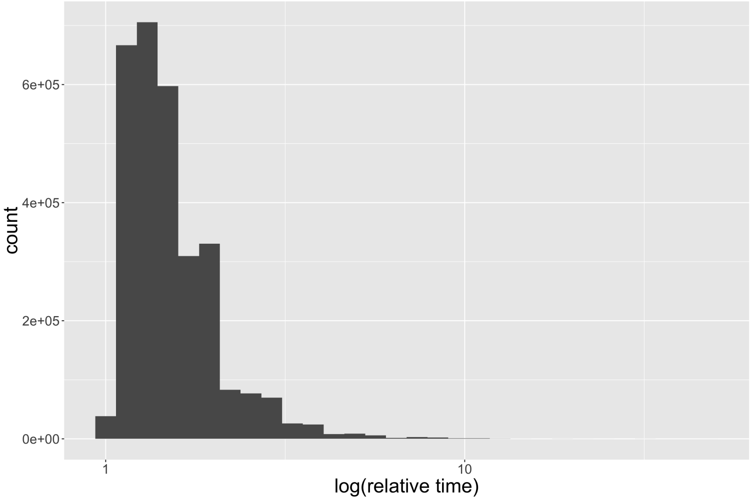
Demonstration of the interactive application

Temporal patterns of congestion



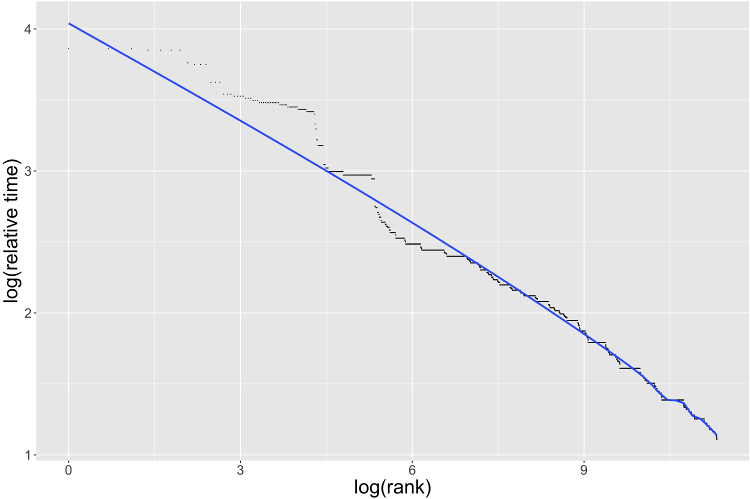
Summary statistics

Distribution of relative times



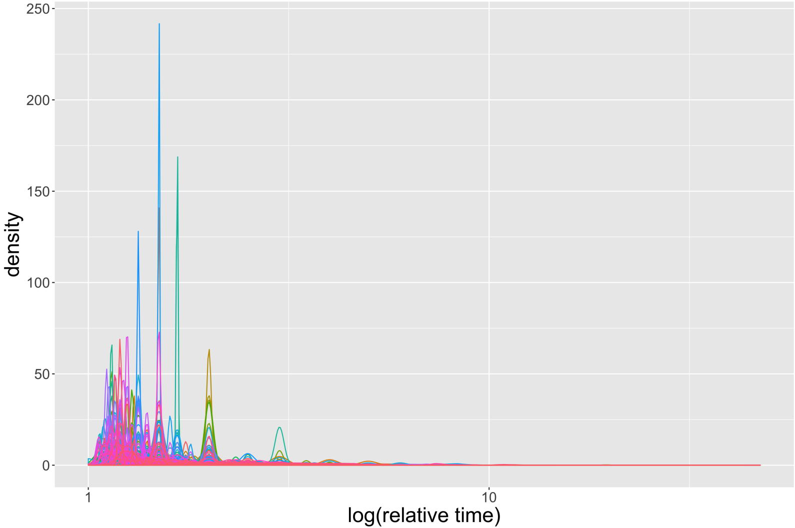
Summary statistics

Rank size law for relative times: signature of a complex system with extreme events



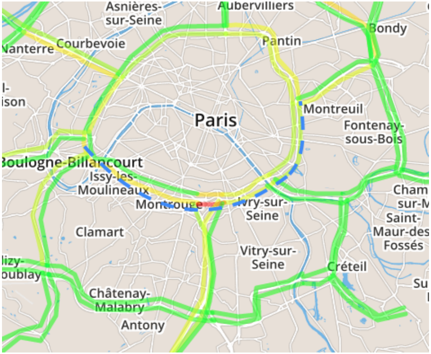
Summary statistics

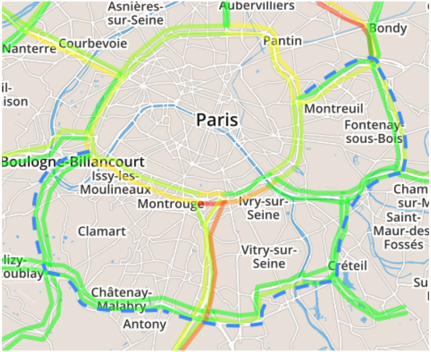
Distribution of relative times by link: identification of critical links



Spatio-temporal Variability : Example

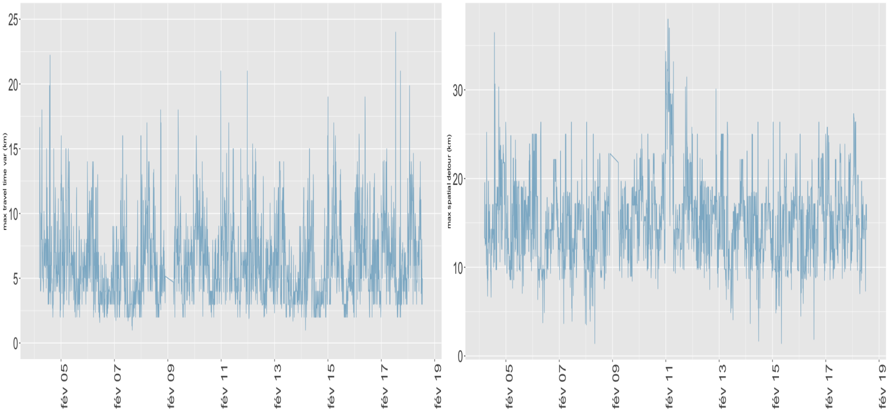
Very high spatial variability on 10min time interval, here on 11/02/2016 00:06-00:16





Spatio-temporal Variability

Maximal travel time and spatial variabilities on a two week sample



Stability of Network Measures

Network Betweenness Centrality

$$b_i = \frac{1}{N(N-1)} \cdot \sum_{o \neq d \in V} \mathbb{1}_{i \in p(o \to d)} \tag{4}$$

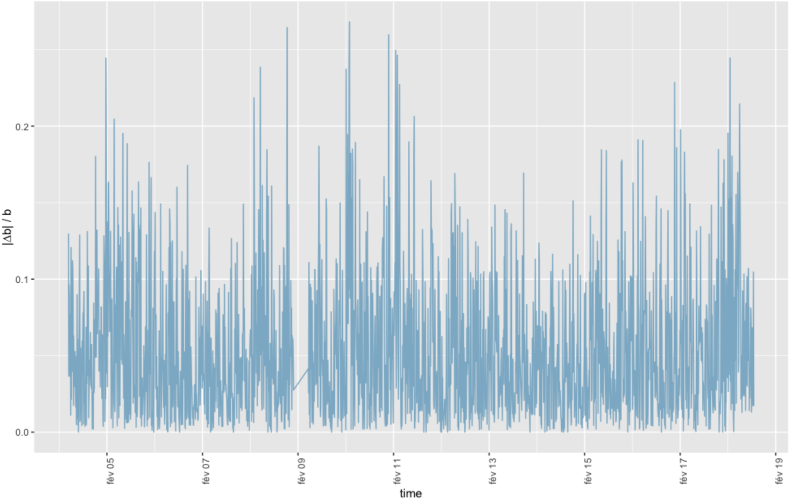
Temporal Maximal Betweenness Variability

$$\Delta b(t) = \frac{|\max_i(b_i(t+\Delta t)) - \max_i(b_i(t))|}{\max_i(b_i(t))} \tag{5}$$

$\rightarrow$ *Reveals either a proportion of rerouted travels (negative variation) or a minimal proportion of load increase for a single node (positive variation)*

Stability of Network Measures

Temporal maximal betweenness variability on a two weeks period



Spatial Heterogeneity

Spatial Autocorrelation as an index of spatial variability, for link i

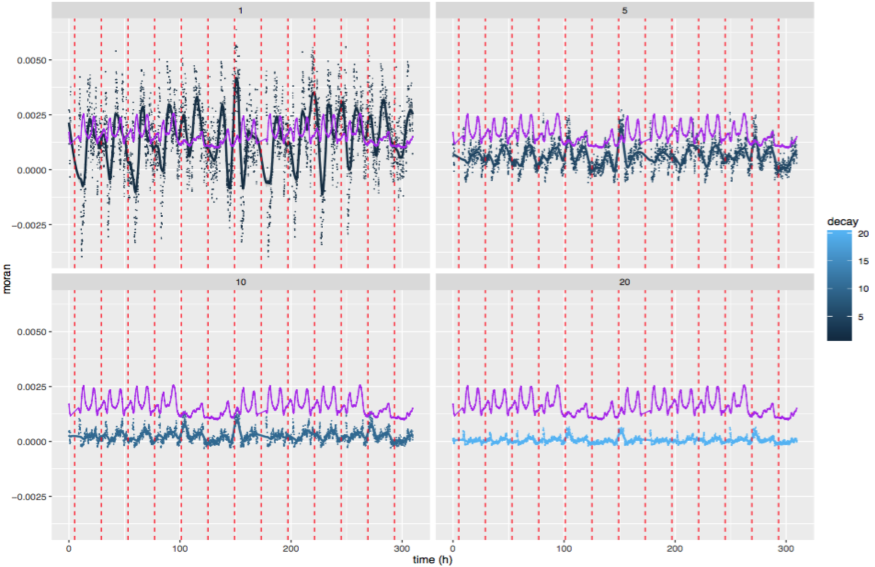
$$\rho_i = \frac{1}{K} \cdot \sum_{i \neq j} w_{ij} \cdot (c_i - \bar{c})(c_j - \bar{c}) \tag{6}$$

with spatial weights $w_{ij} = \exp\left(\frac{-d_{ij}}{d_0}\right)$

$\rightarrow$ *Indirect measure of the spatial stationarity of flows : a decreasing correlation implies a chaotic system*

Spatial Heterogeneity

Spatial autocorrelation on a two weeks period for different decays



Theoretical and Practical Implications

Theoretical Implications

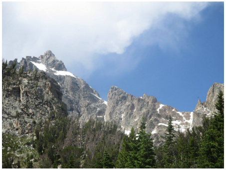
→ Need for more systematic comparison of framework validity ([Kryvobokov et al., 2013] compares two LUTI models e.g.)

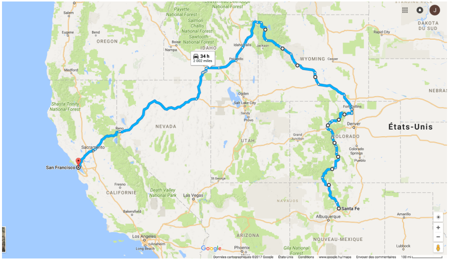
→ Can still be used e.g. for integration within more complex models

Practical Implications

→ Difficulty of transferring academic results to real-world engineering, that can be tied to habits, myths, political interests, etc. [Commenges, 2013] ; [Offner, 1993]

Road Trippin' : Californication (Energy Price)





Geography and Fuel prices

→ In the US you fuel your (necessary big) car everywhere and everyday, and directly feel the strong variability of prices !

Spatio-temporal variability of Fuel Price captures geographical properties of a particular energy market, of the transportation system, of interactions between transportation and territories.

Diverse approaches mostly by economists :

- [Rietveld et al., 2001] cross-border variability
- [Gregg et al., 2009] influence on carbon emissions
- [Combes and Lafourcade, 2005] effective transportation costs
- [Gautier and Saout, 2015] from crude oil price to retail price

Exploratory Spatial analysis

Research Objective : *Construction and Exploratory analysis of a large and detailed dataset of US fuel retail price, focusing on spatio-temporal variability*

$\rightarrow$ Focus on geographical patterns and structures

$\rightarrow$ Complementarity of spatial analysis methods

$\rightarrow$ Interdisciplinary point of view on a fundamentally heterogenous system

Dataset Construction

Crowdsourced Big Data as a new way to unveil structure of complex socio-technical systems

$\rightarrow$ Construction of a large scale dataset covering most of US fuel stations on two month

Requirements : Flexibility, performance and anonymity

Architecture : Pool of proxy tasks to pipe requests through `tor`; manager monitors and launches collection tasks; subtasks crawl and parse target webpages.

Dataset available upon request, "grey area" of semi-open data.

Dataset Summary

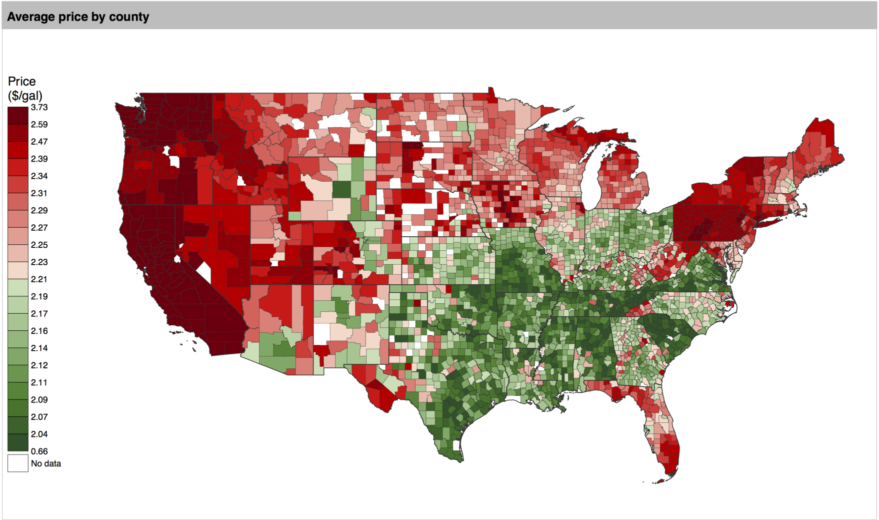
- $41 \cdot 10^6$ unique observations, between January and March 2017 $\rightarrow$ 5,204,398 gas station - day observations for main purchase mode and regular fuel, used in the analysis, aggregated at the county level
- Socio-economic data from US Census Bureau

Table: Descriptive statistics on Fuel Price ($ per gallon)

Mean	Std. Dev.	p10	p25	p50	p75	p90
2.28	0.27	2.02	2.09	2.21	2.39	2.65

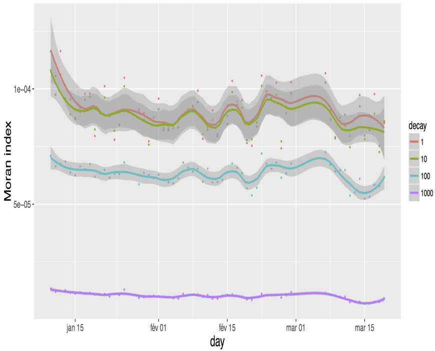
Data Exploration

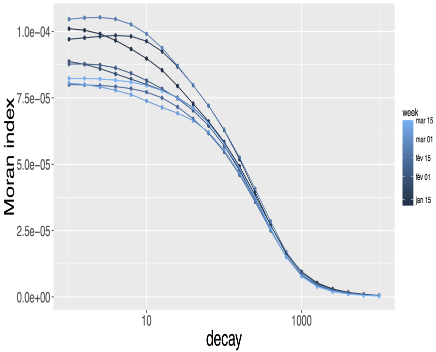
Interactive web-application for spatio-temporal exploration



Spatio-temporal correlations

Variability in space and time of Moran spatial auto-correlation index unveils strong non-stationnarity





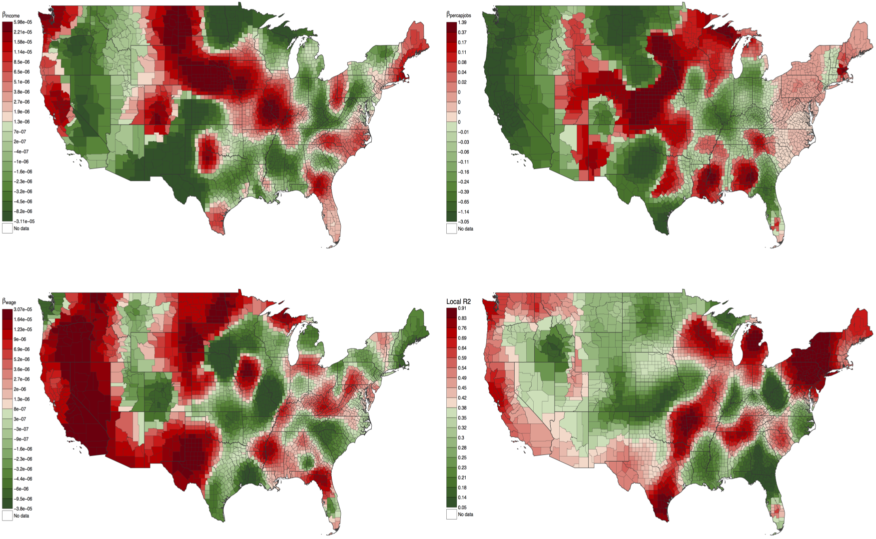
Geographically Weighted Regression

- Geographically Weighted Regression (GWR) [Brunsdon et al., 1996] to tackle spatial non-stationarity : capturing a variable influence in space of explicative variables for prices
- Multi-modeling using corrected AIC for model selection : find the best model and the best bandwidth controlling for overfitting

Best model : $price = \beta \cdot (income, wage, percapjobs)$ with an optimal bandwidth around 75km (22 neighbors with adaptive bandwidth), interpreted as spatial stationarity scale of price processes in relation to economic agents.

Geographically Weighted Regression : Results

Fitted coefficients and R^2 for the best model



Multi-level Regression

Fixed effect regression at the level of the state : multi-level modeling to capture spatial effect of administrative boundaries

$$log(x_i) = \beta_0 + X_i\beta_1 + \beta_{s(i)} + \varepsilon_i, \qquad (7)$$

- Clustering of standard error at the state level motivated by the strong spatial autocorrelation: capture county-level variation controlling for State fixed effect
- Regressing the log of price on a state fixed-effect explains 74% of the variance
- influence of taxes: regressing the log of oil price on the level of state tax gives a R-squared of 0.33%

Multi-level Regression : results

	(1)	(2)	(3)	(4)	(5)
Density		0.016***	0.016***	0.016***	0.015***
		(0.002)	(0.001)	(0.001)	(0.001)
Population (log)		-0.007***	-0.040***	-0.041***	-0.039***
		(0.001)	(0.011)	(0.011)	(0.010)
Total Income (log)			0.031***	0.031***	0.027***
			(0.010)	(0.010)	(0.009)
Unemployment			0.001	0.000	0.000
			(0.001)	(0.001)	(0.001)
Poverty			-0.028**	-0.030***	-0.029**
			(0.011)	(0.011)	(0.011)
Percentage Black				0.000***	-0.000
				(0.000)	(0.000)
Vote GOP					-0.072***
					(0.015)
R-squared	0.743	0.767	0.774	0.776	0.781
N	3,066	3,011	3,011	3,011	3,011

Multi-level Regression : summary

- Strong influence of state-level tax
- Dense urban counties have higher fuel price, but price decreases with population
- Fuel price increases with total income, decreases with poverty
- It decreases with the extent to which a county has voted for a Republican candidate: suggests a circular link
- Overall, local socio-economic features have explanatory power when removing State fixed effect

Implications

Methodological

→ Complementarity of Spatial analysis and econometrics methods : towards integrated approaches to territorial systems

Practical

→ Possible design of territory-targeted car-regulation policies, allowing both sustainability and territorial equity

Possible Developments

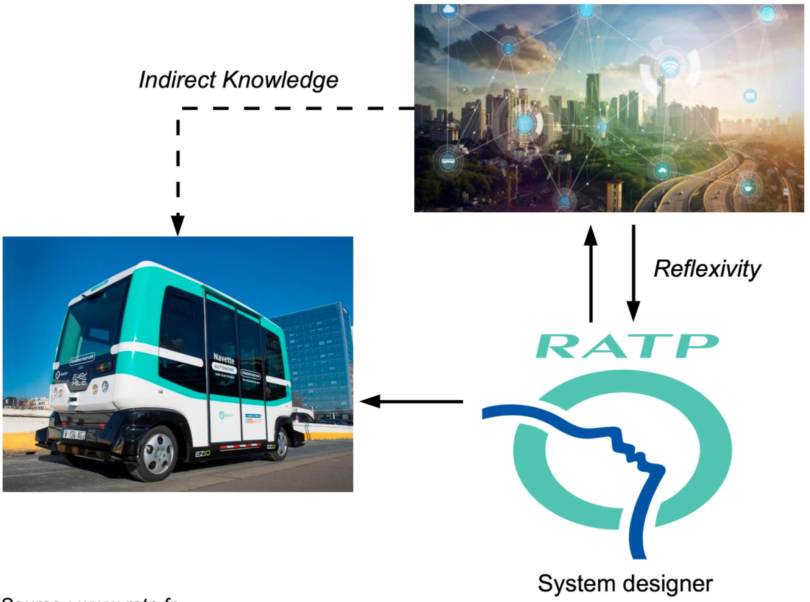
$\rightarrow$ Microscopic data analysis (requires precise geocoding)

$\rightarrow$ Longer time series (collection in progress) and time-series modeling

$\rightarrow$ Parametrization of a large-scale ABM of the spatialized fuel market : investigation of adaptive policies effects at the local and global level

$\rightarrow$ Scales and ontologies to study relations between network and territories

Reflexivity in System Engineering ?



Source : www.ratp.fr

Processes of Knowledge Production

The study of processes of knowledge production as an asset to study complex systems ?

→ Philosophical and epistemological approaches to the nature of knowledge : [Kuhn, 2012]'s structure of scientific revolutions, [Feyerabend, 2010]'s advocacy for diverse viewpoints.

→ Quantitative approaches : beyond simple bibliometrics [Cronin and Sugimoto, 2014]

Following [Morin, 1991], the Knowledge of Knowledge arise from and for the study of Complex Systems : knowledge of the complex is complex knowledge (requisite complexity [Gershenson, 2015])

Knowledge Frameworks

Knowledge Framework : *A systemic framework containing an epistemological component dealing with the nature of knowledge or knowledge production.*

→ Knowledge management : [Durantin et al., 2016] coupling engineering with design paradigms ; [Carlile, 2004] knowledge at the boundaries of disciplines.

→ Meta-modeling frameworks : [Cottineau et al., 2015] multi-modeling ; [Golden et al., 2012] unified formal description of Complex Systems.

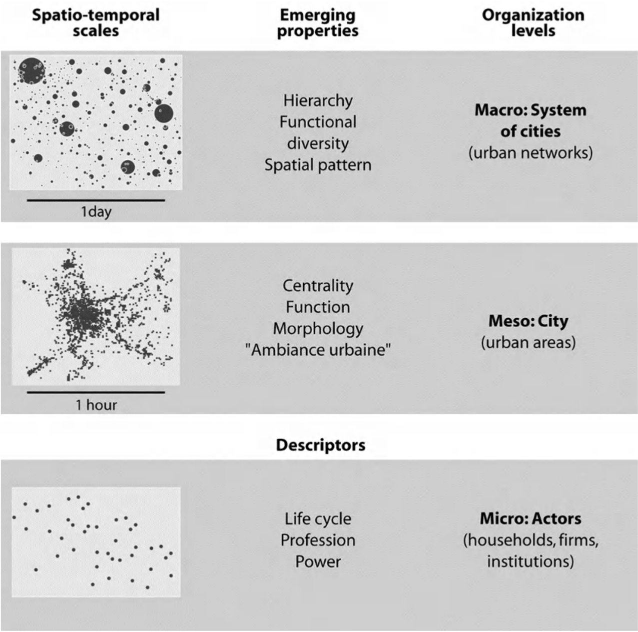
→ Applied frameworks : [Moulin-Frier et al., 2017] typology of approaches in Artificial Intelligence.

Approach and Methodology

Approach : An inductive approach from a case study in Theoretical and Quantitative Geography, developed in the last 20 years (Evolutive Urban Theory [Pumain, 1997])

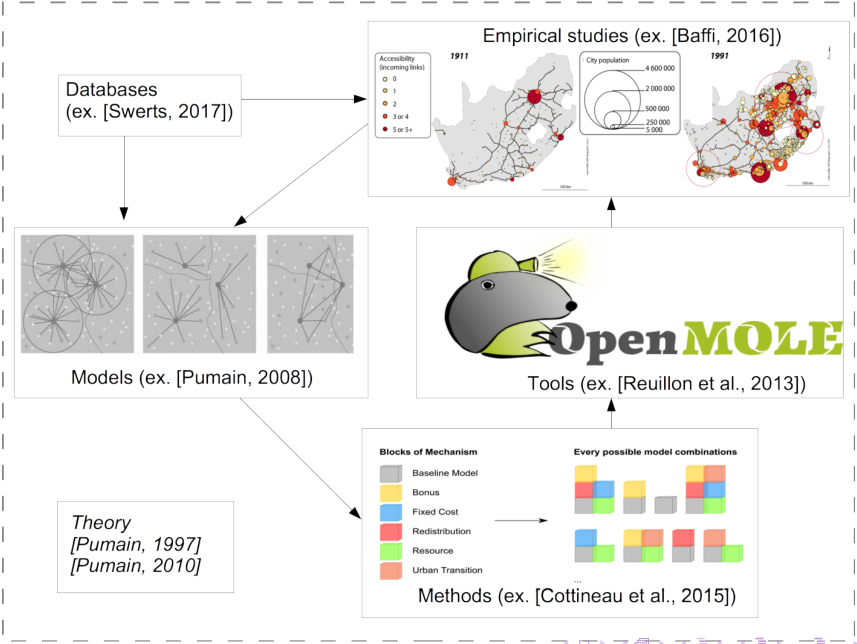
Methodology : Mixed methods. Interview with main contributors of the theory, from different disciplines (D. Pumain, C. Cottineau in Geography, R. Reuillon in Computer Science) ; quantitative analysis of citation network.

Evolutive Urban Theory

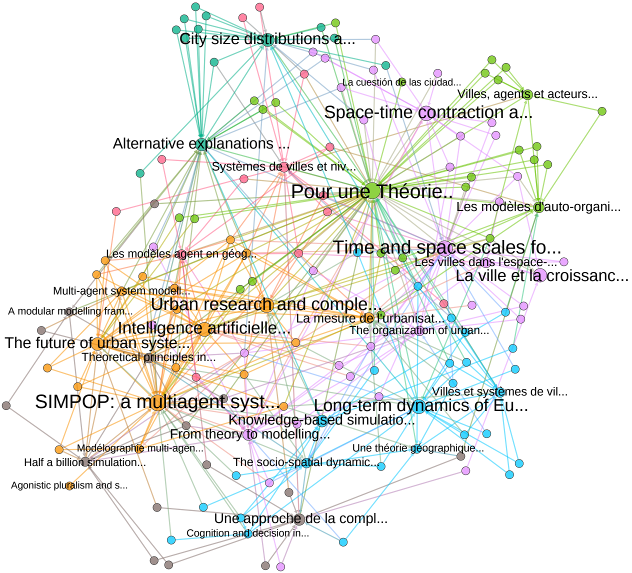


Source :
[Pumain, 2008]

Iterative Construction of Knowledge across Domains



Citation Network Analysis



Core citation network of Evolutive Urban Theory

$|V| = 155$

$|E| = 449$

7 communities, modularity 0.39

Constraints on the Framework

We postulate the following integration constraints for the framework :

- Integration of disciplines, as Complex Systems are mostly interdisciplinary.
- Integration of knowledge domains : no particular type of knowledge must be privileged in the production process.
- Integration of types of methodologies : for example different modeling approaches can be taken into account.

Epistemological Fundations

Giere's cognitive approach to science [Giere, 1990] : cognitive agents have *perspectives* on aspects of the real world.

Scientific perspectivism [Giere, 2010] : *cognitive agents* use *media*, the models, to represent something with a certain purpose.

[Varenne, 2017]'s classification of main model functions : perception and observation, understanding, theory building, communication, decision making.

Knowledge Domains

Definition of Knowledge Domains :

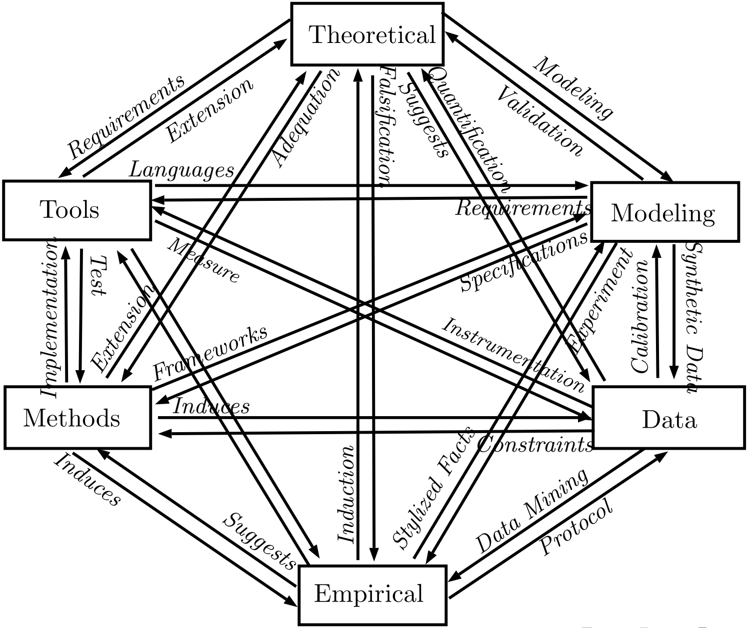
- **Empirical.** Empirical knowledge of real world objects.
- **Theoretical.** Conceptual knowledge, implying cognitive constructions.
- **Modeling.** The model as the formalized *medium* of the perspective.
- **Data.** Raw information that has been collected.
- **Methods.** Generic structures of knowledge production.
- **Tools.** Implementation of methods and supports of others domains.

Co-evolution of Knowledge within domains

Description of the Knowledge Framework :

1. Any scientific knowledge construction on a complex system can be understood as a perspective, decomposed into knowledge domains.
2. Contents within domains *coevolve* [Holland, 2012] between themselves and with other elements of the perspective (including cognitive agents and the purpose).
3. It implies weak emergence [Bedau, 2002] what is consistent with the existence of bodies of knowledge.

Illustration of interactions between domains



Application : Engineering the Metropolitan

Table: Illustration of Knowledge Framework Application

Engineering Issue	Knowledge Domains	Transferability	References
Autonomous Transportation	Empirical, Modeling	Integrated Modeling	[Belmonte et al., 2008]
Innovative Modeling	Modeling, Methods	Method development	[Balbo et al., 2016]
Functional Requirements	Empirical, Tools	Ergonomic tools	[Foot, 2005]
Societal Adaptation	Theoretical, Empirical	Stakeholders involvment	[Foot, 1994], [Hatchuel et al., 1988]
Technical Requirements	Empirical, Modeling	Integrated Modeling	[Moreno Regan, 2016]

Application

$\rightarrow$ Sounds like a generic framework, but as it arises from the structure of complex knowledge itself, is anchored within reflexivity and therefore aimed at a direct application.

$\rightarrow$ Different levels of integration make it particularly suited to study Complex Systems. Specifications or targeted application guidelines would decrease integration ?

Developments

→ Towards a formalisation : perspectives as dataflow machines [Golden et al., 2012] with an ontology [Livet et al., 2010] ; canonic decomposition of ontologies with emergence structure, condition with correspondance with the canonic decomposition of the machine to be investigated.

→ Towards a quantification : applying coupled semantic and citation networks analysis [?], empirical investigation of knowledge domains co-evolutionnary dynamics within a targeted corpus.

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