

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

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Soutenance de Thèse

Institut des Systèmes Complèxes

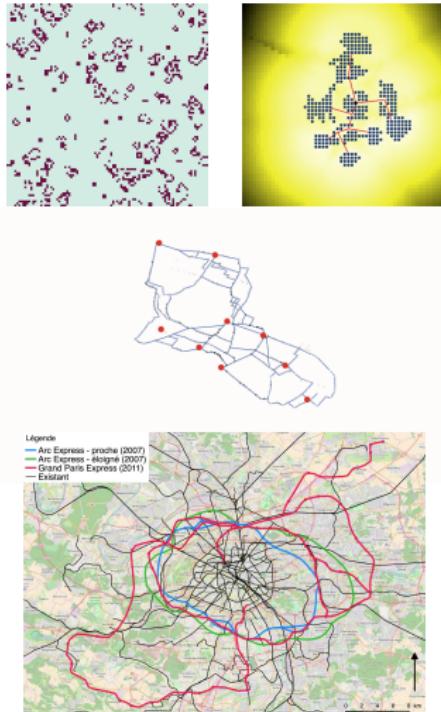
Lundi 11 juin 2018

Une approche originale

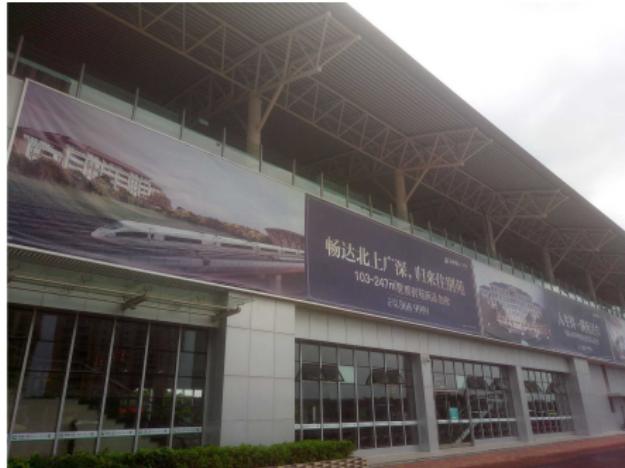
Parcours personnel

- 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

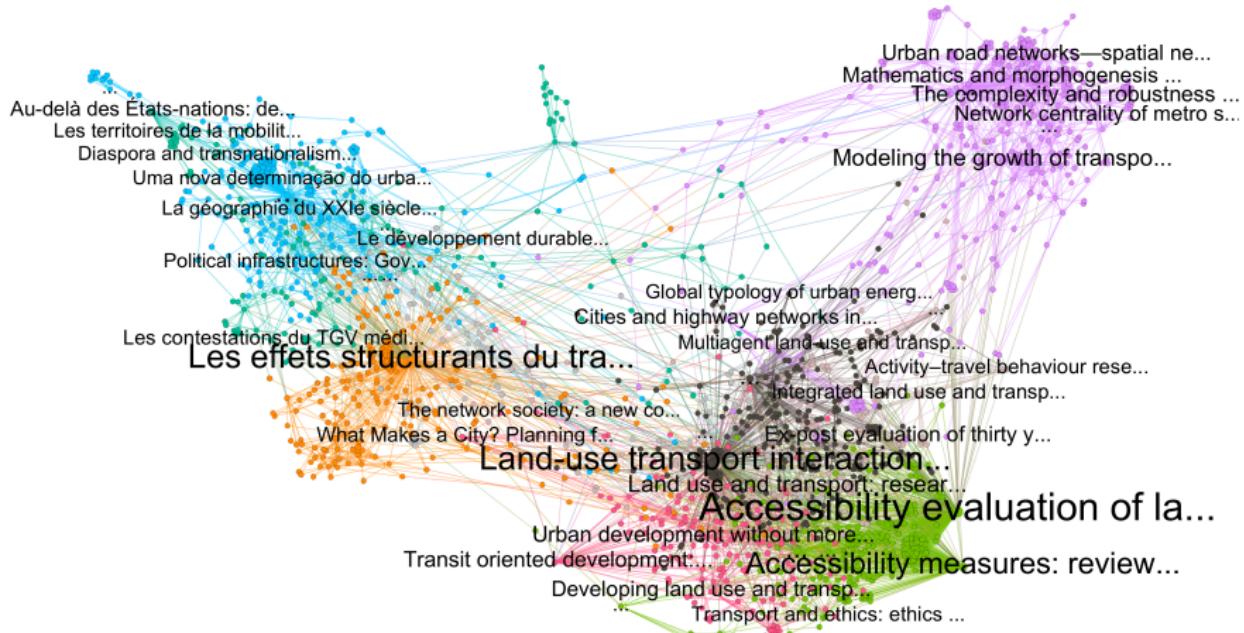
Des dynamiques *co-évolutives* entre réseaux de transport et territoires suggérées par de nombreux travaux (Théorie Evolutive des Villes)

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 :

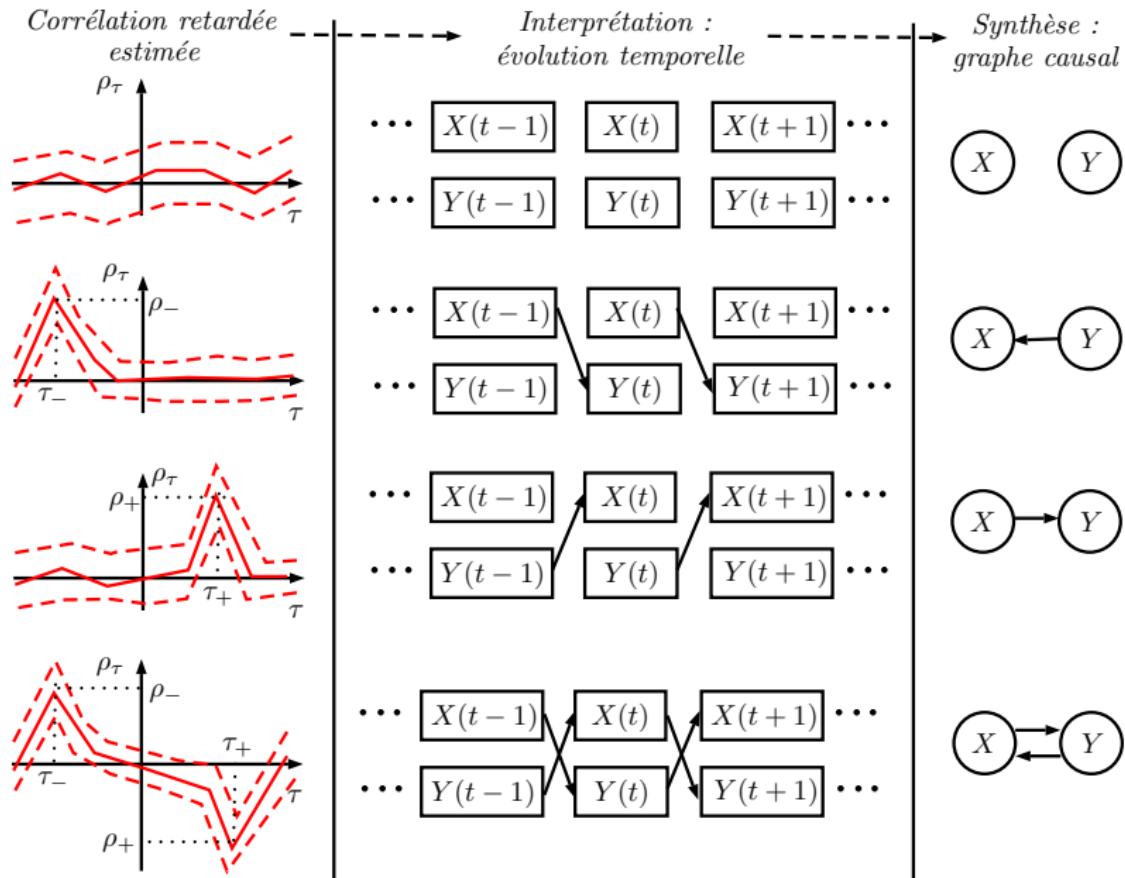
Une définition de la co-évolution à trois niveaux :

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

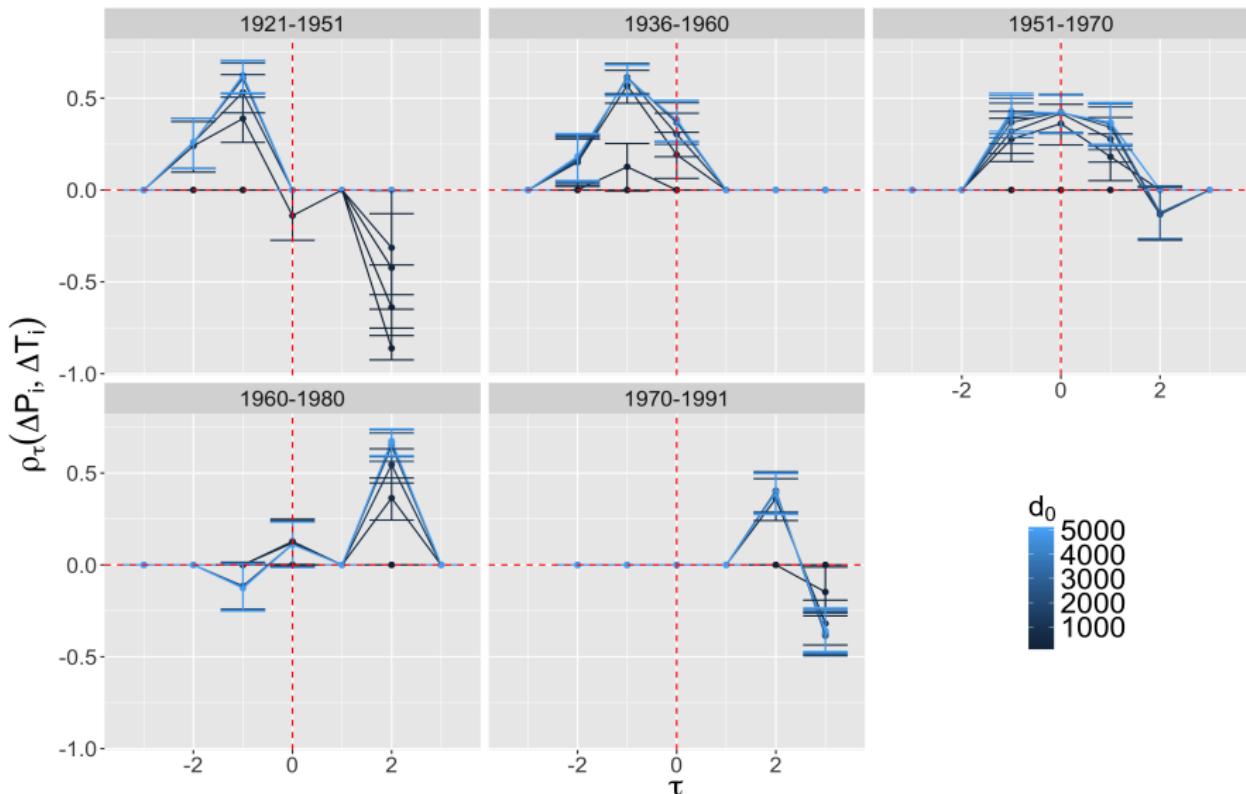
Entrées :

- 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

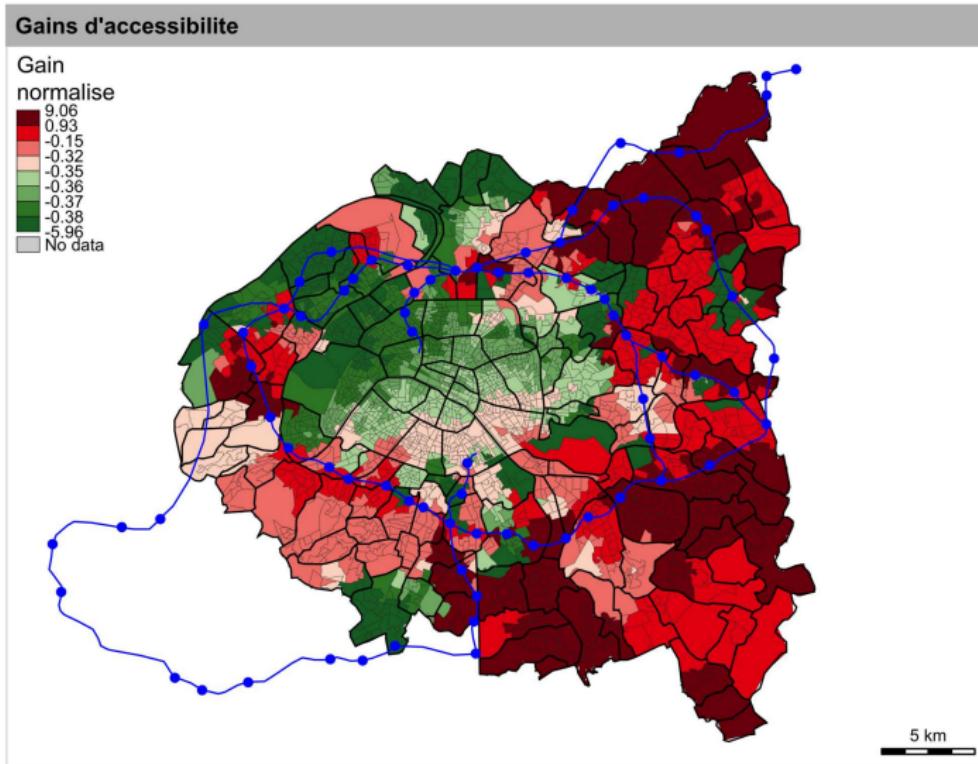


Des observations empiriques contrastées



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

Modèles macroscopiques

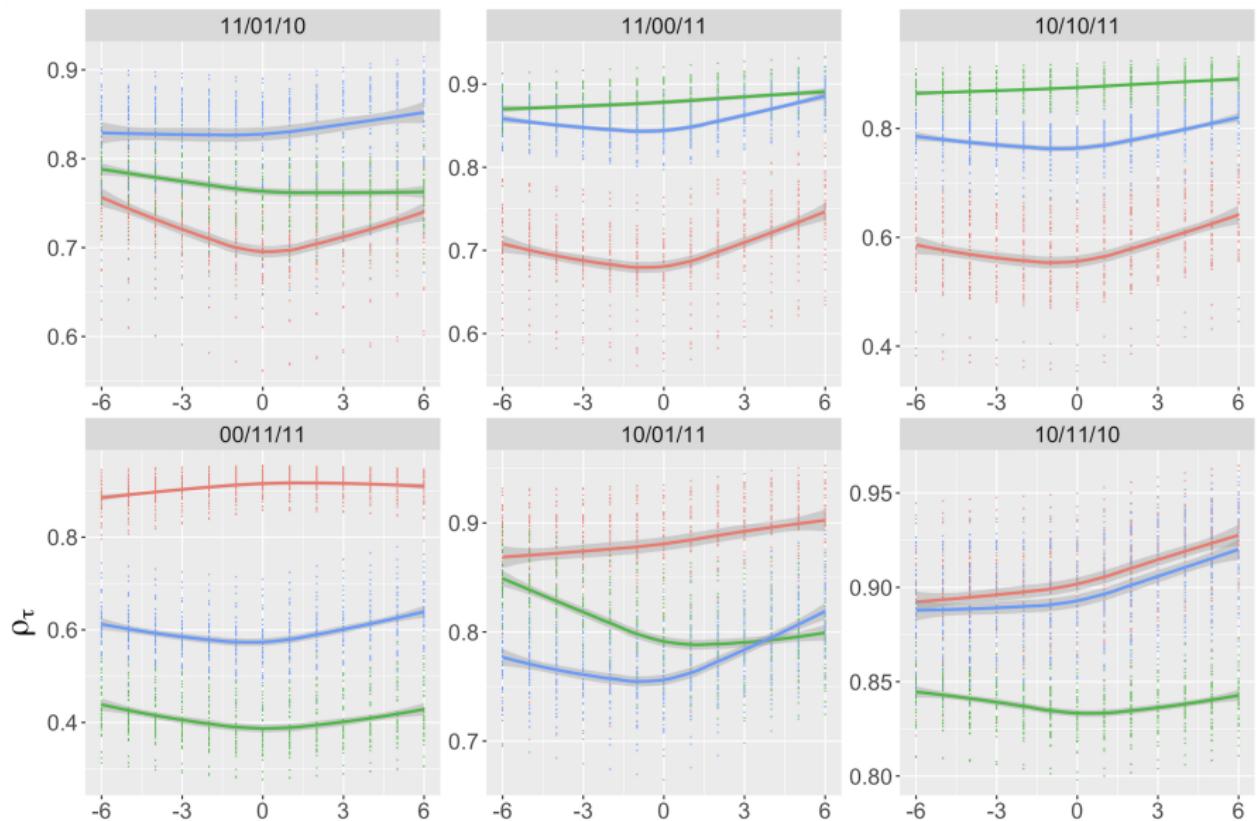
Famille de modèles d'interaction dans un système de villes, basés sur les flux entre villes, incluant effets directs des flux, rétroactions par les flux traversés, rétroactions sur la vitesse du réseau.

Application 1 :

Effets de réseau robustes au surapprentissage 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

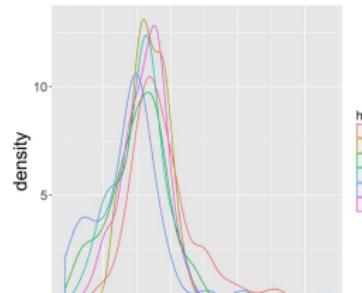
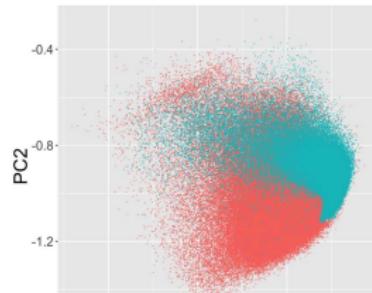
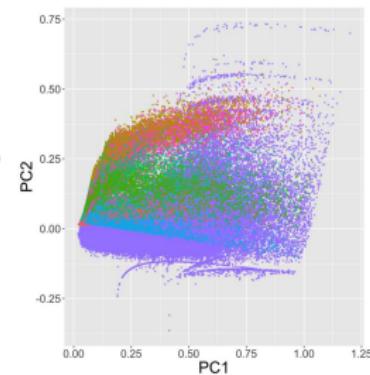
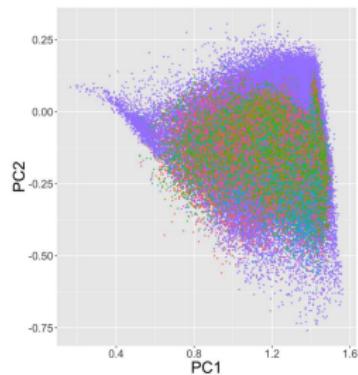
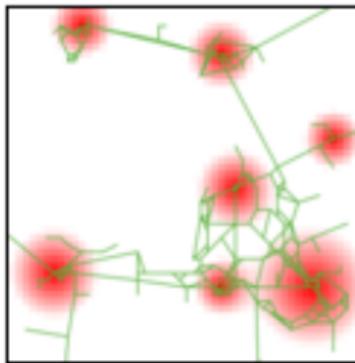


Multiples régimes mis en évidence dans des configurations synthétiques

Modèles mésoscopiques

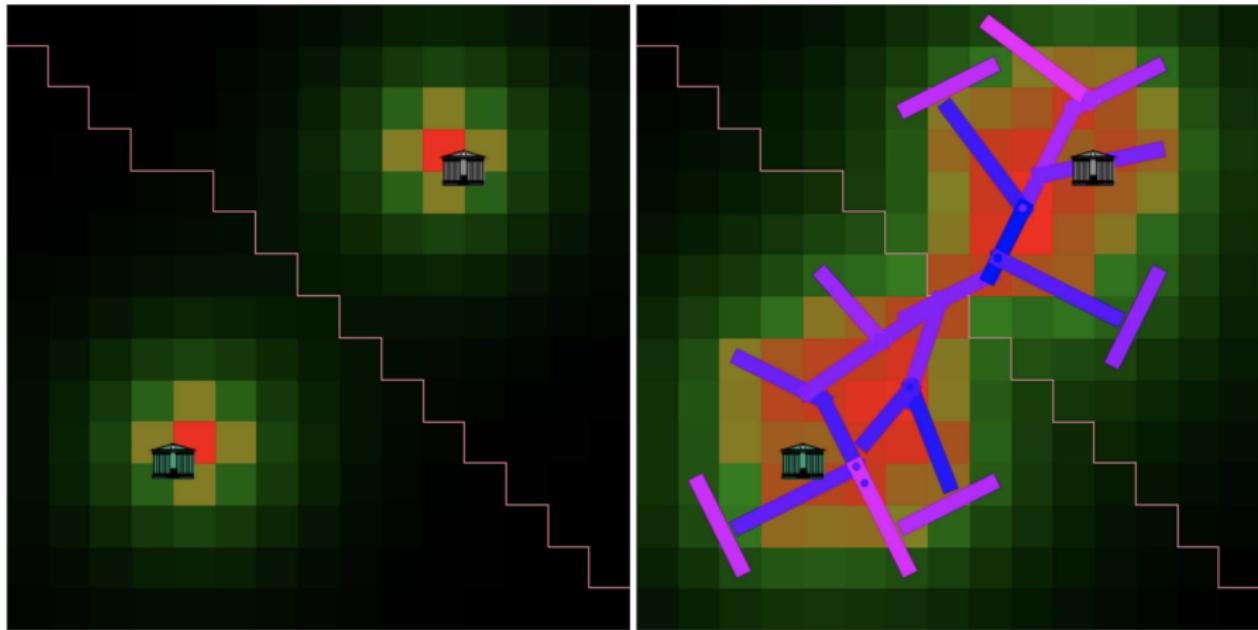
Relation entre forme et fonction (morphogenèse) comme paradigme pour modéliser la co-évolution à l'échelle mésoscopique.

Un modèle de morphogenèse par réaction-diffusion et multi-modélisation de la croissance du réseau

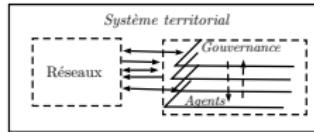


Modèles mésoscopiques

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

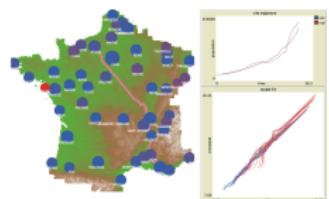
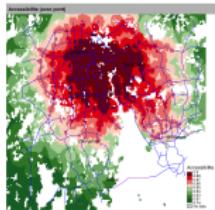


Lecture par les domaines de connaissance

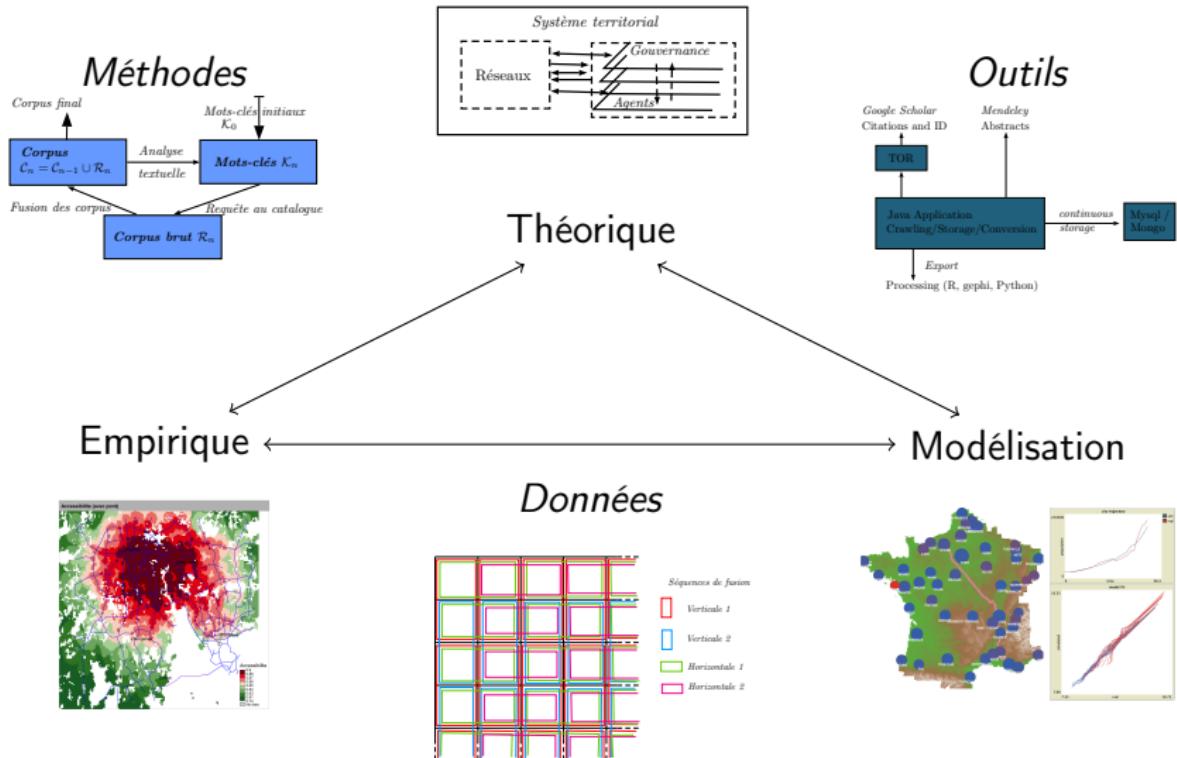


Théorique

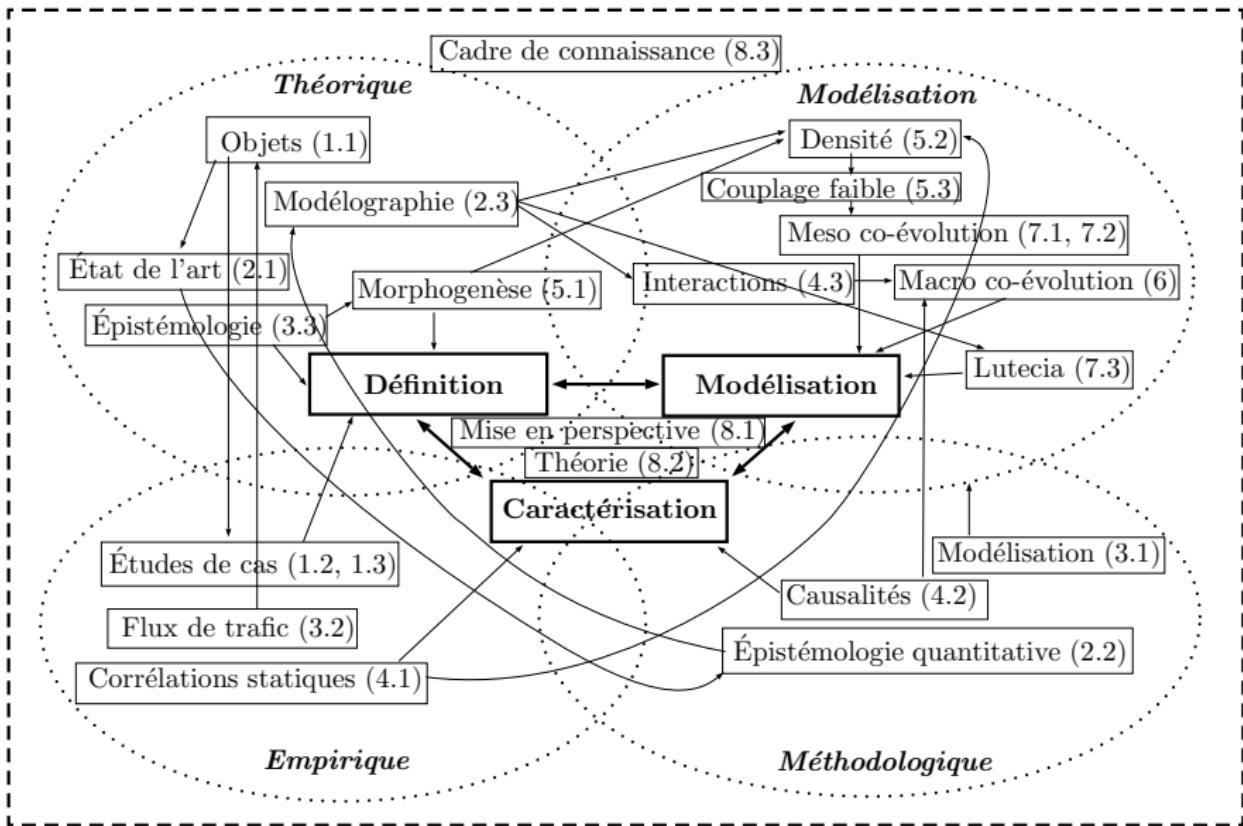
Empirique ← → Modélisation



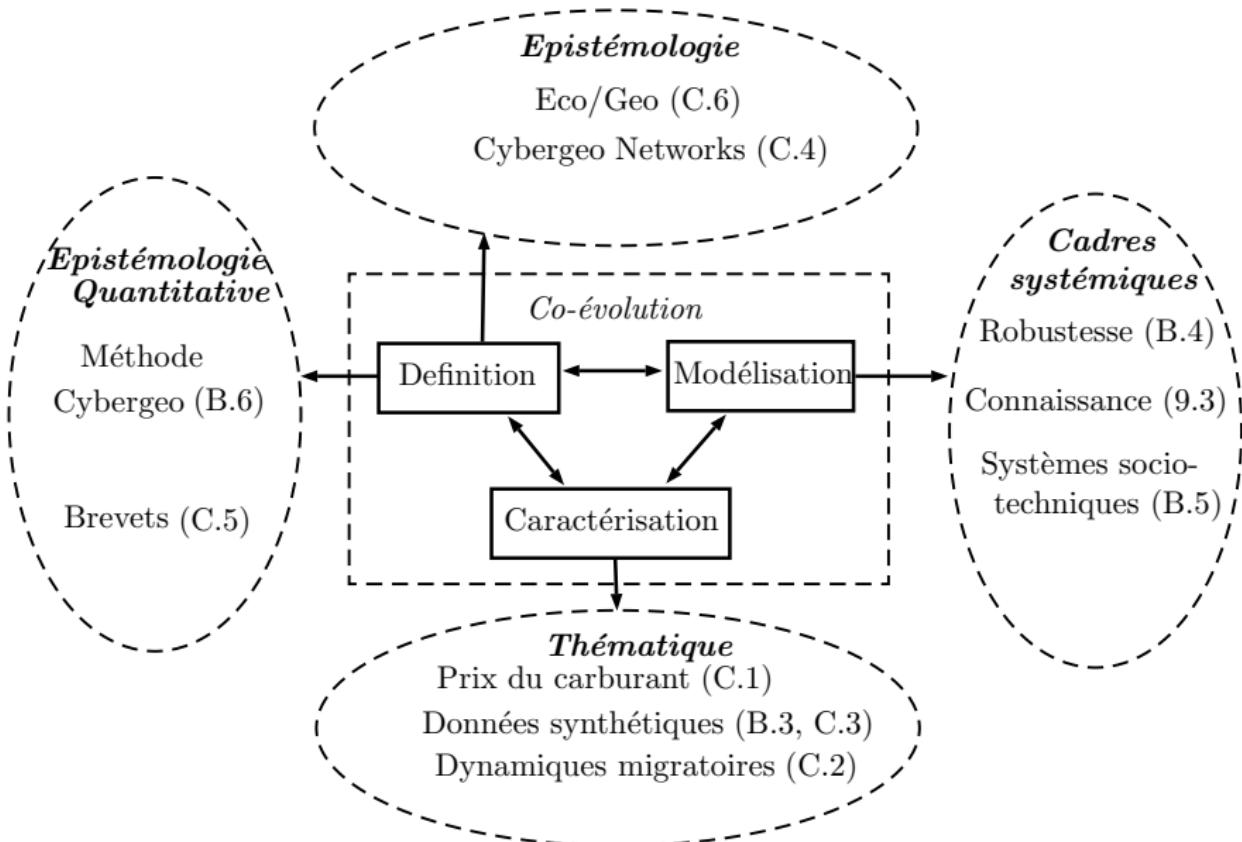
Lecture par les domaines de connaissance



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

What is Morphogenesis ?

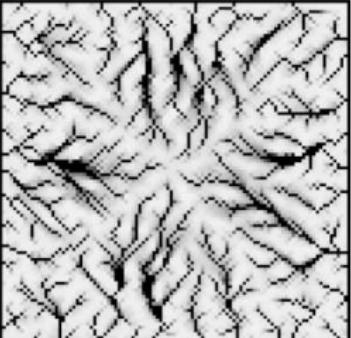
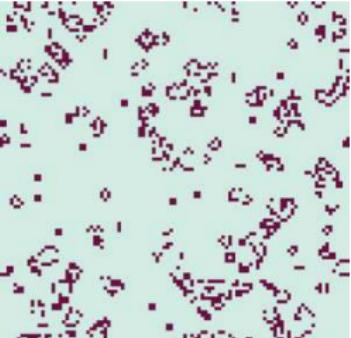
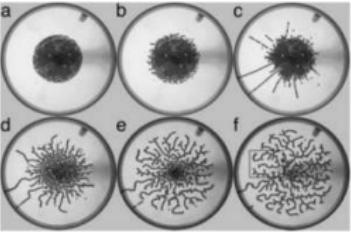
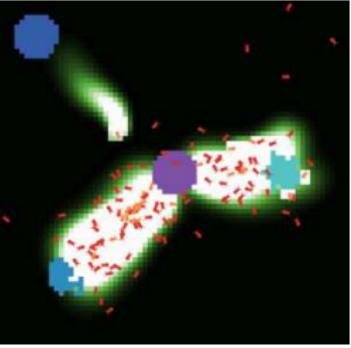
Morphogenesis (*Oxford dictionary*)

- 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 [?]
- 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	Engineered
Non Functional			
Functional			

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

Defining Morphogenesis

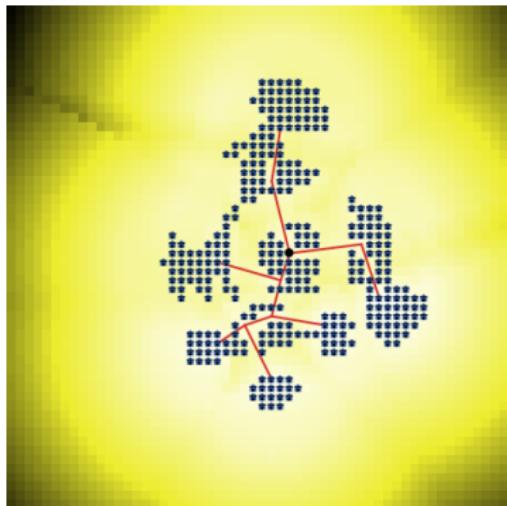
Construction of an interdisciplinary definition in [?] Meta-epistemological

framework of imbricated notions: Self-organization \supseteq Morphogenesis
 \supseteq Autopoiesis \supseteq 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]*

Which models for Urban Morphogenesis ?



Example: a basic hybrid model based on elementary processes for density and network [?]

→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 parsimonious, stylized models: modeling as a tool to understand processes

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

A simple Reaction-diffusion model

→ 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 [?] → 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

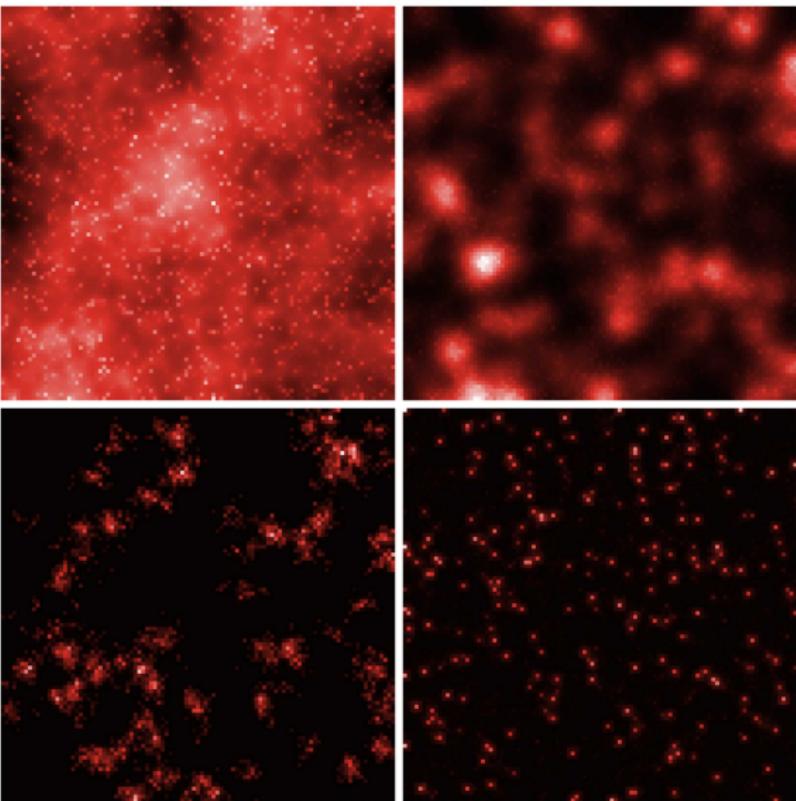
→ Grid world with cell populations $(P_i(t))_{1 \leq i \leq N^2}$. → At each time step:

- 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 .

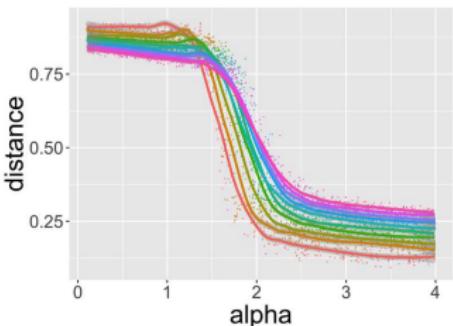
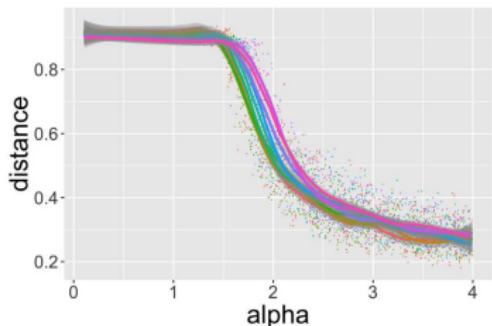
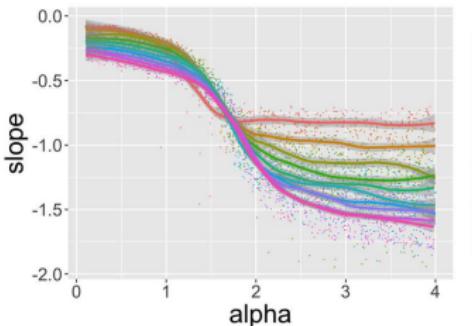
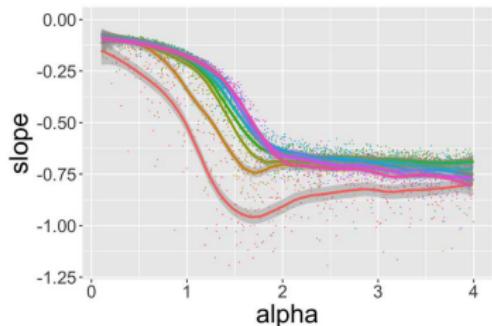
→ Output measured by morphological indicators: Moran index, average distance, rank-size hierarchy, entropy.

Generating Population Distributions



Examples of generated territorial shapes

Model behavior



beta
[3.67e-06, 0.05]
(0.05, 0.1]
(0.1, 0.15]
(0.15, 0.2]
(0.2, 0.25]
(0.25, 0.3]
(0.3, 0.35]
(0.35, 0.4]
(0.4, 0.45]
(0.45, 0.5]

beta
[3.67e-06, 0.05]
(0.05, 0.1]
(0.1, 0.15]
(0.15, 0.2]
(0.2, 0.25]
(0.25, 0.3]
(0.3, 0.35]
(0.35, 0.4]
(0.4, 0.45]
(0.45, 0.5]

Phase transitions of indicators unveiled by exploration of the parameter space (80000 parameter points, 10 repetitions each)

Path-dependence and frozen accidents

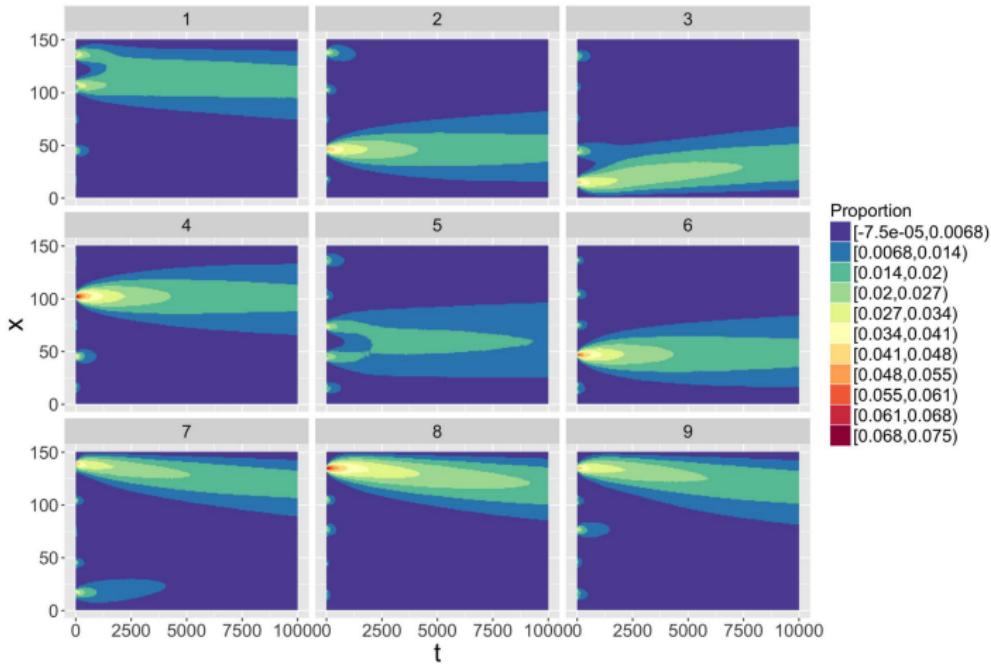
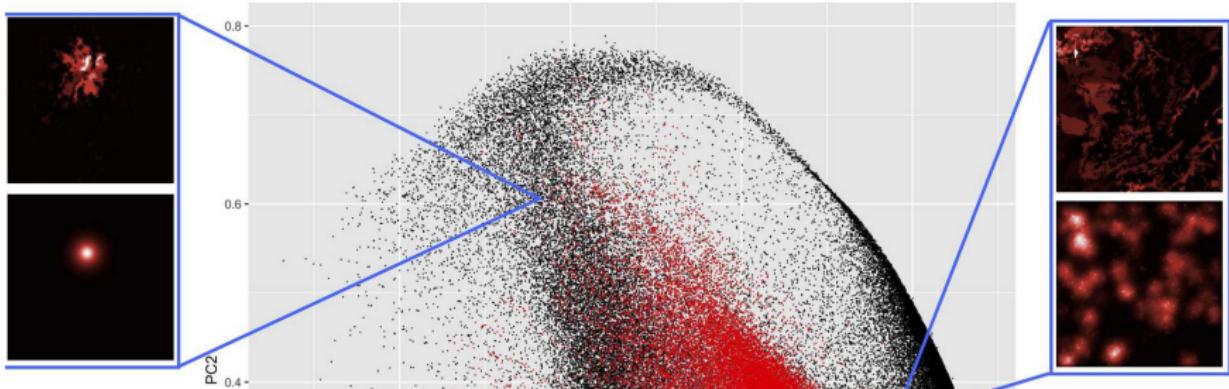
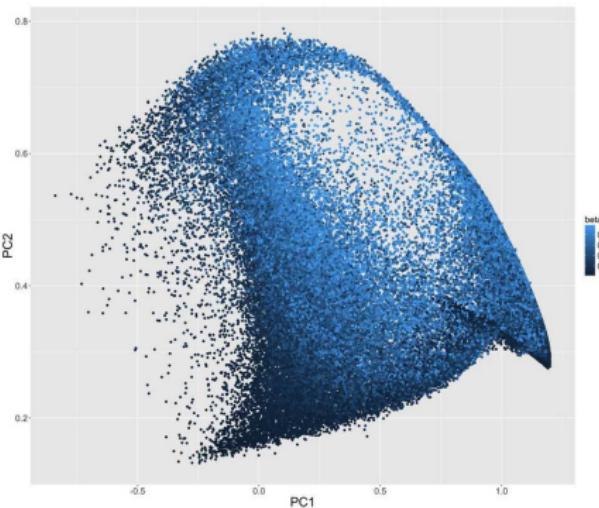
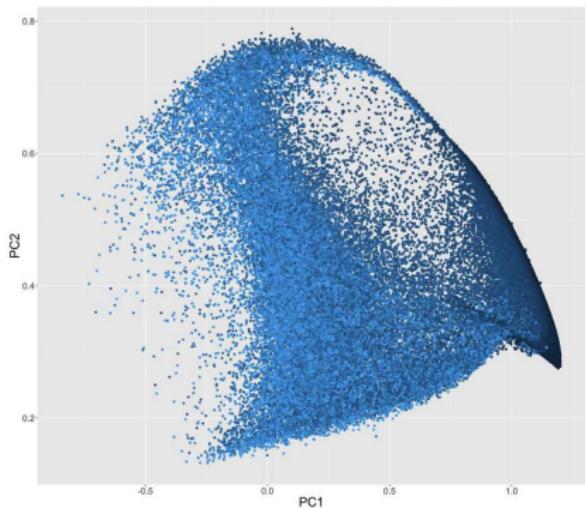


Illustration of path-dependence in a simplified one-dimensional version of the model: cell trajectories in time for 9 independent repetitions from the same initial configuration.

Empirical Data for Calibration

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

Model Calibration



Including more complex processes ?

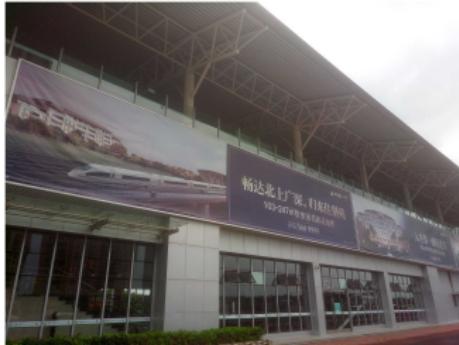
Which ontology to include more complex functional properties ? →

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



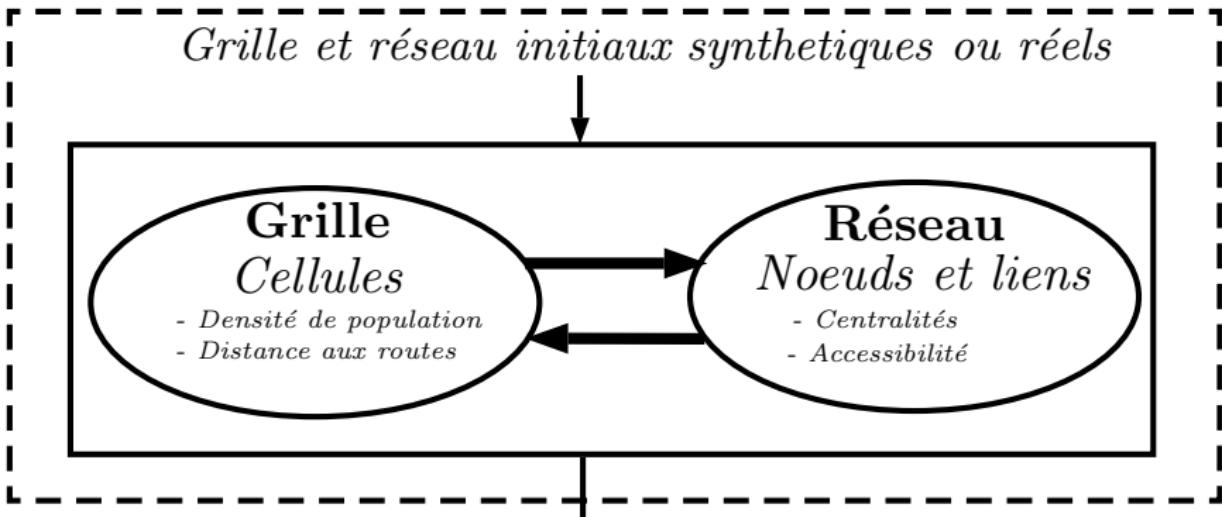
Expanding HSR network in China and ambiguous effects (Source : fieldwork survey)

A Morphogenesis Model of co-evolution

- Coupled grid population distribution and vector transportation network, following the core of [?]
- 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

Intermediate stage for biological network generation

Results : non-stationary gravity 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 $M_k^* = M_k[\alpha_k^*]$ computational models heuristically fitted to the same dataset. With $S_k \simeq M_k^*$, we suppose that $\Delta D_{KL}(M_k^*, M_{k'}^*) \simeq \Delta D_{KL}(S_k, S_{k'})$ 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 ($r_0 = 0.0128, w_G = 1.30e - 4, \gamma_G = 3.80, d_G = 8.4e14, w_N = 0.603, \gamma_N = 1.148, d_N = 7.474$)

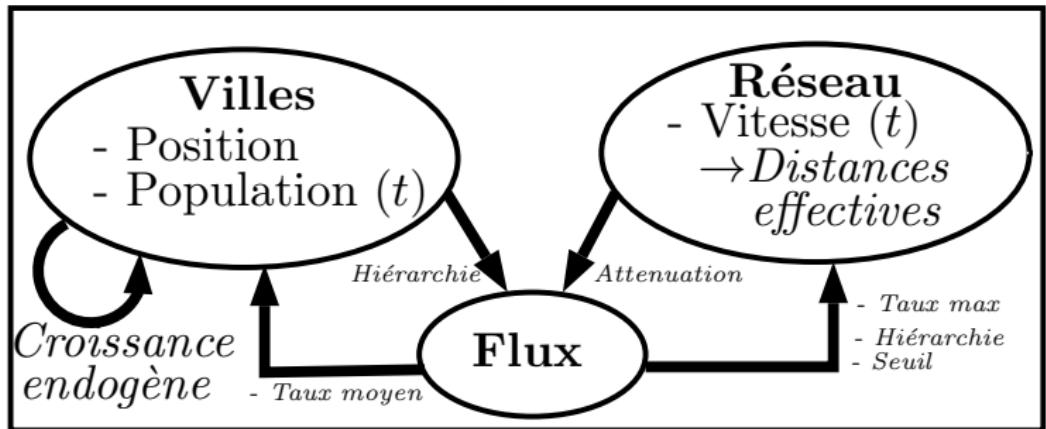
Empirical AIC values

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

Configuration initiale : Système de villes réel ou synthétique



Indicateurs: Hiérarchie, Entropie, Corrélations, Trajectoires diversité and complexité, ajustement données réelles

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

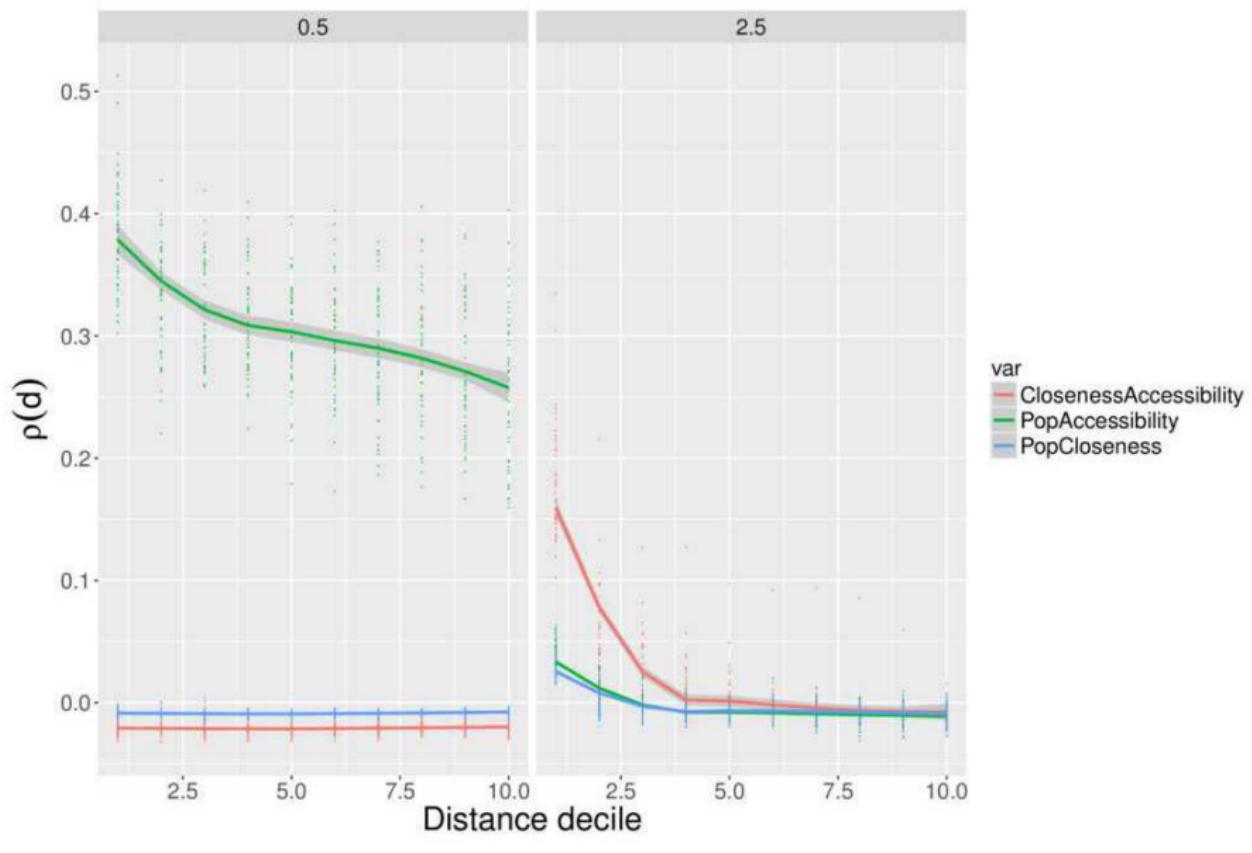
- Hierarchy, Entropy, Summary statistics in time
- Initial-final rank correlation (changes in the hierarchy) for variable X : $\rho [X_i(t=0), X_i(t=t_f)]$
- Trajectory diversity for variable X : with $\tilde{X}_i(t) \in [0; 1]$ rescaled trajectories,

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

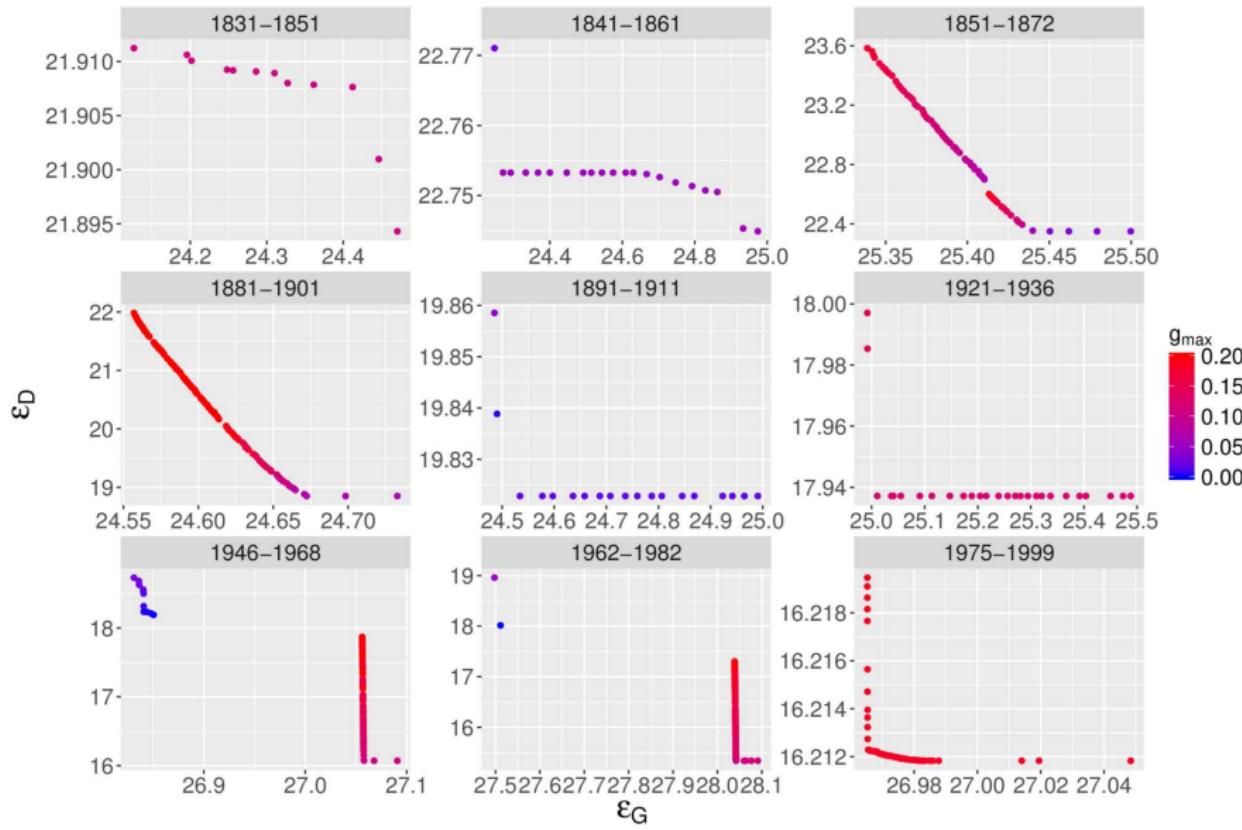
- Average trajectory complexity (number of inflexion points)
- Pearson correlations conditionally to distance
 $\hat{\rho}_d [(X(\vec{x}_1, Y(\vec{x}_2)) || |\vec{x}_1 - \vec{x}_2| \sim d]$
- Lagged return correlations $\hat{\rho}_\tau [\Delta X(t), \Delta Y(t - \tau)]$ (Granger causality)

Model Behavior

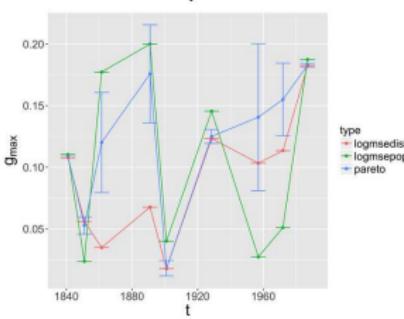
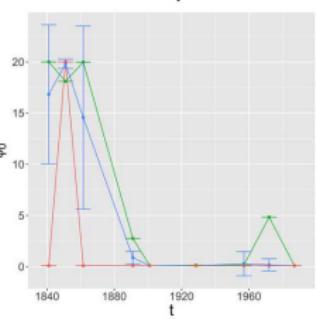
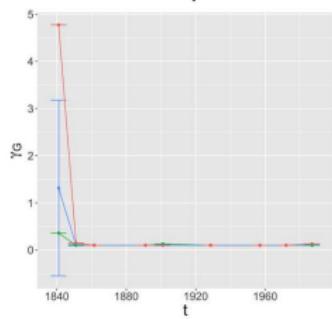
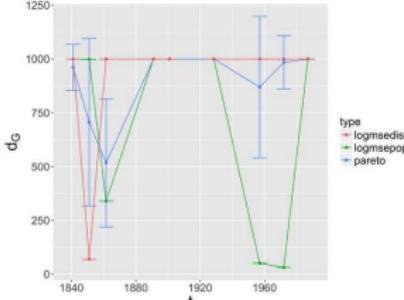
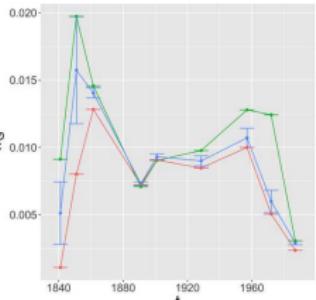
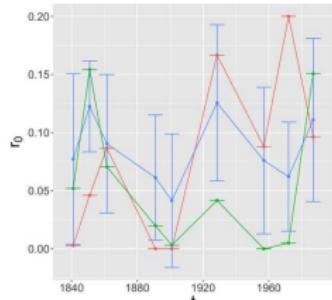
Correlation Patterns



Calibration

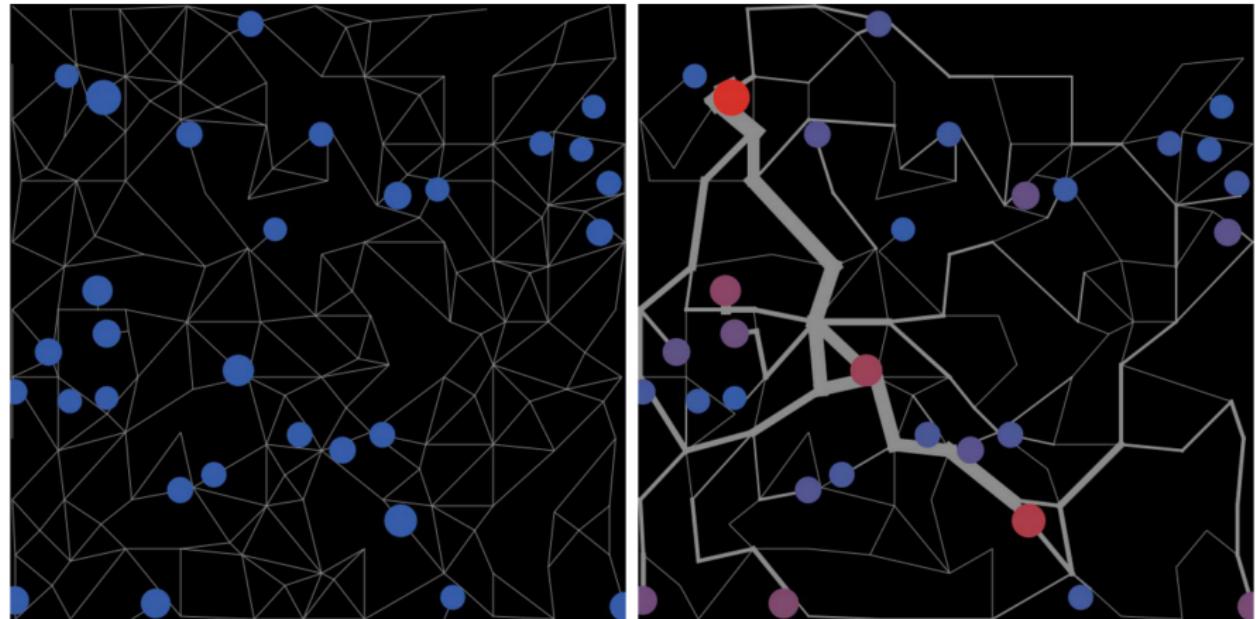


Calibration: Parameters



Model Specification: Physical Network

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



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

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.
-  Batty, M. (1991). Generating urban forms from diffusive growth. *Environment and Planning A*, 23(4):511–544.
-  Bedau, M. (2002). Downward causation and the autonomy of weak emergence. *Principia: an international journal of epistemology*, 6(1):5–50.
-  Doursat, R., Sayama, H., and Michel, O. (2012). *Morphogenetic engineering: toward programmable complex systems*. Springer.

References II



Dupuy, G. (1987).

Vers une théorie territoriale des réseaux: une application au transport urbain.

In *Annales de Géographie*, pages 658–679. JSTOR.



Fujita, M. and Thisse, J.-F. (1996).

Economics of agglomeration.

Journal of the Japanese and international economies, 10(4):339–378.



Jun, J. K. and Hübler, A. H. (2005).

Formation and structure of ramified charge transportation networks in an electromechanical system.

Proceedings of the National Academy of Sciences of the United States of America, 102(3):536–540.

References III



Sayama, H. (2007).

Decentralized control and interactive design methods for large-scale heterogeneous self-organizing swarms.

In *European Conference on Artificial Life*, pages 675–684. Springer.



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.