

# Towards a Theory of Co-evolutive Networked Territorial Systems: Insights from Transportation Governance Modeling in Pearl River Delta, China

J. Raimbault<sup>1,2</sup>

`juste.raimbault@polytechnique.edu`

<sup>1</sup>UMR CNRS 8504 Géographie-cités

<sup>2</sup>UMR-T IFSTTAR 9403 LVMT

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# Complex Urban Systems

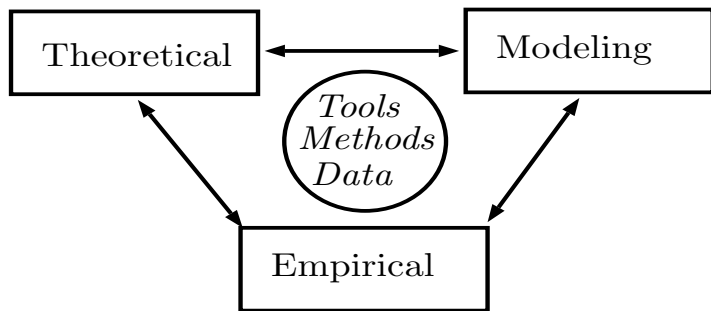
Source : Wikipedia

# Complex Systems Approaches in Science

- Failure of reductionism already highlighted by Anderson in 1972 [Anderson, 1972]
- Yet few domains with Integrative Theories
- Even physics begins to realize the potential of this “New Kind of Science [Wolfram, 2002] : Quantum coherence paradox solved through computational complexity [] ; Very recent theory of emergent gravity solves Dark Matter issue

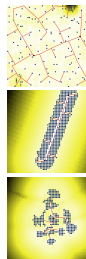
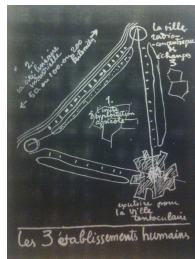
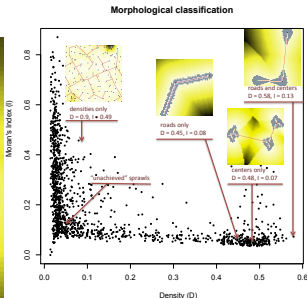
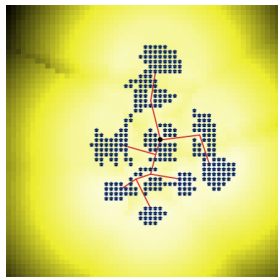
# Theoretical and Quantitative Geography

*Extended framework for TQG [Livet et al., 2010]*



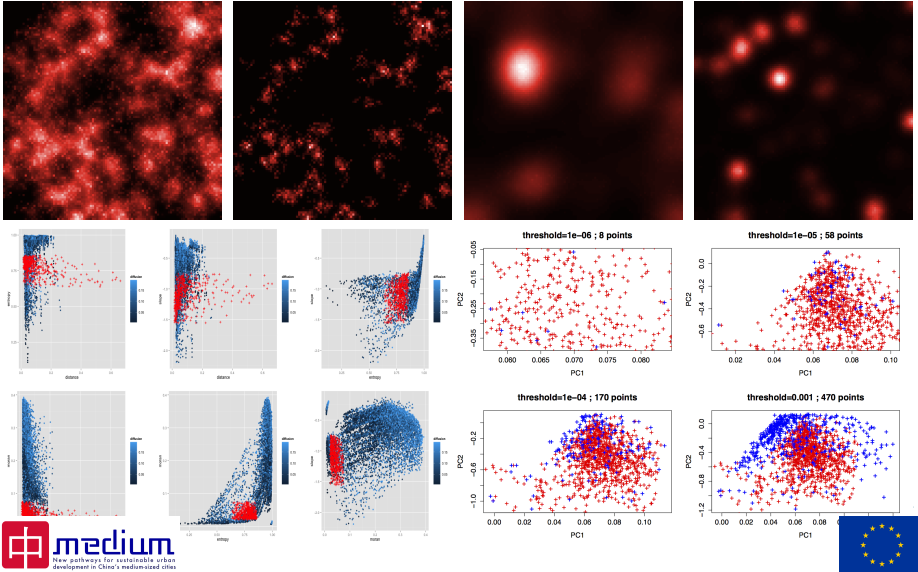
# Meso-scale Coupled Growth

Simple co-evolutionary dynamics produce stylized urban forms at a mesoscopic scale [Raimbault et al., 2014]



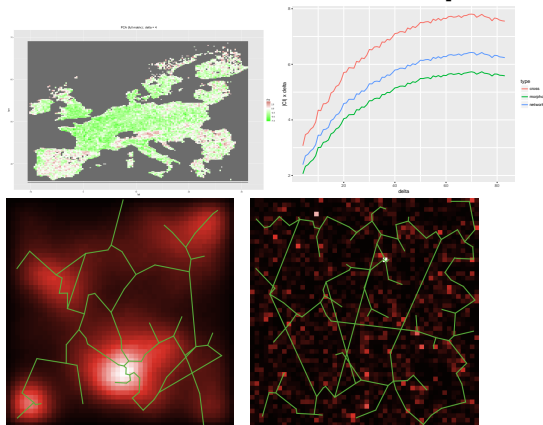
# Aggregation-diffusion Urban Growth

Evidence of autonomous Morphogenetic processes : morphological calibration of an Aggregation-diffusion growth model



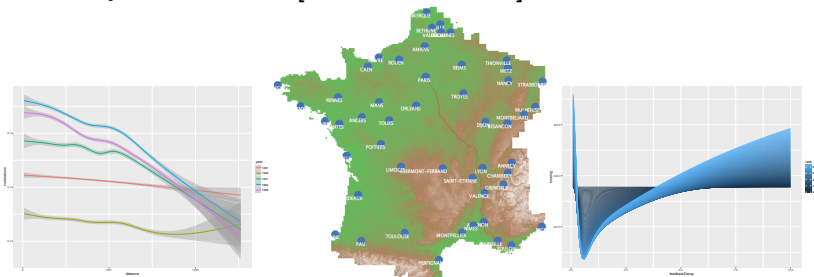
# Coupled Growth and Correlations

Spatial non-stationarity of correlation matrix between urban morphology and network topology [Raimbault, 2016a] ; coupled growth model yield a large range of potential correlations [Raimbault, 2016b]



# Macro-scale Growth and Network Necessity

Macro-scale population growth model reveals physical network effects in French System of Cities [Raimbault, 2016c]





# Theory : Pillars

- ① *Networked Human Territories* → Raffestin approach to territory combined with Dupuy theory of networks.
- ② *Evolutionary Urban Theory* → City Systems as complex Adaptive systems, applied to human settlements in general and thus territorial systems.
- ③ *Urban Morphogenesis* → Morphogenesis as autonomous rules to explain growth of urban form. Used as the provider of modular decompositions.
- ④ *Boundaries and Co-evolution* → Co-evolution as the existence of *niche*, consequence of boundary patterns.

# Theory : Specification

- Previous def. of territorial systems
- Modular decomposition and stationarity : existence of scales
- Feedback loops between and inside scales yield weak emergence, thus complexity
- Morphogenesis gives modular decomposition and co-evolution
- **Main assumption.** Necessity of Networks : networks are necessary component of co-evolutive niches.

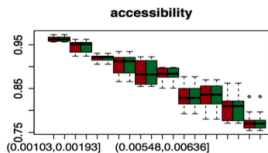
# The LUTETIA Model : Rationale

# The LUTETIA Model : Structure

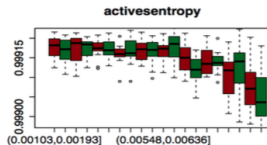
# Governance Modeling

# Model Output : Examples

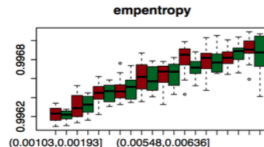
# Model Exploration : Examples



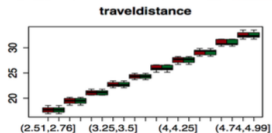
Lambda Accessibility



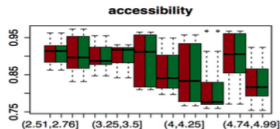
Lambda Accessibility



Lambda Accessibility



Network speed



Network speed

## Application to Delta Pearl River Mega-city Region



# Application to DPR

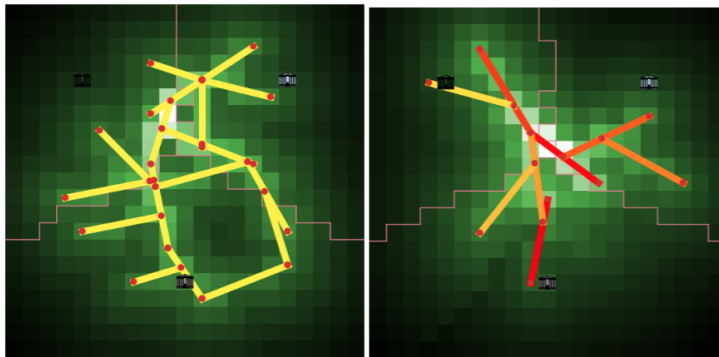


# Conclusion

- All code and data available at <https://github.com/JusteRaimbault/CityNetwork/tree/master/Models> in general ;

## Reserve Slides

# Long Time Limits for Transportation Networks



# Governance Game Specification

Mixed Nash equilibrium probability :

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

Discrete Choice model :

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

then

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

## Lutetia : default parameter values

$$A_{max} = E_{max} = 500; r_A = 1; r_E = 0.8; \gamma_E = 0.9; \gamma_A = 0.65; \beta_I = 1.8; \lambda = 0.005; r_0 = 2$$

$$N_{expl} = 25; I = 0.001; J = 0.0001; v = 5; E_{ext}(t_0) = 3E_{max}; t_f = 4$$

# Lutetia : Land-use Initialization

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

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



# Lutetia : Transportation

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

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

Trajectories then attributed by effective shortest path, and corresponding congestion  $c$  obtained (no Wardrop equilibrium).

Speed of network given by BPR function  $v(c) = v_0 \left(1 - \frac{c}{\kappa}\right)^{\gamma_c}$ . Congestion not used in current studies (infinite capacity  $\kappa$ ).

## Lutetia : Land-use Evolution

Land-Use module : we assume that residential/employments relocations are at equilibrium at the time scale of a tick, that corresponds to transportation infrastructure evolution time scale which is much larger (Bretagnolle, 2009).

We take a Cobb-douglas function for utilities of actives/employments at a given cell

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

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

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

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

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

# Lutetia : Network Distance Computation

## Effective distances computation

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

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