A Macro-scale Model of Co-evolution for Cities and Transportation Networks

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Spatio-temporal Behavior in Complex Urban Systems

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medium
New pathways for sustainable urban development in China's medium-sized cities

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(Left) Hong-Kong-Zhuhai-Macao Bridge ; (Right) Near XiaoLan station

Source - Left : http://www.hzmb.hk ; Right : Photo by author

Co-evolution

→ Co-evolution between networks and territories shown empirically [Bretagnolle, 2009]
→ Models endogeneizing it are very rare ; possible explanation : interdisciplinary question and compartmentalization of disciplines [Raimbault, 2015]
→ Diverse precursor approaches: LUTI models [Wegener and Fürst, 2004]; Network Growth (Geometrical [Courtat et al., 2011], Economical [Xie and Levinson, 2009], Biological [Tero et al., 2010])

Multidisciplinary citation network for studies of relations between networks and territories

Towards Models of Co-evolution

Why model it ? *Insights into dynamical processes in System of Cities ; Perspective of Operational Models*

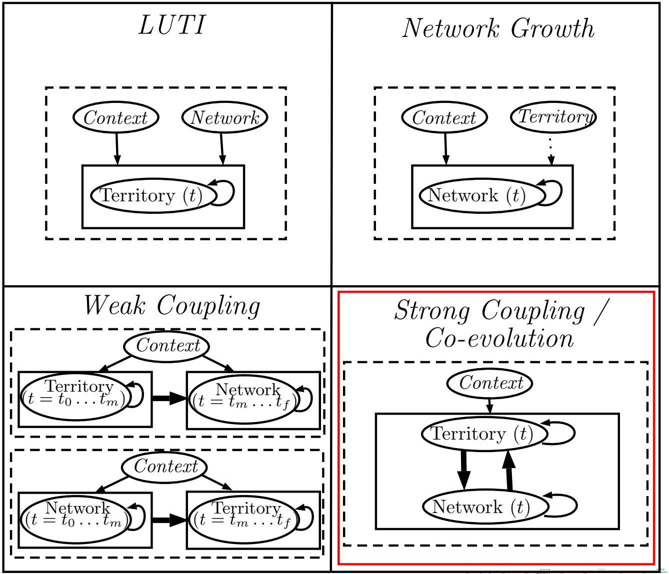
Several possible Scales and Ontologies

- Micro-scale: mostly chaotic regimes, too precise for reasonable models (shown for traffic by [Raimbault, 2017a])
- Meso-scale: Urban Form, Accessibility and Network Shape [Raimbault, 2017b] ; Transportation Governance in Mega-city Regions [Le Néchet and Raimbault, 2015]
- Macro-scale: SimpopNet model [Schmitt, 2014]

Research Objective

→ *Introduce a parsimonious but modular model of co-evolution of cities and networks at the scale of a System of Cities.*

Submodel coupling



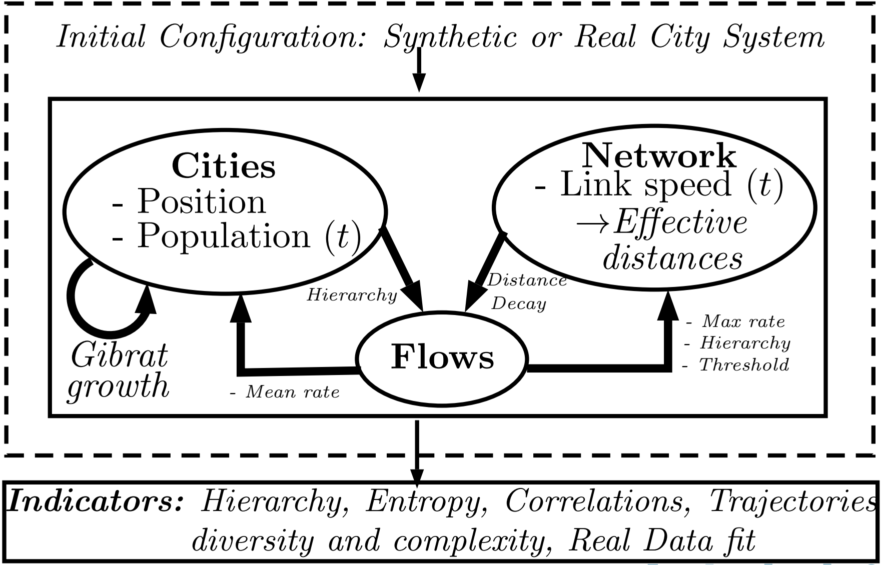
Model : Rationale

Interaction between cities at different orders are main drivers of their growth

- Cities represented by their population follow deterministic growth based on self growth (Gibrat) and interactions with other cities (similar to [Favaro and Pumain, 2011], extension of [Raimbault, 2016c]) ; approach of the Evolutive Urban Theory [Pumain, 1997]
- Drivers of network growth are interaction flow demands
- Adjustable network growth scale and stochasticity level

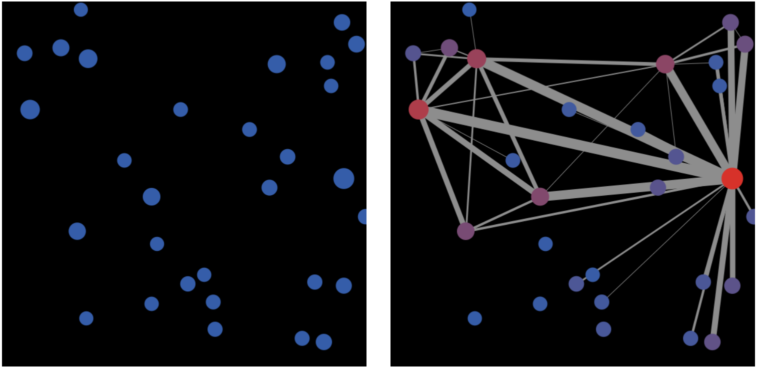
→ Generic for any city system with dynamical population and network data ; tested on synthetic city systems (following Rank-size Zipf's law).

Generic Model



Model Specification : Abstract Network

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

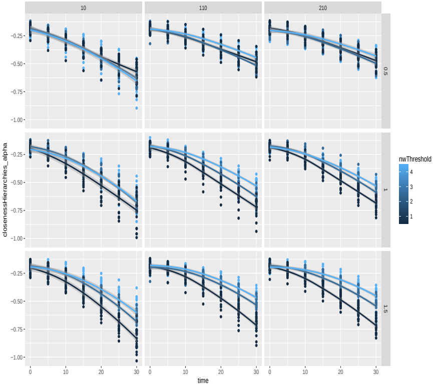


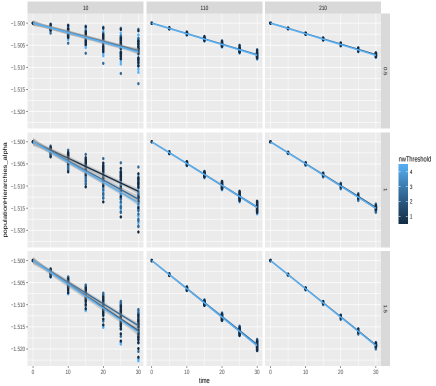
Exemple of run ($t_f = 30$). Level of red gives overall growth and link width flows.

Results: Stylized facts from Model Exploration

Model explored with intensive computation with OpenMole software [Reuillon et al., 2013]

→ *Reinforcement in time of hierarchies for both populations and distances. . .*





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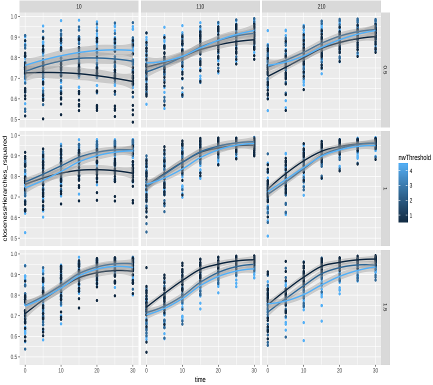
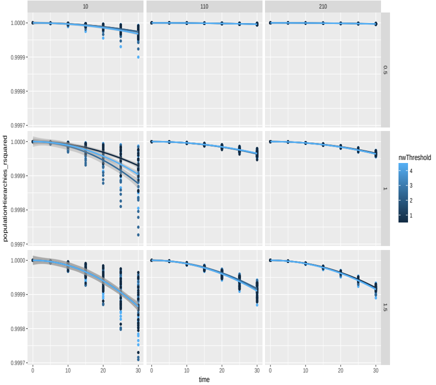
Results

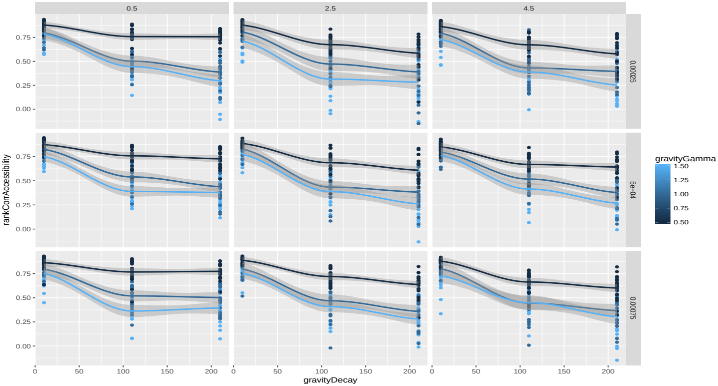
→ *. . . but with inverse deviations from a scaling law.*





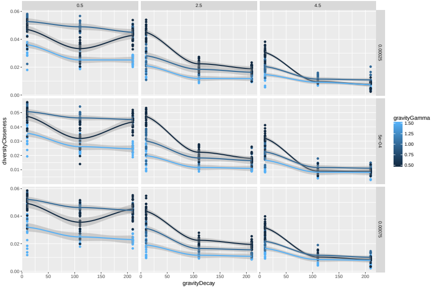
Results

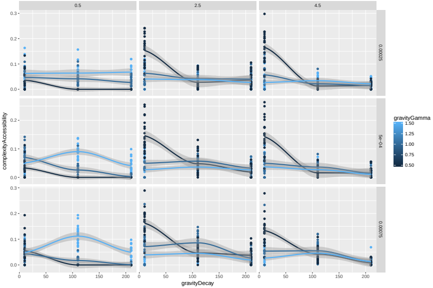
→ *High level of trajectory crossings for accessibilities: change of fate for medium-sized cities*



Results

→ *"Medium" distance interaction ranges yield an optimal regarding equity of distances . . . but is accompanied by a maximal complexity level in a neighboring hierarchy regime.*





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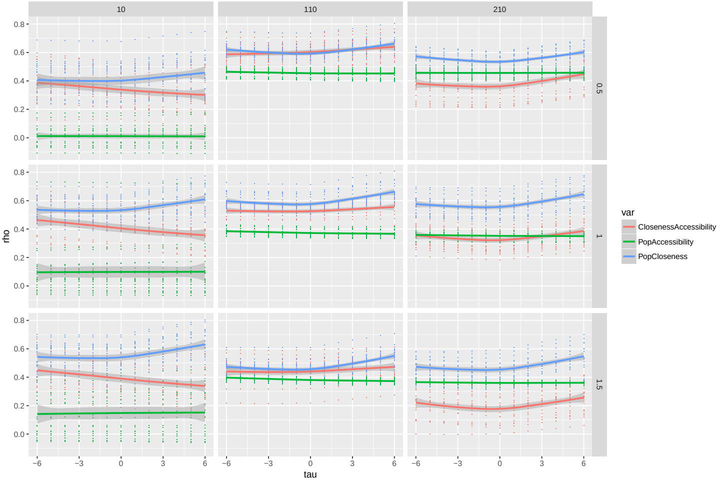
Results

→ *High diversity of lagged correlation regimes ; strong intrication in some cases.*



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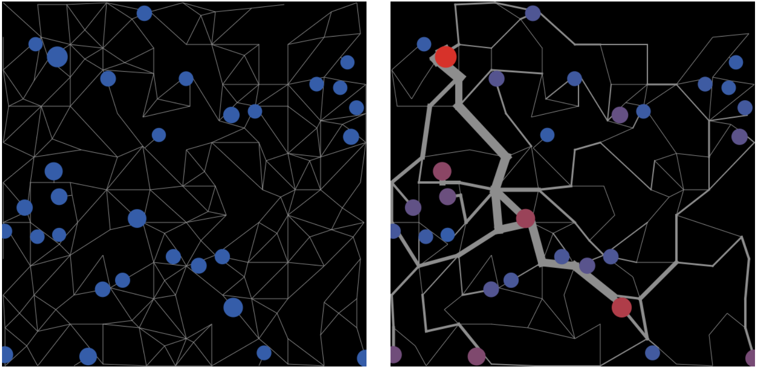
Model Specification: Physical Network

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.*

Further Extensions and Applications

Further Work and Extensions

- Targeted explorations using Genetic Algorithms (e.g. output diversity with PSE [Chérel et al., 2015])
- Potential breakdown / investment network heuristics

Application Case Studies

- French Urban System : Dynamical Railway Network 1850-2000 ; Dynamical Freeways Network (Database in construction)
- Chinese Urban System : High-speed Railway Network 2005-2015
- Comparisons: implication of governance context and planning level on interactions between networks and territories

→ *Does adding co-evolution improve fit on cities populations (correcting for additional parameters) ? How are produced network shapes realistic ?*

Conclusion

→ Very basic co-evolution, i.e. just interplay of cities and distances, without physical real network, already produces diverse regimes and unexpected behavior.

→ Direct applicability of such models ? Especially when applied on real systems, unpredictable bifurcations are the rule - open question of understanding temporal and spatial non-stationarity.

- All code and data available at `https://github.com/JusteRaimbault/CityNetwork/tree/master/Models/MacroCoevol`

Reserve Slides

Evolutive Urban Theory

Definition : *A Geographical Theory aiming at gathering most of known stylized facts on cities and their organisation within territories, in a non-static and out-of-equilibrium perspective, by following them on long time periods and putting an emphasis on structural factors and bifurcations.* [Interview with D. Pumain, 03/2017]

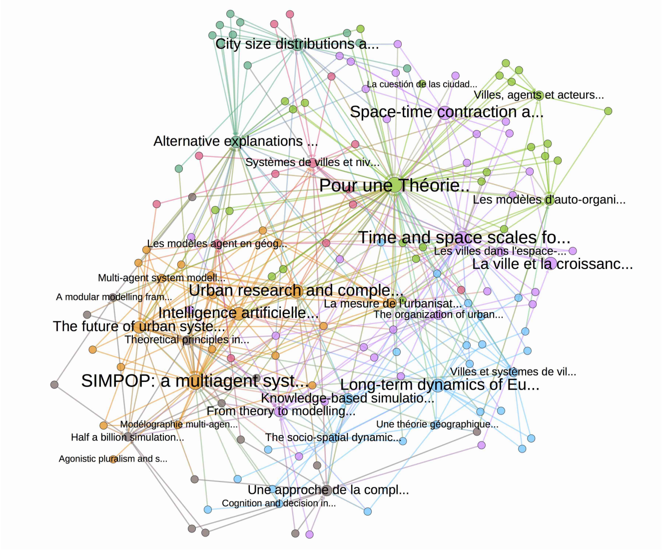
→ Seminal works : theoretical manifest [Pumain, 1997] and modeling [Sanders et al., 1

→ Reciprocal relationship with computer scientists [Interview with R. Reuillon, 04/2017] : OpenMole [Reuillon et al., 2013] et Meta-heuristics [Chérel et al., 2015]

→ Diverse and deep fieldworks ([Swerts, 2013] [Baffi, 2016]), integrated modeling ([Cottineau, 2014] [Schmitt, 2014]), epistemology [Rey-Coyrehourcq, 2015]

→ Theoretical Frame and Methods to renew Ontologies : e.g. Definition of the city [Interview with C. Cottineau, 05/2017]

Evolutive Urban Theory



Citation Network of core references of the Evolutive Urban Theory

Model Formalization : 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 $\vec{\mu}(t+1) = f(\vec{\mu}(t))$

Model Formalization : Interactions

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 of i to the shortest path between k, l

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,

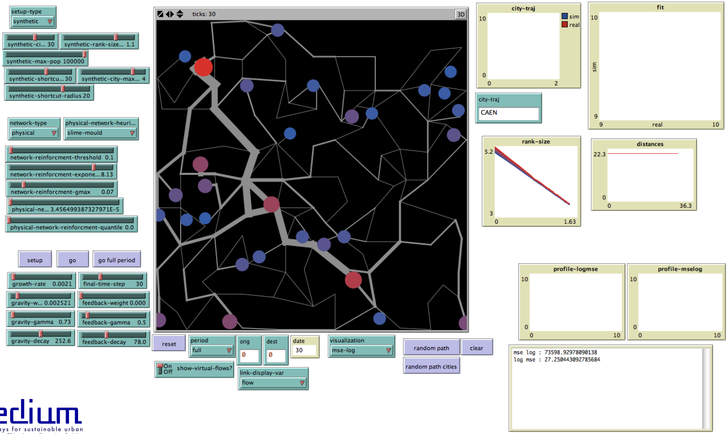
$$\frac{2}{N \cdot (N-1)} \sum_{i<j} \left(\frac{1}{T} \int_t \left(\tilde{X}_i(t) - \tilde{X}_j(t) \right)^2 \right)^{\frac{1}{2}}$$

- 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)

Model Implementation and Exploration

→ Model implemented in NetLogo (heterogeneous coupling, very diverse sub-models) ; explored with OpenMole [Reuillon et al., 2013]

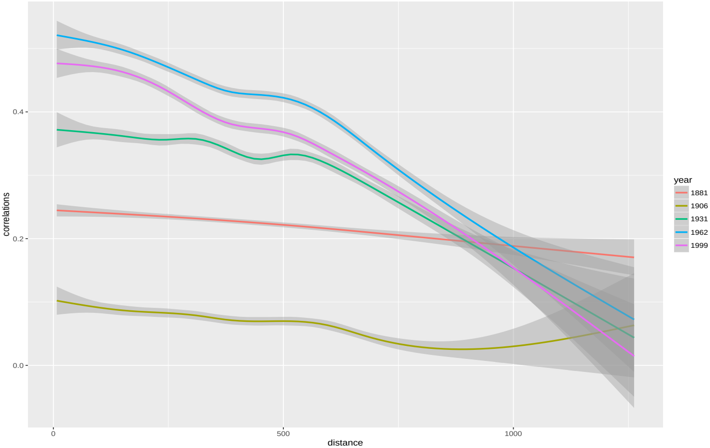
→ Synthetic City-systems : follow Zipf's law with $\alpha \in \{1.0, 1.5\}$ and $N = 30$ cities ; relaxed Central Place Theory (no influence of other's initial size on localization).



Macro Stylized facts

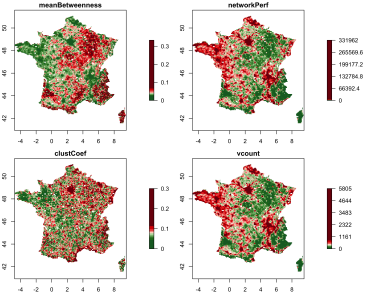
Population data for French-cities (Pumain-INED database : 1831-1999)

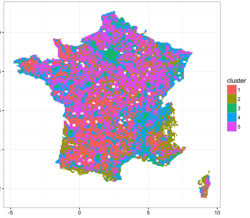
Non-stationarity of log-returns correlations function of distance

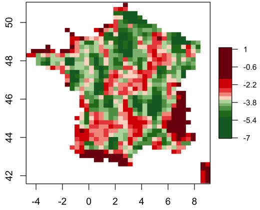


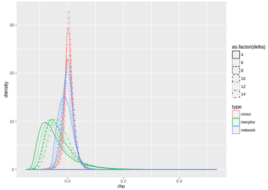
Meso Stylized facts

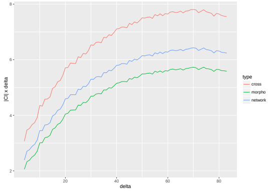
[Raimbault, 2016a]: Data, tools and methods showing the spatial non-stationarity and multi-scalar nature of correlations between urban form and network topology





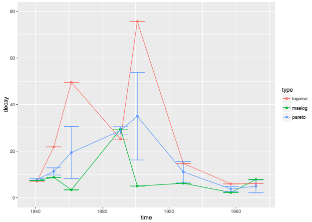


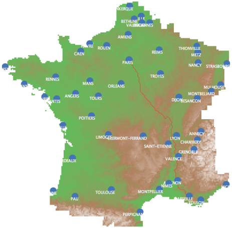


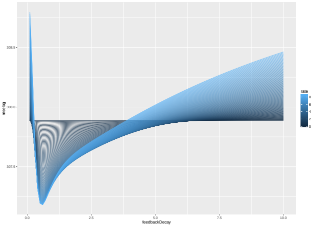


Croissance Macroscopique et Nécessité du réseau

Macroscopic model with static network but based similarly on flows, at the first and the second order, reveals physical network effects for French Urban System (adding feedback of flows fits better the data when correcting for supplementary parameters) [Raimbault, 2016b]

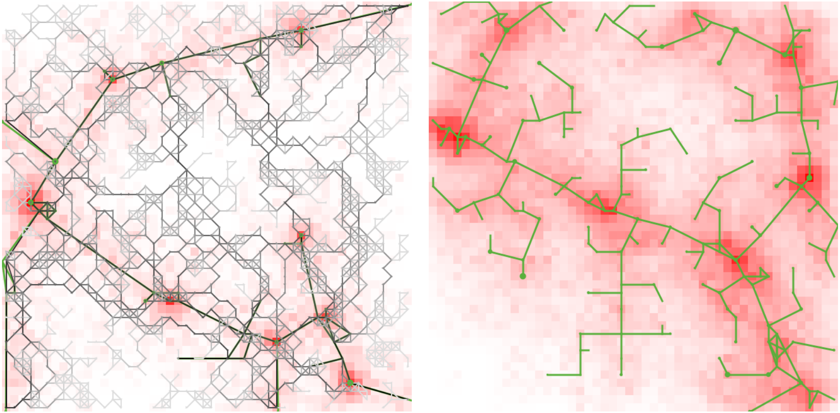






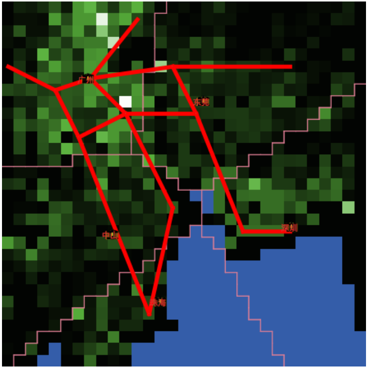
Modeling co-evolution at the Meso-scale

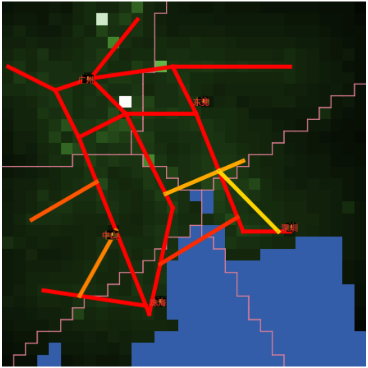
Multi-modeling of co-evolution at the meso-scale [Raimbault, 2017b]



Transportation Governance in Mega-city Regions

Lutecia ([Le Néchet and Raimbault, 2015]): a model of co-evolution that includes governance processes of transportation network extension; application to Pearl River Delta Mega-city Region





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