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

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

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Systems of Cities and Transportation Networks

(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*

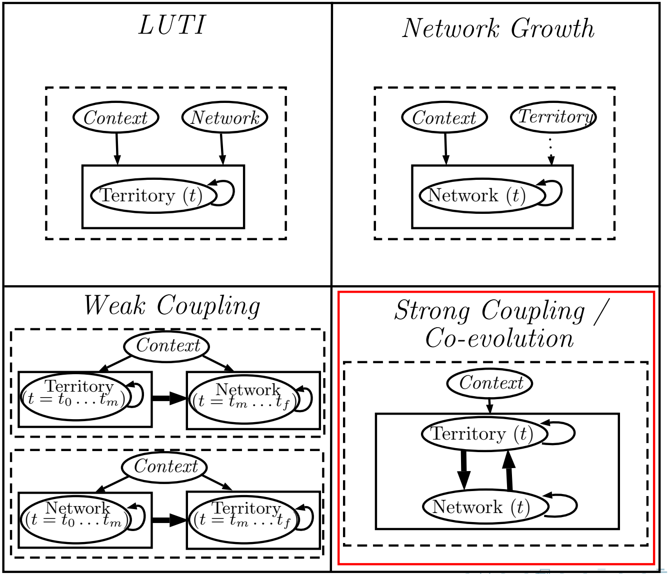
Several possible Scales and Ontologies

- 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



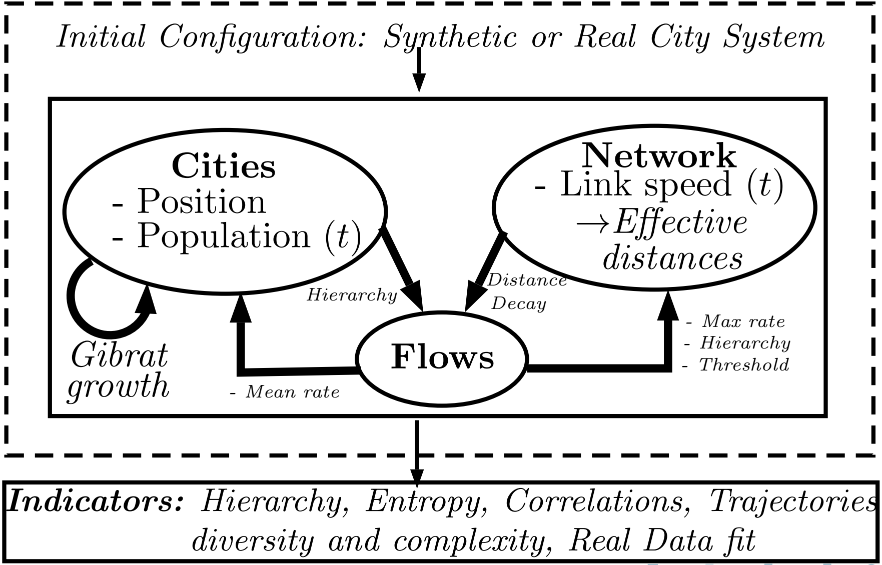
Model : Rationale

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, 2016b]) ; approach of the Evolutive Urban Theory [Pumain, 1997]
- Drivers of network growth are interaction flow demands
- Adjustable network growth scale and stochasticity level

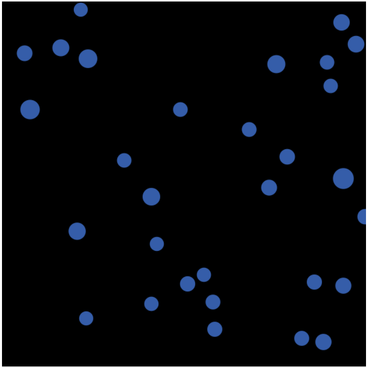
→ Generic for any city system with dynamical population and network data ; tested on synthetic city systems (following Rank-size Zipf's law).

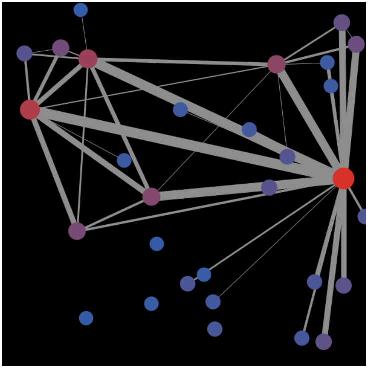
Generic Model



Model Specification : Abstract Network

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

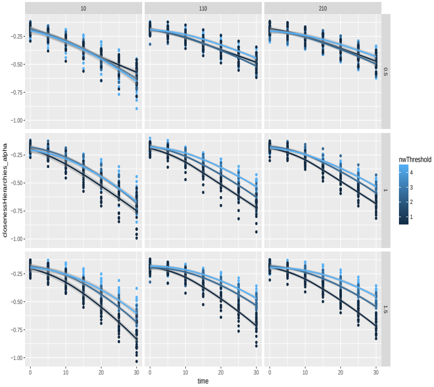


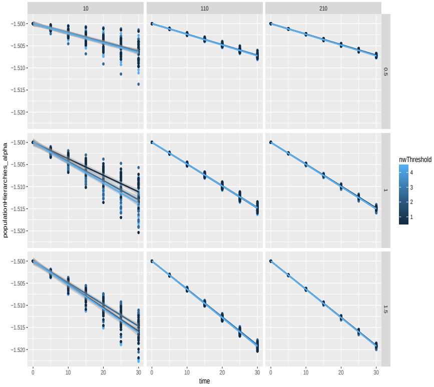


Exemple of run ($t_f = 30$). Level of red gives overall growth and link width flows.

Results: Stylized facts from Model Exploration

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





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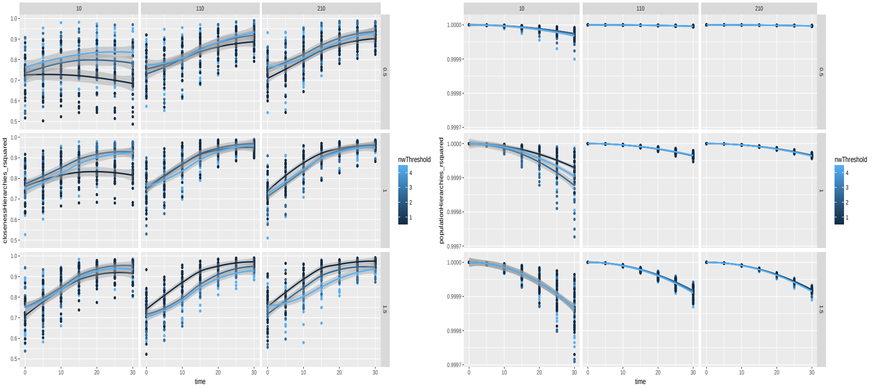
New pathways for sustainable urban development in China's medium-sized cities

Results

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



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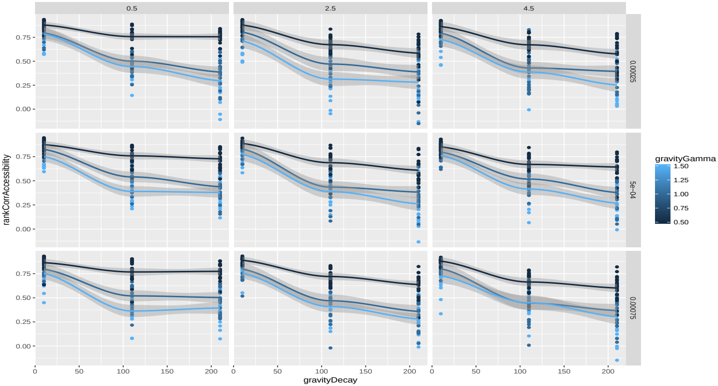
Results

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



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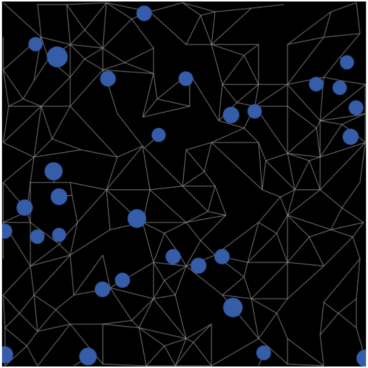
Results

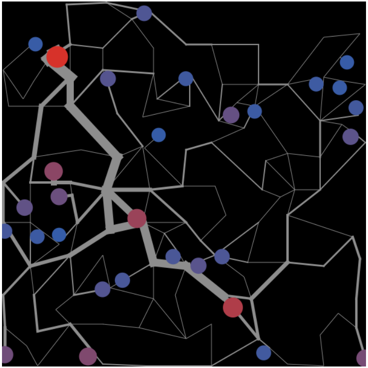
$\rightarrow$

Results

$\rightarrow$

Model : Physical Network





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

$\rightarrow$

$\rightarrow$

- 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]

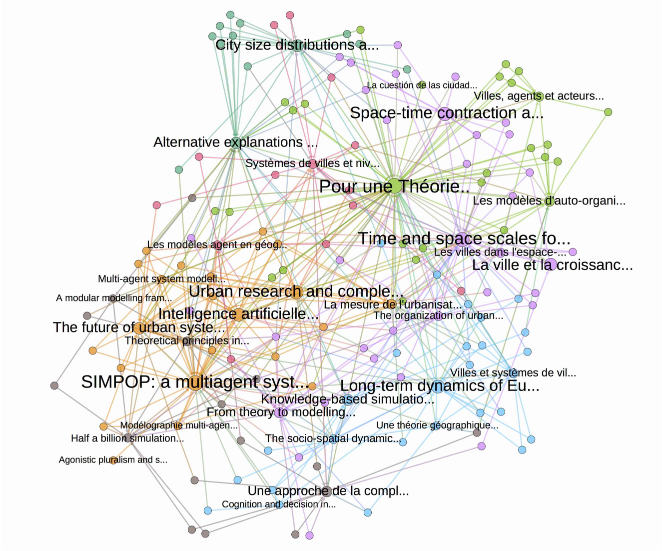
→ Seminal works : theoretical manifest [Pumain, 1997] and modeling [Sanders et al., 1

→ 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 to shortest path between k,l computed with slope impedance $(Z = (1+\alpha/\alpha_0)^{n_0}$ with $\alpha_0 \simeq 3)$

Model Formalization : Network Growth

Model Formalization : Indicators

- 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,

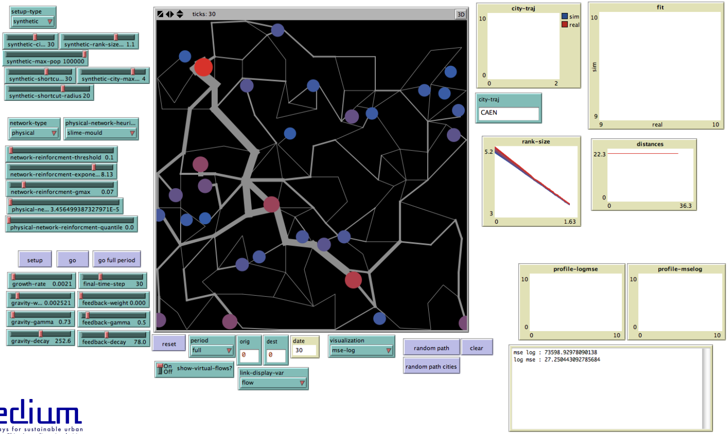
$$\frac{2}{N\cdot(N-1)}\sum_{i<j}\left(\frac{1}{T}\int_t\left(\tilde{X}_i(t)-\tilde{X}_j(t)\right)^2\right)^{\frac{1}{2}}$$

- Average trajectory complexity (number of inflexion points)

Model Implementation and Exploration

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

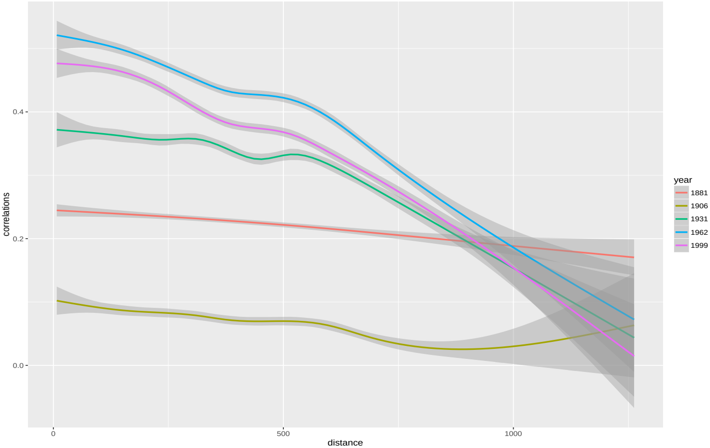
→ Synthetic City-systems : follow Zipf's law with $\alpha \in \{1.0, 1.5\}$ and $N = 30$ cities ; relaxed Central Place Theory (no influence of other's initial size on localization).



Macro Stylized facts

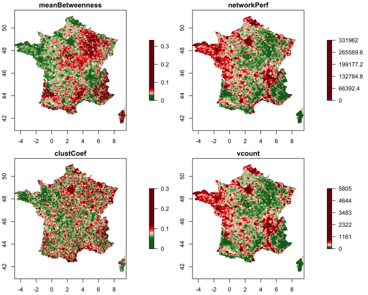
Population data for French-cities (Pumain-INED database : 1831-1999)

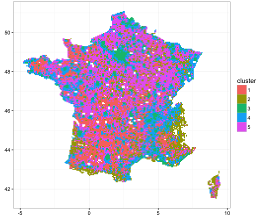
Non-stationarity of log-returns correlations function of distance

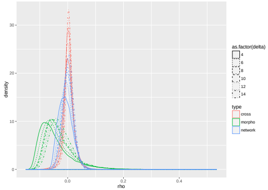


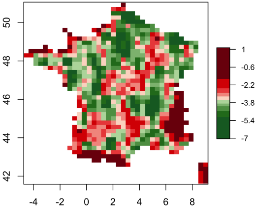
Meso Stylized facts

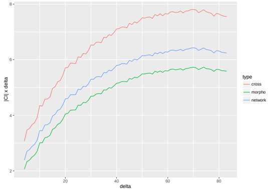
[Raimbault, 2016a]: Data, tools and methods showing the spatial non-stationarity and multi-scalar nature of correlations between urban form and network topology





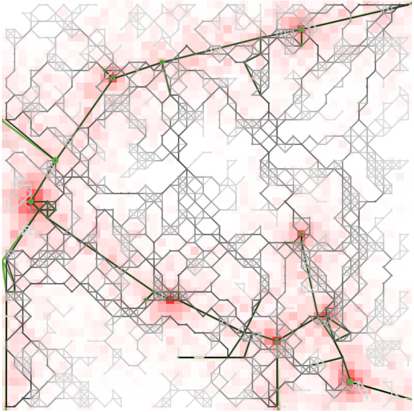


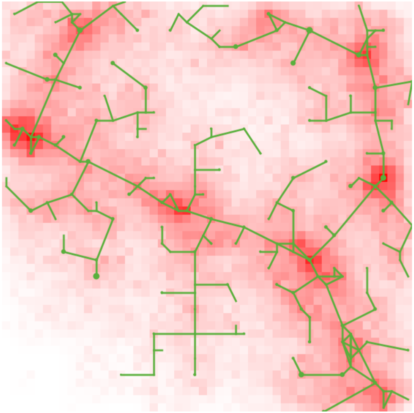




Modeling co-evolution at the Meso-scale

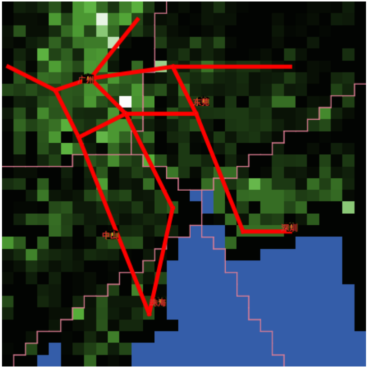
Multi-modeling of co-evolution at the meso-scale [Raimbault, 2017b]

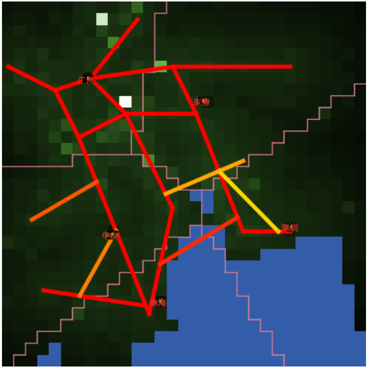




Transportation Governance in Mega-city Regions

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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