Towards multi-scalar models for the co-evolution of transportation networks and territories

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Theo Quant 2019
6 février 2019
Interactions between networks and territories

Central role of interactions between networks and territories in urban systems dynamics

Example: Multifractal planning for the city of Besancon [Tannier, 2017]
Modeling the co-evolution of networks and territories

Models with different ontologies and scales [Raimbault, 2018a]

Macroscopic

Mesoscopic

Interaction model

Urban morphogenesis

Transportation governance
→ Processes included depend on the scale (urban form and function, interactions between cities)

→ Truly multi-scale models (coupling different ontologies and not just geographical ranges, and with a strong coupling between scales) are very rare (inexistent ?), despite a strong need for these [Rozenblat and Pumain, 2018]

**Research objective:** Investigate an hybrid co-evolution model coupling macroscopic city dynamics and mesoscopic network dynamics
**Generic description of the model**

**Initial Configuration:** Synthetic or Real City System

**Cities**
- Position
- Population \( (t) \)

**Network**
- Link speed \( (t) \)
  → Effective distances

**Flows**
- Mean rate
- Max rate
- Hierarchy
- Threshold

**Indicators:** Hierarchy, Entropy, Correlations, Trajectories, diversity and complexity, Real Data fit
Macroscopic interaction model

City 1

City 2

Population

City 3

City 4
Macroscopic interaction model

City 1

City 2

City 3

City 4

Population

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Macroscopic interaction model
Macroscopic interaction model

City 1

City 2

City 3

City 4

Population

Endogenous growth

Direct interaction
Macroscopic interaction model

City 1

City 2

City 3

City 4

Population

Endogenous growth

Direct interaction

Feedback of flows
Macroscopic interaction model

City 1

City 2

City 3

City 4

Population
Endogenous growth
Direct interaction
Feedback of flows
Network adaptation
Making the model hybrid: physical network specification with explicit topology and geographical distribution; link capacity evolution with self-reinforcement

Illustration on a synthetic system of cities
Real physical network

Parametrisation on the French system of cities with temporal windows (see [Raimbault, 2018b]); train network data from [Mimeur et al., 2017]
Model exploration and calibration

Large experience plan and bi-objective calibration on 9 periods → use of genetic algorithms on grid, made smooth with the OpenMOLE software https://next.openmole.org/

OpenMOLE: (i) embed any model as a black box; (ii) transparent access to main High Performance Computing environments; (iii) model exploration and calibration methods.

Come to the demonstration tomorrow, and save the date for the next summer school (2020) ! https://exmodelo.org/
Model behavior

*Qualitatively similar trajectories in time*
Model behavior

Strongly different qualitative behavior for aggregated indicators
Interaction regimes

Less co-evolution regimes: similar results than [Raimbault, 2018f] which explored the SimpopNet model (only 3 against 19 co-evolutive regimes)

Comparison of regimes with strongest entanglement: auto-correlation bias with virtual network; apparent AR(1) behavior with physical network: sensitivity to indicators definition?
Much more mediocre results for distance matrices, improvement for population fit on some time windows: converge with the difficulty to characterize co-evolution with the same data [Raimbault, 2019]?
Several open questions: spatial non-stationarity, nature of inter-scale coupling, level of calibration, operationalization, ...
Implications

→ Such hybrid models closer or further to the actual complexity of co-evolution?

→ Implications for planning still to be determined (two different policy type and level)

Developments

→ Fair comparison of number of interaction regimes using PSE algorithm [Chérel et al., 2015]; fair comparison of calibrations taking into account number of parameters [Piou et al., 2009]

→ Multi-modeling for network growth in the hybrid model, including topological evolution [Raimbault, 2018c]

→ Towards the inclusion of governance processes in co-evolution models [Le Néchet and Raimbault, 2015]
→ Towards multi-scalar models and multi-models, calibrated on several systems of cities [Raimbault, 2018e]: foundations of integrative models for territorial systems

→ Towards an integration of complexities [Raimbault, 2018d] [Raimbault, 2019]: foundations of integrative theories of territorial systems

**Some references**


- Code, data and results at https://github.com/JusteRaimbault/CoevolutionNwTerritories
- Acknowledgements to the European Grid Infrastructure and its National Grid Initiatives (France-Grilles in particular) for the technical support and the infrastructure.
Reserve Slides
Rationale: extend an interaction model for system of cities by including physical network as an additional carrier of spatial interactions

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

→ With $\vec{\mu}(t) = \mathbb{E}\left[\vec{P}(t)\right]$, we generalize this approach by taking $\vec{\mu}(t+1) = f(\vec{\mu}(t))$
Let $\vec{\mu}(t) = E[\vec{P}(t)]$ cities population and $(d_{ij})$ distance matrix

Model specified by

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

with

- $G_{ij} = w_G \cdot \frac{V_{ij}}{<V_{ij}>}$ and $V_{ij} = \left(\frac{\mu_i \mu_j}{\sum \mu_k^2}\right)^\gamma_G \exp\left(-d_{ij}/d_G\right)$

- $N_i = w_N \cdot \sum_{kl} \left(\frac{\mu_k \mu_l}{\sum \mu}\right)^\gamma_N \exp\left(-d_{kl,i}/d_N\right)$ where $d_{kl,i}$ is distance to shortest path between $k, l$ computed with slope impedance ($Z = (1 + \alpha/\alpha_0)^{n_0}$ with $\alpha_0 \simeq 3$)
Given the flow $\phi$ in a link, its effective distance is updated following:

1. For the thresholded case

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

2. For the full growth case

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

where $\gamma_s$ is a hierarchy parameter, $\phi_0$ a threshold parameter and $g_{\text{max}}$ the maximal growth rate easily adjustable to realistic values by computing $(1 + g_{\text{max}})^{t_f}$.
Model Description : 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,

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

- Average trajectory complexity (number of inflexion points)
- Pearson correlations conditionally to distance
  $\hat{\rho}_d [(X(\tilde{x}_1, Y(\tilde{x}_2))|||\tilde{x}_1 - \tilde{x}_2|| \sim d]$
- Lagged return correlations $\hat{\rho}_\tau [\Delta X(t), \Delta Y(t - \tau)]$ (Granger causality)
Complete virtual network between cities, initialized with euclidian distances; thresholded reinforcement of speeds as a function of flows.

Example of run ($t_f = 30$). Level of red gives overall growth and link width flows.
Generation of synthetic systems of cities for model exploration:

- Cities at random locations (farther from each other by a fixed radius $r_0 = 10$); population distribution with a scaling law $P_i = P_0 \cdot i^{-\alpha_S}$ ($\alpha_S$ parameter, $P_0 = 100000$, for $N = 30$ cities)
- Create a grid network with nodes at a fixed distance $r_N = 15$; remove a fixed proportion $p_I = 0.2$ of links; jitter node positions by $\pm r_N$ for each coordinate (avoids ties in shortest routes and oscillating behaviors e.g.)
- Connect cities to the network with euclidian projection to closest link

Applying the method of [Raimbault et al., 2018] for spatial sensitivity to the SimpopNet model, [Raimbault, 2018f] shows that the model is sensible to some (e.g. $\alpha_S$) remains to be checked here.


Space matters: extending sensitivity analysis to initial spatial conditions in geosimulation models. 

Conclusion: Toward a methodology for multi-scalar urban system policies. 
*International and Transnational Perspectives on Urban Systems*, page 385.