A co-evolution agent-based model for systems of cities and transportation networks integrating top-down governance through game theory

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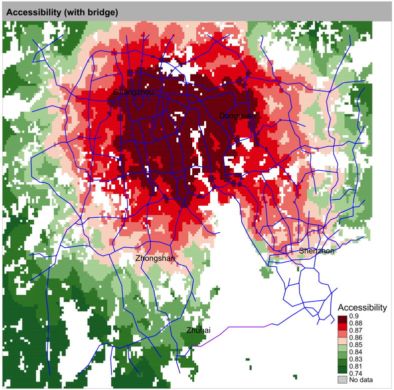
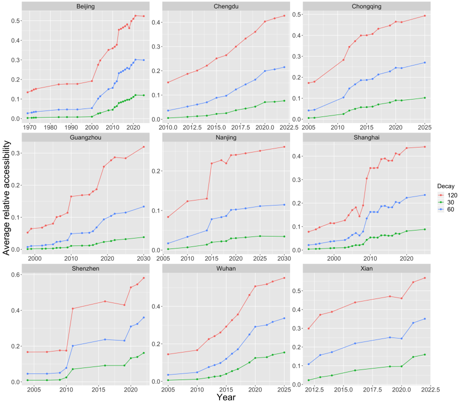
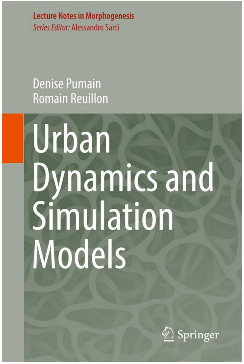




Accessibility as part of complex processes of co-evolution between transportation networks and territories.

Raimbault, J. (2019). Evolving accessibility landscapes: mutations of transportation networks in China. In Aveline-Dubach, N., ed. *Pathways of sustainable urban development across China - the cases of Hangzhou, Datong and Zhuhai*, pp 89-108. Imago. ISBN:978-88-94384-71-0

Urban evolutionary theory



Development of an evolutionary urban theory

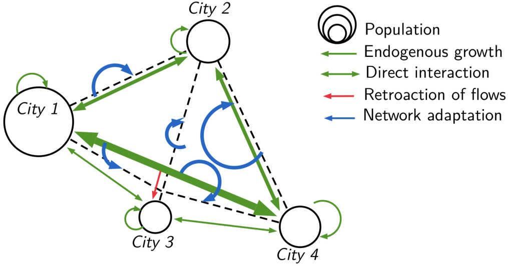
→ Recurrent stylized facts on main systems of cities
→ Construction of simulation models (with an explicative purpose)
→ Tools and methods to explore simulation models

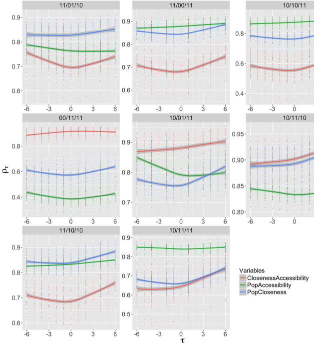
OpenMOLE

Pumain, D. (2018). An evolutionary theory of urban systems. In International and Transnational Perspectives on Urban Systems (pp. 3-18). Springer, Singapore.
Reuillon, R., Leclaire, M., and Rey-Coyrehourcq, S. (2013). OpenMOLE, a workflow engine specifically tailored for the distributed exploration of simulation models. Future Generation Computer Systems, 29(8), 1981-1990.

Co-evolution of cities and transportation networks

System of cities interaction model including network evolution; exhibits multiple co-evolution regimes; calibrated for France 1830-2000.





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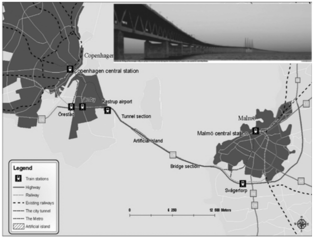
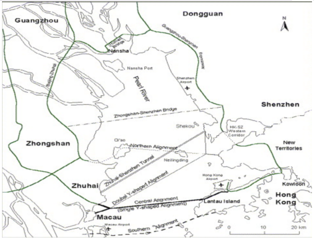
International transport infrastructure projects

UCL

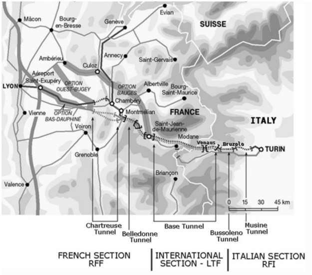


[Khan et al., 2014]



[Yang, 2006]

[Gibb et al., 1992]



[Marincioni and Appiotti, 2009]

Multinational transport investments

At the macroscopic scale: governance of multinational transport investments

- Positive effects of transport investments: [Melo et al., 2013] meta-analysis, [Yii et al., 2018] One-Belt-One-Road economic impact
- Difficult implementation of multinational investments [Tsamboulas, 1984]; many trans-European projects fail in cost-benefit analysis [Proost et al., 2014]
- Example of framework for prioritization based on multi-attribute theory [Tsamboulas, 2007]

Modeling co-evolution with governance processes

- Model of governance choice [Xie and Levinson, 2011a]
- Spatialized simulation model [Xie and Levinson, 2011b]
- LUTI model with evolving network and game theory [Le Néchet and Raimbault, 2015]

Game theory and transportation models

- Competition HSR/airplane [Adler et al., 2010]
- Public-private partnerships [Medda, 2007]
- Public transport integration [Roumboutsos and Kapros, 2008]

Proposed approach

$\rightarrow$ *Interaction of bottom-up and top-down planning processes in network and territories co-evolution*

$\rightarrow$ *Stylized yet applicable simple models accounting for governance processes may be useful tools towards sustainable small scale territorial planning*

Research objective
Explore a co-evolution model for cities and transportation networks at the macroscopic scale, focusing on network evolution rules including governance choices.

Model rationale

$\rightarrow$ *Extend the model of [Raimbault, 2020a] and [Raimbault, 2020b] with two governance levels (national and international) and the game theoretic cooperation module introduced by [Le Néchet and Raimbault, 2015]*

- Cities described by their population $P_i(t)$, linked with a physical transportation network with links described by effective distance $d_l(t)$
- Iterative macro-scale LUTI simulation model: at each time step
  1. Update spatial interaction flows
  2. Evolve cities populations depending on flows
  3. Evolve network speeds depending on link flows assigned in the network

Cities populations

Spatial interaction flows

$$\varphi_{ij} = \left(P_i P_j\right)^{\gamma} \cdot \exp\left(-\frac{d_{ij}}{d_0}\right)$$

Assume growth rate of cities are proportional to cumulated interaction flows as

$$\frac{P_i\left(t+\Delta t\right) - P_i\left(t\right)}{\Delta t} \propto c_{ij} \cdot P_i\left(t\right)^{\gamma} \cdot \sum_j P_j\left(t\right)^{\gamma} \cdot \exp\left(-\frac{d_{ij}}{d_0}\right)$$

with c_{ij} a multiplier parameter equal to 1 if cities are in the same country and $c_0 \leq 1$ otherwise

1. Baseline model: self-reinforcment of link speed according to

$$d_l\left(t+\Delta t\right)=d_l\left(t\right)\cdot\left[1+\Delta t\cdot g_M\left(\frac{1-\left(\frac{\varphi_l}{\varphi_0}\right)^{\gamma_N}}{1+\left(\frac{\varphi_l}{\varphi_0}\right)^{\gamma_N}}\right)\right]$$

for links with $\varphi_l > \varphi_0$, where φ_0 corresponds to the φ_0^q quantile of link flows

2. Estimate for each country k accessibility gains ΔZ_k^N and ΔZ_k^I obtained respectively with national N and international I flows, and corresponding construction costs C_k^N, C_k^I

Payoff matrix

Utility matrix for the two actor game is

0 $\mid$ 1	C	NC
C	$U_i{=}\Delta Z_k^I - \kappa \cdot C_k^I - \frac{J}{2}$	$\begin{cases} U_0{=}\Delta Z_0^N - \kappa \cdot C_0^N \\ U_1{=}\Delta Z_1^N - \kappa \cdot C_1^N - \frac{J}{2} \end{cases}$
NC	$\begin{cases} U_0{=}\Delta Z_0^N - \kappa \cdot C_0^N - \frac{J}{2} \\ U_1 \;\; \Delta Z_1^N - \kappa \cdot C_1^N \end{cases}$	$U_i \;\; \Delta Z_i^N - \kappa \cdot C_i^N$

Mixed Nash equilibrium probabilities

The general mixed Nash equilibrium probabilities are

$$p_{1-i} = -\frac{U_i\left(C,NC\right) - U_i\left(NC,NC\right)}{\left(U_i\left(C,C\right) - U_i\left(NC,C\right)\right) - \left(U_i\left(C,NC\right) - U_i\left(NC,NC\right)\right)}$$

what gives with the payoff matrix

$$p_i = \frac{J}{\left(Z^I_{1-i} - Z^N_{1-i}\right) - \kappa \cdot \left(C^I_{1-i} - C^N_{1-i}\right)}$$

Parameters κ, J are in practiced rescaled such that: (i) given a baseline model run, average cost absolute difference times κ is a fixed proportion k_0 of average absolute accessibility difference; and (ii) collaboration cost J yields a fixed probability p_0 computed on absolute average of the baseline run.

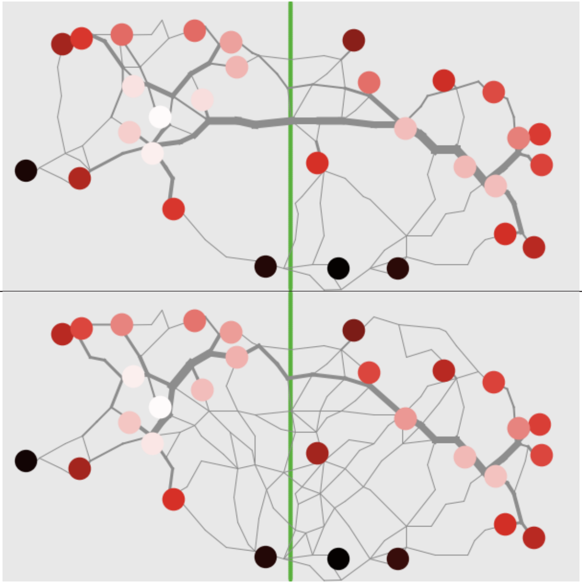
Implementation

- Model implemented in NetLogo (good compromise interactivity / ergonomy), with fast data structures (matrix/table extensions)
- Applied on synthetic systems of cities [Raimbault, 2019b]
- Integrated seamlessly into OpenMOLE [Reuillon et al., 2013] for model exploration `https://openmole.org/`

Experiments

- Saltelli Global Sensitivity Analysis [Saltelli et al., 2008]
- Role of stochasticity
- Grid experiment with role of spatial configuration

Example of simulated systems



Global sensitivity analysis

Indicators: ΔP average population growth; ΔZ average accessibility growth; $\Delta \alpha_P$ population hierarchy change; r_P population rank correlation; g average governance level; C total cost

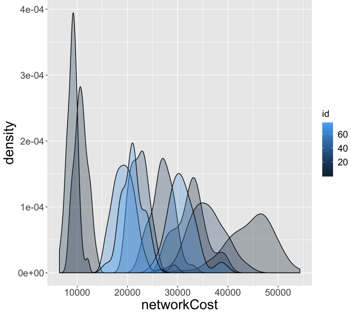
	α_0		γ_G		d_G		c_0		g_{max}		γ_N		φ_0^q		k_0		p_0		S	
	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T
ΔP	0.094	0.22	0.17	0.37	0.07	0.15	0.3	0.59	$7 \cdot 10^{-5}$	0.003	-0.002	$6.9 \cdot 10^{-4}$	-0.002	0.002	-0.001	0.0003	0.002	0.003	0.02	0.06
ΔZ	0.05	0.1	0.02	0.16	0.52	0.8	0.02	0.03	-0.006	0.18	-0.006	0.008	-0.008	0.03	0.0005	0.003	-0.006	0.01	-0.005	0.1
$\Delta \alpha_P$	0.2	0.3	0.3	0.5	0.06	0.12	0.17	0.26	-0.002	0.002	0.0001	0.0003	-0.004	0.001	-0.0007	0.0003	- 0.0008	0.0008	0.01	0.04
r_P	-0.7	0.1	-0.1	0.2	-0.4	0.3	0.26	0.002	-0.09	0.01	0.5	0.01	1.0	0.09	0.1	0.0002	0.3	0.001	0.1	0.07
g	-0.01	0.26	-0.004	0.3	-0.01	0.44	0.03	0.6	-0.03	0.25	-0.02	0.2	-0.05	0.3	-0.01	0.2	0.07	0.7	-0.01	0.5
C	-0.002	0.002	-0.007	0.01	-0.001	0.002	0.002	0.002	0.06	0.09	0.002	0.01	0.8	0.9	-0.0008	0.0005	0.003	0.003	0.04	0.04

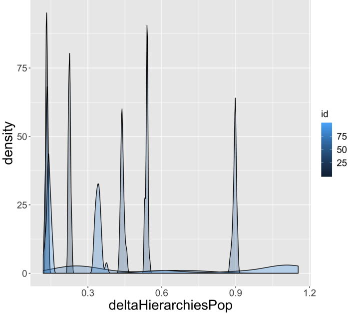
$\rightarrow$ *effect of spatial configuration (seed and hierarchy) [Raimbault et al., 2019]; crossed effects between network, cities and governance*

Role of stochasticity

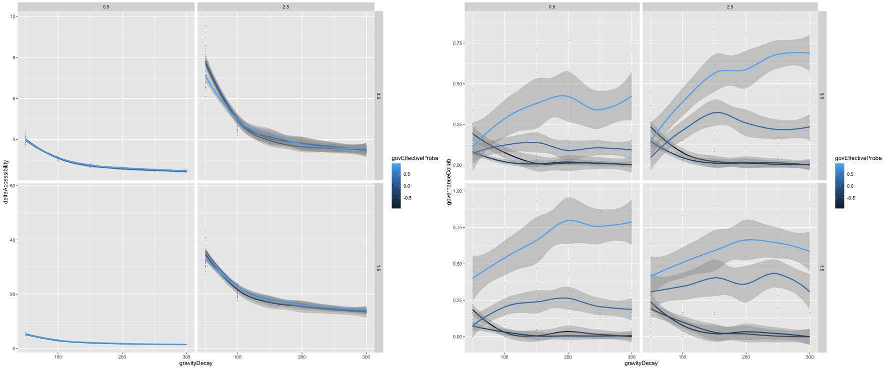
On 100 parameters sampled (LHS) with 100 replications:

- All indicators have a high Sharpe ratio (1st quartile with a minimum of 7.7 expect governance level g with a median at 1.02)
- Distance between average relative to standard deviations are also high (1st quartile higher than 2.3, except for g with a median at 1.2 and r_P with a median of 1.26)





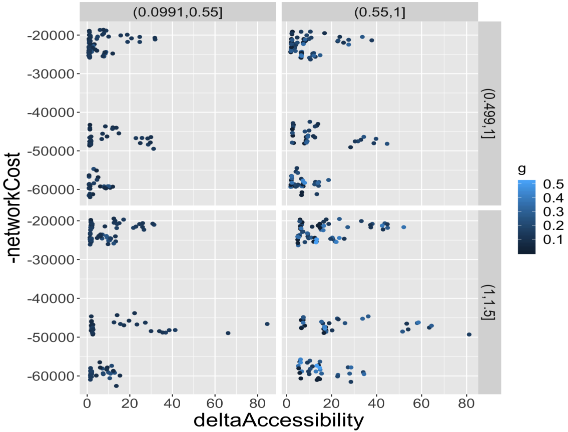
Grid exploration



Rows: hierarchy; columns: γ_G

$\rightarrow$ *Larger span in spatial interaction decrease relative accessibility gain, as do less hierarchical flows; effect of interaction decay on governance level qualitatively changed by* p_0

Optimizing accessibility and cost



Rows: hierarchy; columns: c_0

→ *Intermediate values of governance levels on the optimal Pareto front when international exchanges are intense (right column)*

Discussion

Developments

$\rightarrow$ Towards a macroscopic Land-use Transport model (including other network assignment procedures and congestion)

$\rightarrow$ More elaborated representation of decision-making and governance processes

$\rightarrow$ Integration into a multi-scale model [Raimbault, 2019a]

Applications

$\rightarrow$ Evaluate transportation scenarios/projects in a multinational stake-holders context

$\rightarrow$ Planning for sustainable territories on long time scales

Conclusion

$\rightarrow$ A co-evolution model at the macroscopic scale complexified by including transportation governance

$\rightarrow$ Well understood stylized models as a first step towards policy applications

Open repositories
`https://github.com/JusteRaimbault/CoevolGov` for the model
`https://github.com/JusteRaimbault/Governance` for results

Simulation data at `https://doi.org/10.7910/DVN/WP4V7S`

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