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

J. Raimbault[1,2,3]

[1]Center for Advanced Spatial Analysis, University College London
[2]UPS CNRS 3611 Complex Systems Institute Paris
[3]UMR CNRS 8504 Géographie-cités

E-mail: `juste.raimbault@polytechnique.edu`

Abstract.

1. Introduction

Interactions between networks and territories

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

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.

Raimbault, J. (2020). Indirect evidence of network effects in a system of cities. Environment and Planning B: Urban Analytics and City Science, 47(1), 138-155.

Raimbault, J. (2020). Modeling the co-evolution of cities and networks. In Niel, Z., Rozenblat, C., eds. *Handbook of Cities and Networks*, Edwar Elgar Publishing, *in press*.

International transport infrastructure projects

[4]

[5]

[6]

[7]

Multinational transport investments

At the macroscopic scale: governance of multinational transport investments

- Positive effects of transport investments: [8] meta-analysis, [9] One-Belt-One-Road economic impact
- Difficult implementation of multinational investments [10]; many trans-European projects fail in cost-benefit analysis [11]
- Example of framework for prioritization based on multi-attribute theory [12]

Co-evolution and governance processes

Modeling co-evolution with governance processes

- Model of governance choice [13]
- Spatialized simulation model [14]
- LUTI model with evolving network and game theory [15]

Game theory and transportation models

- Competition HSR/airplane [16]
- Public-private partnerships [17]
- Public transport integration [18]

Proposed approach

Interaction of bottom-up and top-down planning processes in network and territories co-evolution

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.

2. Model

Model rationale

→ *Extend the model of [19] and [3] with two governance levels (national and international) and the game theoretic cooperation module introduced by [15]*

- 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
  - (i) Update spatial interaction flows
  - (ii) Evolve cities populations depending on flows
  - (iii) Evolve network speeds depending on link flows assigned in the network

Cities populations
Spatial interaction flows

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

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

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

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

(i) Baseline model: self-reinforcment of link speed according to

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

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

(ii) Estimate for each country k accessibility gains $\Delta Z_k^{(N)}$ and $\Delta Z_k^{(I)}$ 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
NC $\{U_0 = \Delta Z_0^{(N)} - \kappa \cdot C_0^{(N)} - \frac{J}{2}$
$U_1 = \Delta Z_1^{(N)} - \kappa \cdot C_1^{(N)}$ $U_i = \Delta Z_i^{(N)} - \kappa \cdot C_i^{(N)}$

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

$$p_i = \frac{J}{\left(Z_{1-i}^{(I)} - Z_{1-i}^{(N)}\right) - \kappa \cdot \left(C_{1-i}^{(I)} - C_{1-i}^{(N)}\right)}$$

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.

3. Results

Implementation and experiments

Implementation

- Model implemented in NetLogo (good compromise interactivity / ergonomy), with fast data structures (matrix/table extensions)
- Applied on synthetic systems of cities [20]
- Integrated seamlessly into OpenMOLE [2] for model exploration `https://openmole.org/`

Experiments

- Saltelli Global Sensitivity Analysis [21]
- 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

effect of spatial configuration (seed and hierarchy) [22]; 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)

	α_0		γ_G		d_G		c_0		g_{max}		γ_N	
	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	$6.9 \cdot 10^{-}$
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
$\Delta \alpha_P$	0.2	0.3	0.3	0.5	0.06	0.12	0.17	0.26	-0.002	0.002	0.0001	0.0003
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
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
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

!

Grid exploration Rows: hierarchy; columns: γ_G

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

4. Discussion

Developments

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

More elaborated representation of decision-making and governance processes

Integration into a multi-scale model [23]

Applications

Evaluate transportation scenarios/projects in a multinational stakeholders context

Planning for sustainable territories on long time scales

5. Conclusion

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

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`

[1] Denise Pumain. An evolutionary theory of urban systems. In *International and transnational perspectives on urban systems*, pages 3–18. Springer, 2018.

[2] Romain Reuillon, Mathieu Leclaire, and Sebastien Rey-Coyrehourcq. Openmole, a workflow engine specifically tailored for the distributed exploration of simulation models. *Future Generation Computer Systems*, 29(8):1981–1990, 2013.

[3] Juste Raimbault. Modeling the co-evolution of cities and networks. *Handbook of cities and networks. Rozenblat C., Niel Z., eds. In press*, 2020.

[4] Jamil Khan, Fredrik Pettersson, and Bengt Holmberg. Constructive conflicts in the case of the öresund link. *Planning Theory and Practice*, 15(3):389–389, 2014.

[5] RA Gibb, RD Knowles, and JH Farrington. The channel tunnel rail link and regional development: an evaluation of british rail's procedures and policies. *Geographical Journal*, pages 273–285, 1992.

[6] Chun Yang. The geopolitics of cross-boundary governance in the greater pearl river delta, china: A case study of the proposed hong kong–zhuhai–macao bridge. *Political Geography*, 25(7):817–835, 2006.

[7] Fausto Marincioni and Federica Appiotti. The lyon-turin high-speed rail: the public debate and perception of environmental risk in susa valley, italy. *Environmental management*, 43(5):863–875, 2009.

[8] Patricia C Melo, Daniel J Graham, and Ruben Brage-Ardao. The productivity of transport infrastructure investment: A meta-analysis of empirical evidence. *Regional Science and Urban Economics*, 43(5):695–706, 2013.

[9] Kwang-Jing Yii, Kai-Ying Bee, Wei-Yong Cheam, Yee-Lee Chong, and Ching-Mei Lee. Is transportation infrastructure important to the one belt one road (obor) initiative? empirical evidence from the selected asian countries. *Sustainability*, 10(11):4131, 2018.

[10] Dimitrios A Tsamboulas. Multinational transport investments. *Ekistics*, pages 110–114, 1984.

[11] Stef Proost, Fay Dunkerley, Saskia Van der Loo, Nicole Adler, Johannes Bröcker, and Artem Korzhenevych. Do the selected trans european transport investments pass the cost benefit test? *Transportation*, 41(1):107–132, 2014.

[12] Dimitrios A Tsamboulas. A tool for prioritizing multinational transport infrastructure investments. *Transport Policy*, 14(1):11–26, 2007.

[13] Feng Xie and David M. Levinson. *Governance Choice - A Theoretical Analysis*, pages 179–198. Springer New York, New York, NY, 2011.

[14] Feng Xie and David M Levinson. Governance choice-a simulation model. In *Evolving Transportation Networks*, pages 199–221. Springer, 2011.

[15] Florent Le Néchet and Juste Raimbault. Modeling the emergence of metropolitan transport authority in a polycentric urban region. In *ECTQG 2015*, 2015.

[16] Nicole Adler, Eric Pels, and Chris Nash. High-speed rail and air transport competition: Game engineering as tool for cost-benefit analysis. *Transportation Research Part B: Methodological*, 44(7):812–833, 2010.

[17] Francesca Medda. A game theory approach for the allocation of risks in transport public private partnerships. *International journal of project management*, 25(3):213–218, 2007.

[18] Athena Roumboutsos and Seraphim Kapros. A game theory approach to urban public transport integration policy. *Transport Policy*, 15(4):209–215, 2008.

[19] Juste Raimbault. Hierarchy and co-evolution processes in urban systems. *arXiv preprint arXiv:2001.11989*, 2020.

[20] Juste Raimbault. Second-order control of complex systems with correlated synthetic data. *Complex Adaptive Systems Modeling*, 7(1):1–19, 2019.

[21] Andrea Saltelli, Marco Ratto, Terry Andres, Francesca Campolongo, Jessica Cariboni, Debora Gatelli, Michaela Saisana, and Stefano Tarantola. *Global sensitivity analysis: the primer*. John Wiley & Sons, 2008.

[22] J Raimbault, C Cottineau, M Le Texier, F Le Nechet, and R Reuillon. Space matters: Extending sensitivity analysis to initial spatial conditions in geosimulation models. *Journal of Artificial Societies and Social Simulation*, 22(4), 2019.

[23] Juste Raimbault. A multi-scalar model for system of cities. In *Conference on Complex Systems 2019*, Singapore, Singapore, September 2019.