Multi-modeling urban systems dynamics to explore sustainability trade-offs

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SDG 11: "Make cities and human settlements inclusive, safe, resilient, and sustainable" [Nations, 2015]

→ Cities as a transition state? [Batty, 2018] Incubators of social change and innovation, both the source and solution to sustainability issues? [Pumain, 2010]

→ Environmental Kuznet Curve hypothesis [Dinda, 2004, Stern, 2004]: inverted U-shaped relationship between environmental impact and income per-capita; not validated empirically [Harbaugh et al., 2002]

→ Trade-offs between SDGs in urban systems [Viguié and Hallegatte, 2012]

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Research Article

Trade-offs between sustainable development goals in systems of cities

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Research objective

$\rightarrow$ More dimensions and SDGs with trade-offs?

$\rightarrow$ Several models introduced with the evolutionary urban theory [Pumain, 2018] tackle complementary dimensions (see [Raimbault et al., 2020a] for a benchmark)

Research objective:

Couple several models for complementary dimensions of urban dynamics (innovation, economic exchanges, infrastructure) into a multi-model for the dynamics of urban systems at the macroscopic scale, to explore trade-offs between SDGs in synthetic systems of cities.

Innovation diffusion and urban dynamics

Exploration of trade-offs with two dimensions: urban evolution model [Raimbault and Pumain, 2022]

→ **Innovation diffusion** is a crucial process in artificial life evolutionary systems and open-ended evolution [Bedau et al., 2000]

→ Artificial societies used to study the dynamics of innovation [Zenobia et al., 2009]

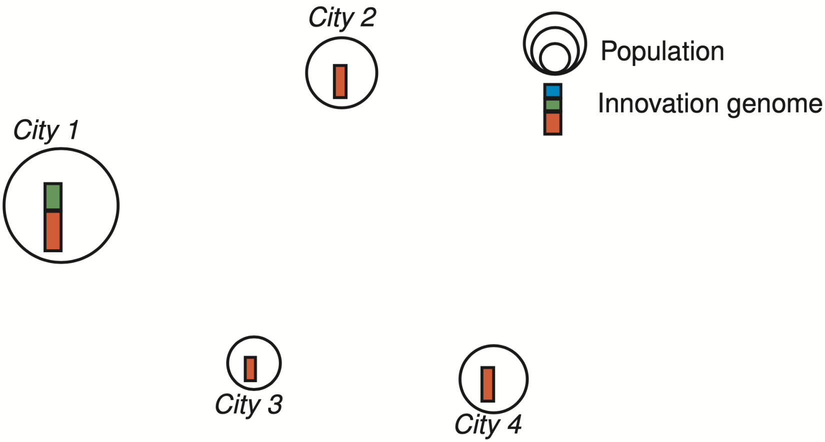
→ Innovations diffuse hierarchically in systems of cities [Hagerstrand, 1968], potential explanation of urban scaling laws [Pumain et al., 2006]

Innovation diffusion as a privileged entry to understand urban evolution

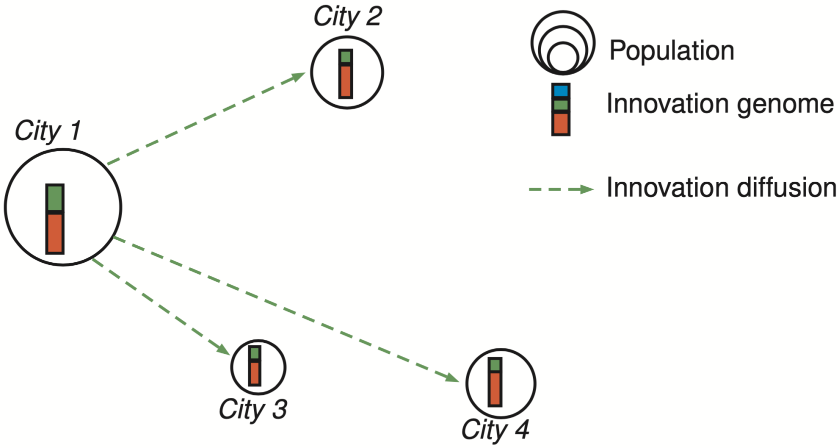
Model rationale

- Agents are cities, macroscopic scale (regional, country, continental) and long time scales (century)
- Cities characterised by their size in terms of population; genome as adoption proportions of innovations (social or technological) for each city (one single dimension to simplify)
- Following [Favaro and Pumain, 2011], attractivity of cities due to level of innovation drive their population growth through spatial interactions; innovation diffuse through an other spatial interaction model [Fotheringham and O'Kelly, 1989]
- Mutations occur in cities as new innovations appear

Model description



Model description



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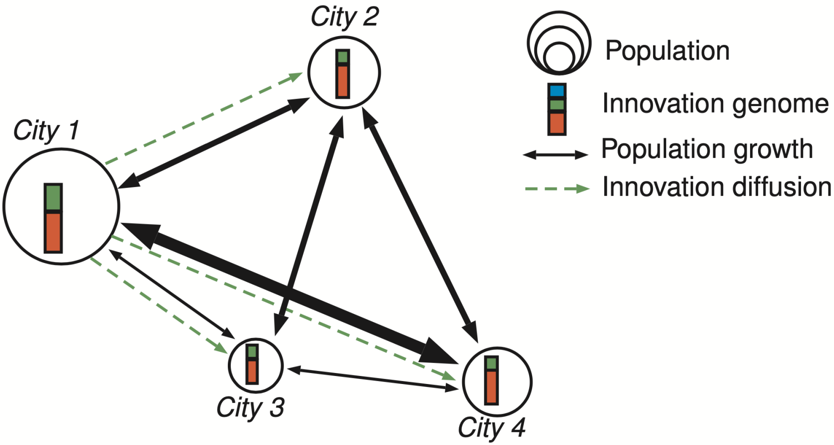

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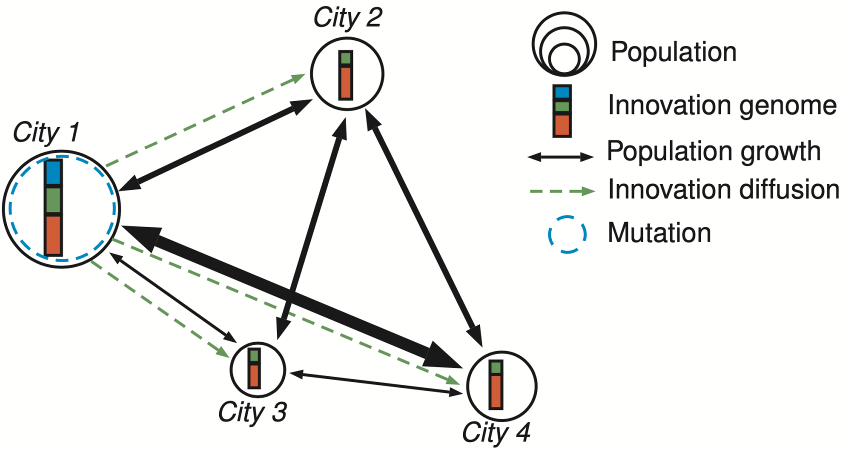


Model formalisation

At each time step, with $P_i(t)$ population, $\delta_{c,i}(t)$ genome, u_c utility of innovation, $p_{c,i,t}$ share of total population adopting innovation c in city i

1. Crossover through the diffusion of innovations

$$\delta_{c,i,t} = \frac{\sum_j p_{c,j,t-1}^{\frac{1}{u_c}} \cdot \exp\left(-\frac{d_{ij}}{d_I}\right)}{\sum_c \sum_j p_{c,j,t-1}^{\frac{1}{u_c}} \cdot \exp\left(-\frac{d_{ij}}{d_I}\right)}$$

2. Population growth through spatial interactions
$P_i(t) - P_i(t-1) = w_I \cdot \sum_j \frac{V_{ij}}{<V_{ij}>}$ with

$$V_{ij} = \frac{P_i(t-1) \cdot P_j(t-1)}{\left(\sum_k P_k(t-1)\right)^2} \cdot \exp\left(-\frac{d_{ij}}{d_G} \cdot \prod_c \delta_{c,i,t}^{\phi_{c,t}}\right)$$

and $\phi_{c,t} = \sum_i \delta_{i,c,t} \cdot P_i(t-1) / \sum_{i,c} \delta_{i,c,t} \cdot P_i(t-1)$
3. Mutations with innovations introduced with probability $\beta \cdot (P_i(t) / \max_k P_k(t))^{\alpha_I}$ and an initial penetration rate r_0; new utility u_c randomly distributed (normal or log-normal) with average current average utility and standard deviation a given parameter σ_U

Synthetic configurations

Model applied on synthetic systems of cities (so that conclusions are independent of geographical contingencies [Raimbault et al., 2019]):

- random positions and rank-size hierarchy $P_i(0) = \frac{P_{max}}{i^{\alpha_0}}$ with $\alpha_0 = 1.0$ and $P_{max} = 100,000$
- regional urban system scale: $N = 30$ cities
- simulated for $t_f = 50$ macroscopic time steps (order of magnitude of a century)

Model parameters for the innovation model

Parameter	Not.	Process	Range	Def.
Number of cities	N	Spatial scale	$[10; 100]$	30
Initial hierarchy	α_0	System of cities	$[0.5; 2.0]$	1
Initial population	P_{max}	System of cities	$[10^4; 10^7]$	10^5
Simulation steps	t_f	Temporal scale	$[10; 100]$	50
Growth rate	w_I	Pop. growth	$[0.001; 0.01]$	0.005
Gravity range	d_G	Crossover	$[0; 2]$	1
Innovation range	d_I	Crossover	$[0; 2]$	1
Innovation rate	β	Mutation	$[0; 1]$	0.5
Innovation hierarchy	α_I	Mutation	$[0; 2]$	1
Innov. utility std.	σ_U	Mutation	$[0.7; 2]$	1
Penetration rate	r_0	Mutation	$[0.1; 0.9]$	0.5
Utility type	-	Mutation	{n;ln}	ln

Implementation

Model implemented in `scala`; relatively large parameter space; integration into the `spatialdata` scala library for spatial sensitivity analysis [Raimbault et al., 2020b]

→ integration into the OpenMOLE model exploration open source software [Reuillon et al., 2013]

Enables seamlessly (i) model embedding; (ii) access to HPC resources; (iii) exploration and optimization algorithms

`https://openmole.org/`

Trade-offs between SDGs

$\rightarrow$ *Which trade-offs between innovation (SDG 9: innovation) and emissions (SDG 14: climate) in systems of cities?*

Application of the urban evolution model, optimising with NSGA2 for conflicting objectives in synthetic systems of cities:

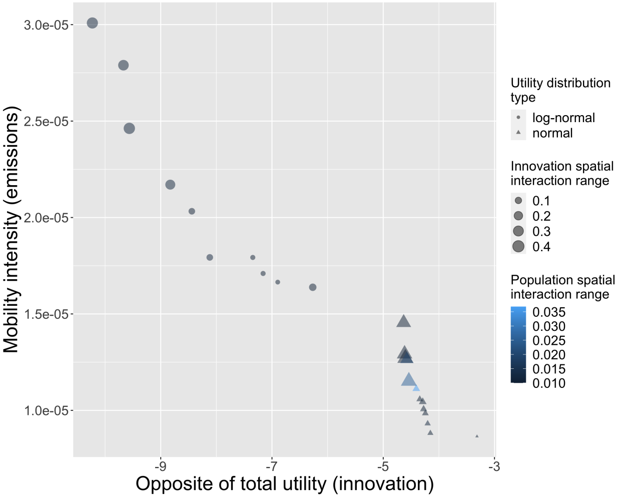
1. total utility of innovations

$$U = \sum_{t,i,c} \delta_{t,i,c} \cdot u_c$$

2. gravity mobility flows as proxy for emissions

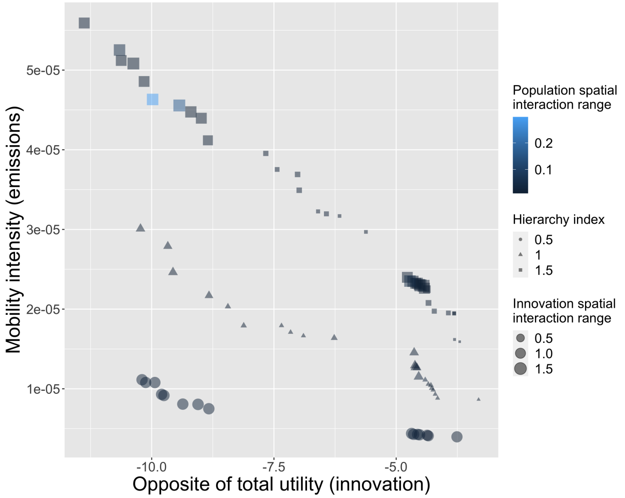
$$E = \sum_{t,i,j} \frac{P_{t,i} P_{t,j}}{P_t^2} \cdot \exp\left(-d_{ij}/d_G\right)$$

Trade-offs between SDG9 and SDG14



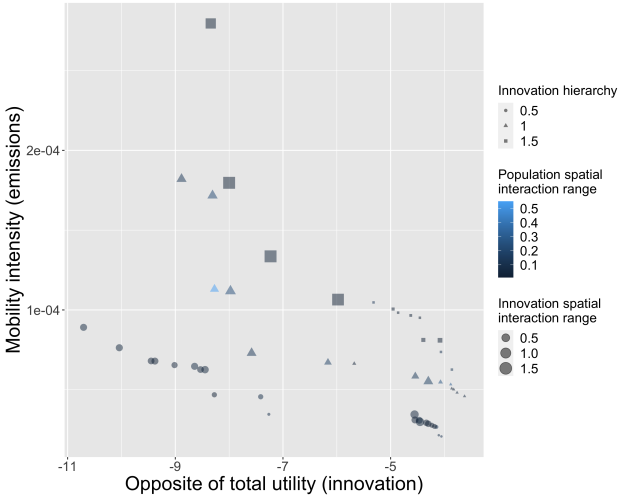
Pareto front confirms the existence of a trade-off

Influence of urban hierarchy



Higher inter-urban inequalities yield stronger trade-offs

Influence of innovation hierarchy



More balanced innovation yield higher utilities and less emissions (dominating Pareto front)

Generic multi-model of urban dynamics

Other dimensions benchmarked by [Raimbault et al., 2020a] to fit population dynamics on several large urban systems

Models integrated:

- Innovation diffusion urban evolution model [Raimbault and Pumain, 2022]
- Marius model for economic exchanges [Cottineau et al., 2015]
- Co-evolution model for cities and infrastructure networks [Raimbault, 2021]

"Semi-weak" coupling of submodels:

$$\begin{aligned} S_0 \rightarrow \left[S_1^{(0)} = M_0(S_0) \rightarrow \ldots \rightarrow S_1^{(K-1)} = M_{K-1}(S_1^{(K-2)}) = S_1 \right] \longrightarrow \ldots \\ \longrightarrow \left[S_T^{(0)} = M_0(S_{T-1}) \rightarrow \ldots \rightarrow S_T^{(K-1)} = M_{K-1}(S_T^{(K-2)}) = S_T \right] \quad (1) \end{aligned}$$

Remarks: strictly weak coupling does not capture dynamics nor synergies; stronger coupling may exist to better capture interdependencies processes (here no specific coupling ontology, only population and distance matrix are shared between submodels)

Economic exchanges model

MARIUS family of models [Cottineau et al., 2015]:

Initial wealth as a power law of population (exponent α_W)

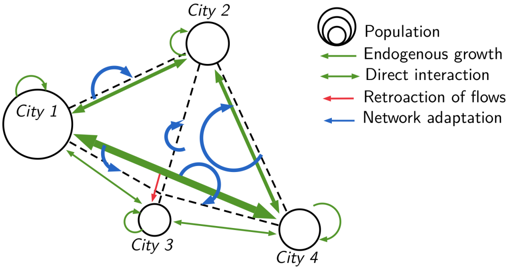
1) Update supply and demands as super-linear functions of population (exponents α_S, α_D)

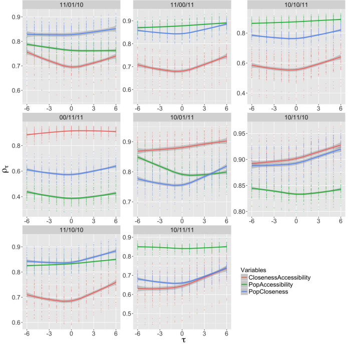
2) Exchange goods according to a gravity potential of interaction (distance decay d_M), supplies and demands; update wealth accordingly

3) Update population such that population difference is a power law of wealth difference (economic multiplier e_M and exponent α_P)

Infrastructure co-evolution model

System of cities interaction model including network evolution.





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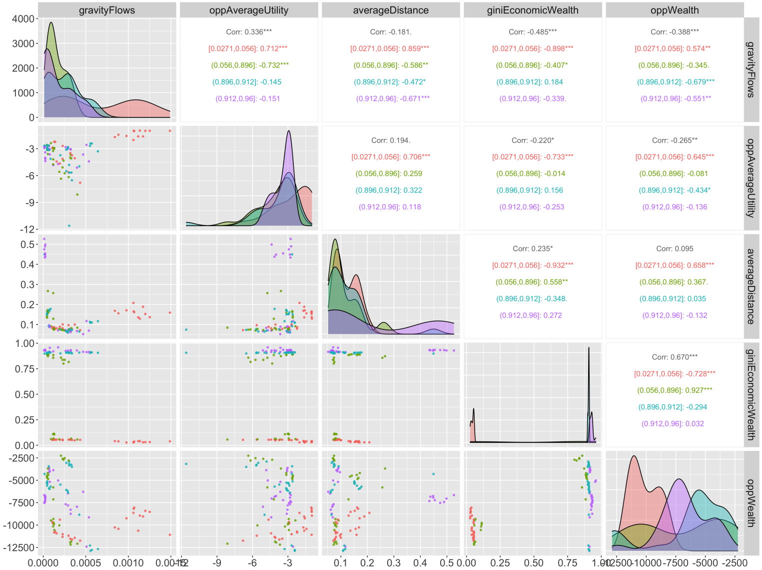
Optimised objectives

Proxies for SDGs:

- Total utility of innovations (SDG 9 "Innovation")
- Total spatial interaction flows across submodels (SDG 13 "Climate")
- Average distance between cities (SDG 9 "Resilient infrastructure")
- Economic inequalities (SDG 10 "Inequalities")
- Total wealth of cities (SDG 8 "Economic Growth")

Optimisation parameters: fixed synthetic urban system parameters but random configurations (10 repetitions); 8 parameters for innovation; 6 parameters for economic exchanges; 6 parameters for co-evolution

Optimisation results



Scatterplots of the 5D Pareto front. Color level: Gini economic wealth.

Discussion

Parametrisation on case studies:

→ Patent data as a proxy for innovation: geolocation of inventors not straightforward [Bergeaud and Verluise, 2021] [De Rassenfosse et al., 2019]; which technological (sub-)classes? Model with one dimension (extension with a matrix genome?); semantic content to better capture innovation diffusion? [Bergeaud et al., 2017]

→ Emissions: inter-urban mobility emissions difficult to capture (need an additional transport model?)

→ Historical infrastructure networks data?

Work in progress

→ Many-objective optimisation: NSGA3 algorithm

→ Empirical stylised facts on possible trade-offs in systems of cities

Future work

→ Towards multi-scale models: quantifying goal 11 (sustainable cities and communities) implies in some cases intra-urban dynamics (mobility, segregation, e.g.)

→ Transfer to policies and planning? Models with multiple functions? [Varenne, 2018] (towards companion modeling and stakeholder involvement)

Conclusion

→ Towards an integrative urban and territorial science applied to sustainable planning at multiple scales

→ Transfer to decision-making, policies and governance? *e-team* of the CSDC campus

To use OpenMOLE (free and open software) and contribute:
`https://openmole.org`

Model code and results open source at
`https://github.com/JusteRaimbault/SDGTradeoffs` and
`https://github.com/openmole/spatialdata`

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