

Complex systems science and urban science: towards applications to sustainability trade-offs in territorial systems

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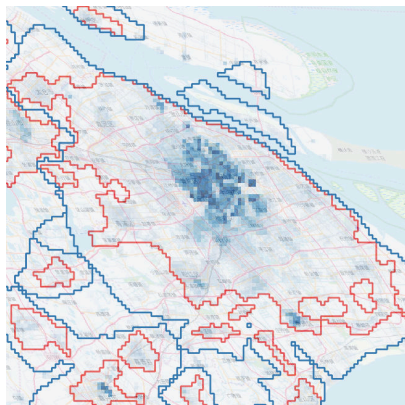
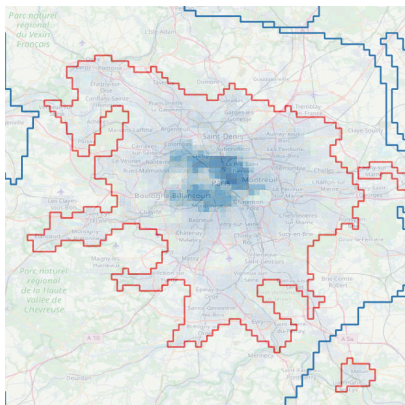
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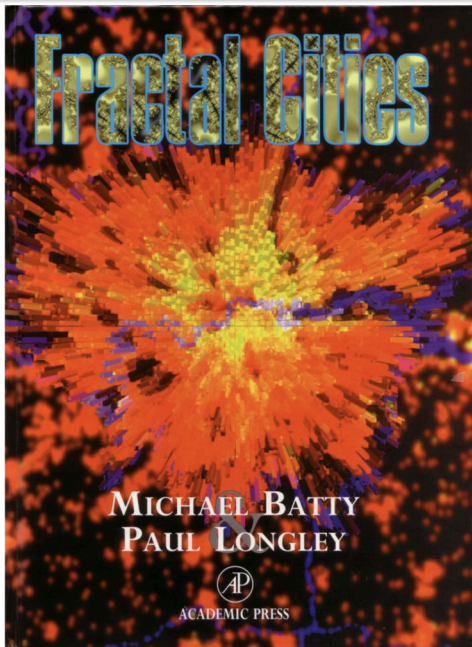
- 1 Complexity and Urban Science
- Perspectives towards sustainable planning
- A model of urban evolution based on innovation diffusion
- Trade-offs between SDGs in systems of cities

Spatial complexity and urban systems



Source: GHSL database [Florczyk et al., 2019]

From quantitative urban geography to an interdisciplinary urban science: urban systems are **multi-scalar**, **multi-dimensional**, **multi-stakeholders**, **multi-objective**, **out-of-equilibrium**, ...



Quantifying urban form using
fractal measures

[Batty and Longley, 1994]

Application to planning:
MUPCity model

[Frankhauser et al., 2018]

Entropy and the gravity model

General gravity model for interactions between two geographical entities

$$\log T_{ij}^{obs} \sim \beta_0 + \sum_k \beta_k \log X_{ik} + \sum_l \beta_l \log X_{jl} + \beta \log f(c_{ij}) + \varepsilon$$

[Wilson, 1971] link with entropy maximisation:

Maximising the entropy

$$W = \frac{\prod_{ij} T_{ij}!}{T!}$$

leads to equiprobable micro-states (one travel by one agent) which aggregate into the observed meso-state (flows) under macro-state constraints $\sum_j T_{ij} = O_i$, $\sum_i T_{ij} = D_j$ and $\sum T_{ij} c_{ij} = C$, gives

$$T_{ij} = A_i B_j O_i D_j \exp(-\beta c_{ij})$$

such that

$$A_i = 1 / \sum_j B_j D_j c_{ij}^{-\beta} \text{ and } B_j = 1 / \sum_i A_i O_i c_{ij}^{-\beta}$$

→ the *doubly constrained* model (origin and destination fixed effects in the statistical model) is derived

→ new models can be derived from the entropy in more general cases: multiple modes, profiles, ...

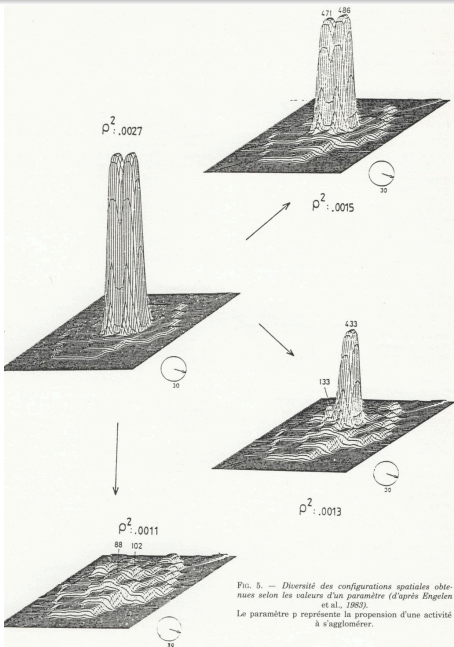
Remarks on the gravity model

→ emergence of simple laws (as for scaling laws): some sort of simplicity?

→ strong parametrisation always needed: no such thing as “universal one-parameter model”, importance of geographical context [Raimbault et al., 2019]

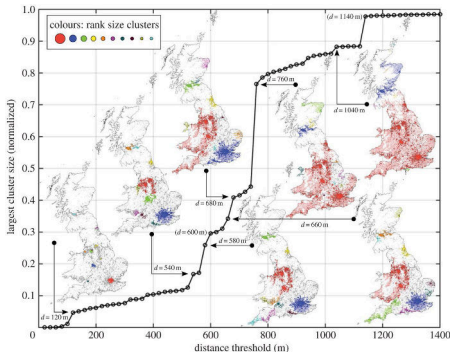
→ analogy not yet transferred to general relativity: an “urban mass” would curb the “urban space-time” around it: changes in accessibility, transportation infrastructure (issues with evolution timescales; no equilibrium; equations not transferable?)

Intra-urban dynamics

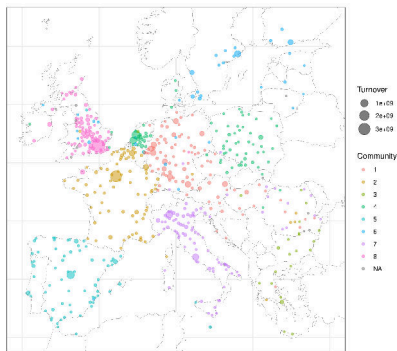


Intra-urban dynamics models based on dissipative structures physics (P. Allen) and on entropy maximisation (A. Wilson) [Pumain et al., 1984]

Urban complex networks

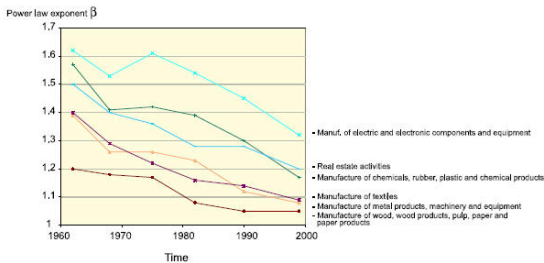
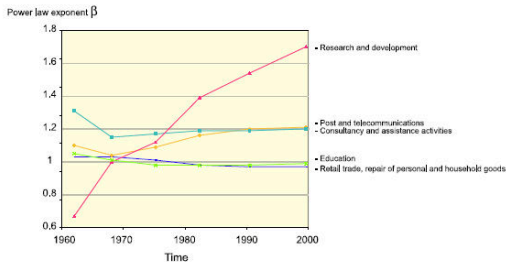


Percolation theory applied to street networks to retrieve endogenous regions [Arcaute et al., 2016]



European firm ownership network [Raimbault et al., 2020c]

Urban scaling

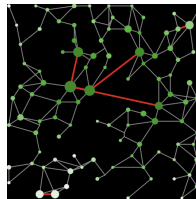
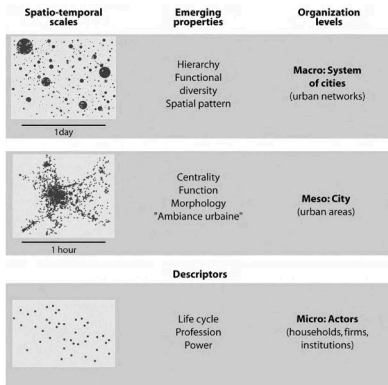


T.P. - ©CNRS, Imagerie et ville - 2005

(Supra/infra-)linear scaling of urban properties: consequence of innovation diffusion cycles? [Pumain et al., 2006]

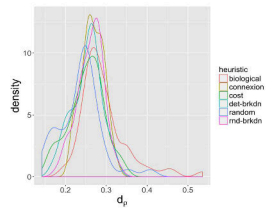
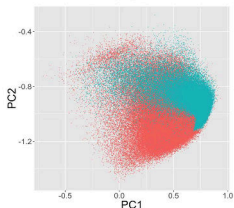
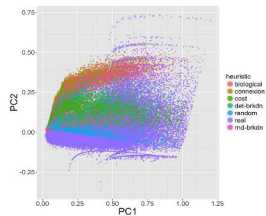
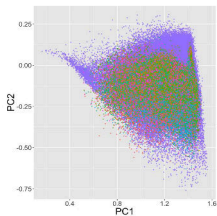
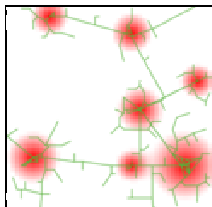
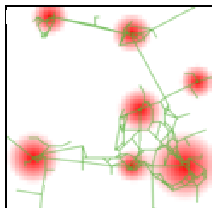
Urban Evolution

Urban evolution extending cultural evolution, cities as agents with their proper genome and evolutionary dynamics?



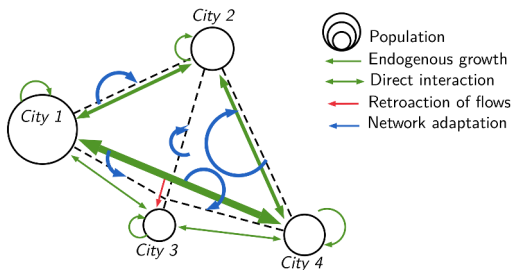
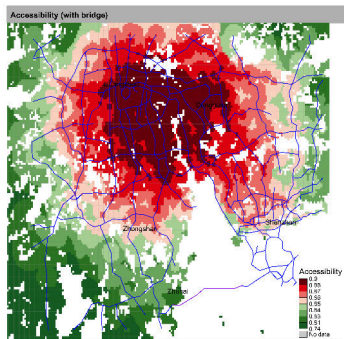
An evolutionary urban theory considering cities as systems within systems of cities [Pumain, 2018]; Simpop 1 model [Sanders et al., 1997]; SimpopNet model [Schmitt, 2014]

Urban morphogenesis



A morphogenesis model with reaction-diffusion and multi-modeling of network growth: complementarity of heuristics, calibration for Europe on forms and their correlations
[Raimbault, 2018a, Raimbault, 2019b]

Co-evolution and land-use transport interactions



A modeling approach to the issue of structuring effects of transport infrastructures: co-evolution of networks and territories

[Raimbault, 2019a, Raimbault, 2020c, Raimbault, 2021c]

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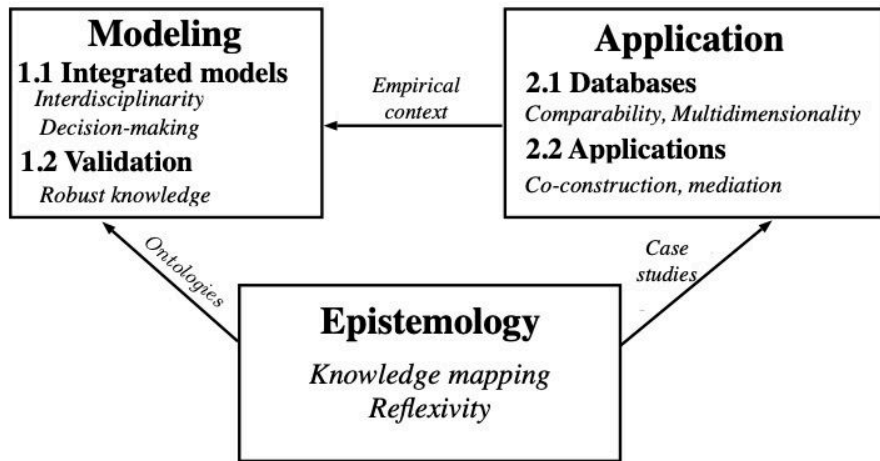
Theoretical/methodological open questions: spatio-temporal complexity; non-stationarity and ergodicity; multi-scale models; model coupling, integration and validation, ...

Discipline-specific questions: urban dynamics, land-use transport interactions, urban morphology, ...

Policies, decision-making and sustainable planning

- how to transfer results into sustainable policies at multiple scales
- how to include multiple stakeholders and objectives
- which trade-offs between sustainable development goals?
- ...

A research project towards integrated models and policies



[Raimbault, 2021b]

Towards harmonised databases for SDGs

- Systematic review of existing databases for different SDGs
- Construction of open, harmonised and multidimensional databases, on consistent and comparable geographical entities

Dimension	SDGs	Existing
Population	All	<i>Global Human Settlement Layer</i> [Florczyk et al., 2019]
GDP	8 (Growth)	[Kummu et al., 2018]
Income	10 (Inequalities)	[Van Zanden et al., 2014]
Transport	11 (Sustainable cities)	No harmonised dataset
Emissions	14 (Climate)	EDGAR [Janssens-Maenhout et al., 2019]
Innovation	9 (Innovation)	No geolocated patent database

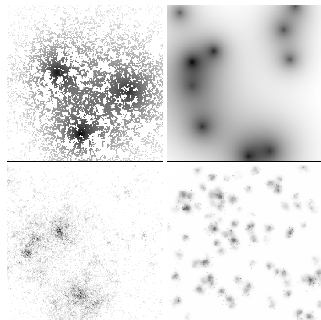
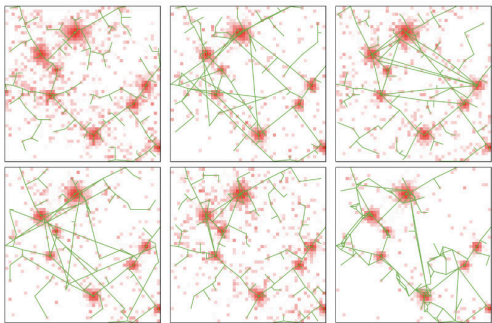
Examples of different SDGs dimensions and existing databases

Current work : *constructing a multimodal four step transport models by linking open components and data with scientific workflow engines*
[Raimbault and Batty, 2021]

Integrated models:

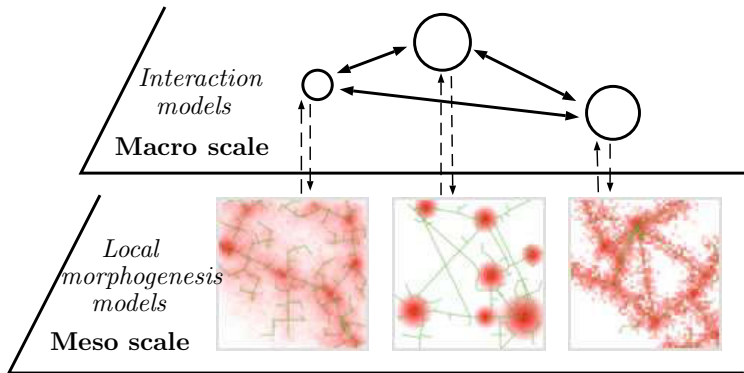
- MATSim model (MATSim Community) for transport
[W Axhausen et al., 2016]
- SPENSER model (University of Leeds) for synthetic population
[Spooner et al., 2021]
- QUANT model (CASA, University College London) for spatial interactions [Batty and Milton, 2021]
- spatialdata library (OpenMOLE community) for data processing
[Raimbault et al., 2020b]

Horizontal integration: multi-modeling and benchmarks



Benchmarking network and urban morphogenesis models
[Raimbault, 2018b, Raimbault, 2020b, Raimbault, 2021a]

Vertical integration: towards multi-scale models



Processes specific to scales, coupling implies dedicated ontologies
[Raimbault, 2021e, Raimbault, 2021d]

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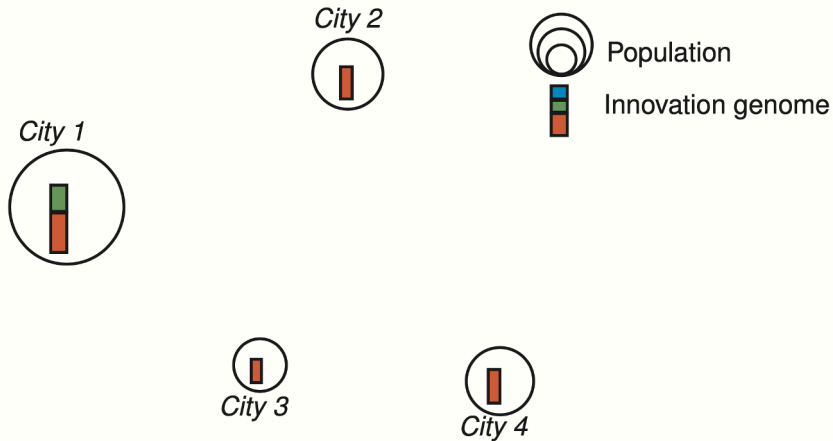
- **Innovation diffusion** is a crucial process in artificial life evolutionary systems and open-ended evolution [Bedau et al., 2000]
- Artificial societies used to study the dynamics of innovation [Zenobia et al., 2009]
- Innovations diffuse hierarchically in systems of cities [Hagerstrand, 1968], potential explanation of urban scaling laws [Pumain et al., 2006]

Innovation diffusion as a privileged entry to understand urban evolution

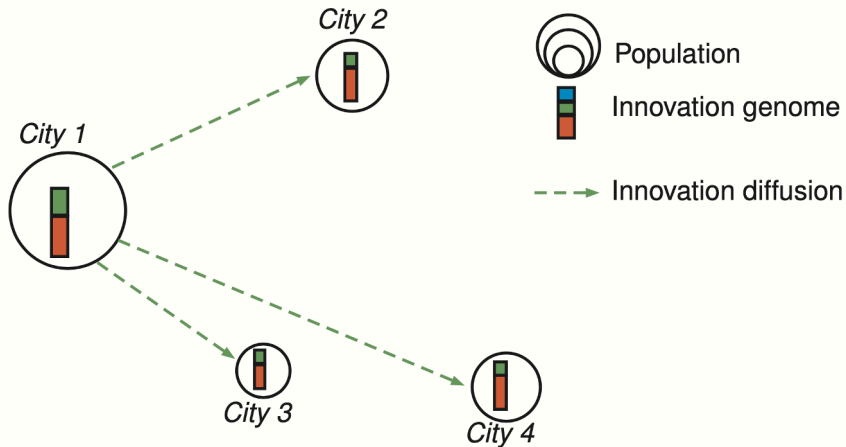
Model rationale

- Agents are cities, macroscopic scale (regional, country, continental) and long time scales (century)
- Cities characterized 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], attractiveness 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

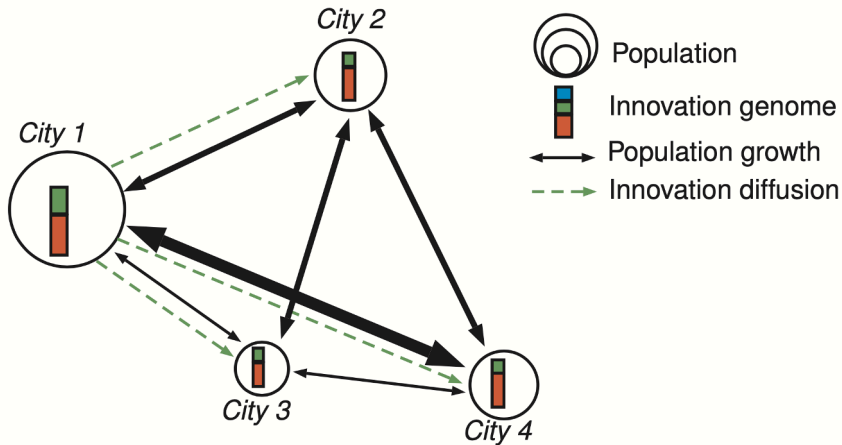
Model description



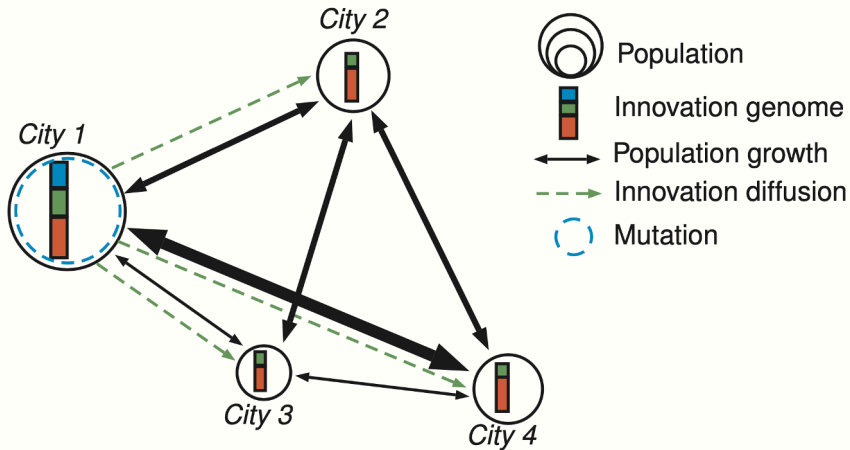
Model description



Model description



Model description



Model formalization

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

$$P_i(t) - P_i(t-1) = w_I \cdot \sum_j \frac{V_{ij}}{\langle V_{ij} \rangle} \text{ with}$$

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

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

- Average diversity

$$D = \frac{1}{t_f + 1} \sum_{t=0}^{t_f} \left(1 - \sum_{i,c} (p_{c,i,t})^2 \right)$$

- Average utility

$$U = \frac{1}{t_f + 1} \sum_{t=0}^{t_f} \sum_{i,c} \delta_{c,i,t} u_c$$

- Innovatitvity

$$I = \frac{\max c}{N \cdot (t_f + 1)}$$

- Population trajectories, summarized by final hierarchy [Raimbault, 2020d]

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

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

Model implemented in `scala`; relatively large parameter space

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



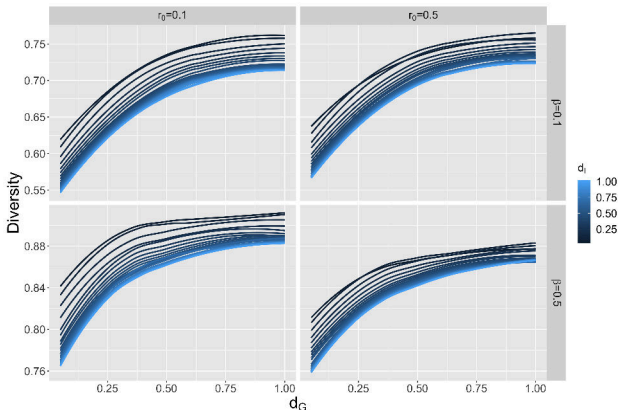
Enables seamlessly (i) model embedding; (ii) access to HPC resources; (iii) exploration and optimization algorithms

<https://openmole.org/>

- Latin Hypercube Sampling of 100 parameter points, 1000 replications for each
- Sharpe ratios have high values for all indicators and all parameters (minimum 1.7 for utility)
- Average and median relative distances defined as $\Delta_{ij} = 2 \frac{|\mu_i - \mu_j|}{\sigma_i + \sigma_j}$ larger than one for all indicators: 50 repetitions in further experiments

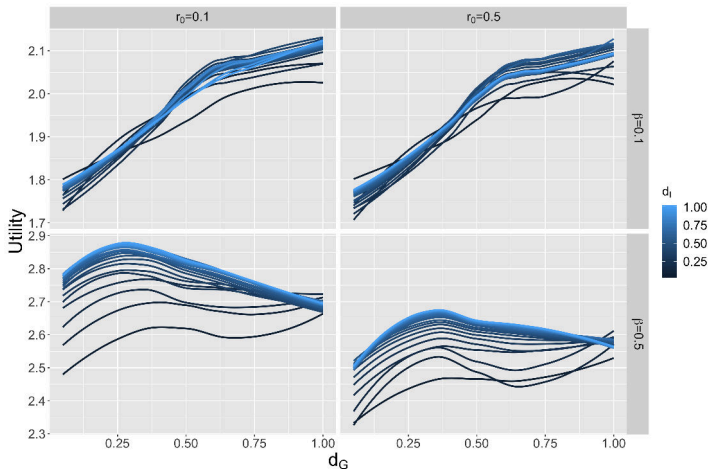
Model exploration: diversity

Grid sampling of the parameter space (23,168 points, 50 replications)
with a finer grid on d_G and d_I ; plots shown at $\alpha_I = 1$ and $\sigma_U = 1$



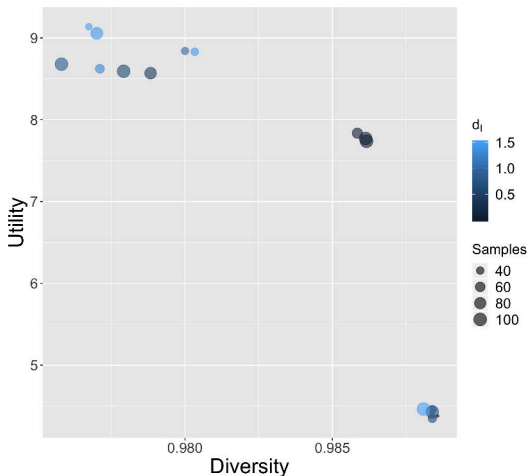
Diversity increases with interaction span with a plateau behavior, decreases with innovation diffusion span

Model exploration: utility



Piecewise behavior for low innovation rates; maximum as a function of d_G for high innovation: emergence of regional innovation clusters?

Model optimization



NSGA2 algorithm to simultaneously optimize utility and diversity: emergence of three compromise regimes; intermediate regime with low level of innovation diffusion

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

→ 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]

Application of the urban evolution model

→ 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:

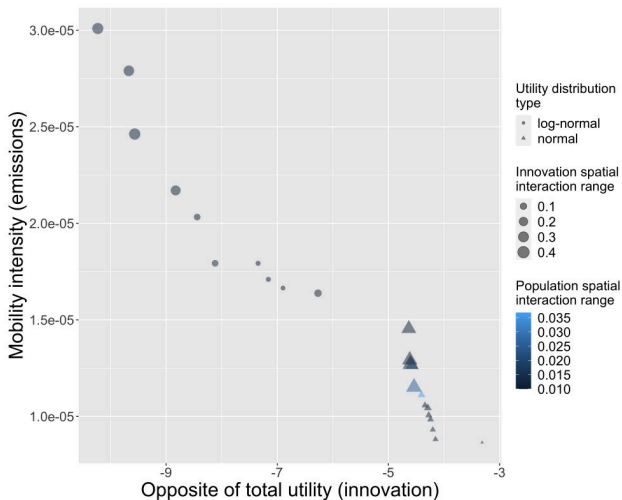
- 1 total utility of innovations

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

- 2 gravity mobility flows as proxy for emissions

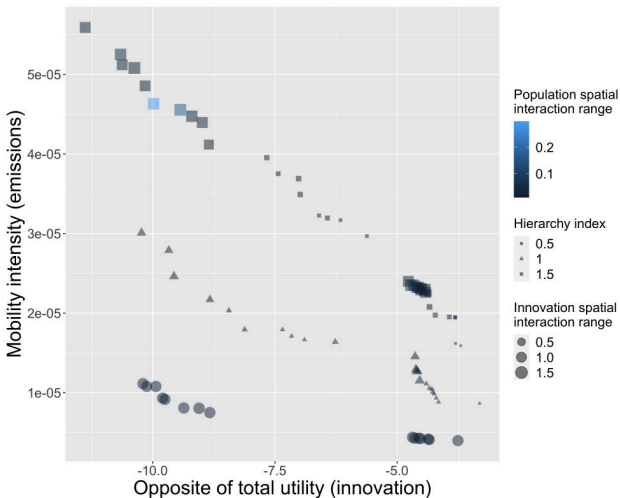
$$E = \sum_{t,i,j} \frac{P_{t,i} P_{t,j}}{P_t^2} \cdot \exp(-d_{ij}/d_G)$$

Trade-offs between SDG9 and SDG14



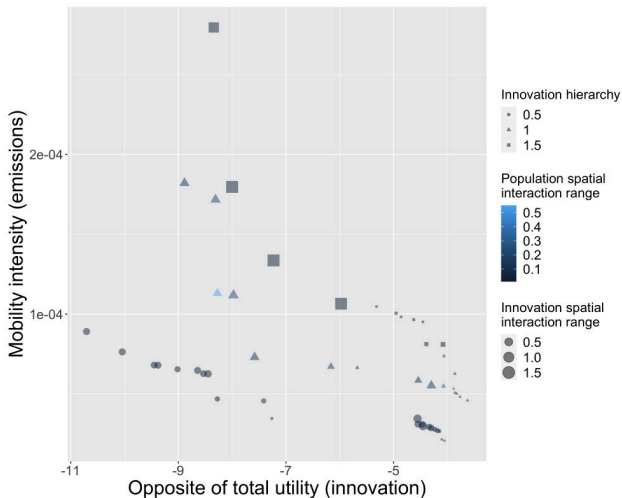
Pareto front confirms the existence of a trade-off

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)*

Extension and link with empirical data

Work in progress: empirical stylised facts on possible trade-offs in systems of cities; model parametrisation with real data (patents and spatialised emissions); extension to other SDGs.

Issues:





- 1 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]
- 2 Emissions: inter-urban mobility emissions difficult to capture (need an additional transport model?)
- 3 Additional dimensions: accessibility and public transport networks, economic prosperity and inequalities
 - coupling with other layers for these dimensions [Raimbault et al., 2020a]
 - many-objective optimisation? (NSGA3)





→ towards an integrative urban (territorial?) science applied to sustainable planning at multiple scales

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





Open repositories for





- Model and results:
<https://github.com/JusteRaimbault/UrbanEvolution>
- Simulation data: <https://doi.org/10.7910/DVN/Q5GKZ0>




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