Integrating urban models and theories

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CSH Workshop - Cities as Complex Systems
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1. Integration of urban models
2. Urban dynamics: trade-offs between SDGs
3. Multiple models of city growth

Large scale urban models are intrinsically flawed and do not reach their goals of long-term application to planning: **Requiem for large scale models in 1973** [Lee Jr, 1973]

Urban analytics and Smart Cities approaches may follow the same path if they ignore the past and the complexity of cities [Batty, 2014]

To foster relevance of large urban models:

- Transparency on data and implementation, reproducibility
- Validation of models and sub-models: from small simple models well validated to larger integrated models

→ Open, reproducible urban models can be shared, coupled into modular integrated models, tested and validated [Banos, 2013]

Proposed research framework

Sustainable urban systems: (i) multiple contradictory objectives; (ii) implemented by stakeholders at different scales, within various information and power contexts; (iii) adaptive on multiple time scales.

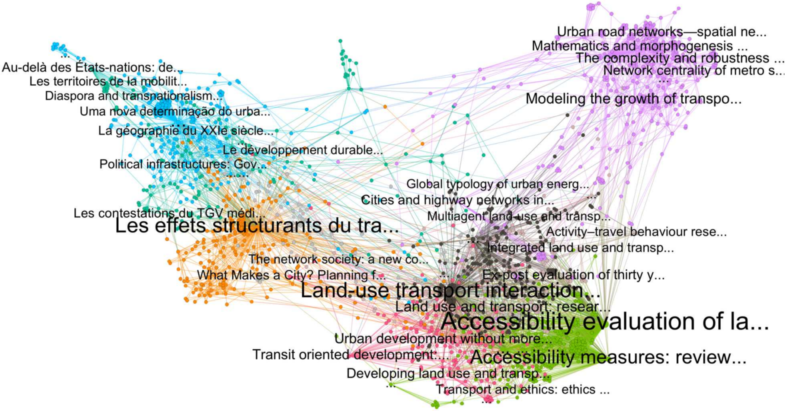
Models are essential tools to (i) capture complexity; (ii) construct integrated perspectives; (iii) link data, empirical stylised facts and decision-making.

$\rightarrow$ **Integrated models** to simulate multiple dimensions of **urban systems** towards decision-making in the context of **sustainable transitions**.

- Horizontal integration (model coupling and interdisciplinarity)
- Vertical integration (multi-scale models)
- Model exploration and validation methods

Horizontal integration: interdisciplinarity

Literature mapping and systematic review tools to enhance integration



Raimbault, J. (2019). Exploration of an interdisciplinary scientific landscape. Scientometrics, 119(2), 617-641.

Implementing horizontal model integration

Work in progress: *constructing a multimodal four step transport models by linking open components and data with scientific workflow engines*

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]

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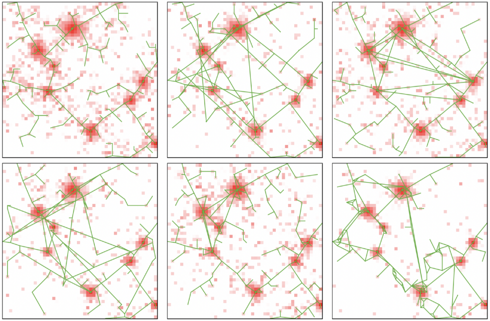
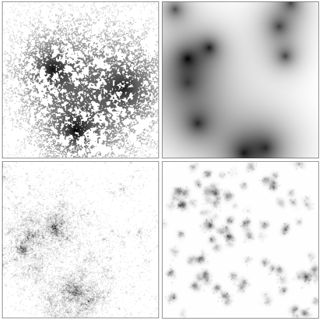
Horizontal integration: multi-modeling and benchmarks





Benchmarking network and urban morphogenesis models

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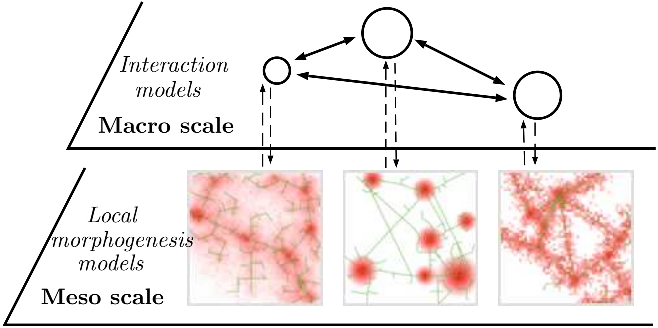
Vertical integration: towards multi-scale models



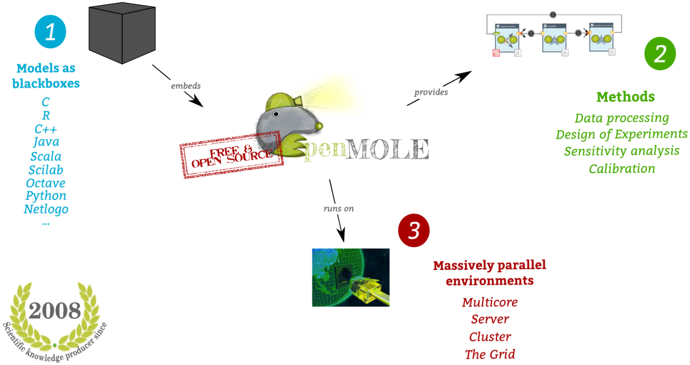
Processes specific to scales, coupling implies dedicated ontologies

Raimbault, J. (2021). Strong coupling between scales in a multi-scalar model of urban dynamics. arXiv preprint arXiv:2101.12725.

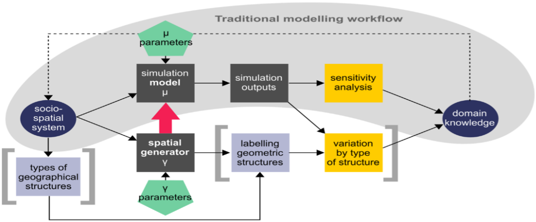
Raimbault, J. (2021). A multiscale model of urban morphogenesis. arXiv preprint arXiv:2103.17241.

Model exploration methods to foster knowledge integration

OpenMOLE software [Reuillon et al., 2013]: *(i) Innovative exploration methods; (ii) Scaling of methods on high performance computing environments; (iii) Scripts to embed and couple models.*



Validation: towards spatial sensitivity analysis



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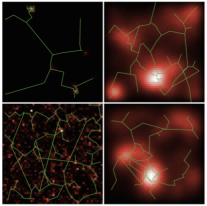
Raimbault, J., Perret, J., & Reuillon, R. (2020). A scala library for spatial sensitivity analysis. *GISRUK 2020 Proceedings, 32.*



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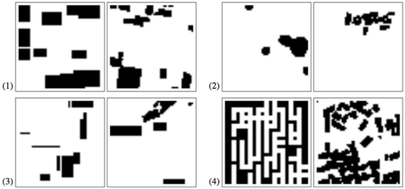

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SDG 11: "Make cities and human settlements inclusive, safe, resilient, and sustainable" [Nations, 2015]

→ 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]

Innovation diffusion and urban dynamics

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

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

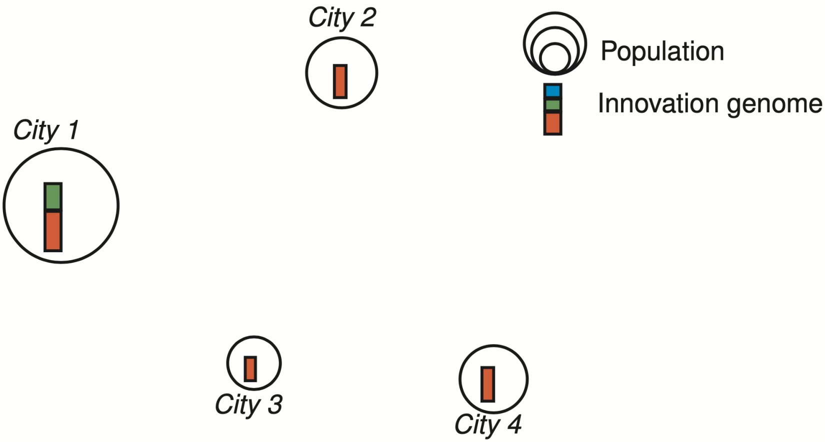
$\rightarrow$ Innovations diffuse hierarchically in systems of cities [Hagerstrand, 1968], potential explanation of urban scaling laws [Pumain et al., 2006]

Innovation diffusion as a privileged entry to understand urban evolution

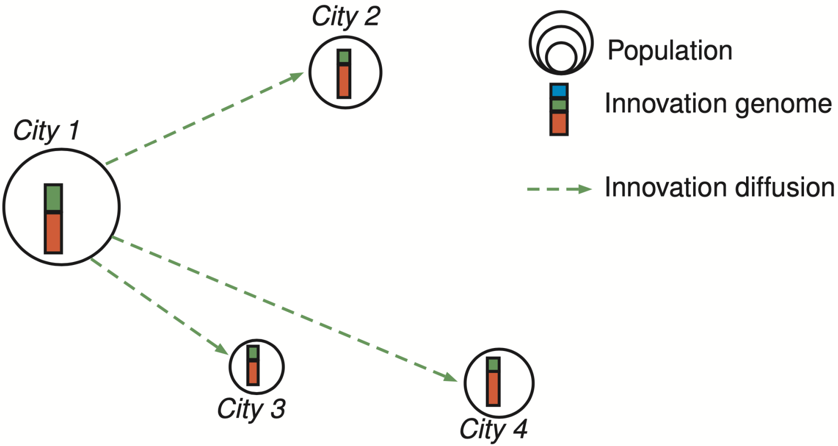
Model rationale

- 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

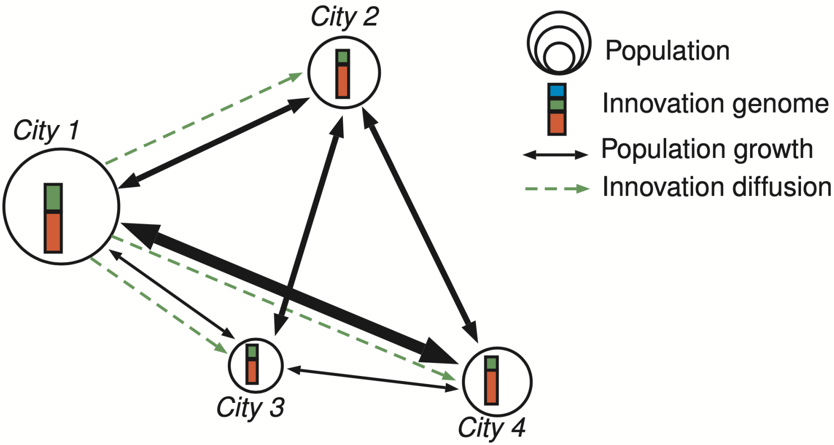
Model description



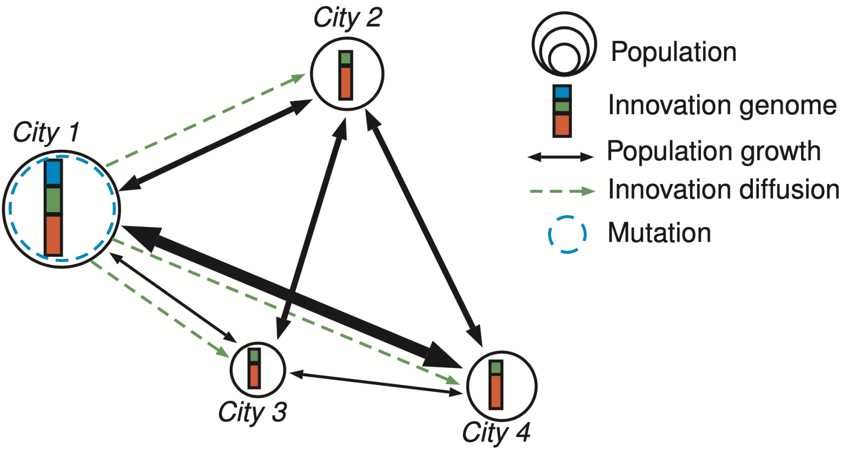
Model description



Model description



Model description



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)

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:

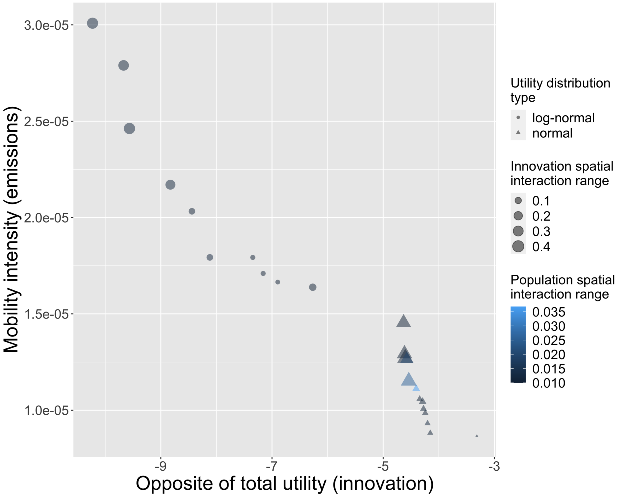
1. total utility of innovations

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

2. gravity mobility flows as proxy for emissions

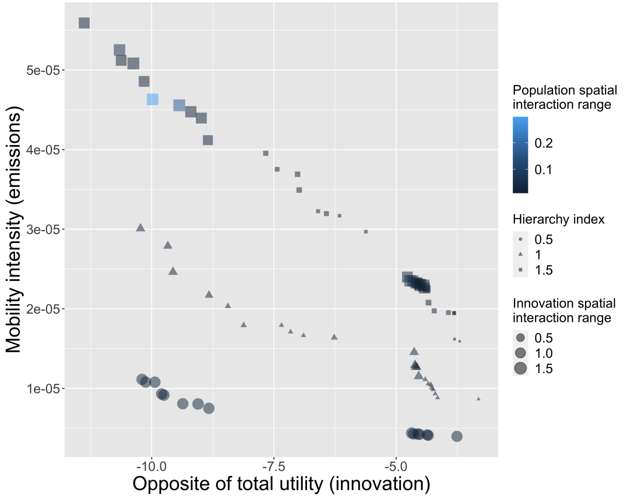
$$E = \sum_{t,i,j} \frac{P_{t,i} P_{t,j}}{P_t^2} \cdot \exp\left(-d_{ij}/d_G\right)$$

Trade-offs between SDG9 and SDG14



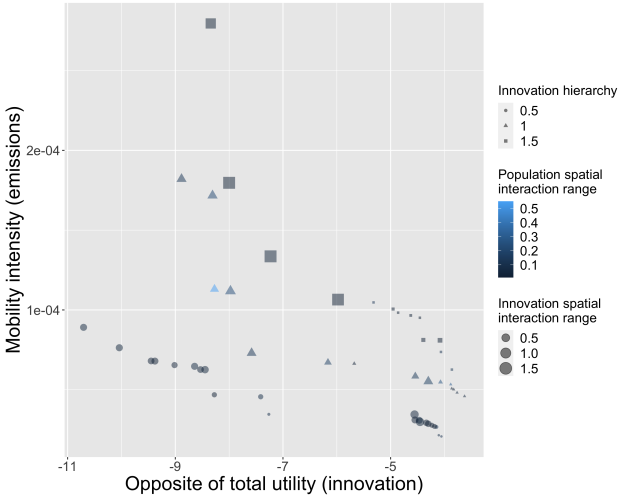
Pareto front confirms the existence of a trade-off

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)

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)

City growth models: Gibrat's legacy

Simple law for city population growth proposed by R. Gibrat in 1931 [Gibrat, 1931]

$$\frac{P_i(t+1) - P_i(t)}{P_i(t)} \sim \eta(t)$$

Proportional growth: growth rates statistical distribution independent of city size

→ Produces a log-normal size distribution [Eeckhout, 2004] (not a Pareto one - Zipf's law)

→ Extended model with minimal size for cities yields Zipf [Gabaix, 1999]; other model with heterogenous variances [Córdoba, 2008]

→ Empirical investigations confirm Gibrat's law seems to hold: US [Ioannides and Overman, 2003], France [Pumain and Moriconi-Ebrard, 1997], but not for China on some time periods [Ning et al., 2022]

→ Issues of city definition for estimation [Berry and Okulicz-Kozaryn, 2012] (as for scaling laws [Cottineau et al., 2017])

Simon and preferential attachment

Herbert Simon in 1955 proposed a model for city growth [Simon, 1955], which is analog to generalised preferential attachment with new entrants [Yamasaki et al., 2006]

→ Extended to include inter-city migrations [Haran and Vining Jr, 1973]

→ Link between Gibrat model and generalised preferential attachment [Raimbault, 2018a]: preferential attachment at the individual level with strength λ and new entrant probability m yields a Gibrat's law in the limit $\lambda \ll 1$ such that

$$\eta_i(t) = 1 + \frac{\lambda}{m \cdot (t-1)}$$

Models benchmarking and validation issues

More elaborated extensions of city growth models, including urban interactions:

Synergetics and migrations [Haag et al., 1992], urban dynamics based on spatial interactions [Pumain, 2012], stochastic model with Taylor's law (conditional variance scales with average) [James et al., 2018], stochastic model with migrations [Verbavatz and Barthelemy, 2020], ...

How to benchmark and validate models?

→ Validation criteria: stationary distribution of population, dynamics, migrations, other dimensions (social, economic), non-linear indicators (rank dynamics), qualitative behavior, ...?

→ Data construction and quality: see Geodivercity ERC project [Pumain, 2020]

→ Which geographical case studies: systems of cities, periods, definition of systems, of cities, ...? [Raimbault et al., 2020a]

→ Potential complementarity of models? Multi-modeling relevant at the mesoscopic scale for population density [Raimbault, 2020], road networks [Raimbault, 2021a], and building layouts [Raimbault and Perret, 2019]

Conclusion

→ **Integrated models** capturing complexity of **urban sustainability** towards **decision-making**.

→ **Robust** knowledge from models obtained with the development of **validation and exploration methods**.

→ **Complementarity** of perspectives, models and theories in an **interdisciplinary** context.

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

Presented model open source at
`https://github.com/JusteRaimbault/UrbanEvolution`

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