Integrating urban models and theories

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Modeling urban complexity

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.

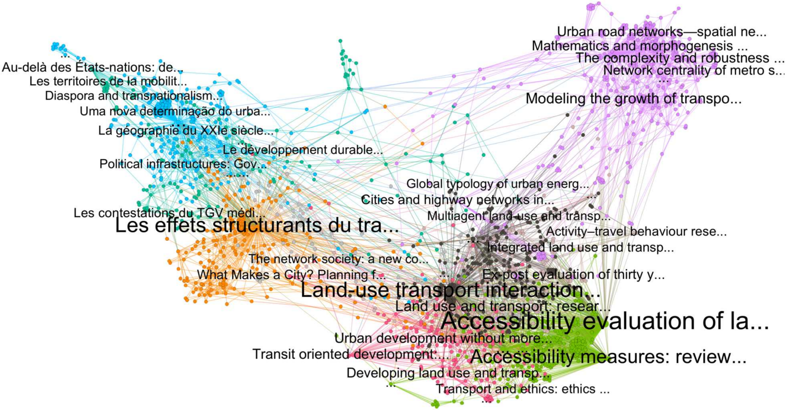
Models are essential tools to (i) capture complexity; (ii) construct integrated perspectives; (iii) link data, empirical stylised facts and decision-making.

$\rightarrow$ **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



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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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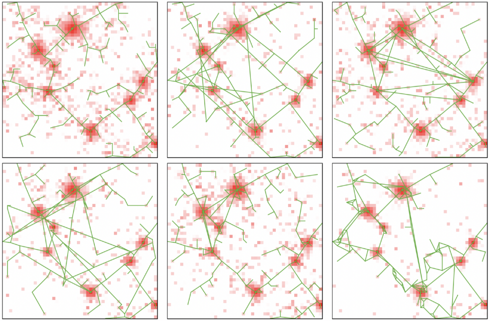
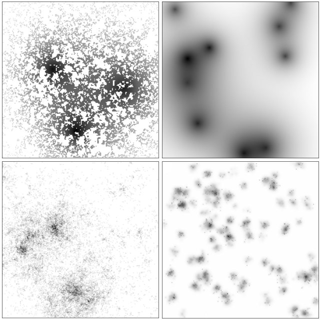
Horizontal integration: multi-modeling and benchmarks





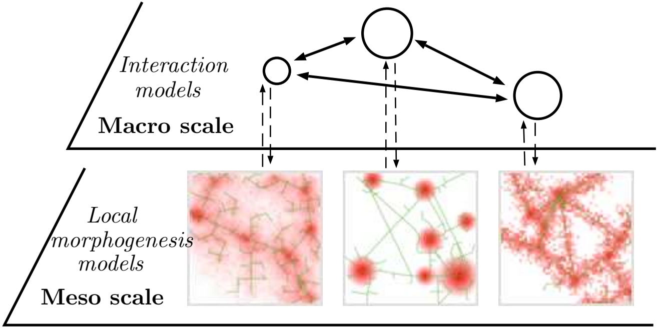
Benchmarking network and urban morphogenesis models

Raimbault, J. (2018). Multi-modeling the morphogenesis of transportation networks. In Artificial Life Conference Proceedings (pp. 382-383). MIT Press, Cambridge.

Raimbault, J. (2020). A comparison of simple models for urban morphogenesis. arXiv preprint arXiv:2008.13277.

Raimbault, J. (2021). Complementarity of generative models for road networks. arXiv preprint arXiv:2109.15206.

Vertical integration: towards multi-scale models



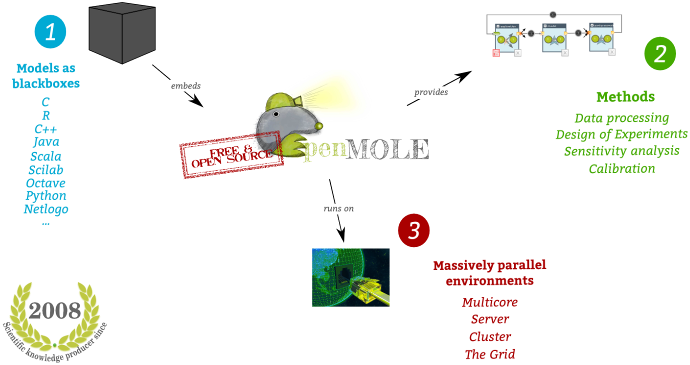
Processes specific to scales, coupling implies dedicated ontologies

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

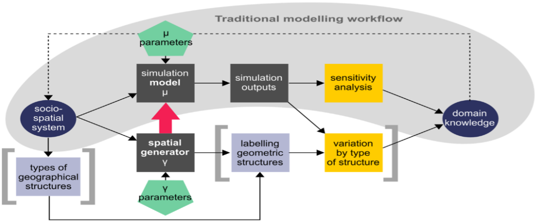
Raimbault, J. (2021). A multiscale model of urban morphogenesis. arXiv preprint arXiv:2103.17241.

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.*

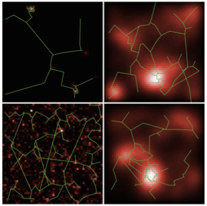


Validation: towards spatial sensitivity analysis

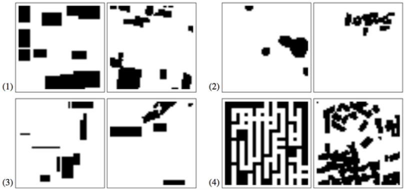


Raimbault, J., Cottineau, C., Le Texier, M., Le Nechet, F., Reuillon, R. (2019). Space Matters: Extending Sensitivity Analysis to Initial Spatial Conditions in Geosimulation Models. *Journal of Artificial Societies and Social Simulation*, *22*(4).

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



Raimbault, J. (2019). Second-order control of complex systems with correlated synthetic data. *Complex Adaptive Systems Modeling*, *7*(1), 1-19.



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1. Integration of urban models
2. Urban dynamics: trade-offs between SDGs
3. Multiple models of city growth

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

→ 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

→ **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]

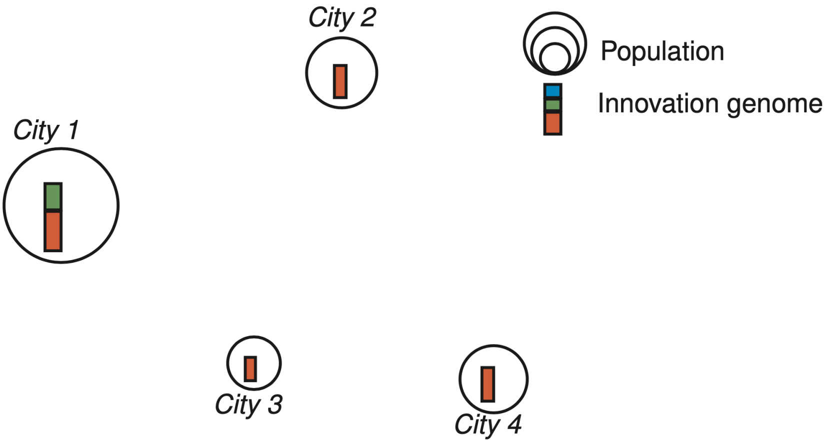
→ Innovations diffuse hierarchically in systems of cities [Hagerstrand, 1968], potential explanation of urban scaling laws [Pumain et al., 2006]

Innovation diffusion as a privileged entry to understand urban evolution

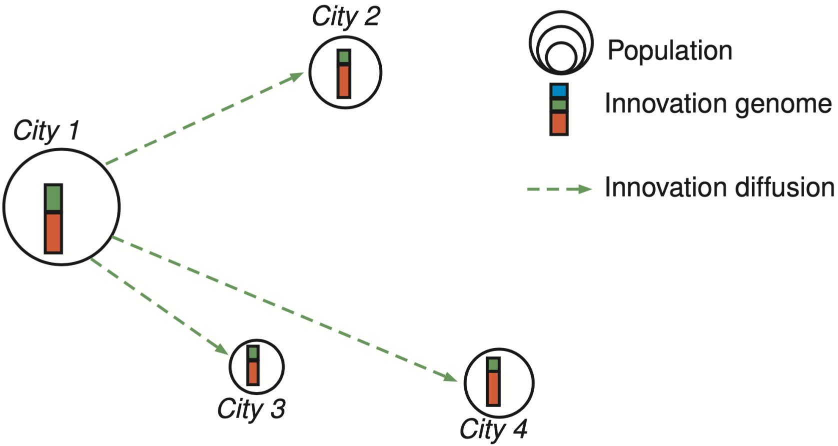
Model rationale

- 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

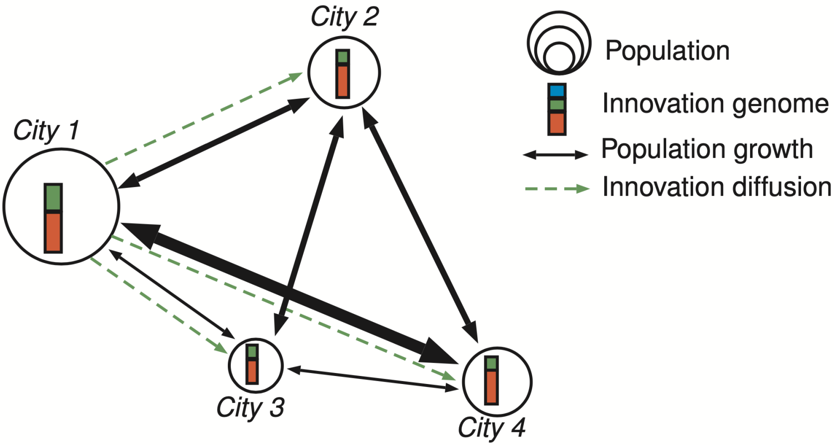
Model description



Model description



Model description



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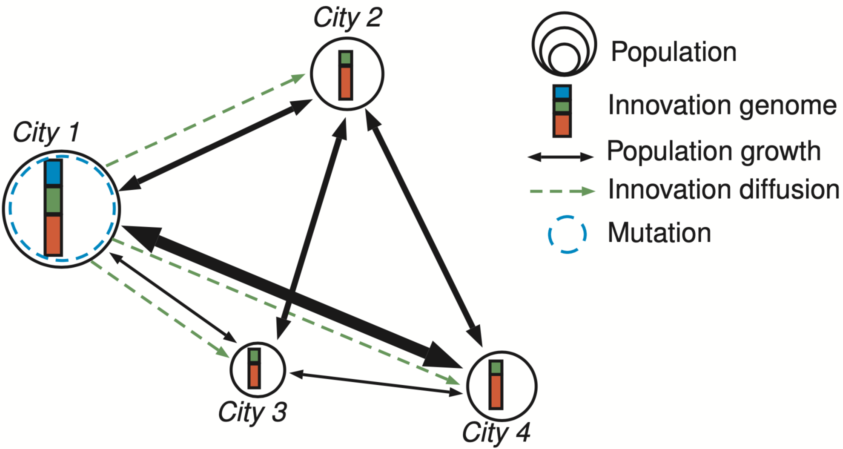


Model formalisation

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)

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:

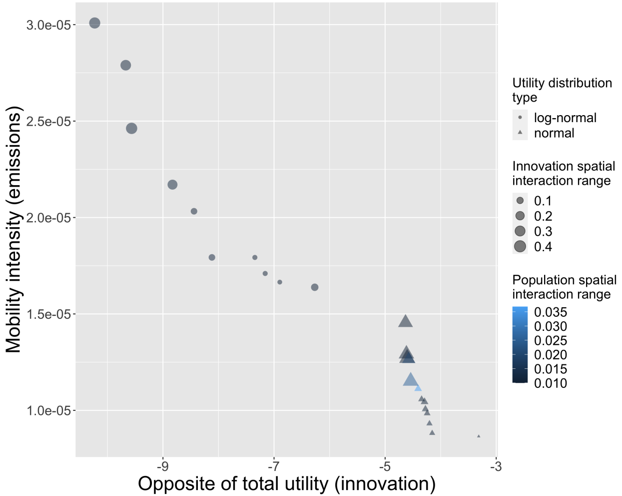
1. total utility of innovations

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

2. gravity mobility flows as proxy for emissions

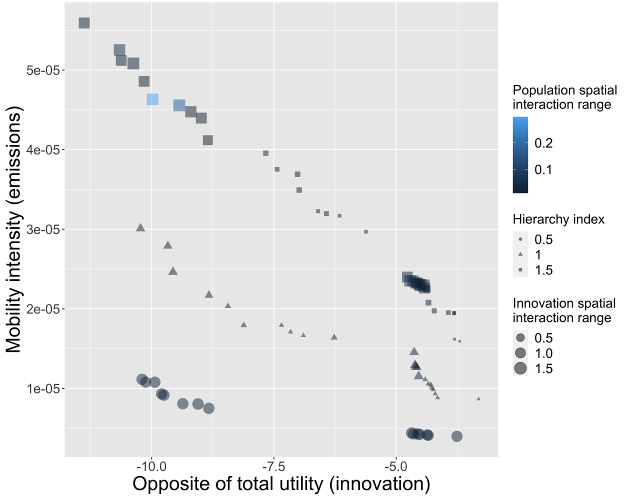
$$E = \sum_{t,i,j} \frac{P_{t,i} P_{t,j}}{P_t^2} \cdot \exp\left(-d_{ij}/d_G\right)$$

Trade-offs between SDG9 and SDG14



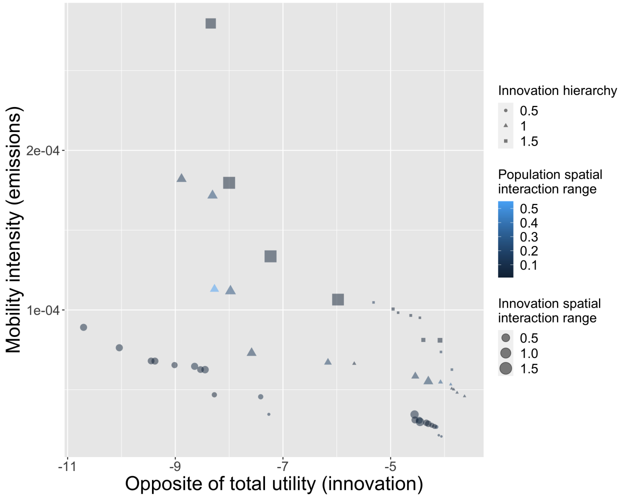
Pareto front confirms the existence of a trade-off

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)

Modèles de transport et modèles urbains

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Simple models of city growth

References I

Banos, A. (2013).
Pour des pratiques de modélisation et de simulation libérées en géographie et SHS.
PhD thesis, Université Paris 1 Panthéon Sorbonne.

Batty, M. (2014).
Can it happen again? planning support, lee's requiem and the rise of the smart cities movement.
Environment and Planning B: Planning and Design, 41(3):388–391.

Batty, M. and Milton, R. (2021).
A new framework for very large-scale urban modelling.
Urban Studies, 58(15):3071–3094.

References II

Bedau, M. A., McCaskill, J. S., Packard, N. H., Rasmussen, S., Adami, C., Green, D. G., Ikegami, T., Kaneko, K., and Ray, T. S. (2000).
Open problems in artificial life.
Artificial life, 6(4):363–376.

Bergeaud, A., Potiron, Y., and Raimbault, J. (2017).
Classifying patents based on their semantic content.
PloS one, 12(4):e0176310.

Bergeaud, A. and Verluise, C. (2021).
Patentcity: A century of innovation: New data and facts.

De Rassenfosse, G., Kozak, J., and Seliger, F. (2019).
Geocoding of worldwide patent data.
Scientific data, 6(1):1–15.

References III

Dinda, S. (2004).
Environmental kuznets curve hypothesis: a survey.
Ecological economics, 49(4):431–455.

Favaro, J.-M. and Pumain, D. (2011).
Gibrat revisited: An urban growth model incorporating spatial interaction and innovation cycles.
Geographical Analysis, 43(3):261–286.

Fotheringham, A. S. and O'Kelly, M. E. (1989).
Spatial interaction models: formulations and applications, volume 1.
Kluwer Academic Publishers Dordrecht.

Hagerstrand, T. (1968).
Innovation diffusion as a spatial process.
Innovation diffusion as a spatial process.

Harbaugh, W. T., Levinson, A., and Wilson, D. M. (2002).
Reexamining the empirical evidence for an environmental kuznets curve.
Review of Economics and Statistics, 84(3):541–551.

Lee Jr, D. B. (1973).
Requiem for large-scale models.
Journal of the American Institute of planners, 39(3):163–178.

Pumain, D., Paulus, F., Vacchiani-Marcuzzo, C., and Lobo, J. (2006).
An evolutionary theory for interpreting urban scaling laws.
Cybergeo: European Journal of Geography.

Raimbault, J. (2018).
Multi-modeling the morphogenesis of transportation networks.
In *European Conference on Artificial Life (ALIFE 2018)*, volume 2018, pages 382–383. MIT Press.

References V

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

Raimbault, J. (2019b).
Second-order control of complex systems with correlated synthetic data.
Complex Adaptive Systems Modeling, 7(1):1–19.

Raimbault, J. (2020).
A comparison of simple models for urban morphogenesis.
arXiv preprint arXiv:2008.13277.

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Complementarity of generative models for road networks.
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arXiv preprint arXiv:2104.14359.

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

Raimbault, J., Denis, E., and Pumain, D. (2020a).
Empowering urban governance through urban science: Multi-scale dynamics of urban systems worldwide.
Sustainability, 12(15):5954.

Raimbault, J. and Perret, J. (2019).
Generating urban morphologies at large scales.
In *The 2019 Conference on Artificial Life*, pages 179–186. MIT Press.

Raimbault, J., Perret, J., and Reuillon, R. (2020b).
A scala library for spatial sensitivity analysis.
arXiv preprint arXiv:2007.10667.

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.

Spooner, F., Abrams, J. F., Morrissey, K., Shaddick, G., Batty, M., Milton, R., Dennett, A., Lomax, N., Malleson, N., Nelissen, N., et al. (2021).
A dynamic microsimulation model for epidemics.
Social Science & Medicine, 291:114461.

Stern, D. I. (2004).
The rise and fall of the environmental kuznets curve.
World development, 32(8):1419–1439.

Viguié, V. and Hallegatte, S. (2012).
Trade-offs and synergies in urban climate policies.
Nature Climate Change, 2(5):334–337.

W Axhausen, K., Horni, A., and Nagel, K. (2016).
The multi-agent transport simulation MATSim.
Ubiquity Press.

Zenobia, B., Weber, C., and Daim, T. (2009).
Artificial markets: A review and assessment of a new venue for innovation research.
Technovation, 29(5):338–350.