Spatial sensitivity analysis of social simulation models

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Validation of simulation models

Typology of **validation methods for simulation models** from a systematic review [Raimbault, 2023]

- prediction
- sensitivity analysis
- uncertainty
- multiple/mixed methods
- benchmark
- calibration
- optimisation
- visualisation
- Pattern Oriented Modelling
- participatory
- exploration
- surrogate

$\rightarrow$ *Methods, standards and definitions strongly depend on disciplines and model functions [Raimbault, 2019c]*

Specificities of socio-spatial systems

→ Spatio-temporal non-stationarity and non-ergodicity [Raimbault, 2019b]

→ Fuzzy and noisy data [Olteanu-Raimond et al., 2015]

→ Genericity/specificity of patterns and processes [Raimbault et al., 2020a]

→ Modifiable Areal Unit Problem [Wong, 2004]

→ Multiscalar systems [Raimbault, 2021b]

Spatial sensitivity analysis

Spatial configurations are model parameters too

- "*Space matters*": impact of spatial configuration on model behavior
- Model behaviours which are robust to spatial configuration
- Model behaviours which are robust to noise in real datasets

$\Longrightarrow$ ***Construction of a generic methodology for spatial sensitivity analysis, including the generation of synthetic data, perturbation of real data and indicators***

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.

Synthetic data: general context

$\rightarrow$ coupling models with spatial configuration generators (spatial synthetic data) gives model sensitivity to space through sensitivity analysis of the coupled model

$\rightarrow$ synthetic urban forms resembling real configurations

$\rightarrow$ at different scales: microscopic (buildings), mesoscopic (population distribution), macroscopic (system of cities)

Synthetic building layouts

At the microscopic scale (district): generating building layouts

- systematic comparison of simple processual generators for building configurations
- introduction of morphological indicators
- calibration on sampled layouts from OpenStreetMap

Raimbault, J., & Perret, J. (2019, July). Generating urban morphologies at large scales. In Artificial Life Conference Proceedings (pp. 179-186). MIT Press.

Synthetic population grids

At the mesoscopic scale: population grids

- a reaction-diffusion model for population distributions
- urban form measures at the mesoscopic scale
- synthetic generators coupling population and road networks

Raimbault, J. (2018). Calibration of a density-based model of urban morphogenesis. PloS one, 13(9), e0203516.

Raimbault, J. (2019). An urban morphogenesis model capturing interactions between networks and territories. In The Mathematics of Urban Morphology (pp. 383-409). Birkhäuser, Cham.

Synthetic systems of cities

At the macroscopic scale: synthetic systems of cities

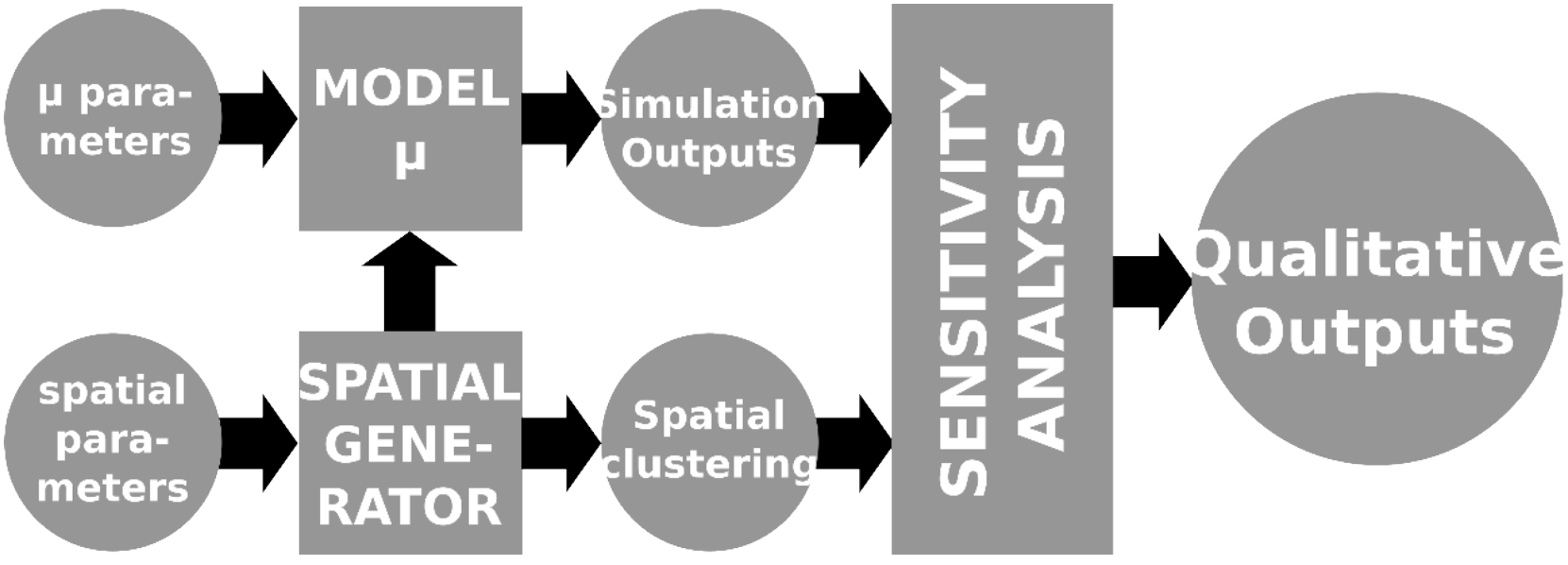
- Evolutive urban theory: systems of cities follow general stylised facts [Pumain, 2018]
- Rank-size law [Pumain et al., 2006]
- Central place theory

$\rightarrow$ *Cities-network co-evolution model explored on synthetic systems of cities*

Raimbault, J. (2021). Modeling the co-evolution of cities and networks. In Handbook of Cities and Networks (pp. 166-193). E. Elgar.

Spatial sensitivity analysis

Generic workflow to test the spatial sensitivity of simulation models



→ Application on the Schelling and Sugarscape models, showing important effects of the spatial configuration

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).

Implementation: integration into OpenMOLE

Library implemented in `scala`: advantages of functional and object programming; Apache Spark; no widely used GIS library in scala.

`https://github.com/openmole/spatialdata`

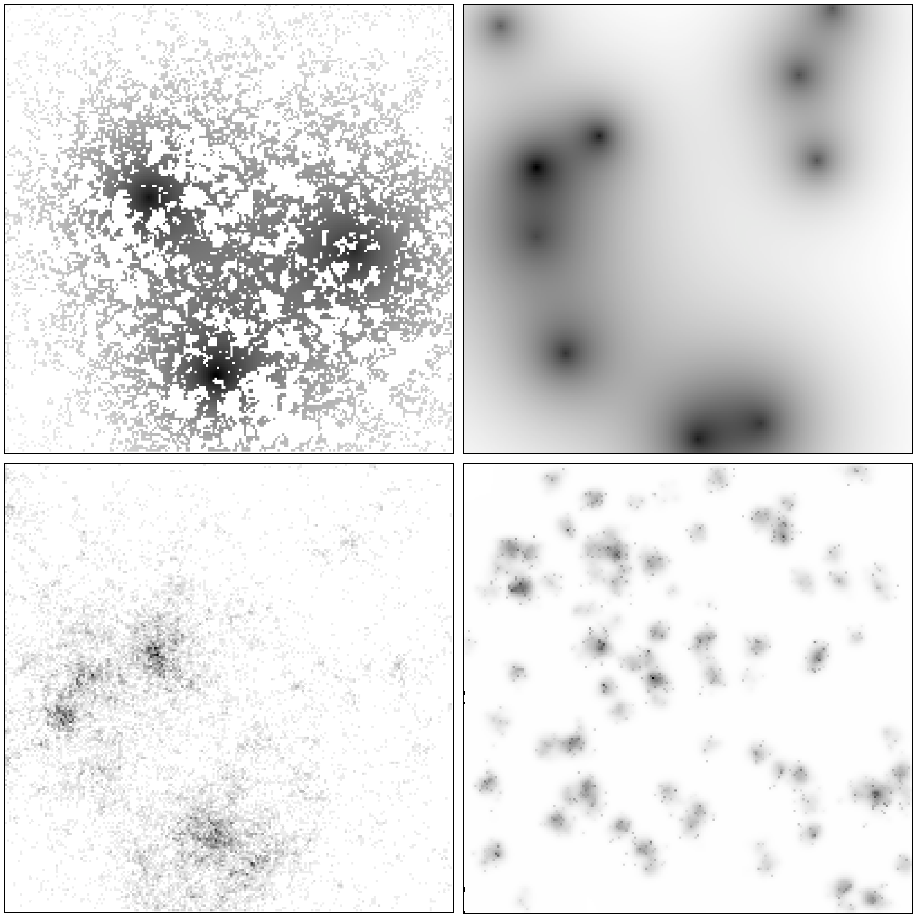
$\rightarrow$ integration into the OpenMOLE model exploration open source software [Reuillon et al., 2013]

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

`https://openmole.org/`

Benchmarking population generators

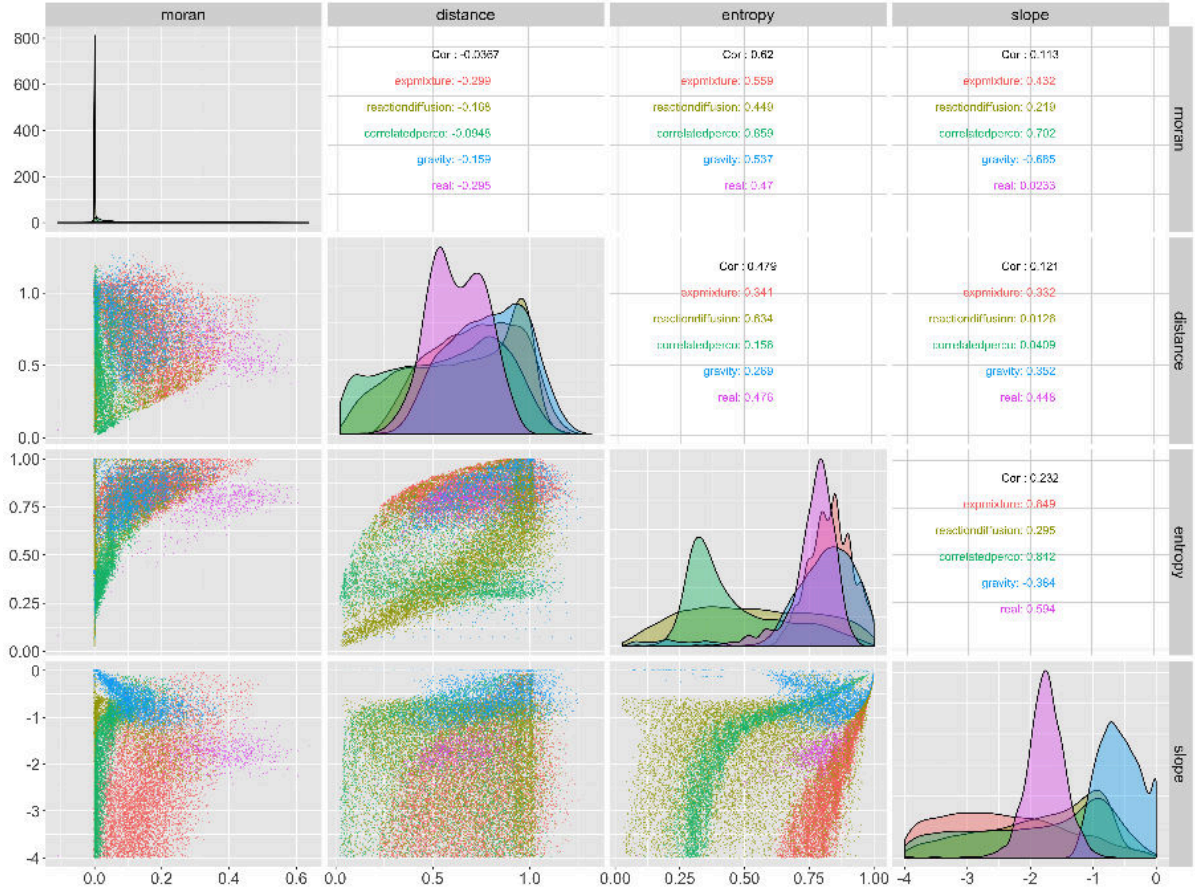
Which complementarity of different urban form generators at the mesoscopic scale (population distribution)?



Comparison of kernel mixture, reaction-diffusion [Raimbault, 2018a], gravity-based model [Li et al., 2021] and correlated percolation [Makse et al., 1998]

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

Complementary feasible space of generators



A diversity-search algorithm [Chérel et al., 2015] provides feasible morphological spaces of the urban morphogenesis models, showing complementarity.

Real data perturbation

→ *How does noise in real data impacts the result ?*

- Impact of missing elements
- Impact of imprecise coordinates or topology
- Matching between spatial datasets to mitigate noise

→ *How does perturbation of real data allows to explore scenarios*

$\Longrightarrow$ spatial sensitivity analysis based on noise propagation between perturbed real input data and simulation models

Issue: "spatial noise" is specific to each type of spatial structure and does not follow standard distributions (for example road networks or building polygons)

→ **how to define small variations in the morphological space?**

Example of spatial noise: BDTopo

Map of Strasbourg building evolution (2012-2022) using IGN BDTopo: change in data specifications leads to split polygons, apparitions of artefacts, perturbations of polygons boundaries

(see Subdense project: `https://github.com/subdense`)

Towards variance-based indicators

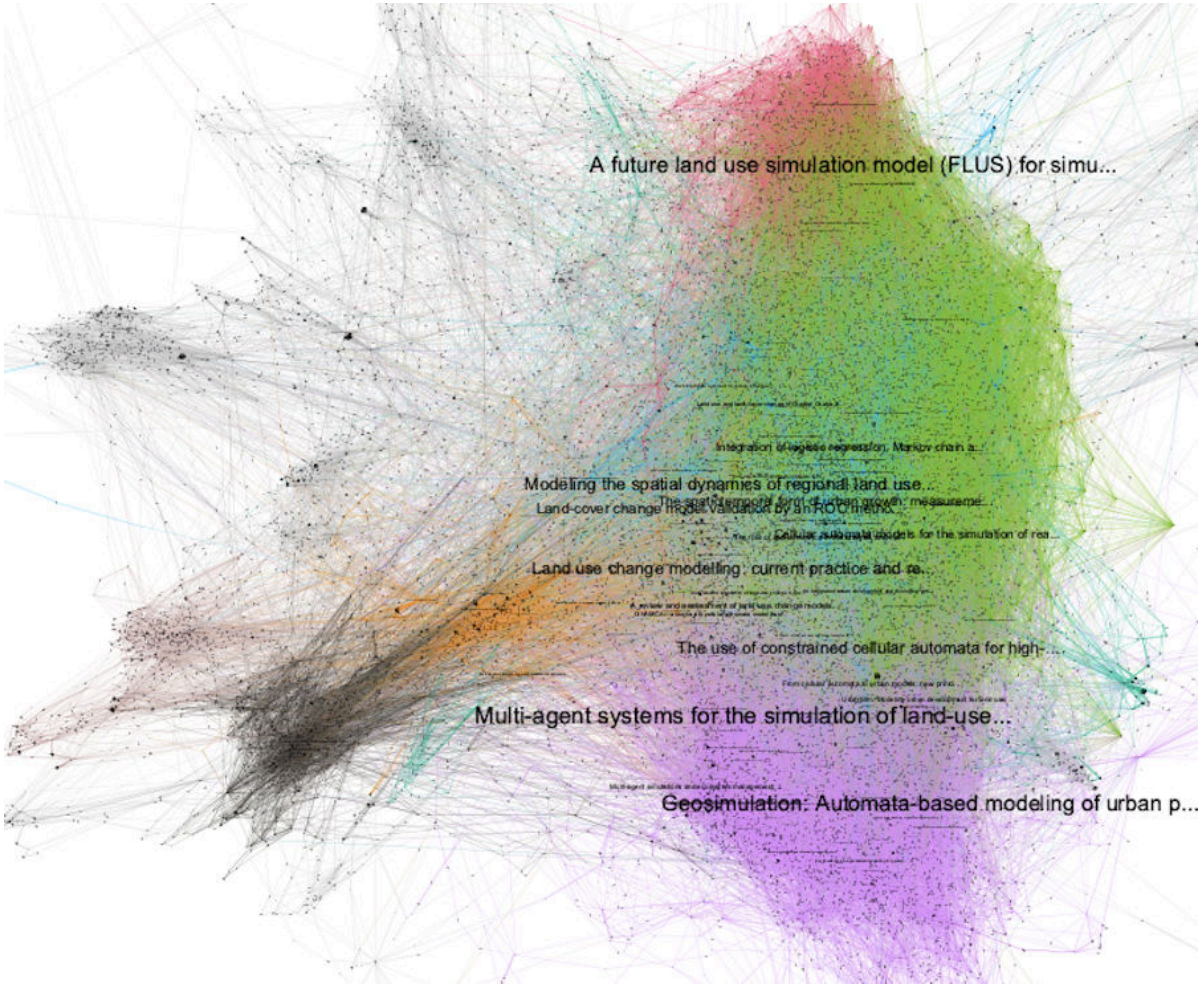
Global Sensitivity Analysis methods [Saltelli et al., 2008] introduce interpretable indicators based on conditional variances, with a robust theoretical statistical background, and are widely established for simulation models

→ *How to compute such indicators with spatial configuration as a parameter?*

→ *For the estimation to be correct, the full space must be sampled with a high discrepancy (using high-dimensional sequences for standard parameters).*

→ *Use diversity search to sample the feasible space of generators, compare with meta-parameter sampling; current application to the Schelling model to compare with the ad-hoc indicators of spatial sensitivity analysis based on distance between phase diagrams.*

Interdisciplinary systematic review



Systematic literature review and mapping of validation methods for simulation methods [Raimbault, 2023]

$\rightarrow$ link with similar approaches in other disciplines such as environmental science dealing with e.g. spatial uncertainty [Koo et al., 2020]

$\rightarrow$ link with approaches focusing more on uncertainty due to processes? (see presentation yesterday by C. De Bezenac)

Discussion: more open questions

- network generative models [Raimbault, 2018b], correlated synthetic data [Raimbault, 2019a]
- domain models: LUTI, urban dynamics
- other disciplines: ecology [Koo et al., 2020], geosciences [Mogheir et al., 2004]?
- link with data driven disciplines ? (planning, architecture, spatio-temporal datamining)
- genericity of some models? (reaction-diffusion)
- synthetic data generation methods (synthetic populations)
- synthetic data at the core of applied statistics methodology (less in spatial statistics?)
- port the library to more classic languages (python, R)

Conclusion

→ **Space matters:** relevance of spatially-explicit models and spatial sensitivity analysis for social simulation.

→ **Generic methodology:** generators included in OpenMOLE, and current and future developments of the `spatialdata` library will be continuously integrated.

→ **Disciplinary context:** need interdisciplinary feedback and more methods and models transfers.

Get the library at `https://github.com/openmole/spatialdata`

Use OpenMOLE `https://openmole.org`

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