Benchmarking road network growth models

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ECTQG 2021
Special Session: Exploration and validation of spatial simulation models
November 4th 2021

Modeling road network growth

Road networks functionally shaping territories [Dupuy, 1987]

$\rightarrow$ path-dependence and implications for sustainable territorial systems on multiple time scales

Multiple driving processes [Barthelemy et al., 2013]

$\rightarrow$ which models to understand such growth?

Examples of transportation network growth models:

- Transportation governance [Raimbault and Le Néchet, 2021]
- Investments in public transport [Cats et al., 2020]
- Multi-modal networks [Cats and Birch, 2021]
- Bicycle networks design [Szell et al., 2021]
- Network morphogenesis [Tirico et al., 2018]
- Geometrical processes [Courtat et al., 2011]

$\rightarrow$ Models proposed in the literature are validated/explored in their own context, often not compared beyond null models

$\rightarrow$ Need for model benchmarks to build integrated theories

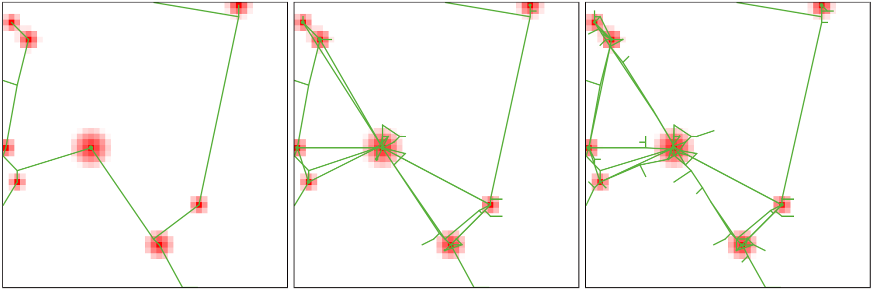
Research objective:

Compare road network growth models with diverse types of processes, integrated into a common multi-modeling framework, with a focus on feasible space using a diversity search algorithm

Road network generation multi-model

At each time step, with a fixed population density:

1. Add new nodes preferentially to population and connect them
2. Variable heuristic for new links, among: nothing, random, **gravity-based deterministic breakdown** [Raimbault, 2019a], gravity-based random breakdown ([Schmitt, 2014]), cost-benefits ([Louf et al., 2013]), **biological network generation** ([Tero et al., 2010])



Deterministic breakdown link addition

Model explored in [Raimbault, 2019a]

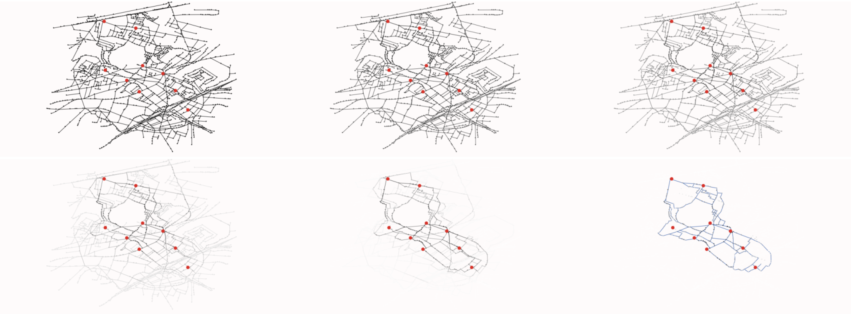
1. Gravity potential given by

$$V_{ij}\left(d\right)=\left[\left(1-k_h\right)+k_h\cdot\left(\frac{P_iP_j}{P^2}\right)^{\gamma}\right]\cdot\exp\left(-\frac{d}{r_g\left(1+d/d_0\right)}\right)$$

2. $k \cdot N_L$ links are selected with lowest $V_{ij}\left(d_N\right)/V_{ij}\left(d_{ij}\right)$ (strong demand compared to offer), among which the N_L links with this highest rate (lest costly links) are realised
3. Network is planarised

Biological network link addition

Model introduced by [Tero et al., 2010]: exploration and reinforcement by a slime mould searching for ressources

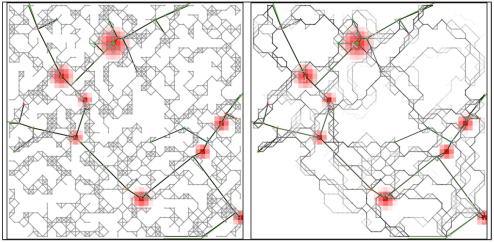


Application to the design of optimal bus routes in [Raimbault, 2018a]

Biological network link addition

Adding new links with biological heuristic:

1. Create network of potential new links, with existing network and randomly sampled diagonal lattice
2. Iterate for k increasing ($k \in \{1, 2, 4\}$ in practice) :
   - Using population distribution, iterate $k \cdot n_b$ times the slime mould model to compute new link capacities
   - Delete links with capacity under θ_d
   - Keep the largest connected component
3. Planarize and simplify final network



Intermediate stage for biological network generation

Model parameters

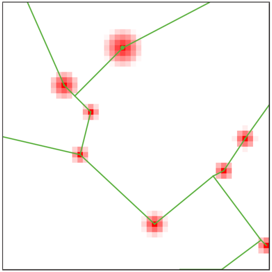
Heuristic	Param.	Name	Process	Domain	Default
Base	l_m	added links	growth	0; 100	10
	d_G	gravity distance	potential	0; 5000	500
	d_0	gravity shape	potential	0; 10	2
	k_h	gravity weight	potential	0; 1	0.5
	γ_G	gravity hierarchy	potential	0.1; 4	1.5
Random	γ_R	random selection	hierarchy	0.1; 4	1.5
	θ_R	random threshold	breakdown	1; 5	2
Cost-benefits	λ	compromise	compromise	0; 0.1	0.05
Biological	n_b	iterations	convergence	40; 100	50
	θ_b	biological th.	threshold	0.1; 1.0	0.5

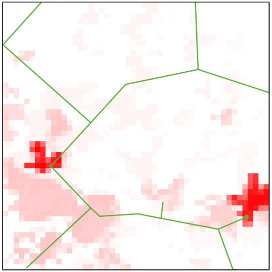
Model setup

Synthetic setup: rank-sized monocentric cities, simple connection with bord nodes to avoid bord effects

Real setup: Population density raster at 500m resolution (European Union, from Eurostat)

Initial network: skeleton connecting centres





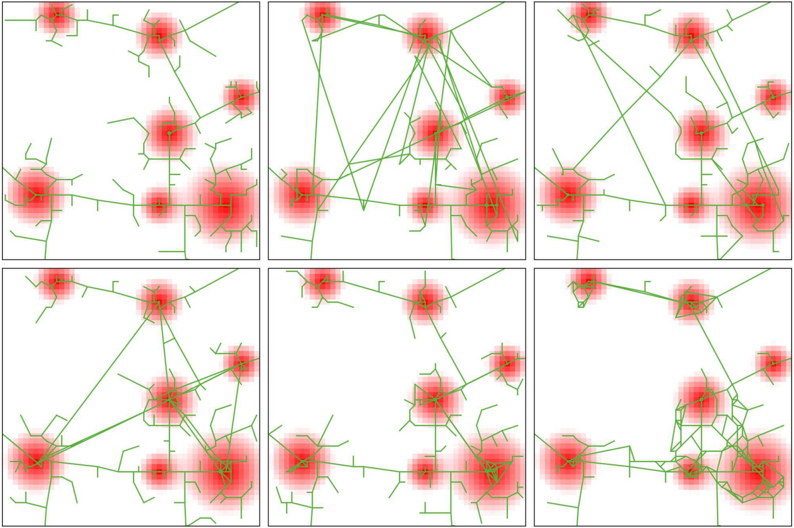
Stopping conditions: fixed network size or maximal steps

Network Indicators

Network Topology measured by:

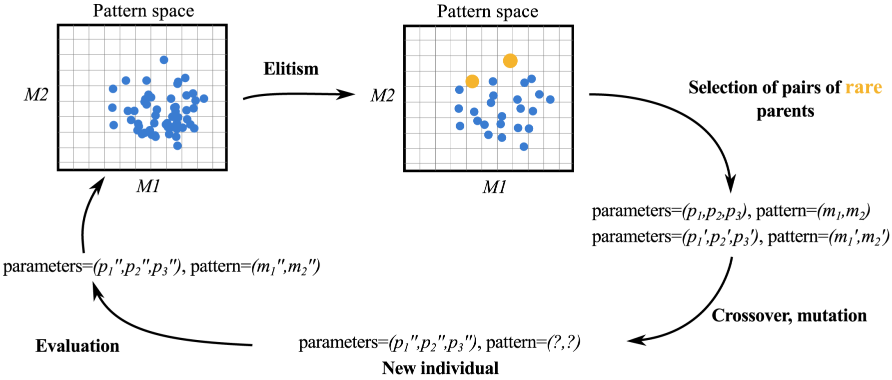
- Average betweenness and closeness centralities
- Efficiency (network pace relative to euclidian distance)
- Mean path length, diameter

Example of generated networks



In order: connection; random; deterministic breakdown; random breakdown; cost-driven; biological.

Pattern Space Exploration algorithm



Source: [Chérel et al., 2015]

OpenMOLE integration

→ Models implemented in NetLogo (scala implementation in progress [Raimbault et al., 2020])

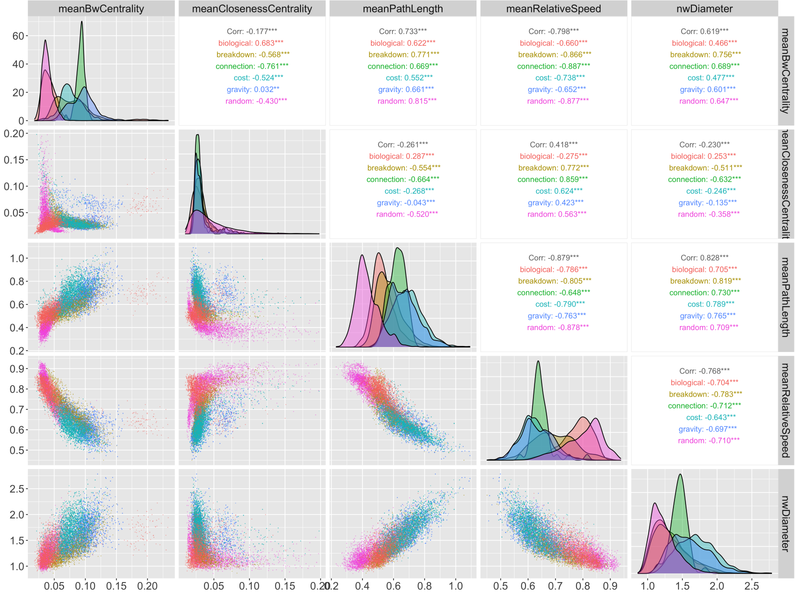
→ Integrated into OpenMOLE model exploration open source software [Reuillon et al., 2013]

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

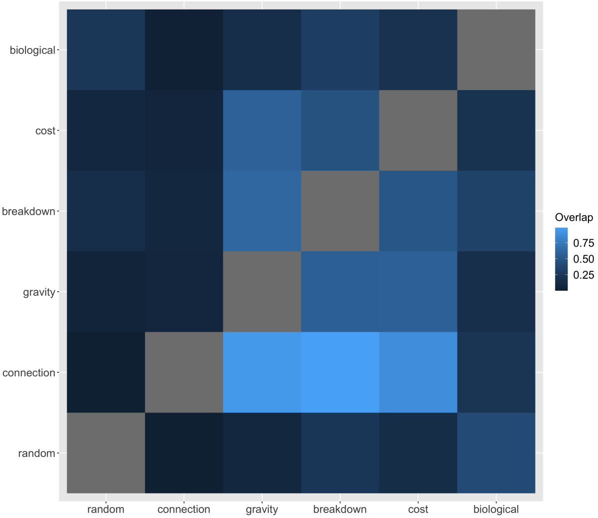
`https://openmole.org/`

→ PSE run separately for each model for 5000 generations

Indicators feasible space



Hypervolume intersections



Directed relative overlaps between estimated hypervolumes of point clouds

Discussion

$\rightarrow$ Complementarity of models to generate diverse networks: models not only with different purposes but also "output contexts"

$\rightarrow$ Comparison with real networks / calibration (work in progress on GHS FUAs, see [Raimbault, 2019b] for OSM 50km windows)

$\rightarrow$ Extension with other models [Molinero and Hernando, 2020] [Tirico et al., 2018] (work in progress)

$\rightarrow$ Diversity search algorithms and dimensionality reduction (work in progress)

$\rightarrow$ Application: link between calibrated parameters and sustainability indicators? [Raimbault, 2018b]

Conclusion

$\rightarrow$ Complementarity of models and processes for road network growth (similar result for population density morphogenesis [Raimbault, 2020]

$\rightarrow$ Which models to integrate? Open science/platforms for model sharing and benchmarking; typology/classification of processes, models, disciplines?

Use and contribute to OpenMOLE

`https://openmole.org`

Open repository

`https://github.com/JusteRaimbault/NetworkGrowth`

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