Multi-modeling the morphogenesis of transportation networks

J. Raimbault[1,2,*]

juste.raimbault@iscpif.fr

[1]Complex Systems Institute, Paris, UPS CNRS 3611 ISC-PIF
[2]UMR CNRS 8504 Géographie-cités

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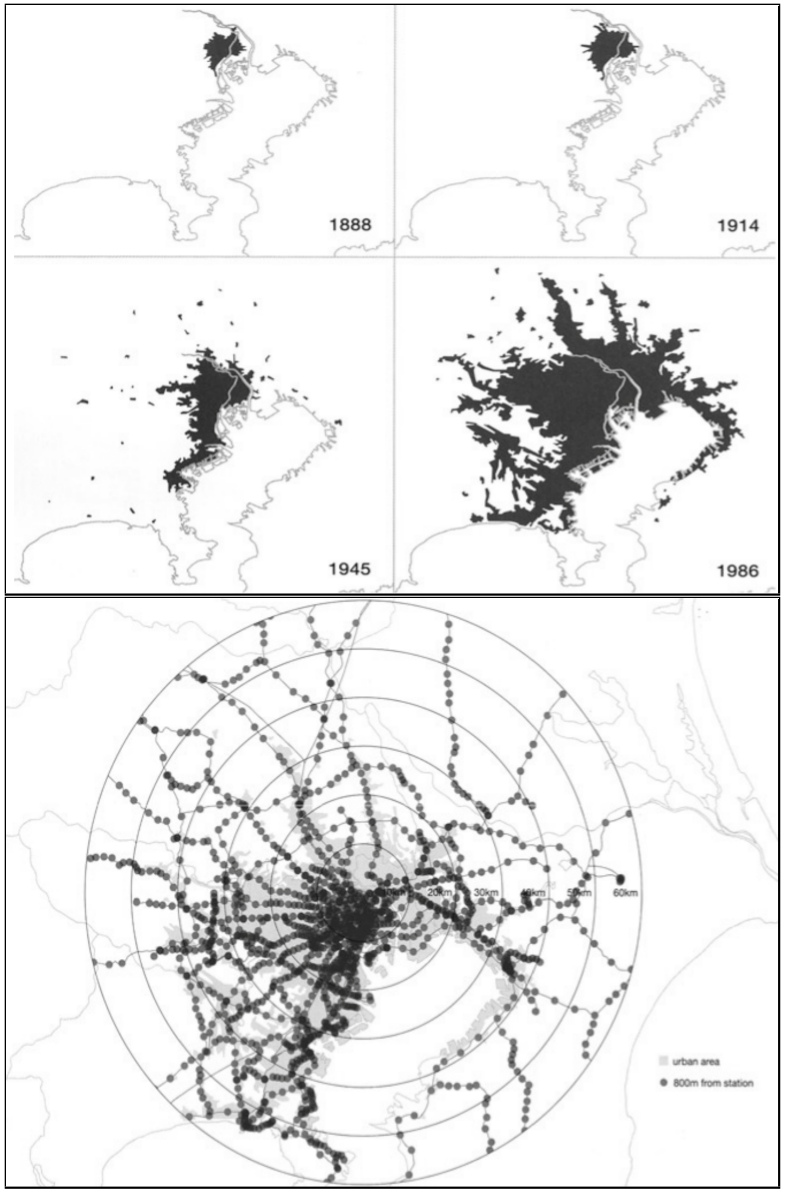
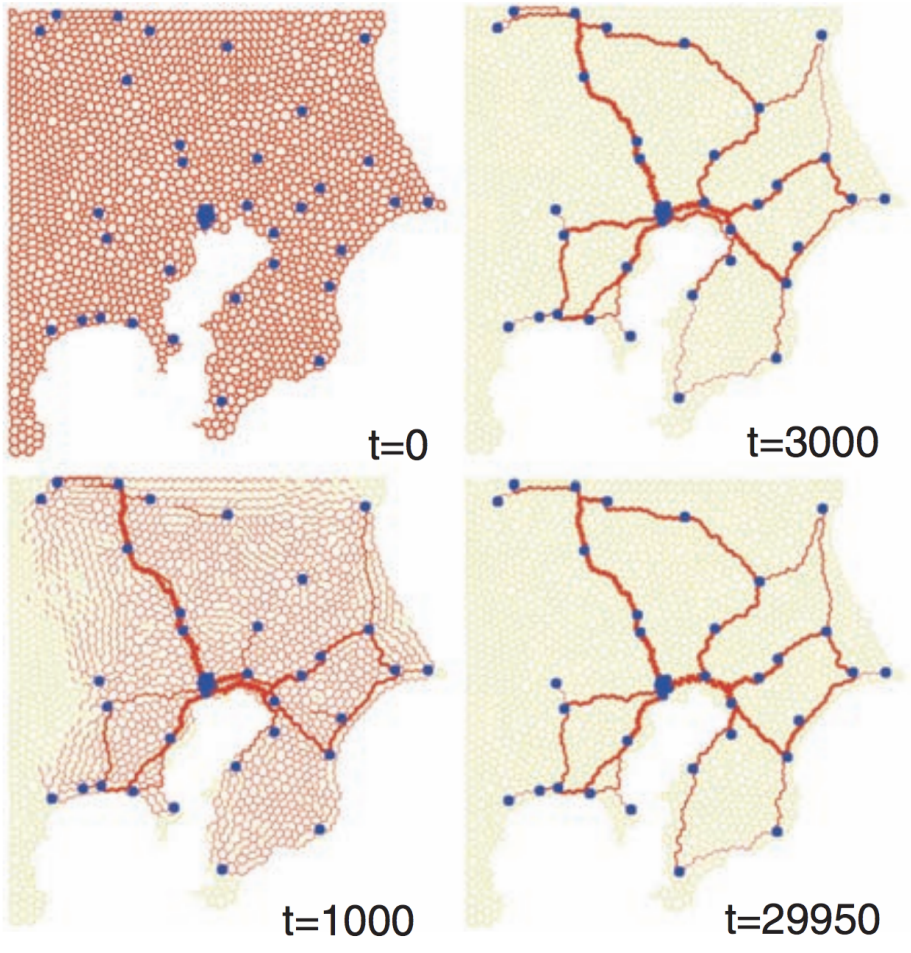
Urban growth and network growth

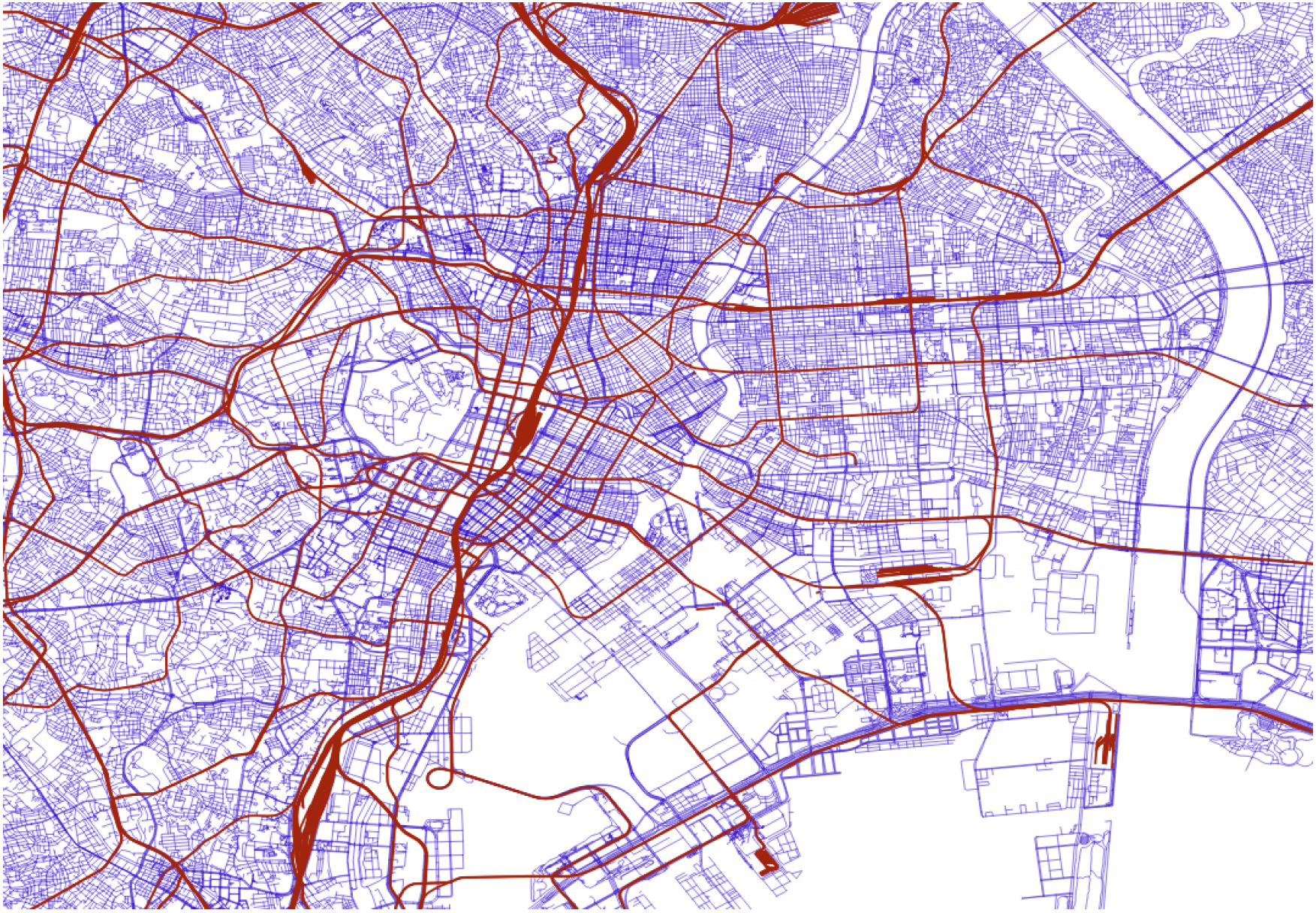


Source:
[Okata and Murayama, 2011]



Source: [Tero et al., 2010]

Transportation networks



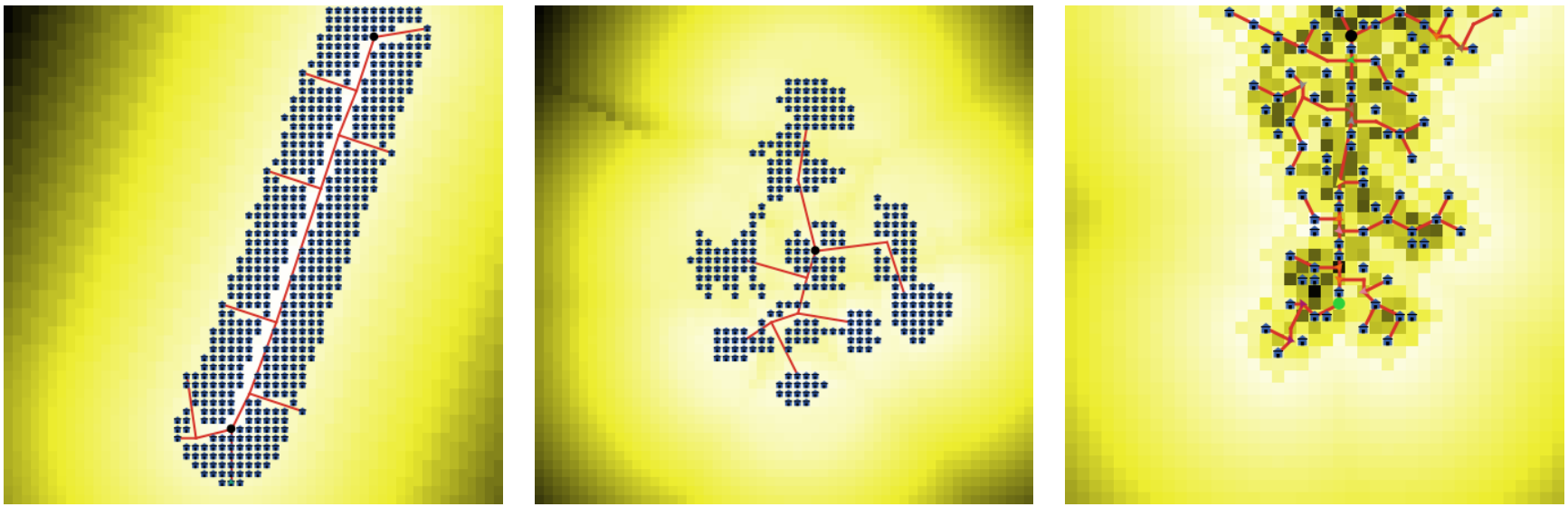
Source: OpenStreetMap

Morphogenesis of transportation networks

Is the city alive ? **No**

Is the city ALife ? **Kind of**

→ Cities (territorial systems) are morphogenetic [Doursat et al., 2012]



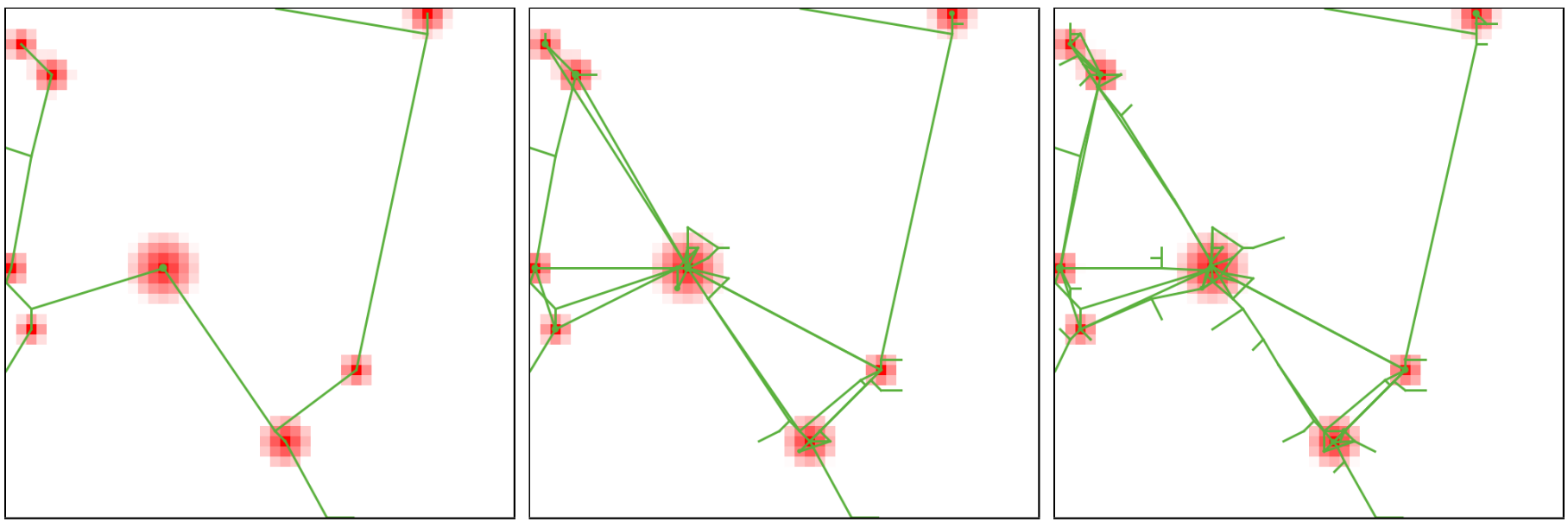
Stylized urban forms [Raimbault et al., 2014]

Research objective: *Understand the morphogenesis of transportation networks (road network), taking into account multiple concurrent processes through multi-modeling*

Road network generation algorithm

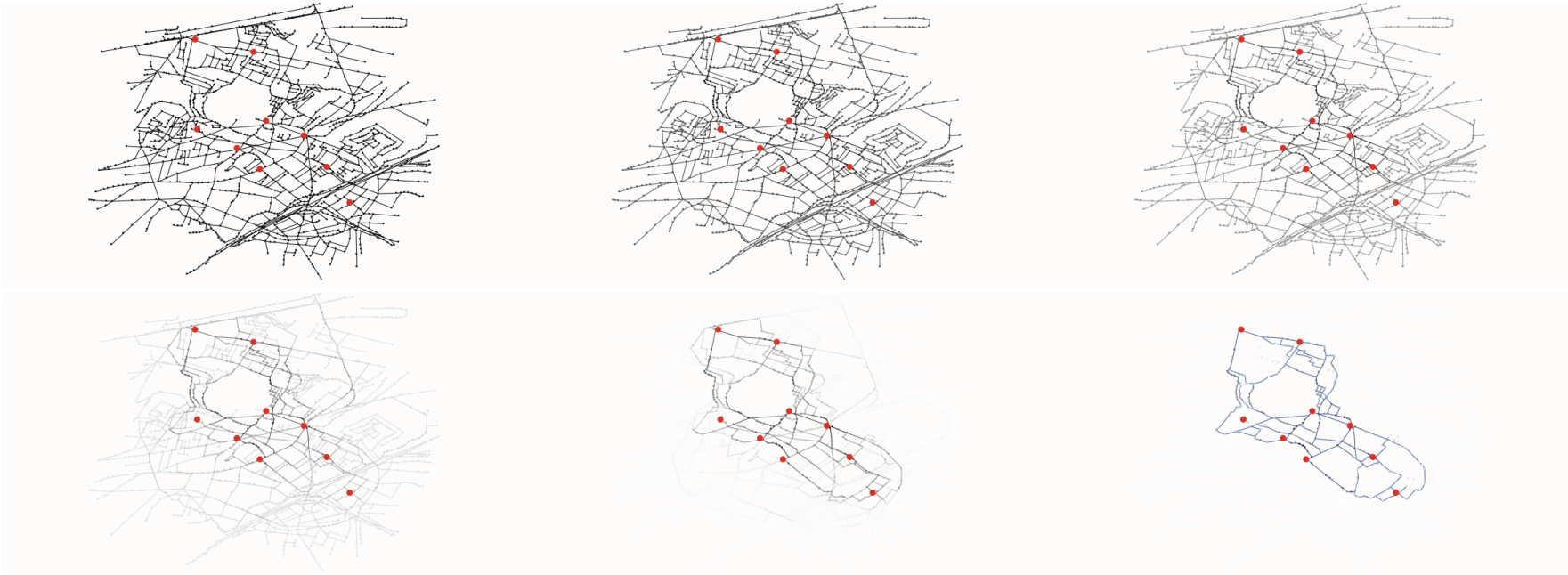
At each time step, with a fixed population density:

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



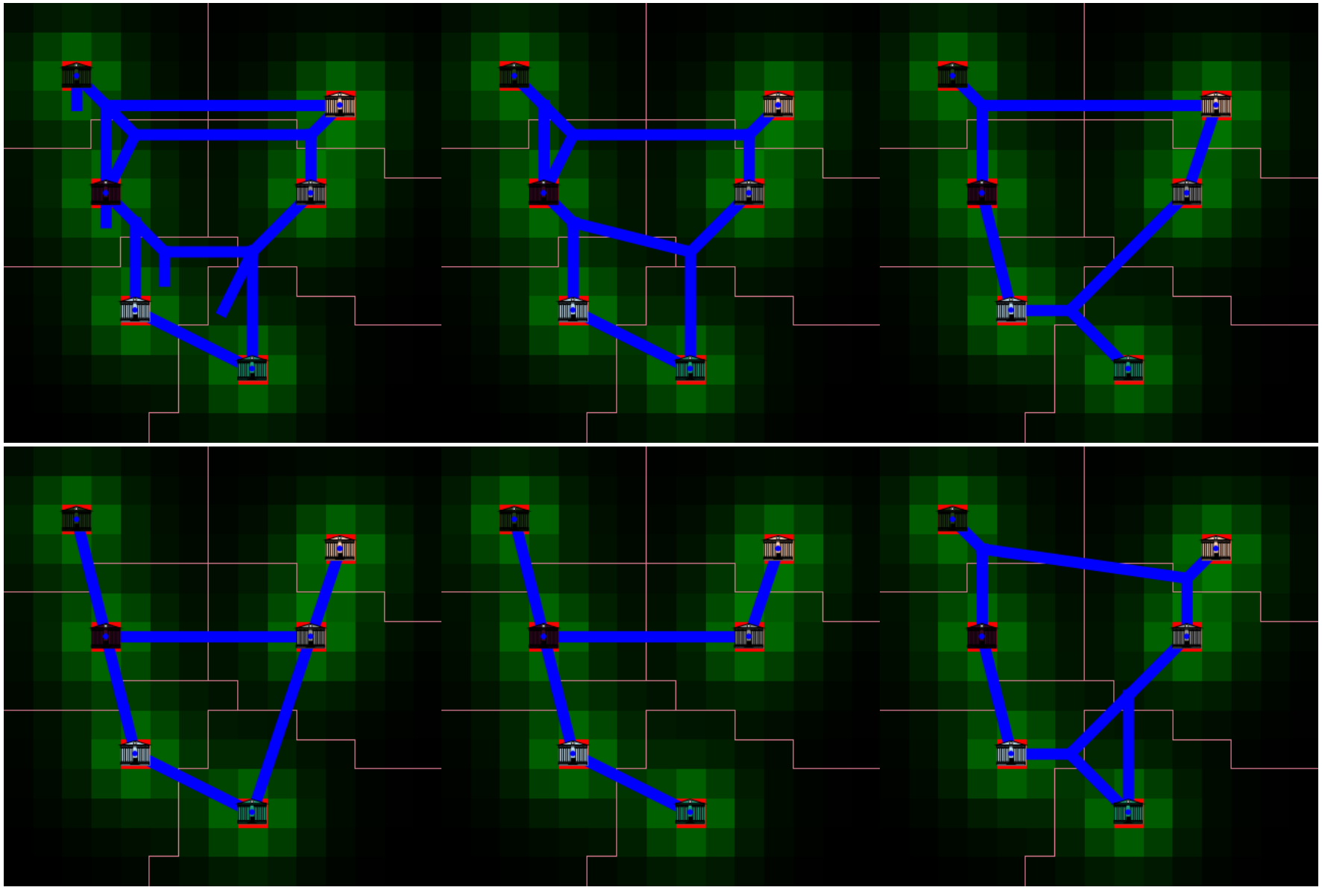
Biological network generation

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



Application to the design of optimal bus routes

Application: generating synthetic networks

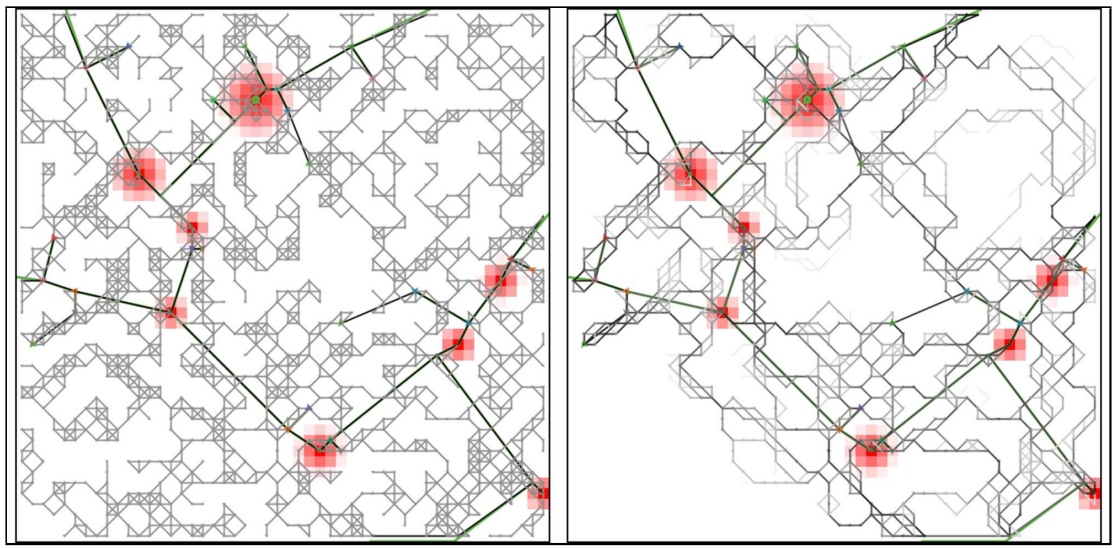


Generation of Pareto optimal (cost/robustness) transportation networks: transportation scenarios for a land-use model

Biological Network generation

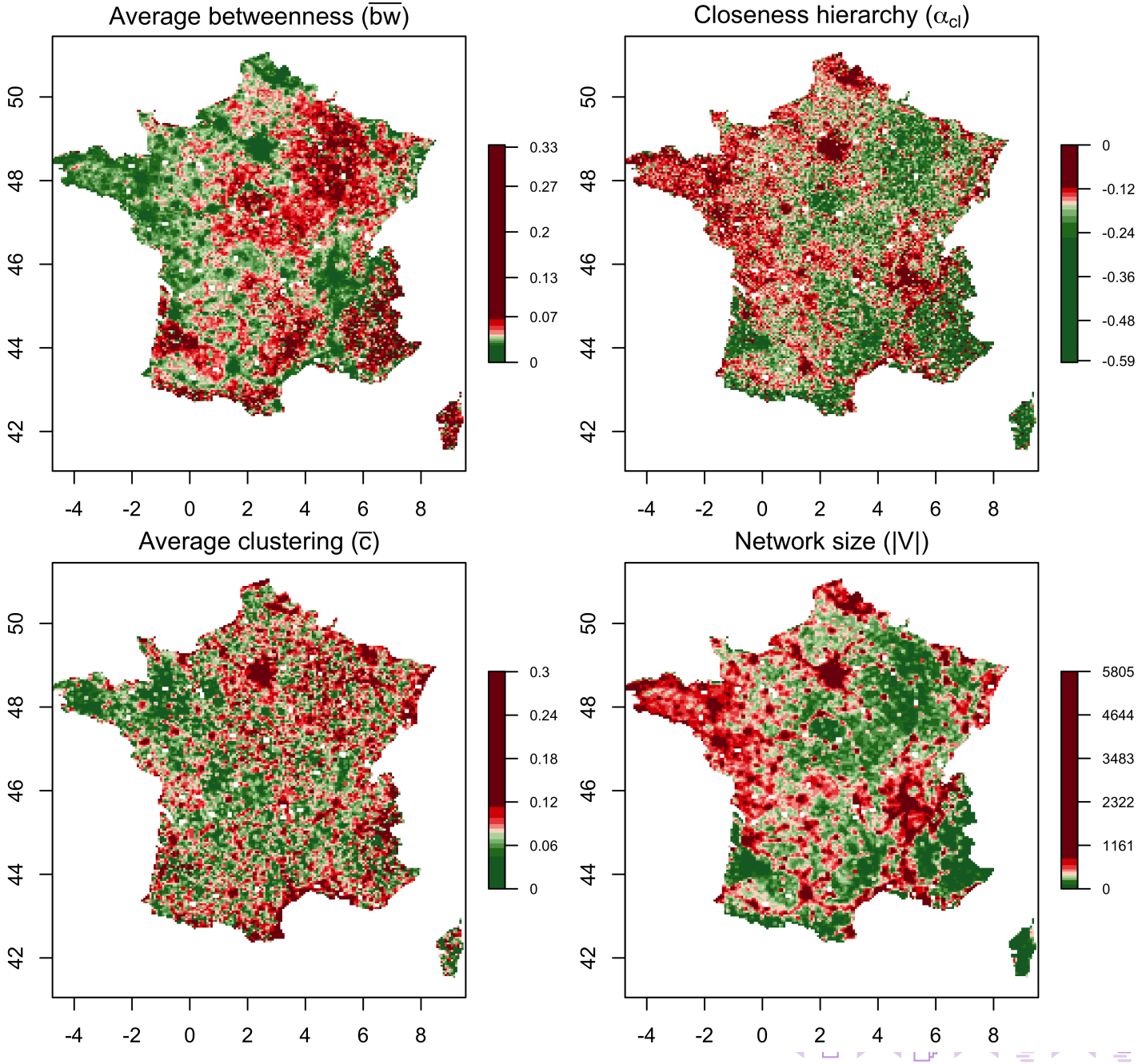
Adding new links with biological heuristic:

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

Empirical Data : network indicators



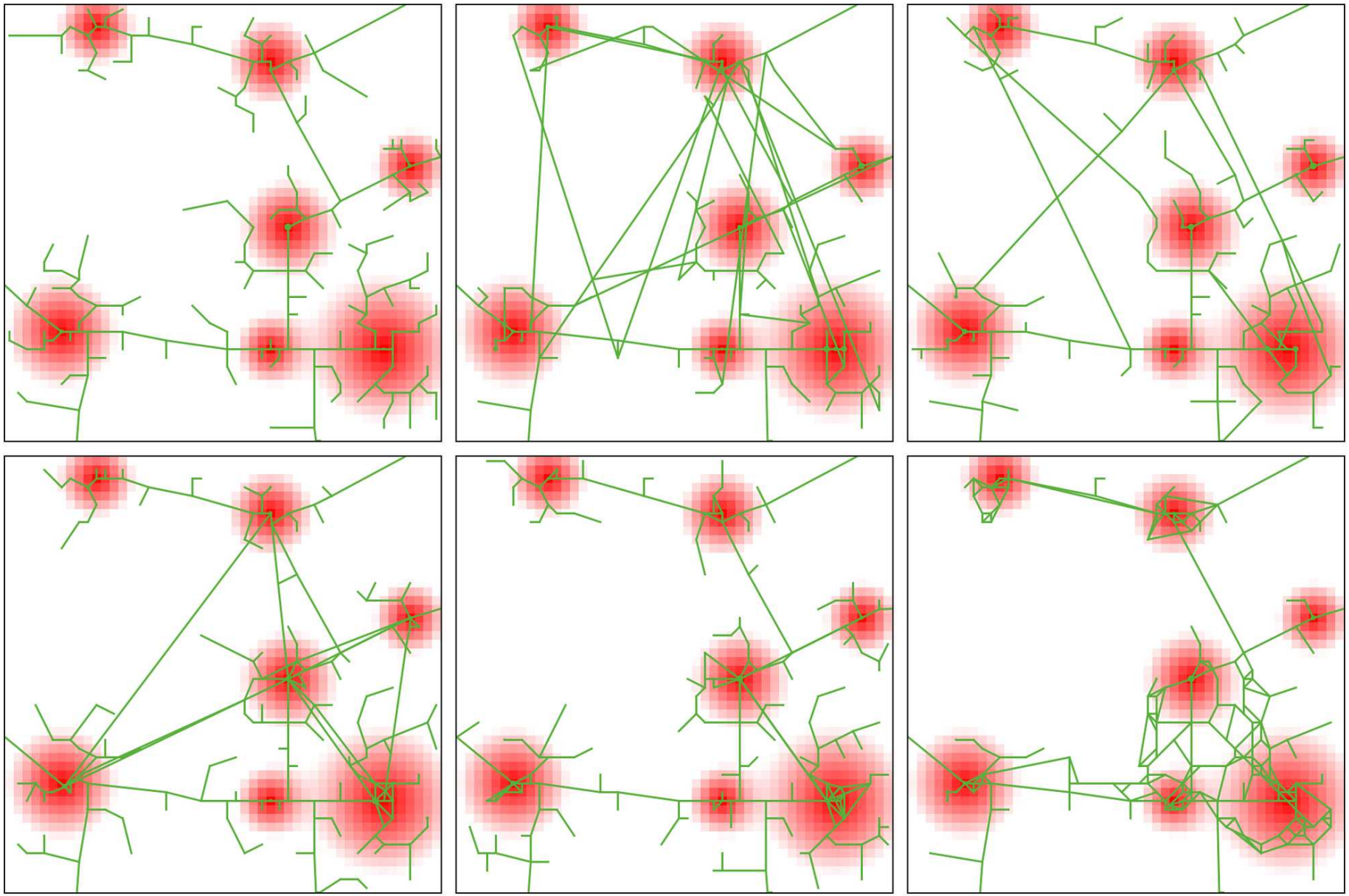
Model exploration

Computationally intensive: high-dimensional parameter space and possible spatial setup.

$\rightarrow$ use of grid computing, made smooth with the OpenMOLE software
`https://next.openmole.org/`

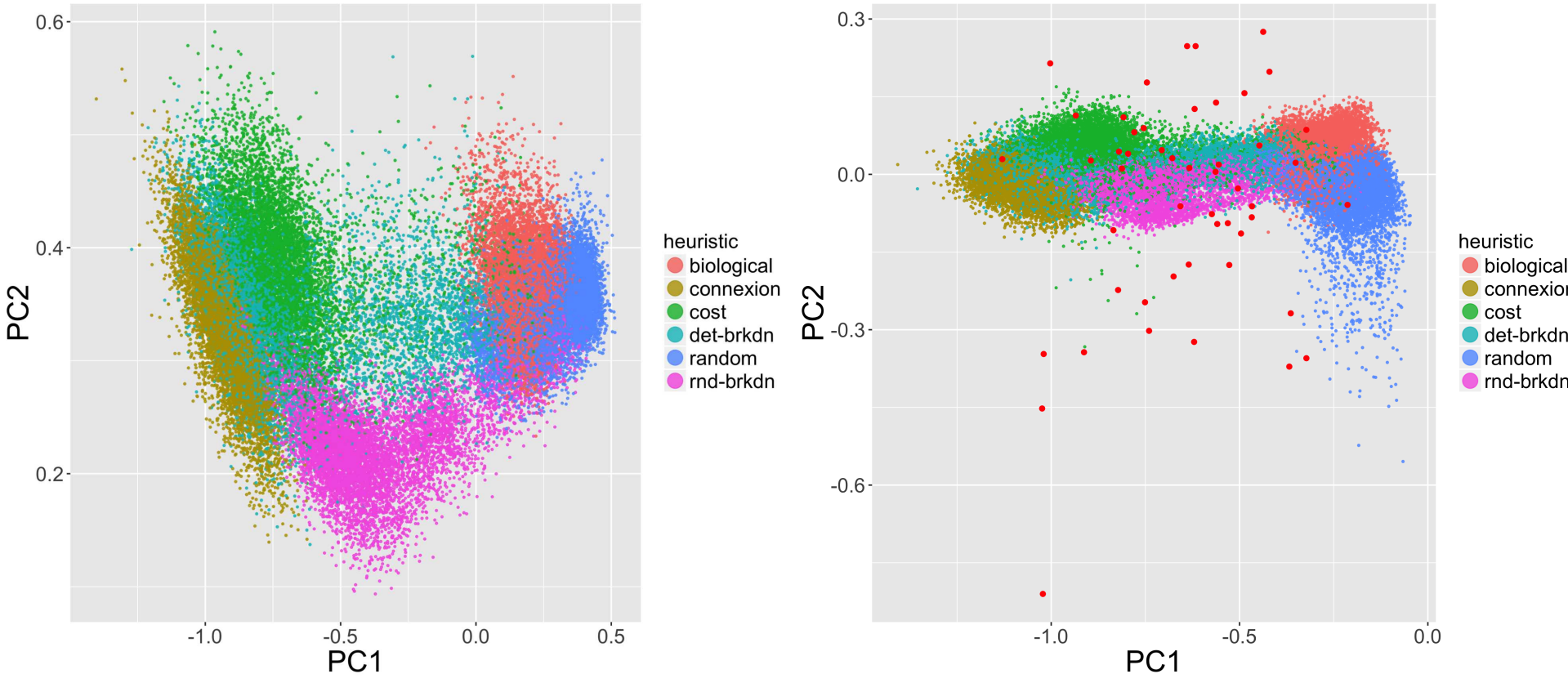
OpenMOLE: (i) embed any model as a black box; (ii) transparent access to main High Performance Computing environments; (iii) model exploration and calibration methods.

Example of generated networks



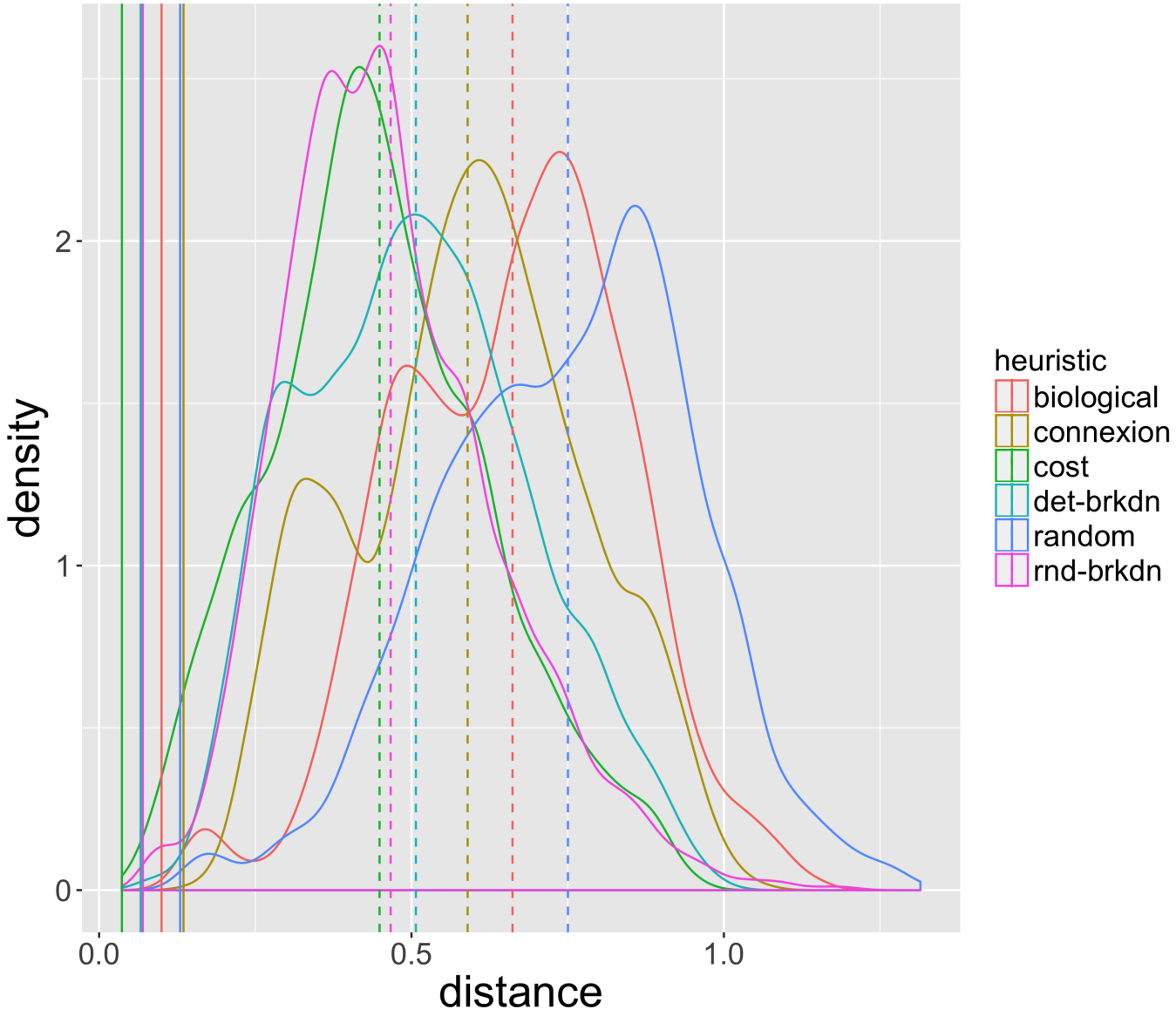
In order: connection; random; deterministic breakdown; random breakdown; cost-driven; biological.

Feasible space of network indicators



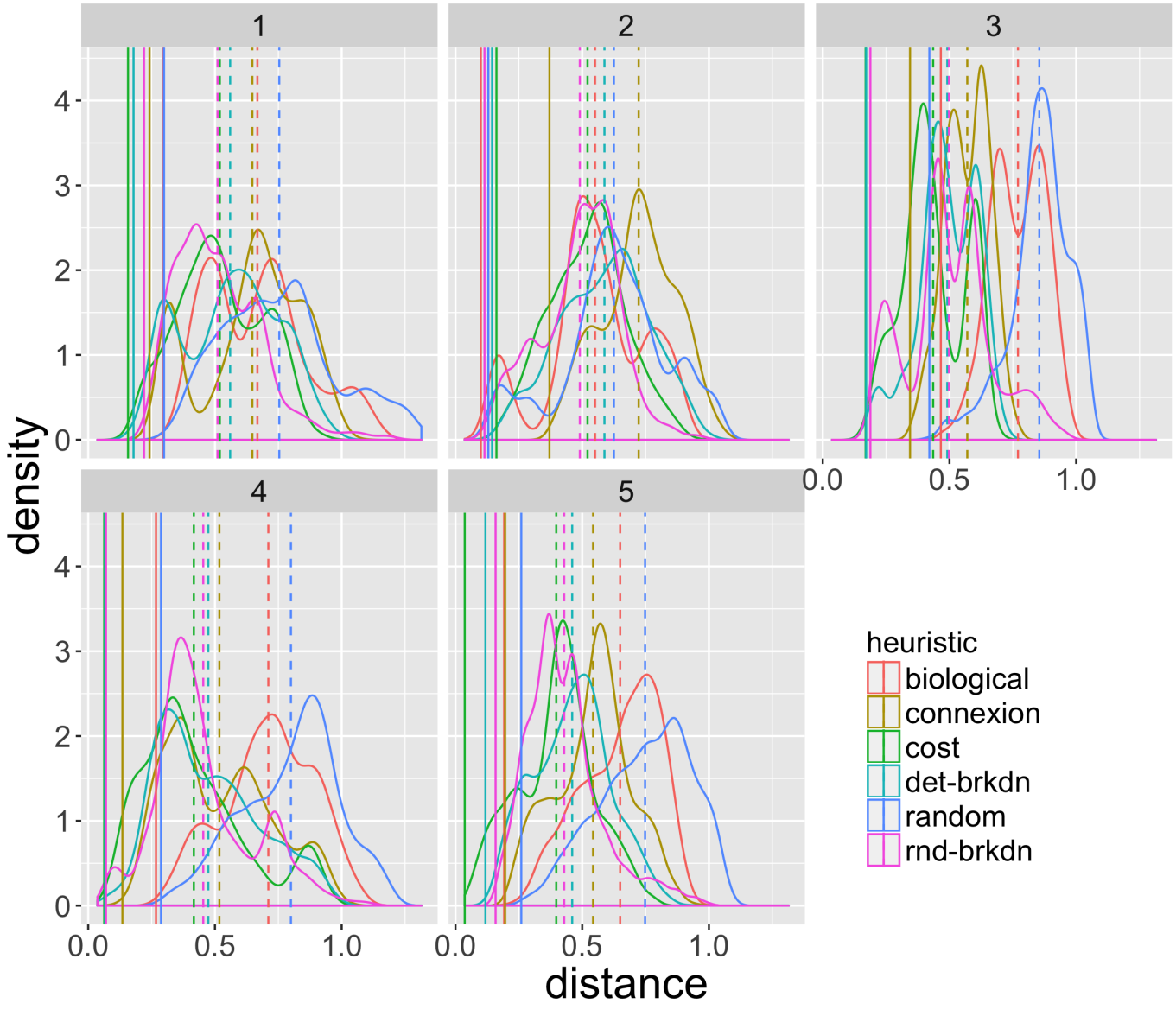
Simulated points obtained with a LHS sampling (240000 runs, 5 repetitions for each parameter point), for real density setups (50 grids). (Left) Feasible points cloud in a reduced network indicator space; (Right) Same points with the sample of real points

Distance to real networks



Distribution of distances to topologies of real networks

Distance to real networks by density morphology



Distribution of distances to topologies of real networks, conditioned by classes of population density morphology

Discussion

Implications

→ Simple processes sufficient to produce reasonable networks: evidence for morphogenesis ?

→ Complementary of various processes to cover the feasible space and produce existing topologies.

Developments

→ Dynamical calibration requires (quasi-inexistent) data.

→ Targeted calibrations to establish potential correspondances between processes and network topology.

→ Compare network generation heuristics in a "fair" way (correcting for additional parameters, open question for models of simulation).

Conclusion

$\rightarrow$ Several road network morphogenesis processes explored: **need for more coupling and comparison of models.**

$\rightarrow$ With more refined urban characteristics and other dimensions ? **Need for more interdisciplinarity.**

Related works

Raimbault, J., Banos, A., & Doursat, R. (2014). A hybrid network/grid model of urban morphogenesis and optimization. Proceedings of 4th ICCSA 2014. arXiv:1612.08552.

Raimbault, J. (2017). Calibration of a Density-based Model of Urban Morphogenesis. arXiv preprint arXiv:1708.06743.

Raimbault, J. (2018). An Urban Morphogenesis Model Capturing Interactions between Networks and Territories. arXiv preprint arXiv:1805.05195.

Open repository (code, data and results) at
`https://github.com/JusteRaimbault/CityNetwork`

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Reserve Slides

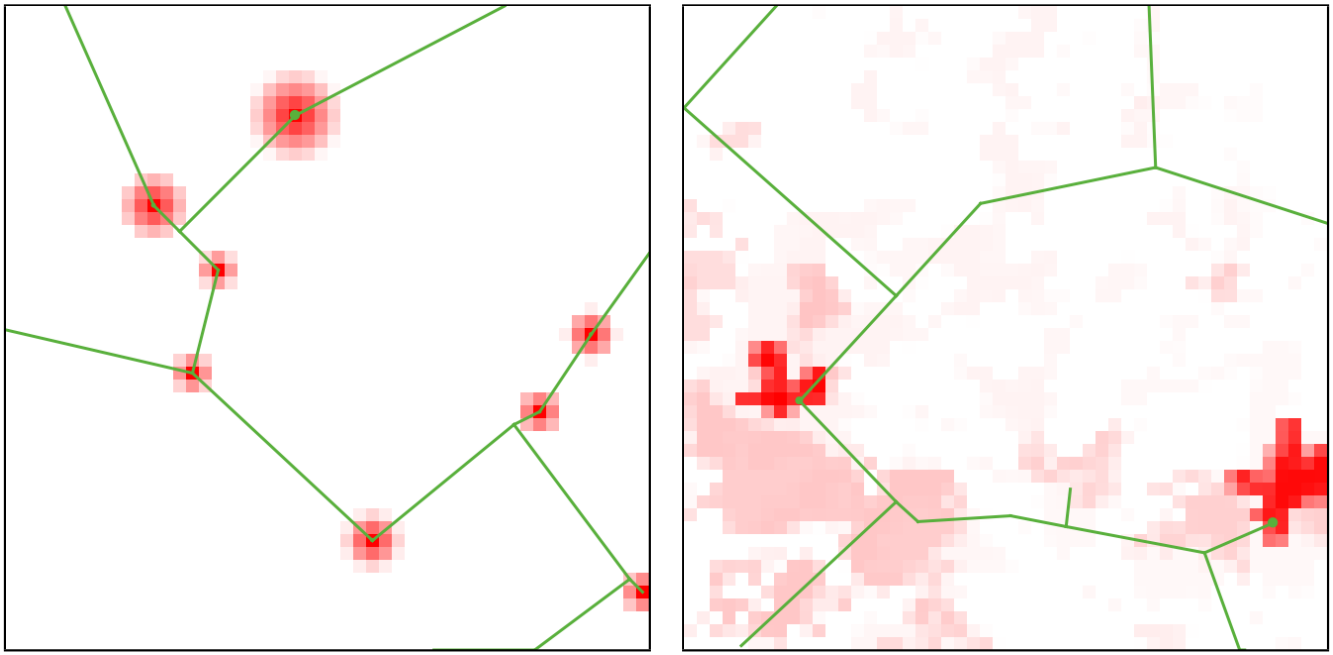
Model parameters

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)



Stopping conditions: fixed final time; fixed total population; fixed network size.

Network Indicators

Network Topology measured by:

- Betweenness and Closeness centralities: average and hierarchy
- Accessibility (weighted closeness)
- Efficiency (network pace relative to euclidian distance)
- Mean path length, diameter

Network nodes

Network baseline extension:
Adding a fixed number n_N of new nodes : for patches such that $d_r < d_0$, probability to receive a node is

$$p = P/P_{max} \cdot (\delta_M - \delta)/\delta_M$$

Nodes connected the shortest way to existing network.

Biological network morphogenesis model

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

Settings :

- Initial homogeneous network of tubes ij of length L_{ij}, variable diameter D_{ij}, carrying a flow Q_{ij}.
- Nodes i with a pressure p_i.
- N nodes are origin/destination points : randomly at each step one becomes source $p_{i_+} = I_0$ and one other sink $p_{i_-} = -I_0$

Biological network evolution

At each iteration :

1. Determination of flows with Kirchoff's law (electrostatic analogy) : Ohm's law $Q_{ij} = \frac{D_{ij}}{L_{ij}} \cdot (p_i - p_j)$ and conservation of flows $\sum_{j \to i} Q_{ij} = 0, \sum_{j \to i_\pm} Q_{i_\pm j} = \pm I_0$
2. Evolution of diameters (γ reinforcement parameter) by

$$\frac{dD_{ij}}{dt} = \frac{|Q_{ij}|^\gamma}{1 + |Q_{ij}|^\gamma} - D_{ij}$$

$\rightarrow$ Extraction of the final network after convergence given a threshold parameter for diameters

$\rightarrow$ Multi-scale model : diameters are constant during an iteration to obtain equilibrium flows

Biological network: indicators

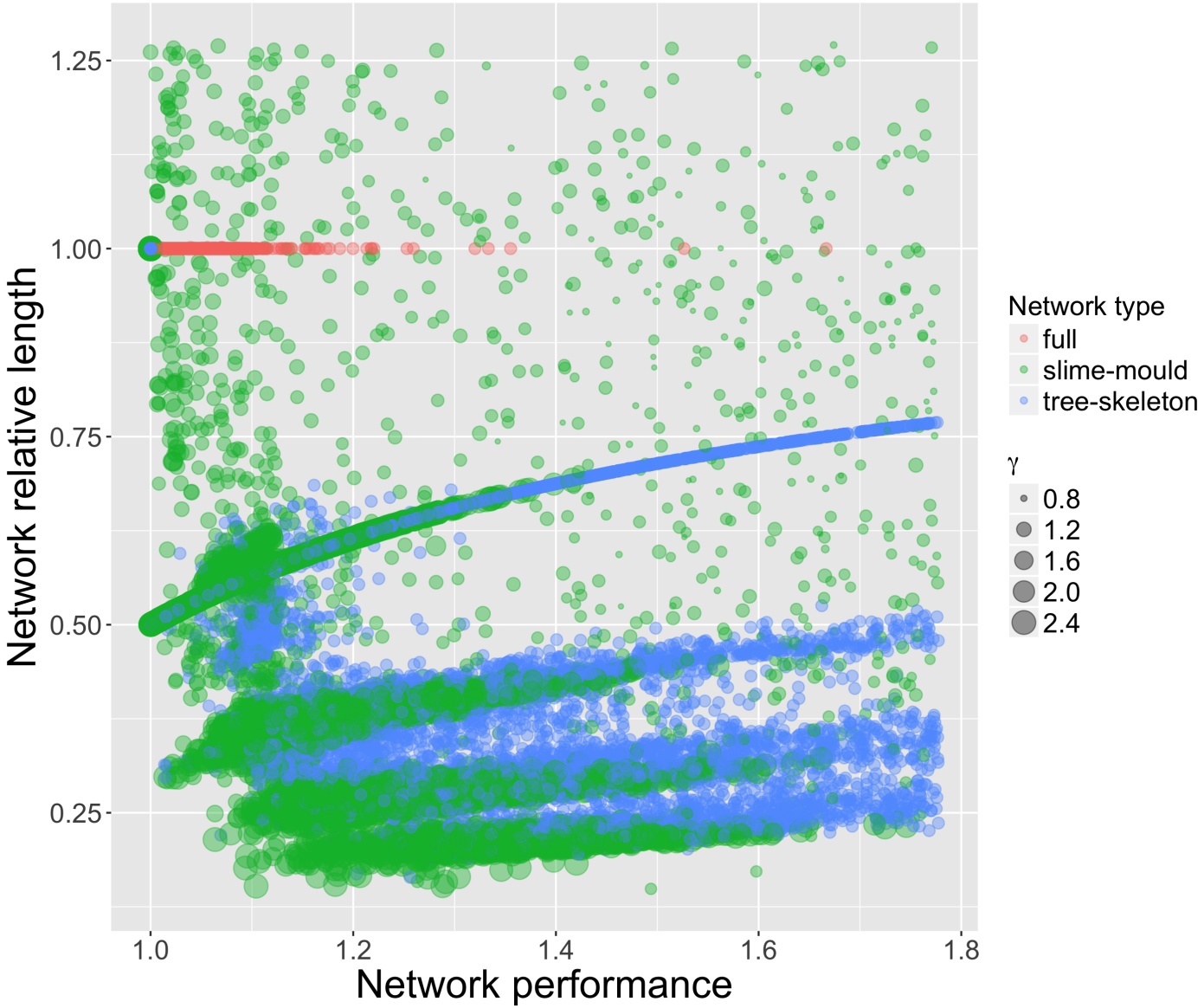
Behavior of the model evaluated with performance indicators for generated network (V_f, E_f), that are contradictory objectives :

- Construction costs $c = \sum_{ij \in E_f} D_{ij}(t_f)$
- Average performance [Banos and Genre-Grandpierre, 2012]

$$v = \frac{1}{|V_f|^2} \sum_{i,j \in V_f} \frac{d_{i \to j}}{||\vec{i} - \vec{j}||}$$

- Robustness (*Network Trip Robustness* index [Sullivan et al., 2010])

Biological network: optimal networks



Exploration of parameter space for synthetic network generation

Deterministic breakdown Network generation

1. Gravity potential given by

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

2. $k \cdot N_L$ links are selected with lowest $V_{ij}(d_N)/V_{ij}(d_{ij})$, among which N_L links with highest (lest costly) are realized
3. Network is planarized

Results: components

With average betweenness centrality $\bar{bw}$ and average closeness centrality $\bar{cl}$, diameter r, average path length $\bar{l}$, relative speed v_0

Simulated point cloud:
$PC1 = -0.51\bar{bw} - 0.45\bar{l} + 0.57v_0 - 0.43r + 0.05\bar{cl}$ and
$PC2 = -0.45\bar{bw} + 0.17\bar{l} + 0.33v_0 + 0.8r + 0.1\bar{cl}$

Herfindhal index (20 width grid): first quartile at 0.54, a median at 0.76 and a third quartile at 1

Distance to real configurations:
$d(1,2) = \sqrt{(\bar{bw}_1 - \bar{bw}_2)^2 + (\bar{cl}_1 - \bar{cl}_2)^2 + (\bar{l}_1 - \bar{l}_2)^2}$, we use
$d_{min} = \min_j d(S, R_j)$

Real point cloud: $PC1 = 0.12\bar{bw} - 0.09\bar{cl} + 0.98\bar{l}$ and
$PC2 = -0.20\bar{bw} - 0.97\bar{cl} - 0.06\bar{l}$

Population morphology classes

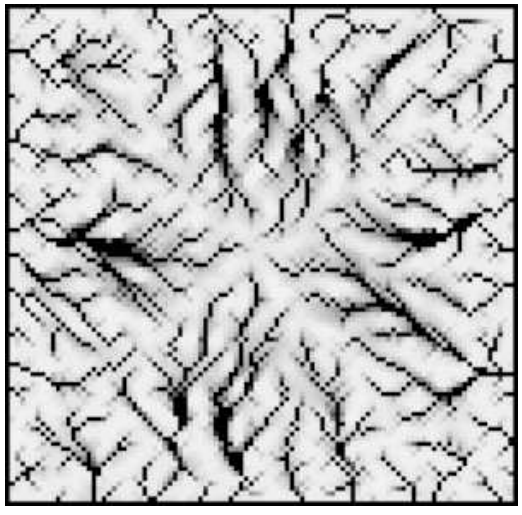
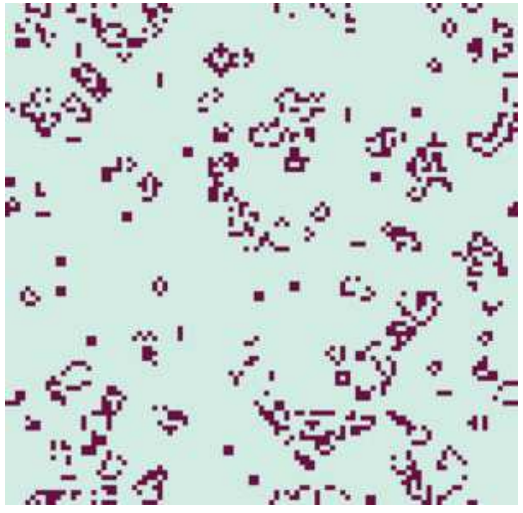
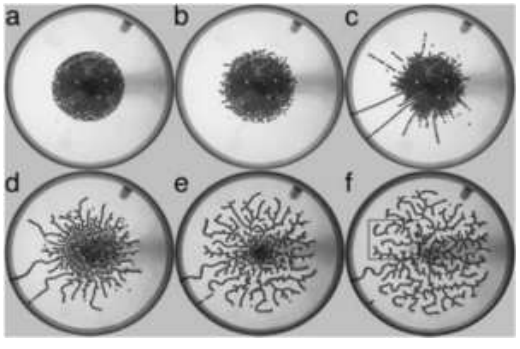
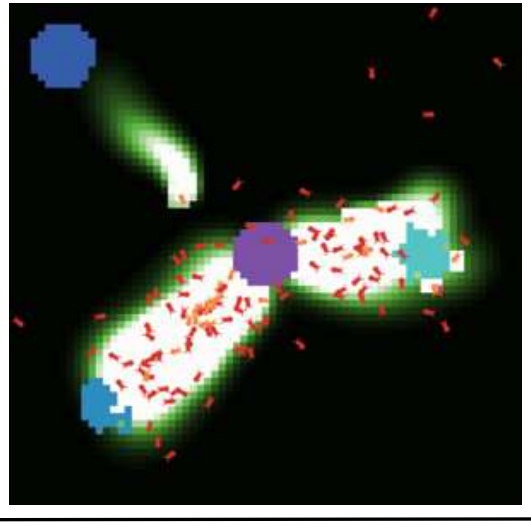
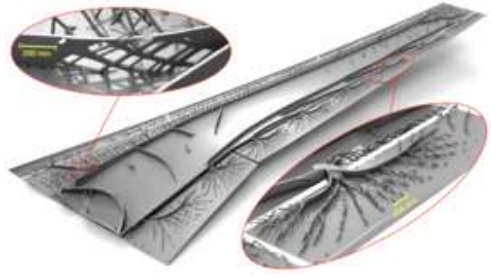
With 10 grids per class:

- Class 5: lowest Moran, high distance, hierarchy and entropy; numerous population centers that are localized and dispersed.
- Class 4: highest entropy and hierarchy; a small number of localized centers.
- Class 3: lowest distance and entropy; diffuse population.
- Class 2: highest Moran; one or a few centers with consequent size.
- Class 1: intermediate values for all indicators; a certain number of centers of intermediate size.

Population morphology classes

Class	Moran I	Distance $\bar{d}$	Entropy $\mathscr{E}$	Hierarchy γ
1	0.23	0.66	0.76	0.62
2	0.47	0.50	0.75	0.53
3	0.21	0.42	0.57	0.65
4	0.24	0.75	0.90	0.87
5	0.15	0.76	0.84	0.72

What is Morphogenesis ? Examples

	Physical	Biological	Enginereed
Non Functional			
Functional			

Sources (in order by column). Ants, Erosion, Game of Life: NetLogo Library ; Arbotron [Jun and Hübler, 2005]; Industrial design [Aage et al., 2017]; Swarm chemistry [Sayama, 2009]

What is Morphogenesis ?

Morphogenesis (*Oxford dictionary*)

1. *Biology* : The origin and development of morphological characteristics
2. *Geology* : The formation of landforms or other structures.

History of the notion

→ Started significantly with embryology around 1930 [Abercrombie, 1977]

→ Turing's 1952 paper [Turing, 1952], linked to the development of Cybernetics

→ first use in 1871, large peak in usage between 1907-1909, increase until 1990, decrease until today. *Scientific fashion ?*

Interdisciplinary Definition of Morphogenesis

Construction of an interdisciplinary definition in [Antelope et al., 2016]

Meta-epistemological framework of imbricated notions:
Self-organization $\supsetneq$ Morphogenesis $\supsetneq$ Autopoiesis $\supsetneq$ Life

Properties:

- Architecture links form and function
- Emergence strength [Bedau, 2002] increases with notion depth, as bifurcations [Thom, 1972]

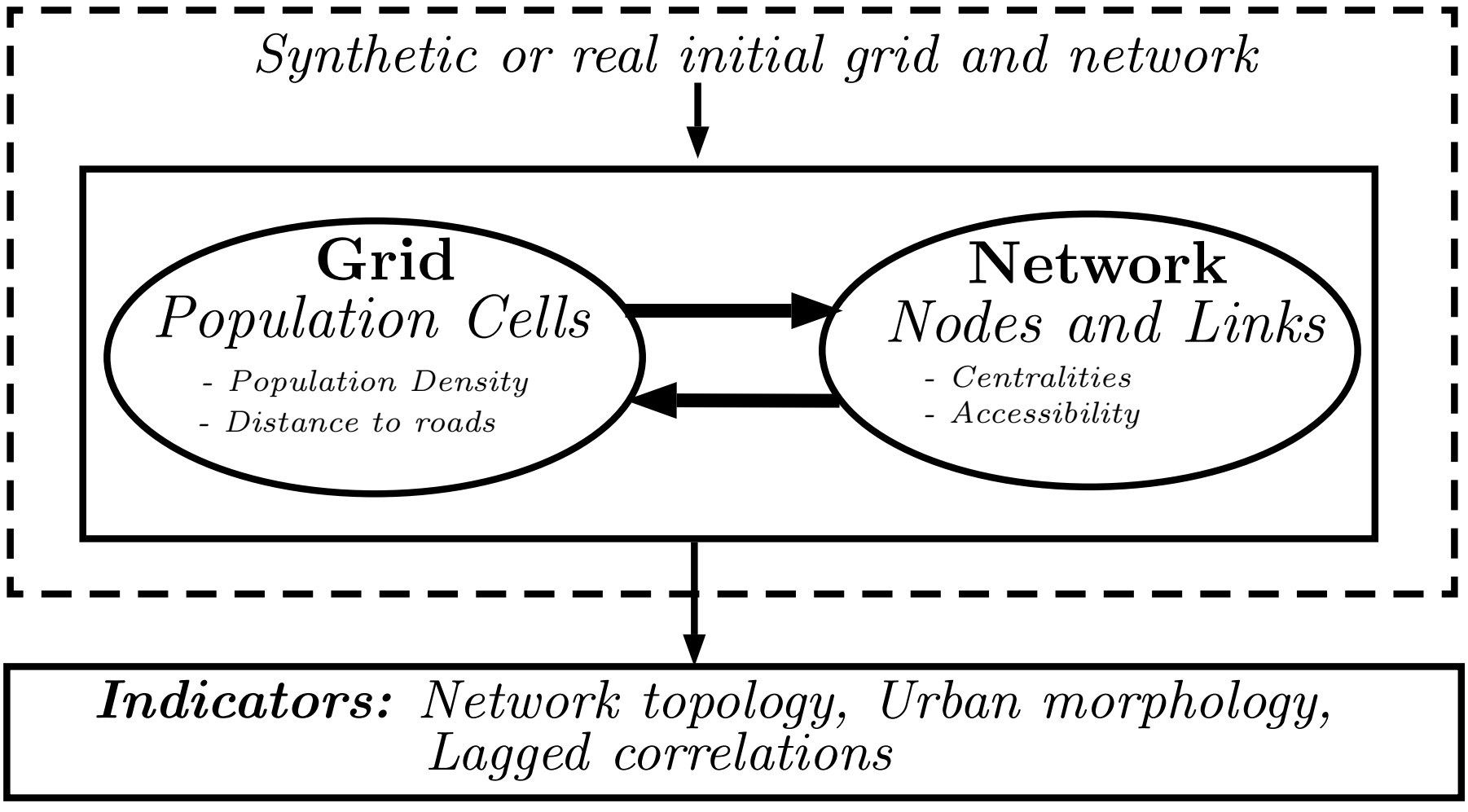
Definition of Morphogenesis : *Emergence of the form and the function in a strongly coupled manner, producing an emergent architecture [Doursat et al., 2012]*

Modeling Urban Morphogenesis

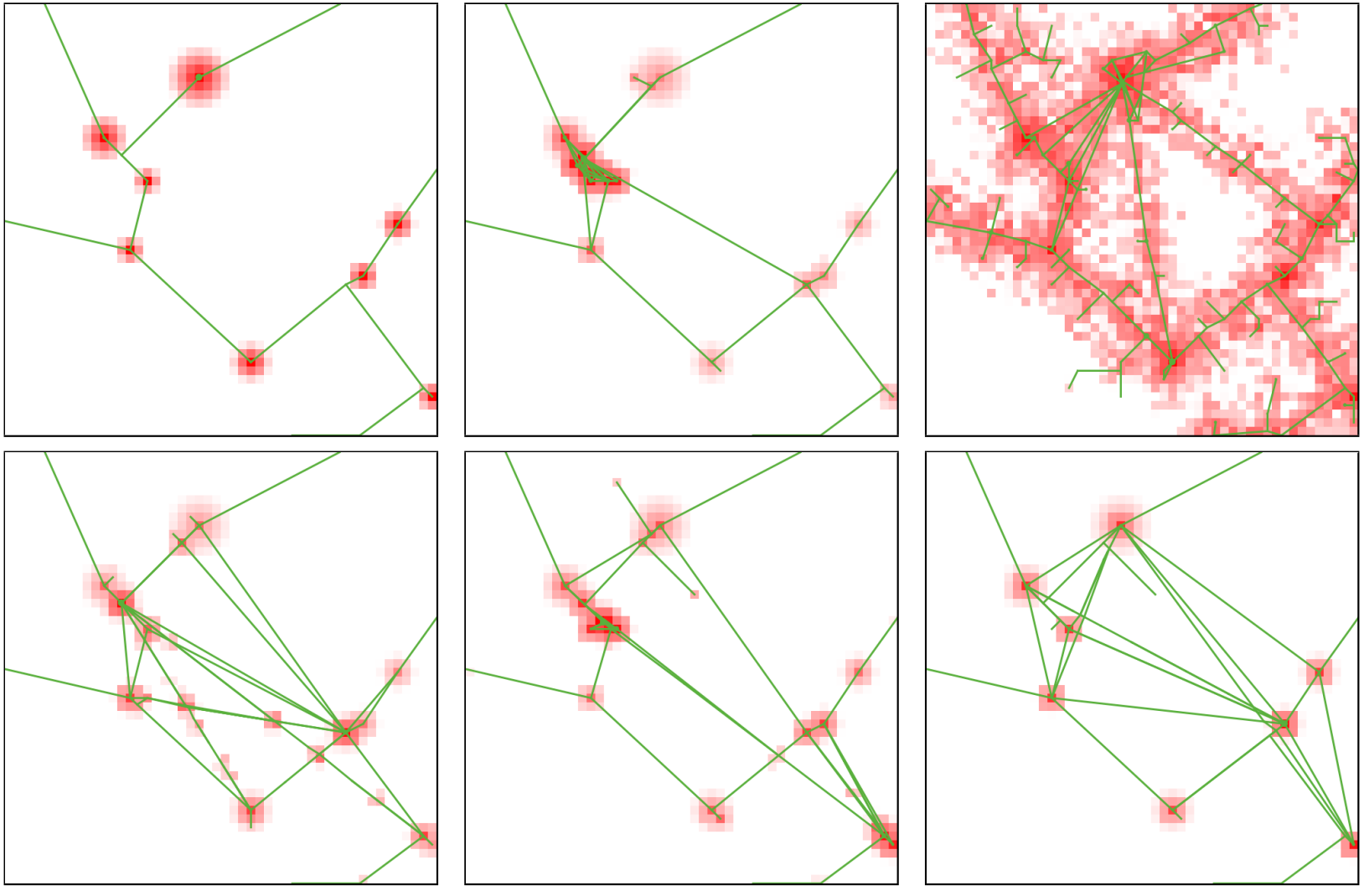
More or less explicit use of the concept of Morphogenesis in Urban Simulation, depending on the scale and the approach.

- [Makse et al., 1998] correlated growth
- [Murcio et al., 2015] multi-scale migration and percolation
- [Bonin et al., 2012] qualitative differentiation of urban function
- [Achibet et al., 2014] procedural model at the micro-scale
- [Caruso et al., 2011] micro-economic model of sprawl
- [Bonin and Hubert, 2014] urban economics morphogenesis, only work to explicitly mention the morphogen

Extension into a co-evolution model



Generated Urban Shapes: urban form



In order: setup; accessibility driven; road distance driven; betweenness driven; closeness driven; population driven.

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