Multi-modeling the morphogenesis of transportation networks

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ALife 2018

Tokyo

July 26th 2018

Is city alive ? **No**

Is city ALife ? **Kind of**

$\rightarrow$ Cities (territorial systems) are morphogenetic

Network Generation

At fixed time steps :

1. Add new nodes preferentially to new 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

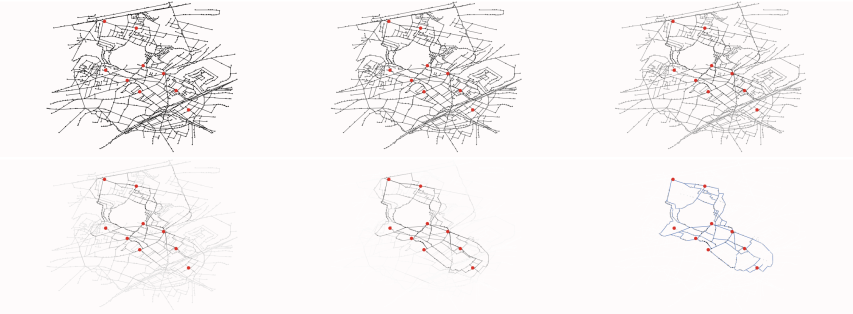
Settings :

- 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 $p_{i_-} = -I_0$

Application : Optimal Network Design

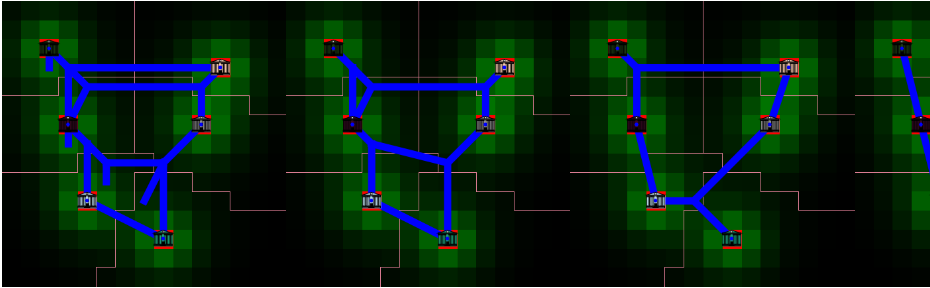
→ Mission of prospective for Romainville city : itinary of an intra-urban shuttle with imposed stops.

→ NP-hard problem similar to a Travelling Salesman Problem, but multi-objective (cost, speed, robustness). The bottom-up network generation applied on the initial street network gives a compromise solution.

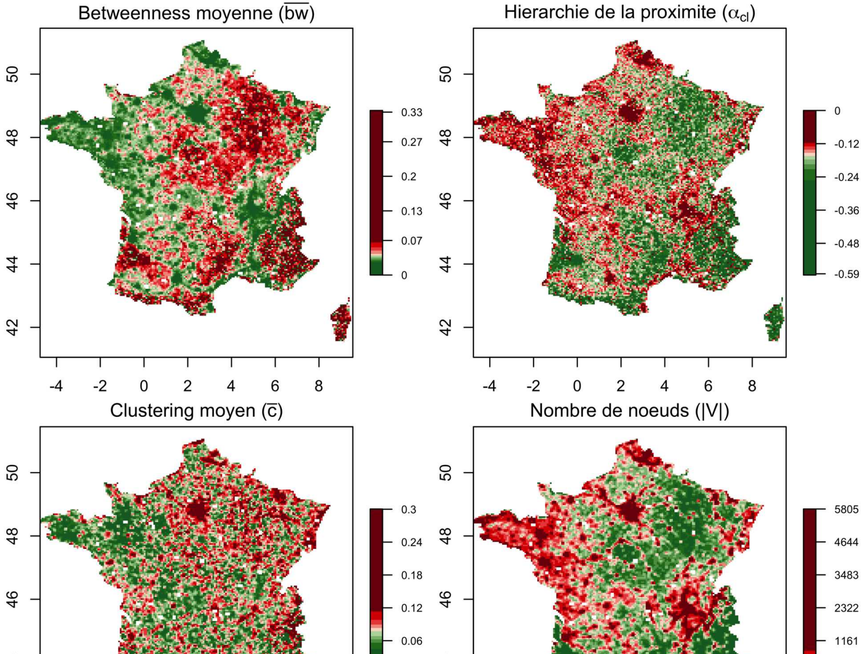


Progressive convergence of the network towards an optimal network connecting the fixed points (in red), starting from the initial street network.

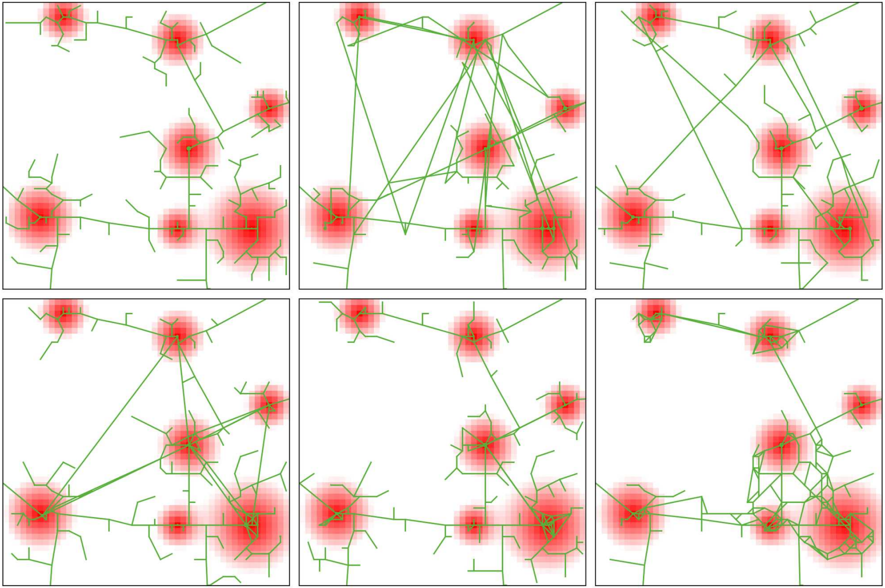
Application: Generating optimal networks



Empirical Data : network indicators

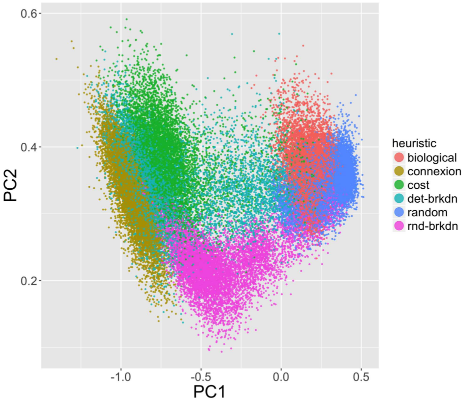


Example of generated networks

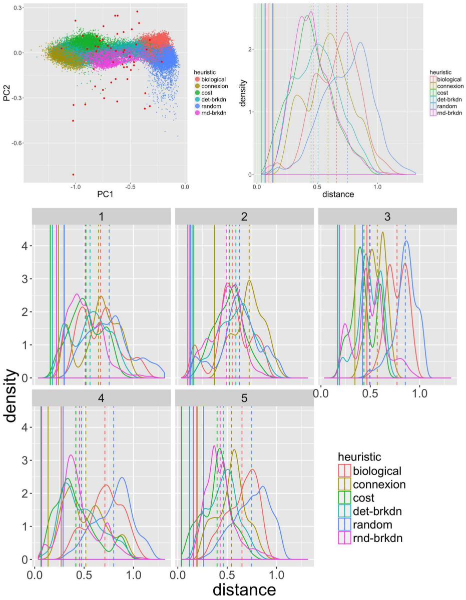


In order: connection; random; deterministic breakdown; random breakdown; cost-driven; biological.

Feasible space of network indicators



Distance to real networks



Comparison of feasible space for network indicators with fixed density

(Left) Feasible spaces by morphological class and network heuristic; (Right) Distribution of distances to topologies of real networks

Discussion

Implications

(*Optimisation*)→ Morphogenesis models (in the sense of strong links between form and function) are an appropriate tool to find optimal urban designs.

(*Explication*)→ Simple model reproducing observed urban forms for both population distribution and road network : which intrinsic dimension to the urban system and its morphological aspect ?

Developments

→ Towards dynamical calibrations ? Need of dynamical data

→ Investigate the link between spatial non-stationarity and non-ergodicity through simulation by the model

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

Conclusion

→ Several urban morphogenesis at the mesoscopic scale explored: **need for more coupling and comparison of models.**

→ At the macro scale of the system of cities ? **Need for multi-scale models.**

→ With more refined urban characteristics and other dimensions ? **Need for more interdisciplinarity.**

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Open repository (code, data and results) at
`https://github.com/JusteRaimbault/CityNetwork`
Acknowledgments : We thank the *European Grid Infrastructure* and its *National Grid Initiatives* (*France-Grilles* in particular) to give the technical support and the infrastructure.

Reserve Slides

Network morphogenesis model

Model studied by [?] : exploration and reinforcement by a slime mould searching for ressources

Settings :

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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

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]

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

- Robustness (*Network Trip Robustness* index [?])

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

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

Biological Network generation

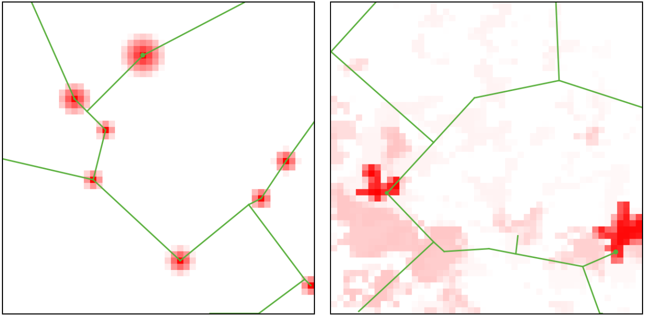
Adding new links with biological heuristic:

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

Model setup

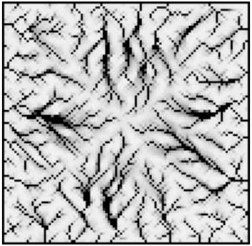
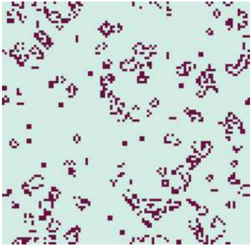
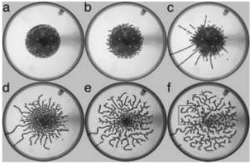
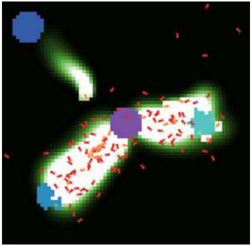
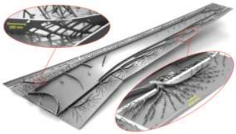
Synthetic setup: rank-sized monocentric cities, simple connection with bord nodes to avoid bord effects

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



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

What is Morphogenesis ? Examples

	Physical	Biological	Engineereed
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 [?]

Proposition of an Interdisciplinary Definition of Morphogenesis

Construction of an interdisciplinary definition in [?]

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]*

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 [?]

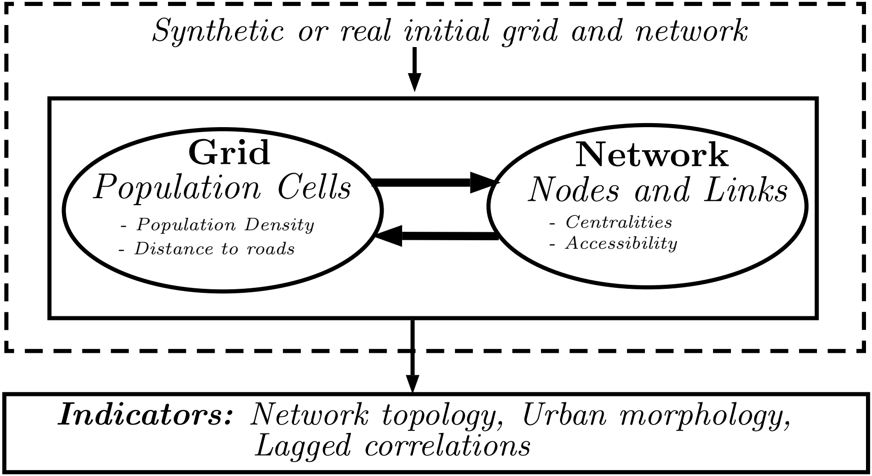
→ Turing's 1952 paper [Turing, 1952], linked to the development of Cybernetics

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

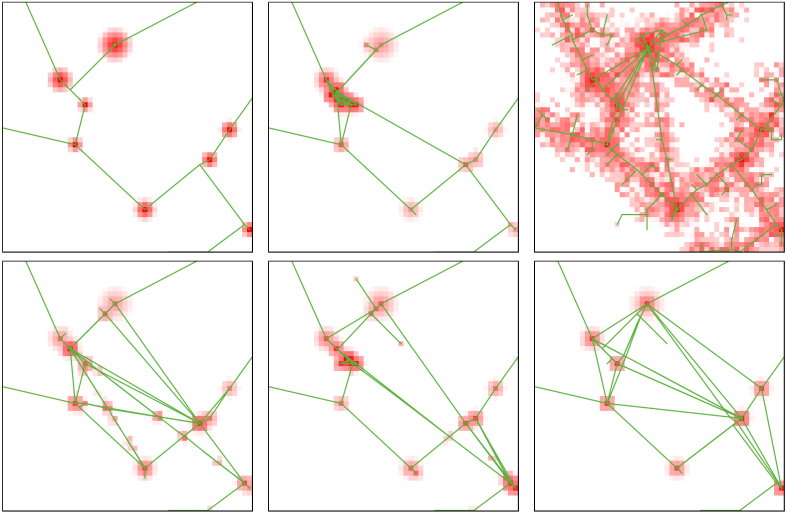
More or less explicit use of the concept of Morphogenesis in Urban Simulation, depending on the scale and the approach.

- [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
- [?] 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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