Morphogenesis of urban systems

Modelling the co-evolution of human transport and urban forms

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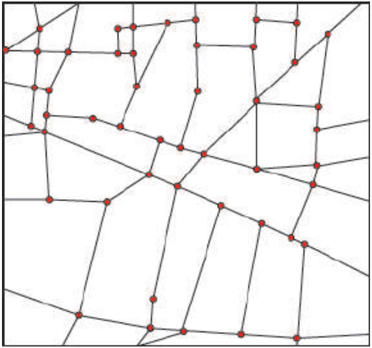
Overview

Morphogenesis of urban systems. Modelling the co-evolution of human transport and urban forms

Keywords: street network model, urban morphogenesis, complex systems, spatial networks, reaction-diffusion system, multi-modal transportation networks

Morphogenesis of urban systems



Cities as complex systems

Cities are composed by many distinct heterogeneous elements. Unexpected behaviours emerge from local and decentralized interactions [3, 5, 2].

The underlying networks

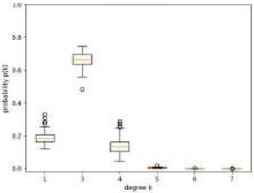
Street network: the backbone of the city.
Geometric planar graph: nodes are embedded in Euclidean space and links represent the physical support of the system [4].

Focus: morphogenesis of street networks

The process by which self-organized systems develop their shapes and specialize subpart of systems [1].
In an **urban system**, elements (e.g. population, socio-economical actors) shape and transform the urban form (e.g. streets, built-up).

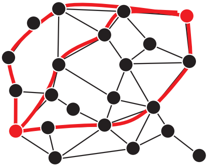
Properties of street networks [6, 7]

Vertex degree distribution



Hierarchies

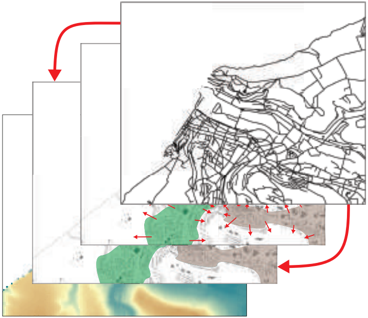
Robustness



Spatial patterns

Observation: cities as an overlapping of interrelated layers

- **Environment**
  Geomorphology of the region of space
- **Urban fabrics**
  Physical elements of city
- **Urban forms**
  Properties arranged as spatial patterns
- **Contrasting forces**
  Spatial patterns influence the transformation
- **Street network**
  Around streets properties arrange
- **Feedback**
  Streets affect other elements



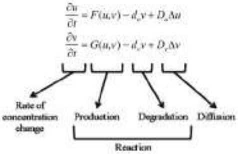
Street network morphogenesis

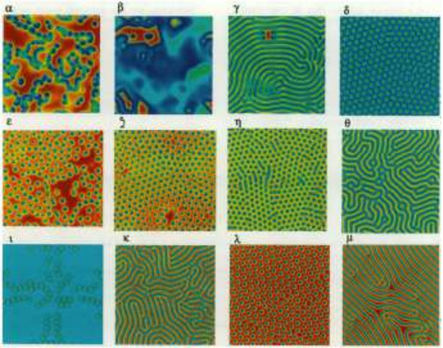
The result of different interconnected levels of dynamics and elements

Inspiration: pattern formation with reaction-diffusion theory

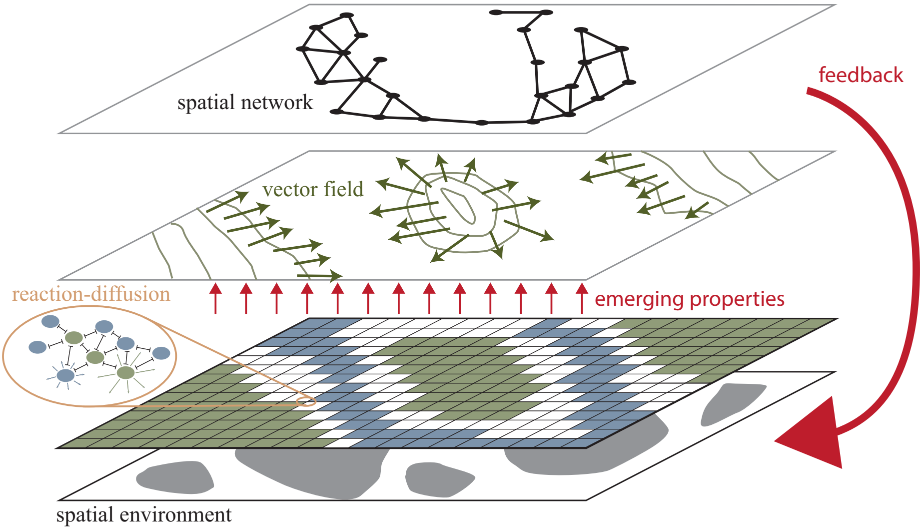
Morphogens

Form-producing elements. In a living system, their concentrations induce the cells to differentiate [1]





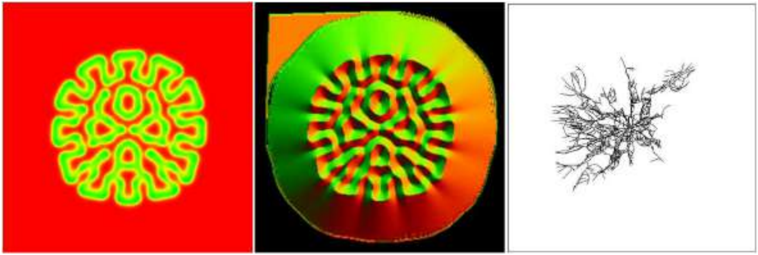
Modelling street network morphogenesis [8]



Simulations

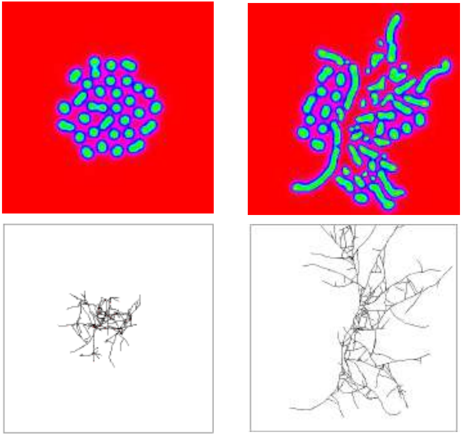
Pattern *holes*

Pattern *mazes*

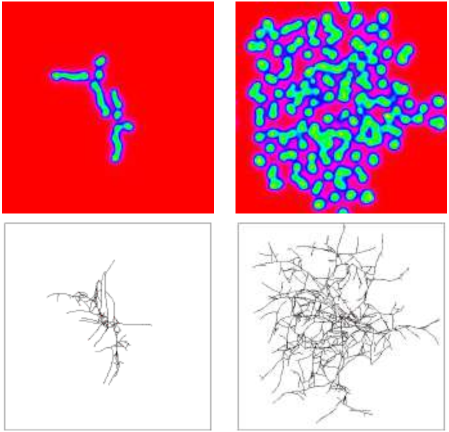


A complex behaviour

Without feedback



With feedback



- mixed patterns in R-D layer
- elaborate structures in the network
- feedback controls the growth rate of the network

Model behaviour

Motivation

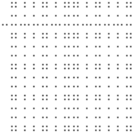
Understand the behaviour of the model comparing results to theoretical and empirical data.

Dataset

- French department cities
- urban area of Le Havre
- theoretical geometric planar graph
- simulated graphs

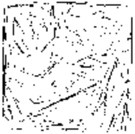
French department cities

Theoretical geometric planar graphs

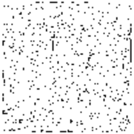


Grid

Deterministic



Probabilistic



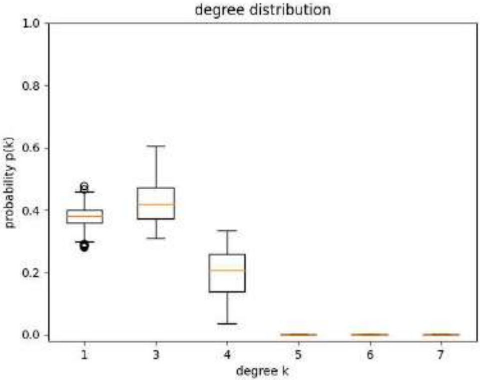
Delaunay

Gabriel

Euclidean tree

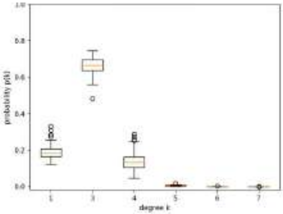
Degree distribution

Simulated networks

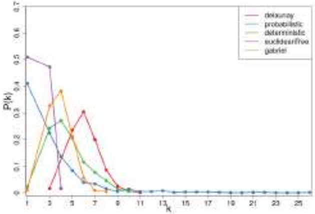


The shape of the distribution is similar to cities

French cities



Theoretical graphs



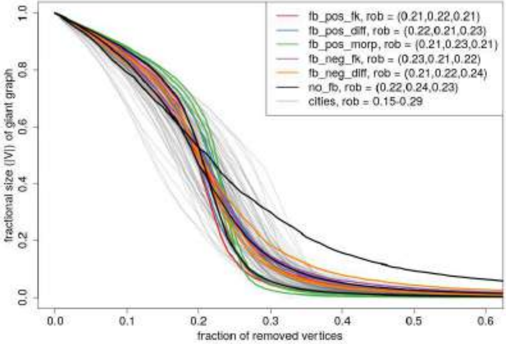
Robustness

Robustness of systems

The capacity to accomplish its task and work after the failure of some elements.

Computation

- giant component
- remove a number of vertices
- compute the size
- robustness: the value of fraction of vertices required for the giant component to reach the 50 % of the size of the graph
- average over 100 runs



- cities are between the tree graph and other theoretic graphs
- simulated networks have a similar robustness of cities

Scale invariance

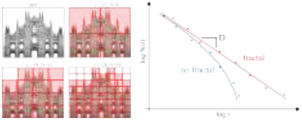
Scale invariance of systems

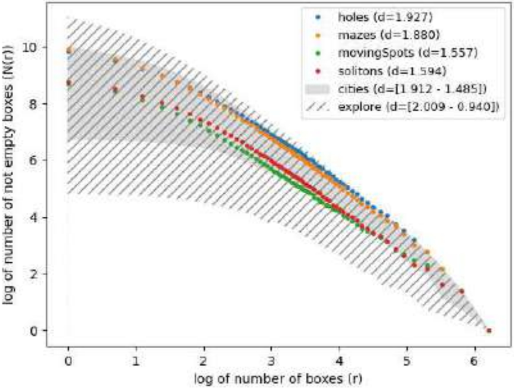
Similar properties at different scales of observation

→ **Fractal theory**

Boxing counting

The relation between the minimum number of boxes to include vertices and the size of the box





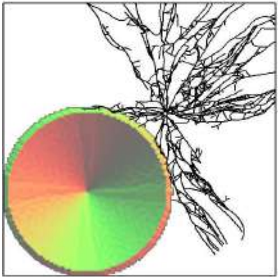
The degree of multi-fractality of real and simulated networks are similar

Combine different vector fields

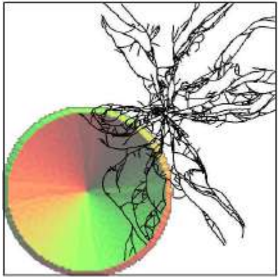
Motivation

Spatial (static) constraints (orography, rivers, sea...) impact the formation of streets.
The model allows us to combine different vector fields

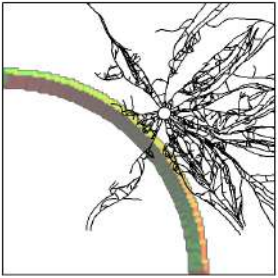
Sea



Hill

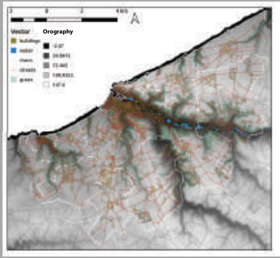


River



An application in urban growth: Fécamp town

Fécamp, France



The model also allows to consider:

- the orography
- the built-up density
- green area
- political decisions

Spatial distribution of the betweenness centrality


(a) initial configuration


(b) mazes

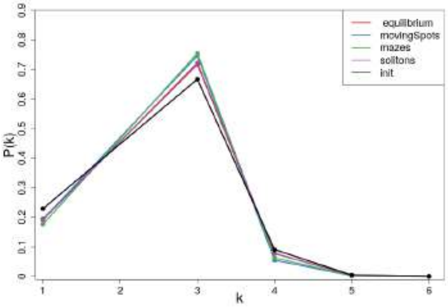

(c) moving spots


(d) solitons

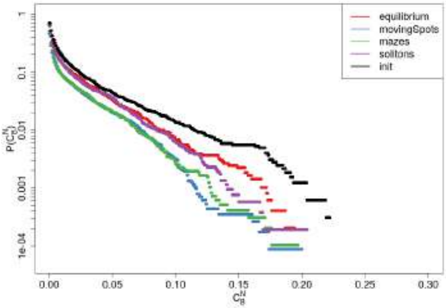
Fécamp town - observed properties

- simulated networks (coloured lines) conserve the main characteristics of the starting network (black lines) with variations
- more organic forms (many tree-like structures and bifurcations)

Vertex degree distribution



Betweenness centrality distribution



Morphogenesis of urban systems - Conclusion

Model behaviour

- Dynamics are completely decentralized and driven by feedback over layers
- Properties of real street networks and simulated networks are similar [8]
- The model can be used to investigate the morphogenesis of street networks and help urban planners

Morphogenesis of street networks

An unpredictable combination of endogenous factors (rate of growth, randomness, topology, geometry) and exogenous dynamics (patterns, feedback) to the network.

Reaction-diffusion theory

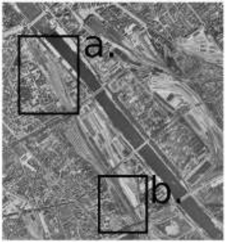
- Morphogens: spatially embedded, interact each others, are involved in competition/cooperation processes, move and may arranged with regularity
- In an urban application, morphogens can represent real activators or inhibitors of urban growth (e.g. population, economical factor and political actions)
- An early "proof": simple and decentralized mechanisms (reaction-diffusion) may be behind the morphogenesis of street networks

Perspectives: co-evolution of human transport and urban forms

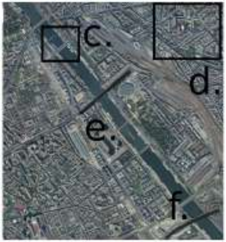
Limits

- Morphogens: are they able to represent decisions of individuals?
- Dynamics over the network. How we can consider it?
- Morphogenesis = growth + transformation. How we can consider both?

An example: Quai de Bercy (Paris)



(a) 1960



(b) 2020

- a. transformation of the train station
- b. a new residential area
- c. a new bridge
- d. reorganization of streets
- e. the enlargement of a bridge
- f. a new motorway bridge

Mobility play a crucial role in morphogenesis of urban forms

Co-evolution of human transport and urban forms

mobility modes transform the urban forms → new urban forms impact the mobility

To consider

- new mobility modes and new lifestyles
- humans move over a multimodal (multilayer) transportation network
- individual are decision makers

Technical challenge

The computational framework must integrate:

- an evolving multi-modal transportation network
- micro-simulation of individuals

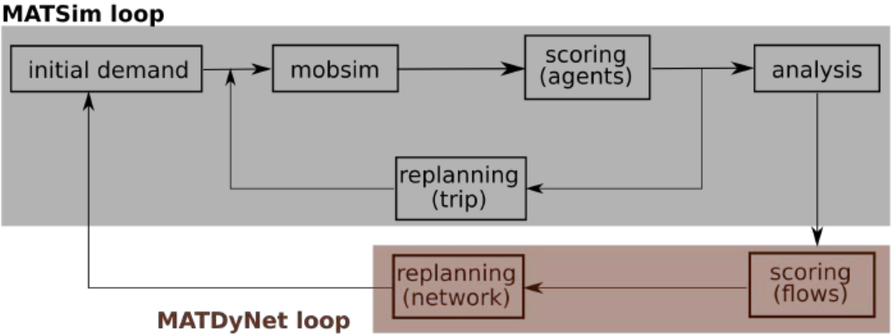
Co-evolution of human transport and urban forms

MATSim

- multi-agent transport simulation framework
- decision makers represented individually ("agents")
- daily activity-travel patterns ("plans")
- modular and extendable

MATDyNet

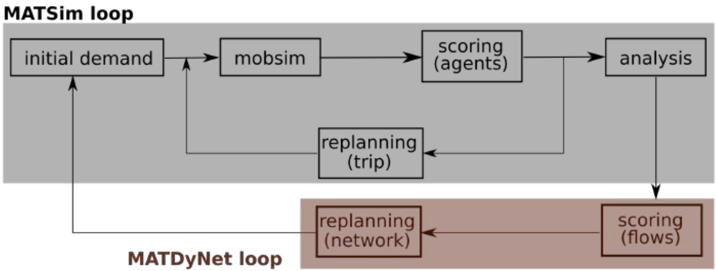
- evolving multi-modal transportation network
- network transform locally in accordance to emerging traffic situations



Co-evolution of human transport and urban forms

Next steps

- formalize and develop the MATDyNet library (Python)
- build a dataset about 2 study cases (Paris and Beijing)
- quantitatively measure the transformation of the network (connectivity, robustness, geometrical and topological characteristics)
- evaluate the impact to urban mobility (congestion, pollution, accessibility)
- make scenarios and evaluate the impact of individual behaviours or policymaker decisions to cities



Thank You

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Turing, A. M. (1952). "The Chemical Basis of Morphogenesis". In: *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 237.641, pp. 37–72.

Pumain, D. et al. (1989). *Villes et auto-organisation*. Paris: Economica. 191 pp.

Portugali, J. (2006). "Complexity Theory as a Link between Space and Place". In: *Environment and Planning A* 38.4, pp. 647–664.

Barthelemy, M. (2011). "Spatial networks". In: *Physics Reports* 499.1, pp. 1–101.

Batty, M. (2013). *The New Science of Cities*. Publisher: The MIT Press. Cambridge: The MIT Press.

Fusco, G. and M. Tirico (2016). "Configurational Approaches to Urban Form: Empirical Test on the City of Nice (France)". In: *Procedings of the 9th INPUT International Conference on Innovation in Urban and Regional Planning*. Ed. by S.-I. DIST. Turin: SiTI, pp. 376–382.

Tirico, M. et al. (2019). "Morphogenesis of Complex Networks: A Reaction Diffusion Framework for Spatial Graphs". In: *Complex Networks and Their Applications VII*. Ed. by L. M. Aiello et al. Studies in Computational Intelligence. Springer International Publishing, pp. 769–781.

Tirico, M. (2020). "Morphogenesis of complex networks. An application in urban growth". PhD thesis. Le Havre: Le Havre Normandy University. 203 pp.