A model of urban evolution based on innovation diffusion

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Abstract

Introduction

Urban systems are complex as they combine technical artefacts with socio-economic dynamics at multiple temporal and spatial scales. An understanding of processes driving their dynamics is an important aspect for shaping sustainable policies, and a sustainable design and management of cities (Lobo et al., 2020). Multiple disciplines and viewpoints have proposed such insights from a complexity perspective (Pumain and Raimbault, 2020), and Artificial Life approaches have shown promising results to study urban systems, both through conceptual contributions such as interpreting cities through biological metaphors (Batty and Marshall, 2009), but also through modeling and simulation for urban growth including cellular automata and evolutionary computation (Raimbault, 2020a).

A stream of research tightly linked to ALife relates to concepts of *Urban Evolution*. These build in a sense on Cultural Evolution (Mesoudi, 2001), which aims at understanding changes in social knowledge as evolutionary processes involving replication, mutation, selection. It bears similarities with biological evolution but is not reducible to it, and for example uses the concept of *meme* as transmission units comparable to genes. Both biological and cultural evolution can be linked into common frameworks and models, implying the coupling of different timescales (Bull et al., 2000). In terms of urban studies, the concept of urban evolution is less formalized than cultural evolution and can be understood in multiple ways. Votsis and Haavisto (2019) use the concept of Urban DNA to characterize morphological properties of cities such as population density or the role of the road network. Similarly, Kaya and Bölen (2017) describe cities based on their morphological properties as a product of their dynamics. Wu and Silva (2011) link the parameters of a cellular automaton model of urban growth to intrinsic properties of urban regions, which should play a role in their overall evolution. In Economic Geography, the concept of co-evolution is used mostly for urban agents such as firms and stakeholders (Gong and Hassink, 2019). At the macroscopic scale of urban systems, Pumain (2018) proposes an evolutionary theory to study systems of cities as complex adaptive systems, in which interactions between cities play a crucial role. Corresponding simulation models were proposed with different thematic focus, for example by Cottineau et al. (2015) with economic exchanges and by Raimbault (2020b) with infrastructure networks. There still however remains a lack of models which would operationalize the concept of urban evolution in a way close to its biological and cultural counterparts.

Besides, a central concept bridging ALife and evolution with the study of urban systems is the concept of innovation diffusion.

Urban evolution model

Rationale

The core idea of the model is to build on a concept of "Urban DNA" which would capture evolution processes as in biological evolution and cultural evolution, i.e. a kind of genome that cities would be exchanging and which would undergo mutation processes. A suitable candidate is to build on the concept of *meme* introduced in the field of cultural evolution. However, several particularities must be stressed out when working with urban systems.

D'Acci (2014)

Batty (2009)

Blommestein and Nijkamp (1987) describes a model of innovation diffusion and urban dynamics with endogenous demand for innovations, but in which the spatial component only influences prices of innovations.

Deffuant et al. (2005) give an example of an elaborated model for adoption dynamics at the microscopic level.

Effective channels for the diffusion of innovations are multiple, and can for example be urban firm linkages (Rozenblat and Pumain, 2007).

Model description

Our model is inspired from the urban dynamics model of Favaro and Pumain (2011), for which crossover and mutation processes were explicited and

Model dynamics Innovation occur along dimensions $1 \leq d \leq D$, and are indexed by their order of apparition c.

The crossover between urban genomes relies on spatial processes of innovation diffusion, following a spatial interaction model given by

$$\delta_{c,i,t} = \frac{\sum_j p_{c,j,t-1}^{s_c} \exp\left(-\lambda_s d_{ij}\right)}{\sum_c \sum_j p_{c,j,t-1}^{s_c} \exp\left(-\lambda_s d_{ij}\right)}$$

The sizes of cities evolve according to their performance in terms of innovation, i.e. more innovative cities are more attractive, with $G_{ij} = w_G \cdot \frac{V_{ij}}{<V_{ij}>}$ such that

$$V_{ij} = \frac{p_i p_j}{\left(\sum_k p_k\right)^2} \exp\left(-\lambda_m d_{ij} \prod_c \delta_{c,i}^{\phi_c}\right)$$

with $\phi_c = \sum_i p_{i,c} / \sum_{i,c} p_{i,c}$

Mutation corresponds to the introduction of new innovations with utility $s_{c+1} = g_0 \cdot s_c$ in a randomly chosen city with a hierarchy parameter α_I, if global adoption share ϕ_c is larger than a threshold θ_I. Initial utility s_0 is a parameter. New innovation has an initial penetration rate r_I in the city.

Synthetic setup

Indicators

Results

The model is implemented in `scala` and integrated into the OpenMOLE software (Reuillon et al., 2013) for numerical experiments. OpenMOLE allows embedding models in any language as black boxes, provides a transparent access to high performance computing infrastructures, and model exploration and validation methods such as sensitivity analysis, design of experiments, and calibration methods. Experiments are designed through workflows using a Domain Specific Language (Passerat-Palmbach et al., 2017).

Parameter explored in experiments are

Model exploration

The sharpe ratios estimated on repetitions as sample standard deviation relative to absolute sample mean have high values for all indicators (min. 3.9 and median 12.1 for diversity; min. 3.0 and median 6.2 for innovation; min. 1.7 and median 3.6 for utility; min. 26 and median 257.3 for population hierarchy), what means that stochastic noise is not an issue for interpreting indicator values. We also study the distance between points

Discussion

Several extensions and applications would be possible to this first model exploration. First, the innovation space in our model remained unidimensional. (Hidalgo et al., 2007) (Bergeaud et al., 2017) Second, applying the model to real system of cities Raimbault (2018) Finally,

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