Multi-agents models for the simulation of urban systems

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Evolutionary theory of urban systems

Urban systems are complex adaptive systems. Their evolution combines:
- a specific history of settlement in a territory
- and a generic dynamics that is proper to settlement systems: stylised facts at macro-level generated by interactions between individual settlements differentiated by size and functions

Exploring this complex systems dynamics with the help of multi-agent models, partly driven by harmonised historical urban data bases and validated by multiscale processing of simulations.
Urban systems organisational emergent properties

Pumain (ed), 2006
Hierarchy in Natural and Social Sciences, Springer

Lima, CISEPA, Denise Pumain, December 2011
Constructive multi-levels interactions

Pumain (ed), 2006
Hierarchy in Natural and Social Sciences, Springer

Lima, CISEP
Stylised facts from evolutionary theory

Hierarchical differentiation of city sizes emerging from interurban interaction (competition > cooperation)

Persistence of urban hierarchies (long term) and specialisation (medium term) despite many local and temporal fluctuations in cities profiles and individual trajectories (firms, households)

Functional geodiversity from innovation cycles generated by interurban competition and emulation

Systemic (proactive) partial diffusion of innovations:
  • Hierarchical selection (top down and bottom up)
  • Emergence of specialised cities
  ➔ Growth impulse to large cities and specialised ones
Theoretical testing

Conditions of emergence of urban systems:

Usual hypothesis:

• economic surplus (from agriculture) + political/religious social organisation (historians, archaeologists, cf Bairoch, etc.)

• One more hypothesis: simultaneous emergence of a system of cities

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SIMPOP: a multi-agents system

first application of MAS in geography!

Bura, Guérin-Pace, Mathian, Pumain, Sanders

Main results:

➡ No emergence if no spatial interactions
➡ Emergence of a polycentric hierarchised system of cities even if homogeneous initial conditions
➡ A renewed innovation flow is necessary for maintaining structural properties of the system of cities

But: 400 settlements only
two levels only (meso-macro)
Exemple of the SIMPOP model: simulation of the emergence of a polycentric system of cities

Starting from a rather regular distribution of settlements, a system of cities emerges, with a strong hierarchical and spatial organization

Source: Bura, Guérin-Pace, Mathian, Pumain, Sanders, 1996, 1997  
*Lima, CISEPA, Denise Pumain, December 2011*
Emerging hierarchical differentiation of the settlement system (rank-size distribution)

Source: SIMPOP model

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Originality of SIMPOP2 Model

**Scale**: national or continental integrated urban systems, long term

**Cities are agents**: collective, immobile, heterogenous, evolving entities

**Main attributes**: location, resources (labour force, capital), functions (10 types)

**Three levels**: individual (firm or mayor, for scenarios), cities (local governance), national or multinational (global governance)

**Rules**: stylised facts from comparative study of the observed evolution of integrated urban systems

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Historical data trends serve as commands for the System.

Our approach:

- Historical data injection
- Outputs observations

Classic approach:

- Data injection
- Outputs observations

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Further Simpop instances

http://www.simpop.parisgeo.cnrs.fr

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The Simpop instances

- Design of the Simpop1 model
- Design of the Simpop2 generic model
- EuroSim model
- simpopNano model

- Simulations on the Rhône Alpes subregion
- Simpop2 European LT model
- Simpop2 US and South Africa models
Aim of the model

- To improve our evolutionary theory of urban systems (a generic model)

- The model as a filter:

To analyse the role of geographical features and processes (location, access to resources, situation in information networks, mobility speed, range and intensity, innovation adoption, selection) in shaping urban dynamics.
A generic model for simulating a diversity of urban systems

How rules have to be adapted for simulating different types of urban system’s evolution:

- Old settlement systems (ex. Europe)
- New settlement systems (ex. South Africa, USA)
- Developing countries having experienced colonialism (ex. India)

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Endogenous dynamics in SIMPOP2

At city level: two time scales

- short term interaction: trade networks between cities according to three kinds of spatial interaction (depending on functional type)

- long term competition for attracting innovation (adopting new functions) according to successful results in short term trade

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Exogenous dynamics in SIMPOP2

- **Innovation cycles** (creating new urban functions):
  - Long distance trade (1300-1800)
  - First industrial revolution (1800-1900)
  - Electricity and car manufacturing (1900-1950)
  - Information technologies (1950-2000)

- **Adoption of new functions**
  - General rules (hierarchical diffusion, from large cities to smaller towns) and strategic local or global governance (specialisation)

- **Increase in interaction speed and frequency**
  - Hierarchical selection: short-circuiting of smaller towns

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Computer Software for SIMPOP2

- Developed with the Swarm multi-agent framework, implemented in a object-oriented language (Objective-C)

- Approximately 20,000 lines of code running on a dedicated server

- A separated Java client application for experimentation, visualization of the results and calibration

Lima, CISEPA, Denise Pumain,

Swarm hierarchical modeling approach

A snapshot of the java application

T. Louail 2008
SIMPOP’s ontology (computational)
Exchange market (1)
exchanges of messages and selection of economic partners

Supply side: City i
demand side: City j

Supply to each city of the network, proportionally to their potential demand
Selection among the suppliers according to technicality and low cost

Source: Eurosim, TiGrESS report, 2006
Rules for urban spatial interaction

- According to three types of functions:

* **distance constraint** and competition (central functions, regional trade and services)

* **proximity and exclusivity** (administrative and political control)

* **network control** (long distance) with or without boundary constraints (manufacturing, finance, tourism)

Source: Sanders et al. 2006
Constitution of each citys’ network

step 1: the potential network

step 2: selection of the cities

Frequent overlapping between the networks of different cities

Source: Eurosim, TiGrESS report, 2006
An iteration

Start

For each city and function
Compute supply
Compute demand

For each city

Acquire / loss function

Compute labor force division

Compute growth

Trade

For each city and function
Compute trade networks

For each city and function
Dispatch supply to the network

For each city and function
Satisfy demand from received supplies

Supply and customer left ?

Yes

No

End

Steps in iteration

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Computation of resulting economic and demographic growth

Demographic growth of city i at t+1 is the sum of 3 components

\[ P_{i}^{t+1} = P_{i}^{t} + (\Delta^{1}P_{i}^{t} + \Delta^{2}P_{i}^{t} + \Delta^{3}P_{i}^{t}) \]

(1) Demographic trend

\[ \Delta^{1}P_{i}^{t} = \alpha^{t} \times G_{h}^{t} \times P_{i}^{t} \]

(2) Labor force attractiveness for each urban function k of city i

\[ \Delta^{2}P_{i}^{t} = \sum_{k} P_{ik}^{t \rightarrow t+1} \]

(3) Market returns

\[ \Delta^{3}P_{i}^{t} = \beta^{t} \times \min(\Delta w_{i}^{t};0)/W^{t} \]

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## Main variables and parameters

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>State variables</td>
<td>Population, Wealth, Labor force by urban function</td>
</tr>
<tr>
<td>Contextual variables (exogenously defined for each urban system)</td>
<td>population and wealth: Mean growth rates</td>
</tr>
<tr>
<td></td>
<td>Date of emergence of each function</td>
</tr>
<tr>
<td></td>
<td>Productivity, demand, added value, for each function</td>
</tr>
<tr>
<td>Intermediate variables (endogenous)</td>
<td>Unsold goods, Unsatisfied demand</td>
</tr>
<tr>
<td></td>
<td>Size of the networks</td>
</tr>
<tr>
<td>Key parameters (calibrated)</td>
<td>Range of exchanges associated to the different functions</td>
</tr>
<tr>
<td></td>
<td>Size of exchange networks for specialized cities</td>
</tr>
<tr>
<td></td>
<td>Attraction level on labor force</td>
</tr>
<tr>
<td></td>
<td>% of valuable customers</td>
</tr>
<tr>
<td></td>
<td>Returns from the market on urban growth</td>
</tr>
<tr>
<td></td>
<td>Barrier effects of boundaries</td>
</tr>
</tbody>
</table>
Initial situation
(theoretical pattern, sizes randomly generated)
Central functions trade networks (low level)
Central function trade networks (high level)
Specialised functional network (1936)

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Specialised functional network (2000)
Model validation in MAS

Is validation only an ex-post problem?
Too many games of imagination?

Validation starts while constructing the model:

➔ Retro-ductive (or abduction) methods: the model as a substitute to experimenting theories

Feedback theory/modelling/observations
= Use of existing knowledge and social surveys for fixing parameters values and rules, and even for chosing the agents

➔ immersion of the same model in different geographical contexts = « comparative » method

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Discussion: model validation

Too many rules and parameters? (as complex systems theoreticians say)

- « Second order » networks (abstract flows) because of computer’s capacity, but possible validation by observation of specialised networks

➡ Multiscale ‘validation’
Multi-scale validation
Europe: results of simulation at system’s level

- Evolution of total population 1500-2000

<table>
<thead>
<tr>
<th>Key parameters</th>
<th>Attraction level (ex. central2)</th>
<th>Market return</th>
<th>Share of exogenous growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300-1800</td>
<td>0.5 to 0.8</td>
<td>0.5 to 1</td>
<td>1/3</td>
</tr>
<tr>
<td>1800-2000</td>
<td>0.8 to 3</td>
<td>1 to 7</td>
<td>1/3</td>
</tr>
</tbody>
</table>
Multi-scale validation
Europe: results of simulation at system’s level

Evolution of the labour force (1500-2000)

- Central function (level2)
- Long-distance trade
- Industrial revolution
- Central function (level3)
- Electricity, automobile
- Central function (level4)
- Knowledge society
## Multi-scale validation: meso level (rank-size slopes)

<table>
<thead>
<tr>
<th>Year</th>
<th>Observed Slope</th>
<th>Observed R²</th>
<th>Simulated Slope</th>
<th>Simulated R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>0.72</td>
<td>0.97</td>
<td>0.66</td>
<td>0.98</td>
</tr>
<tr>
<td>1600</td>
<td>0.74</td>
<td>0.99</td>
<td>0.70</td>
<td>0.98</td>
</tr>
<tr>
<td>1700</td>
<td>0.80</td>
<td>0.99</td>
<td>0.75</td>
<td>0.98</td>
</tr>
<tr>
<td>1800</td>
<td>0.69</td>
<td>0.99</td>
<td>0.75</td>
<td>0.98</td>
</tr>
<tr>
<td>1850</td>
<td>0.77</td>
<td>0.99</td>
<td>0.78</td>
<td>0.98</td>
</tr>
<tr>
<td>1950</td>
<td>0.91</td>
<td>0.99</td>
<td>0.89</td>
<td>0.98</td>
</tr>
<tr>
<td>2000</td>
<td>0.94</td>
<td>0.99</td>
<td>0.94</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Europe 1300-2000
Multi-scale validation: meso-level

Europe: Number of cities by size class

<table>
<thead>
<tr>
<th>Size Class</th>
<th>1500</th>
<th>1800</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 1 million</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>500-1000</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>100-500</td>
<td>4</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>50-100</td>
<td>17</td>
<td>16</td>
<td>35</td>
</tr>
<tr>
<td>25-50</td>
<td>37</td>
<td>73</td>
<td>83</td>
</tr>
<tr>
<td>10-25</td>
<td>135</td>
<td>230</td>
<td>473</td>
</tr>
</tbody>
</table>

Lima, CISEPA, Denise Pumain, December 2011
Multi-scale validation: micro-level

Individual trajectories of cities

Lima, CISEPA, Denise Pumain, December 2011
Simulated and observed city sizes in 2000 (initial situation: observed locations in 1300)

Bretagnolle, Pumain, 2008

Lima, CISEPA, Denise Pumain, December 2011
A global city function since Middle Age

<table>
<thead>
<tr>
<th>Dates</th>
<th>Highest rank of well adjusted cities</th>
<th>Observed data (thousands)</th>
<th>Simulated pop. of largest city</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>2</td>
<td>Paris, 225</td>
<td>125</td>
</tr>
<tr>
<td>1700</td>
<td>3</td>
<td>Paris, 500; Napoli, 300</td>
<td>210; 202</td>
</tr>
<tr>
<td>1800</td>
<td>3</td>
<td>London, 948; Paris, 550</td>
<td>534; 533</td>
</tr>
<tr>
<td>1950</td>
<td>5</td>
<td>London, 8900; Paris, 6100</td>
<td>2780; 2650</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ruhr, 4000; Berlin, 3500</td>
<td>2630; 2510</td>
</tr>
<tr>
<td>2000</td>
<td>3</td>
<td>Paris, 10500; London, 9200</td>
<td>7000; 6900</td>
</tr>
</tbody>
</table>
Validation through systems comparison

Can the urbanisation processes of the generic SIMPOP2 model simulate both old and recent urban systems?

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Old urban systems: path dependence
New urban systems: space filling then path dependence

Source: Census of the U.S.

Source: Census of South Africa
Observed urban growth in United States

Data base: A. Bretagnolle, 2008
Simulating United States urban dynamics

- Simulation 1650-2000 with the parameters values calibrated on theoretical Europe leads to:
  - underestimation of total population since 18th century
  - decrease in labour force in central and long distance trade functions as early as 1740
  - stagnation of Western then Southern cities (despite local resources)
  - strong underestimation of the largest cities (New York, Chicago, San Francisco, Los Angeles, Dallas, Miami…)

Lima, CISEPA, Denise Pumain, December 2011
United States: which adaptations of the generic model are necessary?

- 1 timing the activation of cities with emerging urban functions

Source: Bretagnolle, 2007
United States: adaptation of the generic model (2)

- Simulation: «Mushrooming» cities are not growing fast enough

- Creation of a temporary locational initial advantage: *frontier* (1790-1900)

- Rule: cities within the frontier receive for 30 years a higher rate of population growth
United States: adaptation of the generic model (3)

Central2 (left), Central3 (right) and associated exchange networks in 1870

Bretagnolle, 2007

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growth impulses also come from outside (18th-20th century)

Long distance trade networks in 1840
11 cities
range 2000 km (all cities connected through river and maritime shipping or railways).

Bretagnolle, 2007
Introduction of an exogenous demand

To compensate the lack of national customers, an international demand stimulates the production of the specialized functions.

Figure: 2nd industrial revolution, exchanges networks in 1880

Bretagnolle, 2007
United States: adaptation of the generic model (6)

 Locating resources basins for random activation of cities acquiring specialised functions (Cycle 2 and cycle 3)

Manufacturing (1830-1870)

Gold and mineral resources (1870-1890)

Oil (1890-1930)

Bretagnolle, 2007
Urban sizes in 2000, United States
(observed and simulated with adapted SIMPOP2)

(Bretagnolle, 2007)
SIMPOP2: contrasting the evolutions of European and US urban systems

To catch the specific history of urban settlements in US, parcimonious adaptation of rules from the generic SIMPOP model (as calibrated on European system) was necessary:

- belated emergence of central places
- strong incentive from international exchanges on urban growth
- frontier effect: momentary effect on urban growth (mushroom cities)
- migration of new urban functions to new cities stronger than reinvestment on old sites
MAS for measuring urban dynamics properties and predicting future evolution

Europe: « full world » system

United States: « Frontier » urbanization

South Africa: « Frontier » and dual system

India: « full world » and dual

China: « full world », dual, and planned!

Lima, CISEPA, Denise Pumain, December 2011
EUROSIM: Predicting the future of the European urban system

Lena Sanders, Hélène Mathian, 2006

1-multiscale validation
2- testing scenarios

aggregate trajectories
Hierarchical structure analysis (rank-size, primacy)
Concentration analysis

Trajectories of cities

main, December 2011
SimpopNano: location of the Simpop2 urban functions agents at intra-city scale

Thomas Louail, PhD, 2010
Comparing Urban Dynamics on different spatial patterns

PhD Thomas Louail, 2010 and Bretagnolle, Delisle, 2009
Three stages in urban dynamics for the series of SIMPOP models

1- Agrarian economy
   Local resources
   (SimpopLocal)

2- Market economy
   Network returns
   (SimpopNet)

3- Knowledge economy
   Environmental intelligence
   (SimpopClim)

SIMPOP models: France Guérin-Pace, Lena Sanders, Hélène Mathian
with Stéphane Bura, Benoît Glisse, Thomas Louail (and Jacques Ferber, Alexis Drogoul, Jean-Louis Giavitto, Guillaume Hutzler)
and Anne Bretagnolle

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Further research in urban GeoDiverCity

1 A dedicated platform for multiscale model validation: SimpopProcess (S. Rey, T. Louail, H. Mathian, A. Banos)

2 Integration of micro-level economic and spatial processes in the dynamics of geographical entities (F. Paulus, C. Vacchiani-Marcuzzo, S. Baffi, A. Banos)

3 Settlement systems and global change: how policies about sustainability can reorient the future of cities? A comparison US-Europe-India-China (E. Swerts, C. Schmitt)

4 Co-evolution of networks and settlements over human evolution (Lena Sanders, Hélène Mathian, Anne Bretagnolle, Céline Vacchiani-Marcuzzo, S. Martin, F. Delisle, S. Baffi)
Thank you for your attention!

http://simpop.parisgeo.cnrs.fr