UMR GEOGRAPHIE-CITES

Multi-agents models for the simulation of urban systems

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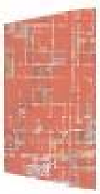
Evolutionary theory of urban systems

Urban systems are complex adaptive systems

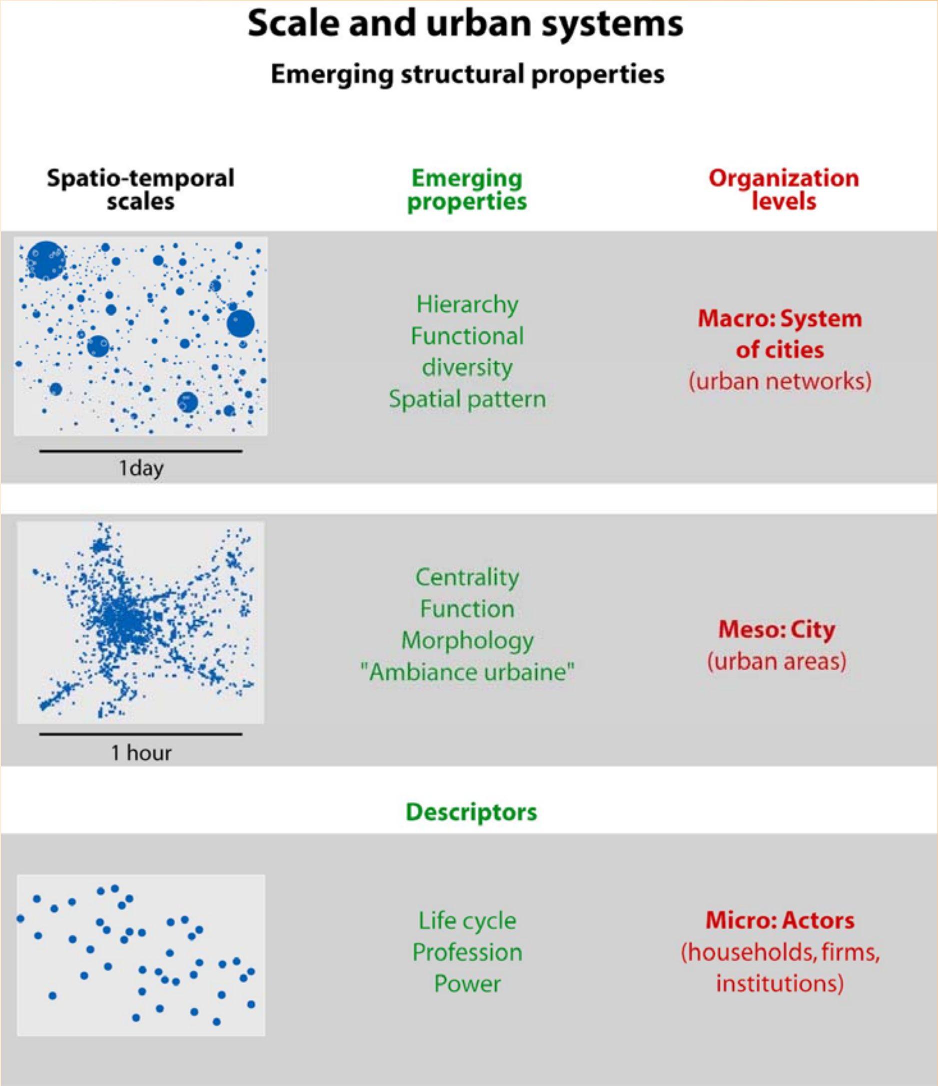
Their *evolution* combines:

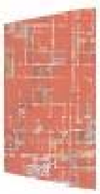
- a specific *history* of settlement in a territory
- and a generic *dynamics* that is proper to settlement systems : stylised facts at macro-level generated by interactions between individual settlements differentiated by size and functions



➔ 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

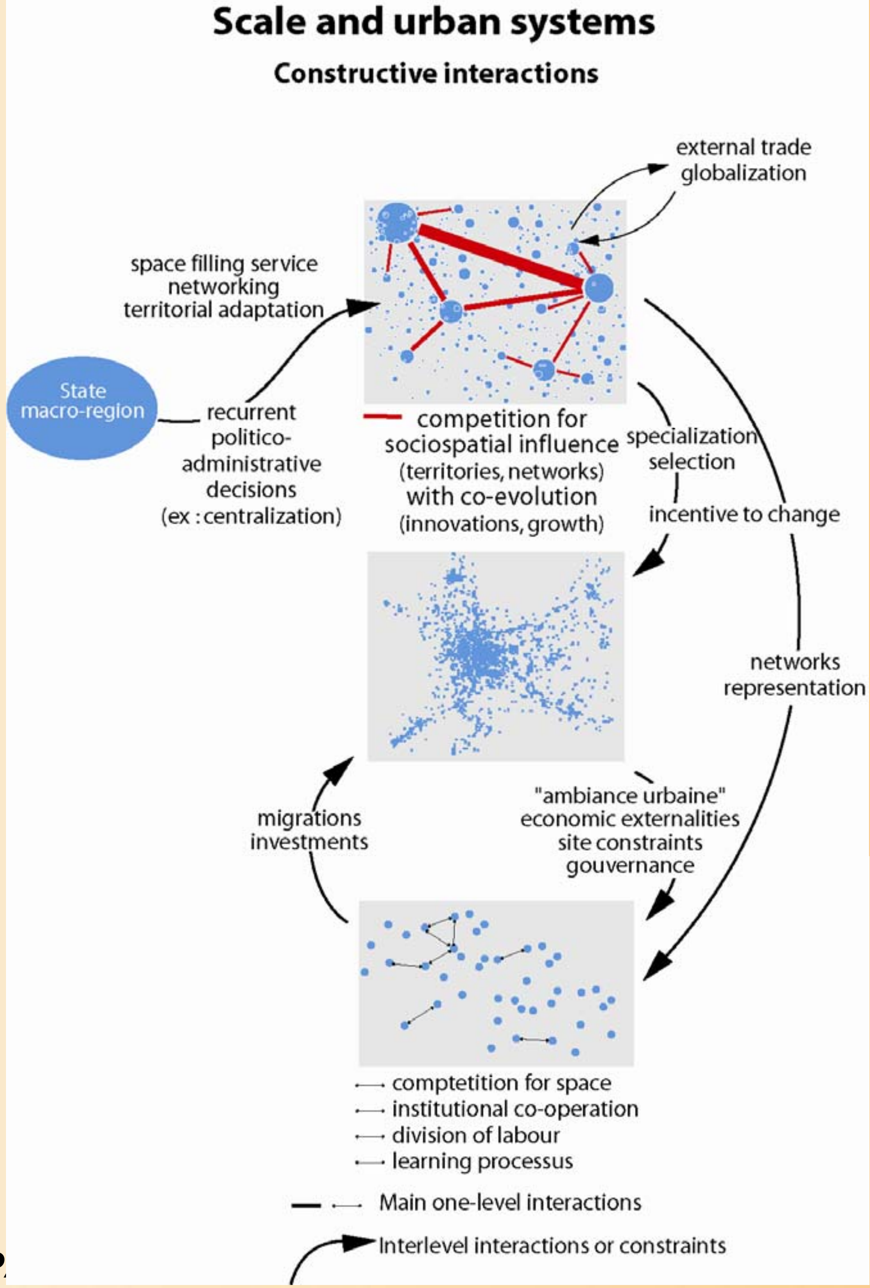




Pumain (ed), 2006 Hierarchy in Natural and Social Sciences, Springer

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)

Persistance 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

SIMPOP: a multi-agents system

first application of MAS in geography !

Bura, Guérin-Pace, Mathian, Pumain, Sanders

Multi-agent systems and the dynamics of a settlement system. *Geographical Analysis*, 1996, 2, 161-178

Main results:

➔No emergence if no spatial interactions

➔Emergence of a polycentric hierarchised system of cities even if homogeneous initial conditions

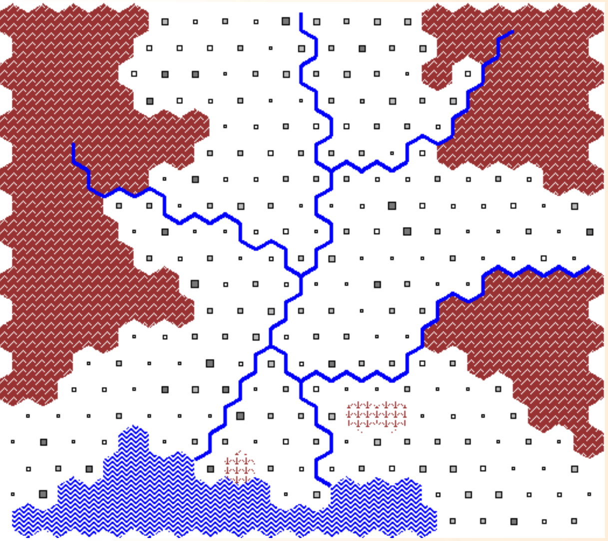
➔A renewed innovation flow is necessary for maintaining structural properties of the system of cities

But: 400 settlements only

two levels only (meso-macro)

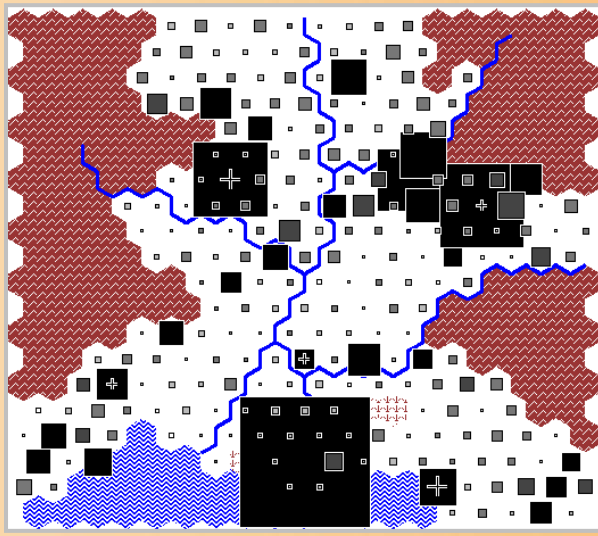
Exemple of the SIMPOP model:
simulation of the emergence of a polycentric system of cities

t=100



t=1700

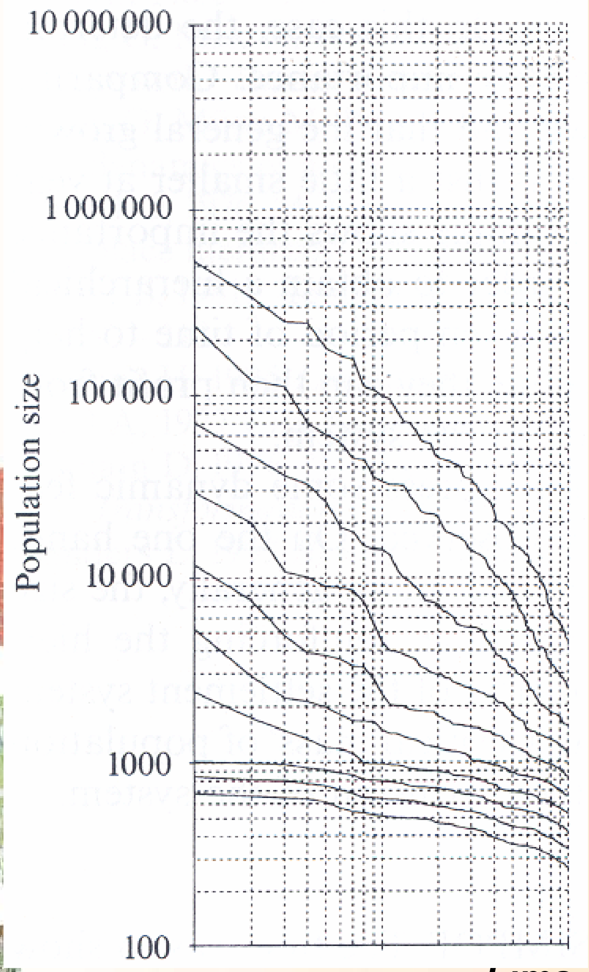
t=2000

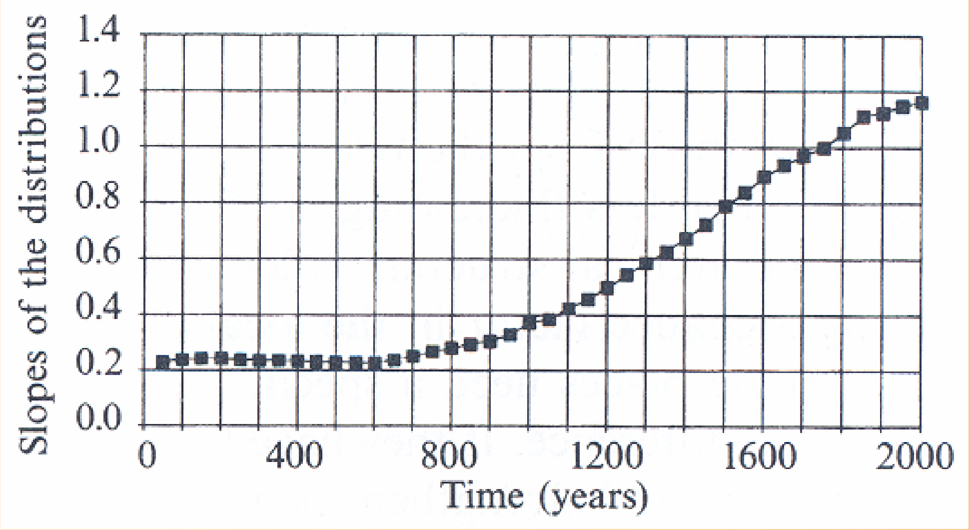


Starting from a rather regular distribution of settlements, a system of cities emerges, with a strong hierarchical and spatial organization

Source: Bura, Guérin-Pace, Mathian, Pumain, Sanders, 1996, 1997

Emerging hierarchical differentiation of the settlement system (rank-size distribution)





t = 2000

t = 1600

t = 0

Source: SIMPOP model

Originality of SIMPOP2 Model

Scale: national or continental integrated urban systems, long term

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

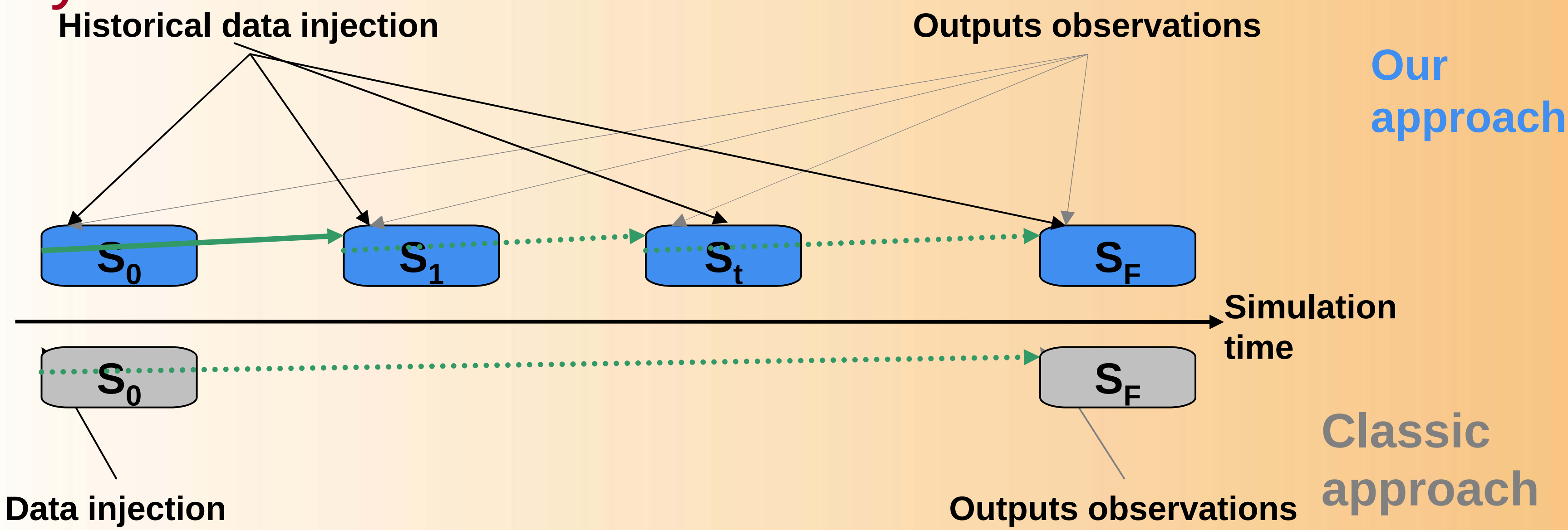
Main attributes: location, resources (labour force, capital), functions (10 types)

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

Historical data-driven simulations

Historical data trends serve as commands for the System



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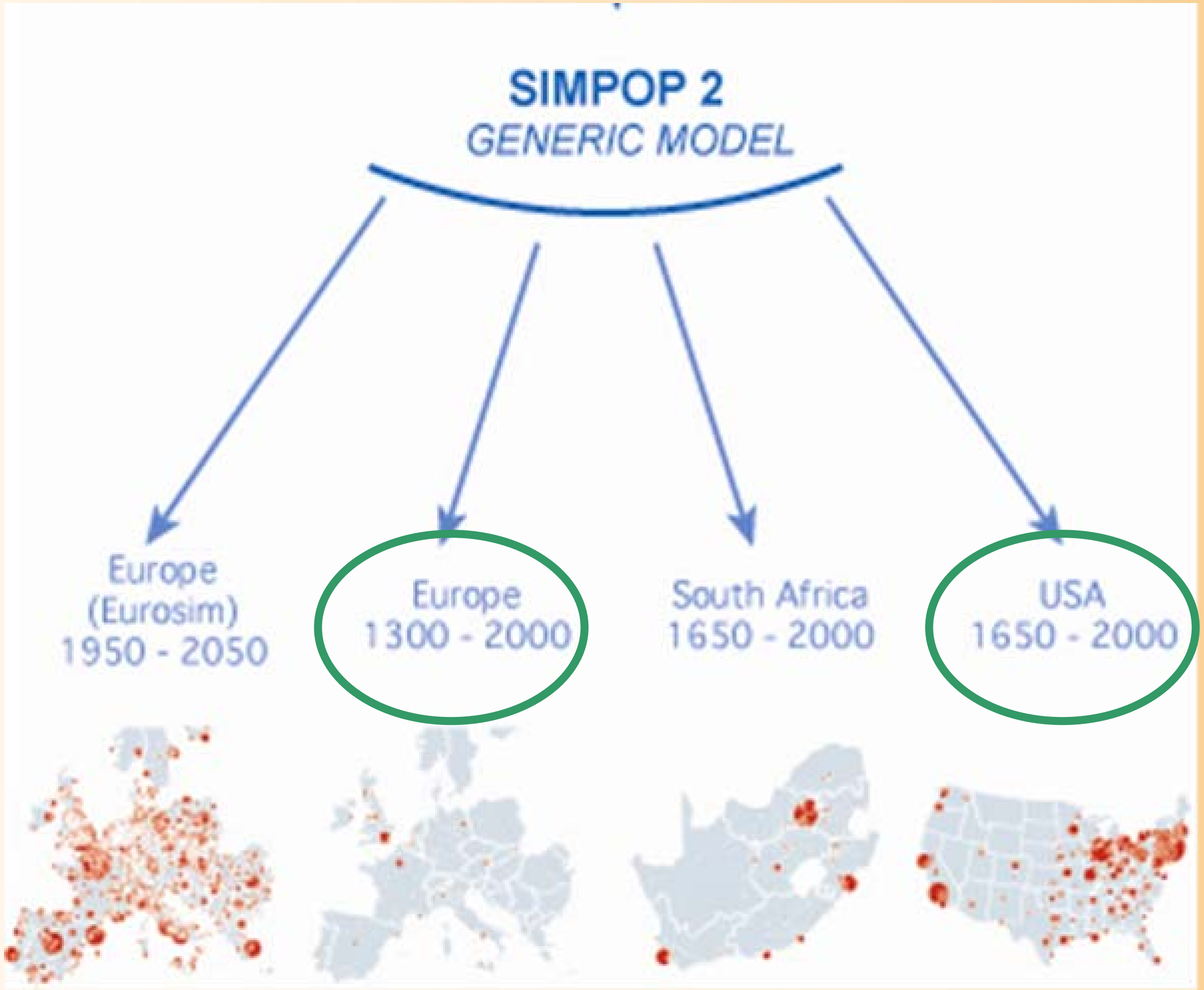
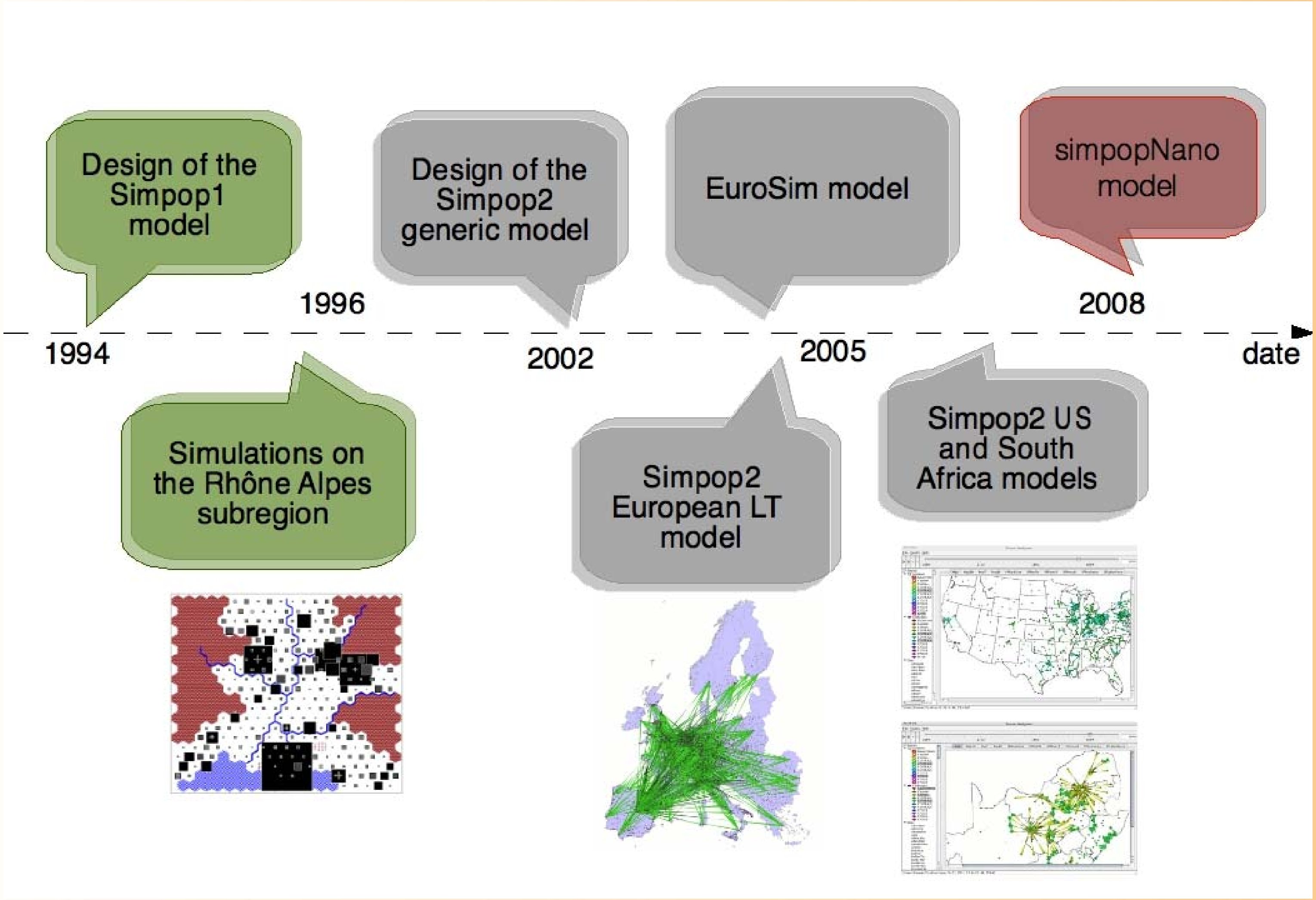
Further Simpop instances



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

The Simpop instances



Aim of the model

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

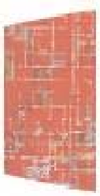
- **The model as a filter**:

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)

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

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)

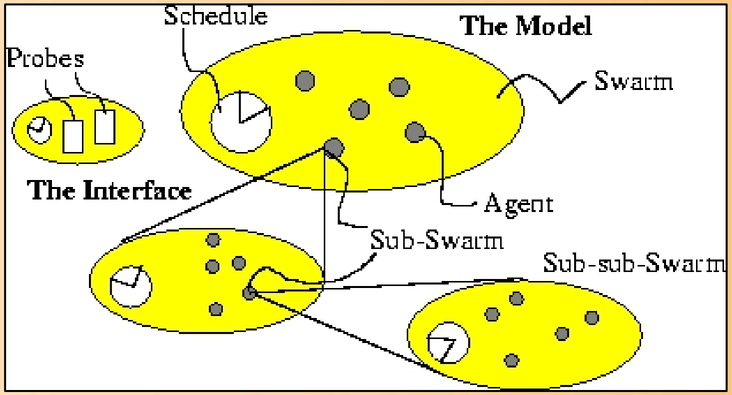
➔ **Increase in interaction speed and frequency**

Hierarchical selection : short-circuiting of smaller towns

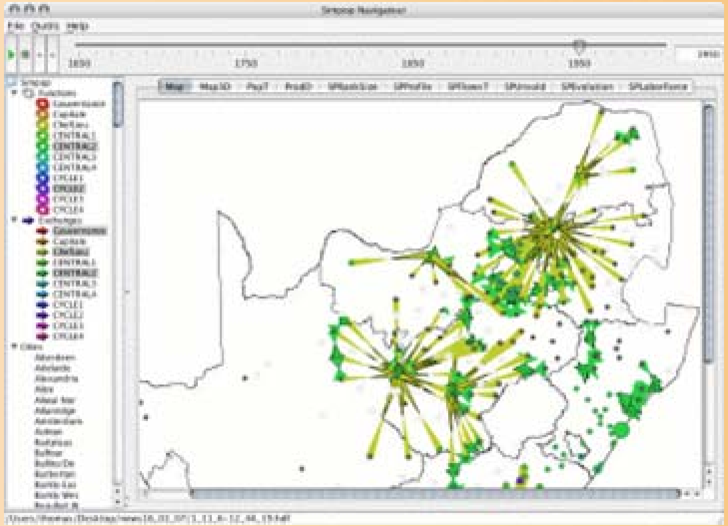
Computer Software for SIMPOP2

- 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

Swarm hierarchical modeling approach



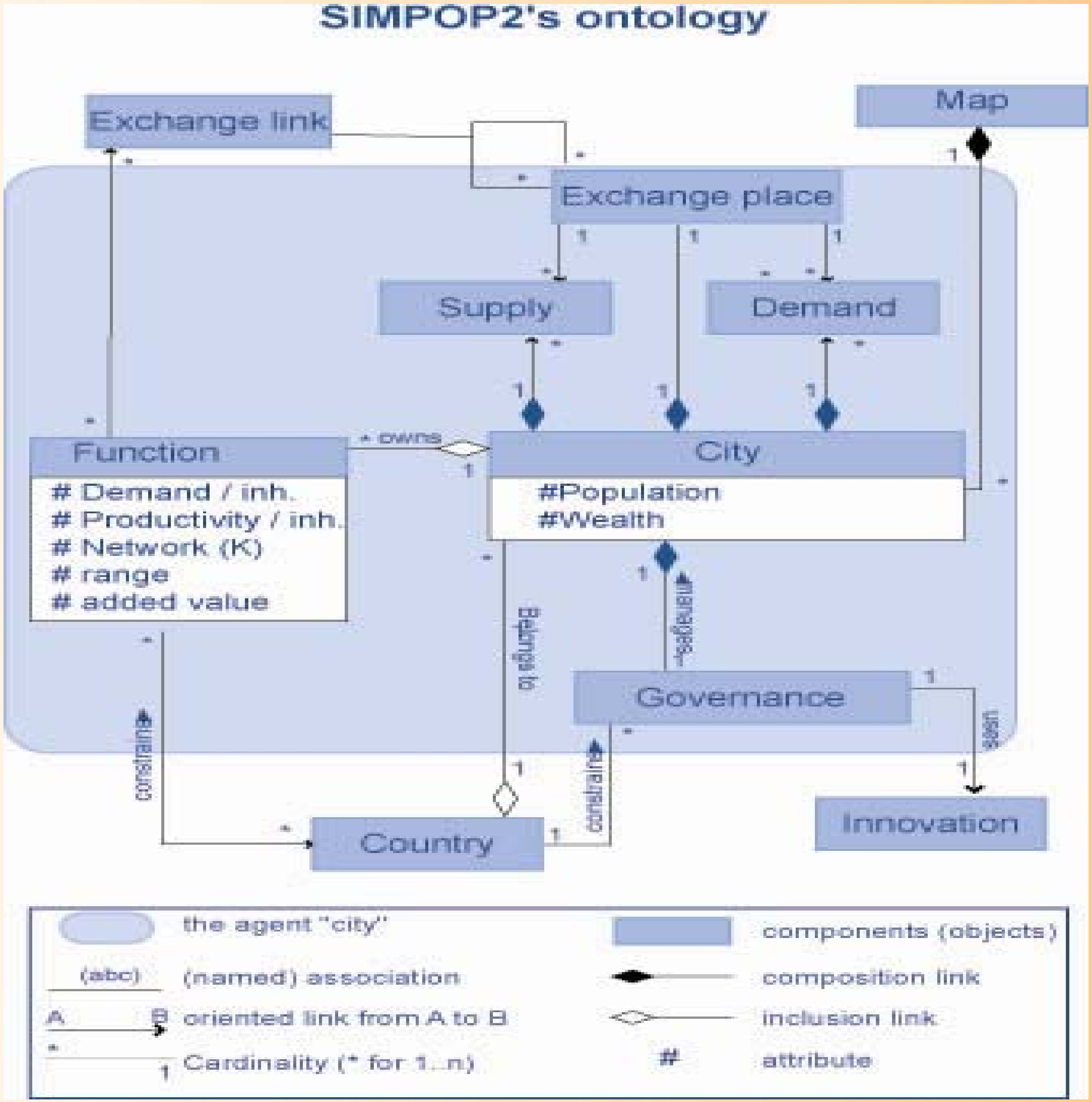
A snapshot of the java application



Lima, CISEPA, Denise Pumain,

T. Louail 2008

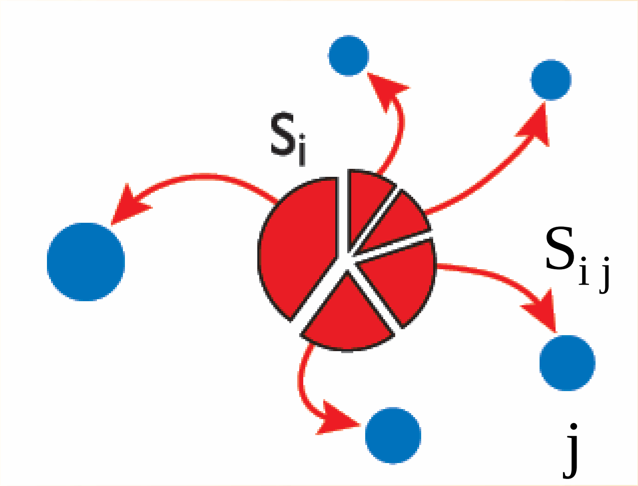
SIMPOP’s ontology (computational)



Exchange market (1)

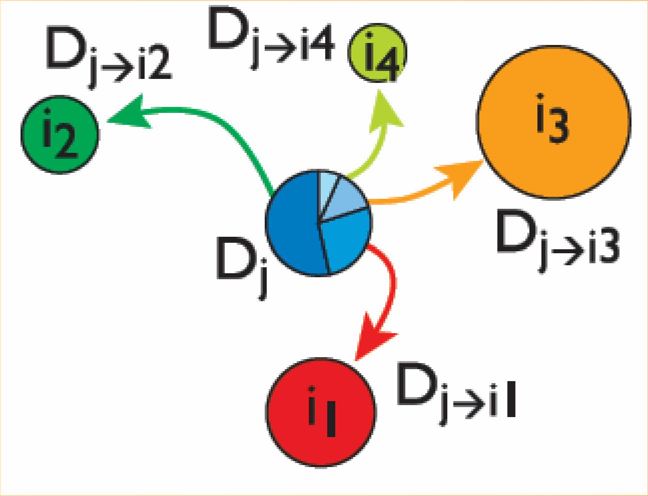
exchanges of messages and selection of economic partners

supply side : City i



Supply to each city of the network, proportionally to their potential demand

demand side: City j



Selection among the suppliers according to technicality and low cost

Source: Eurosim, TiGrESS report, 2006

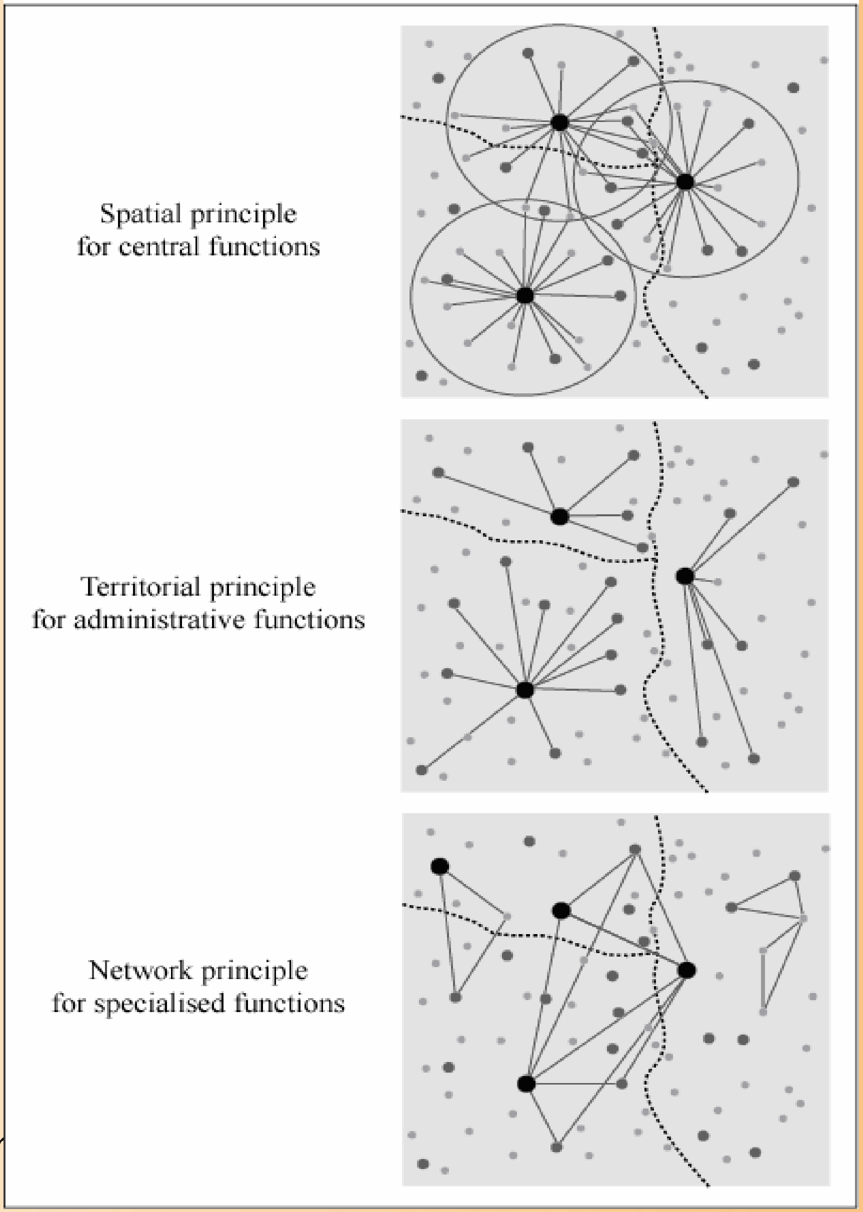
Rules for urban spatial interaction

-According to three types of functions:

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

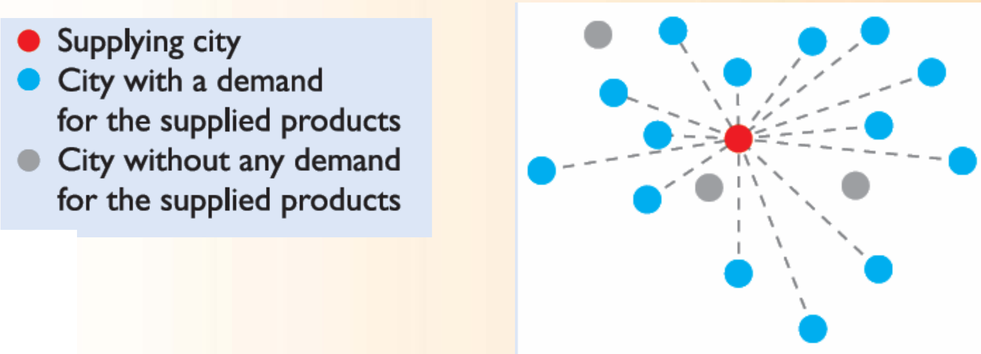
* **proximity and exclusivity** (administrative and political control)

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



Source: Sanders et al. 2006

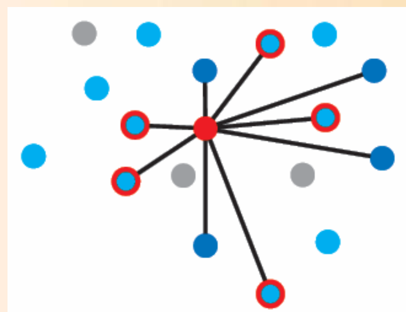
Constitution of each citys' network



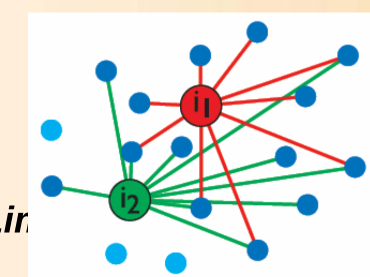
step 1: the potential network

Valuable customer from preceding periods

random drawing to complete the network



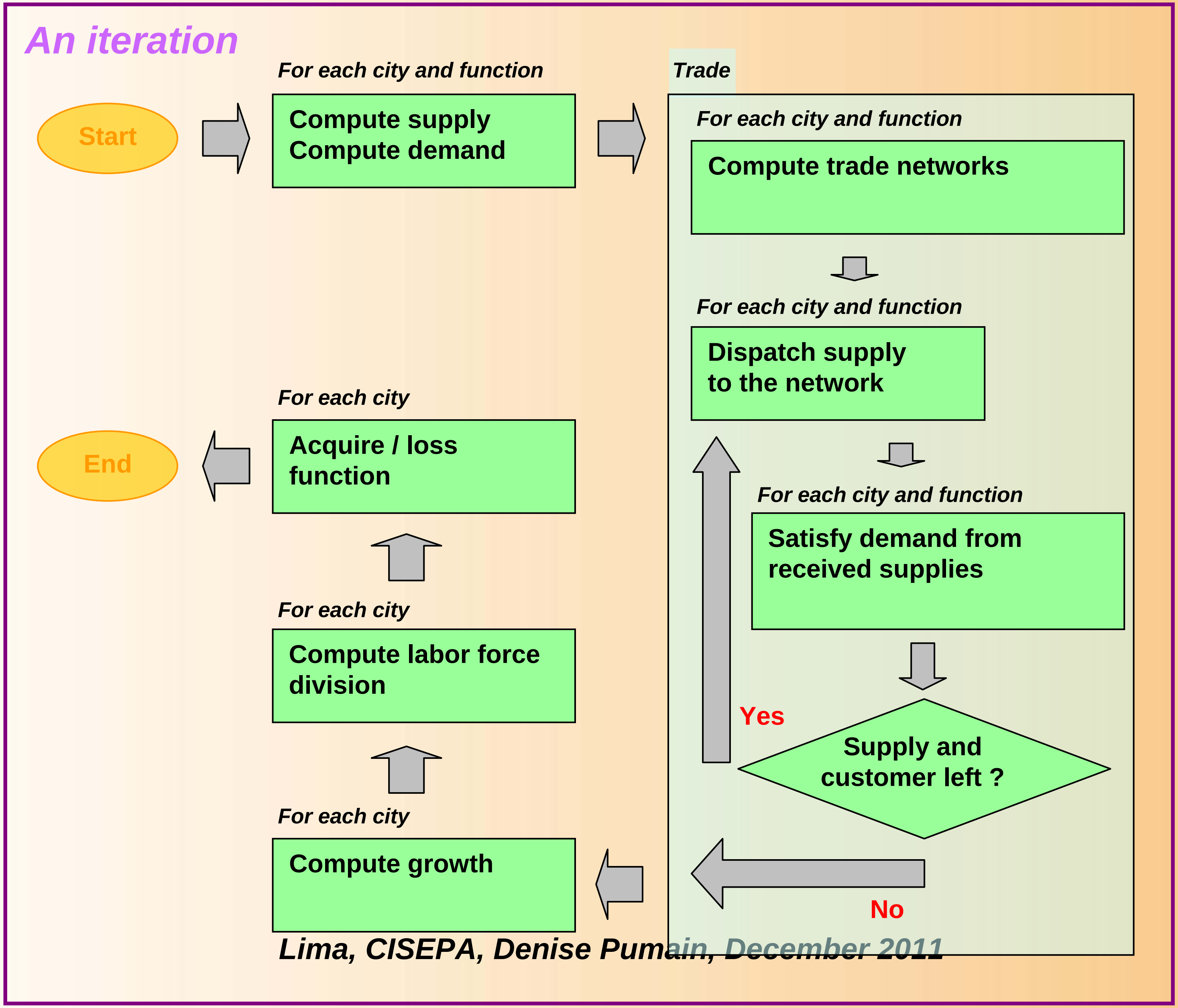
step 2: selection of the cities



Frequent overlapping between the networks of different cities

Source: Eurosim, TiGrESS report, 2006

Steps in iteration



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

$$\Delta^1 P_i^t = \alpha^t * G_h^t * P_i^t$$

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

$$\Delta^2 P_i^t = \sum_k P_{ik}^{t \to t+1}$$

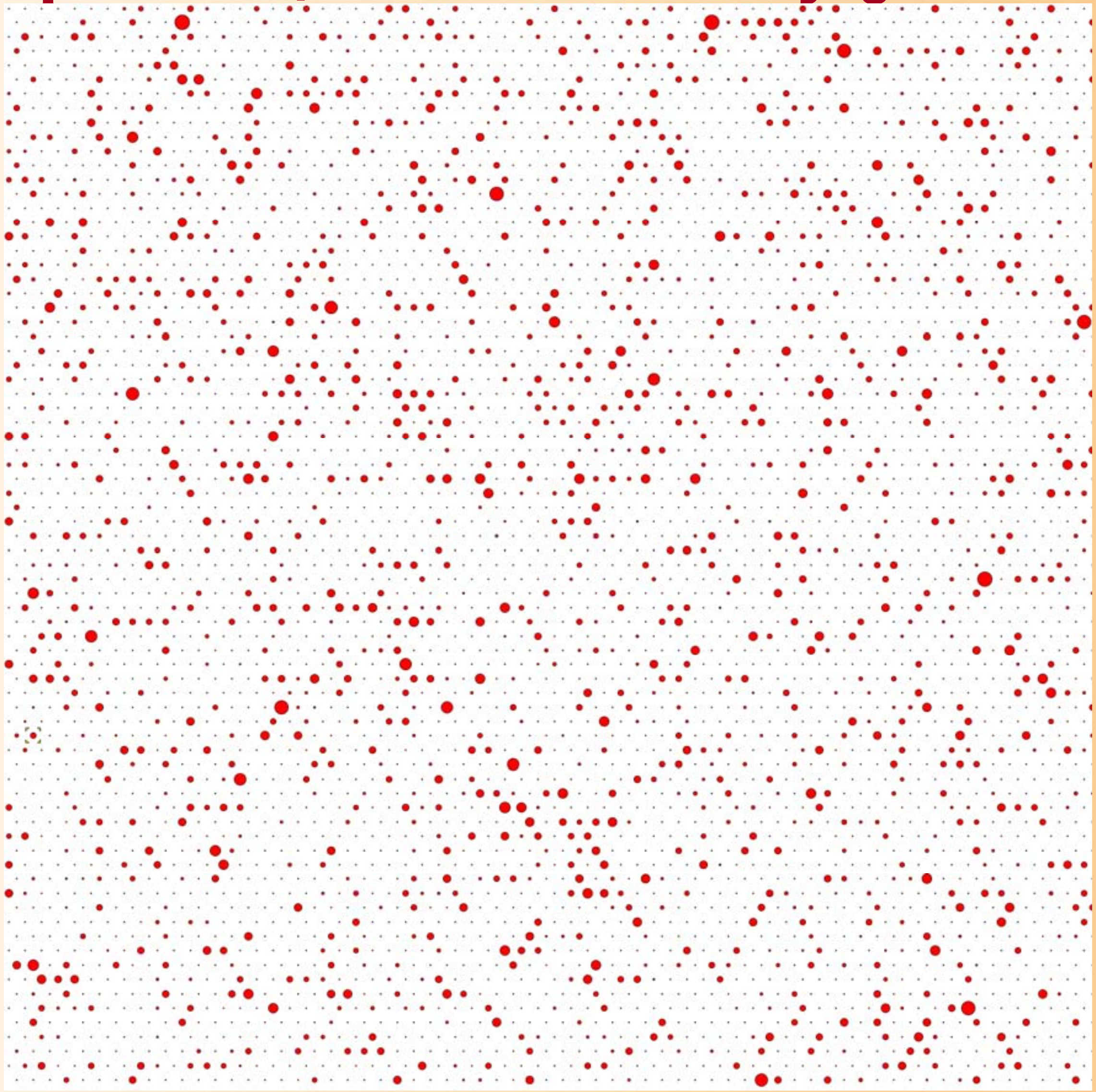
(3) Market returns

$$\Delta^3 P_i^t = \beta^t * \min(\Delta w_i^t ; 0) / W^t$$

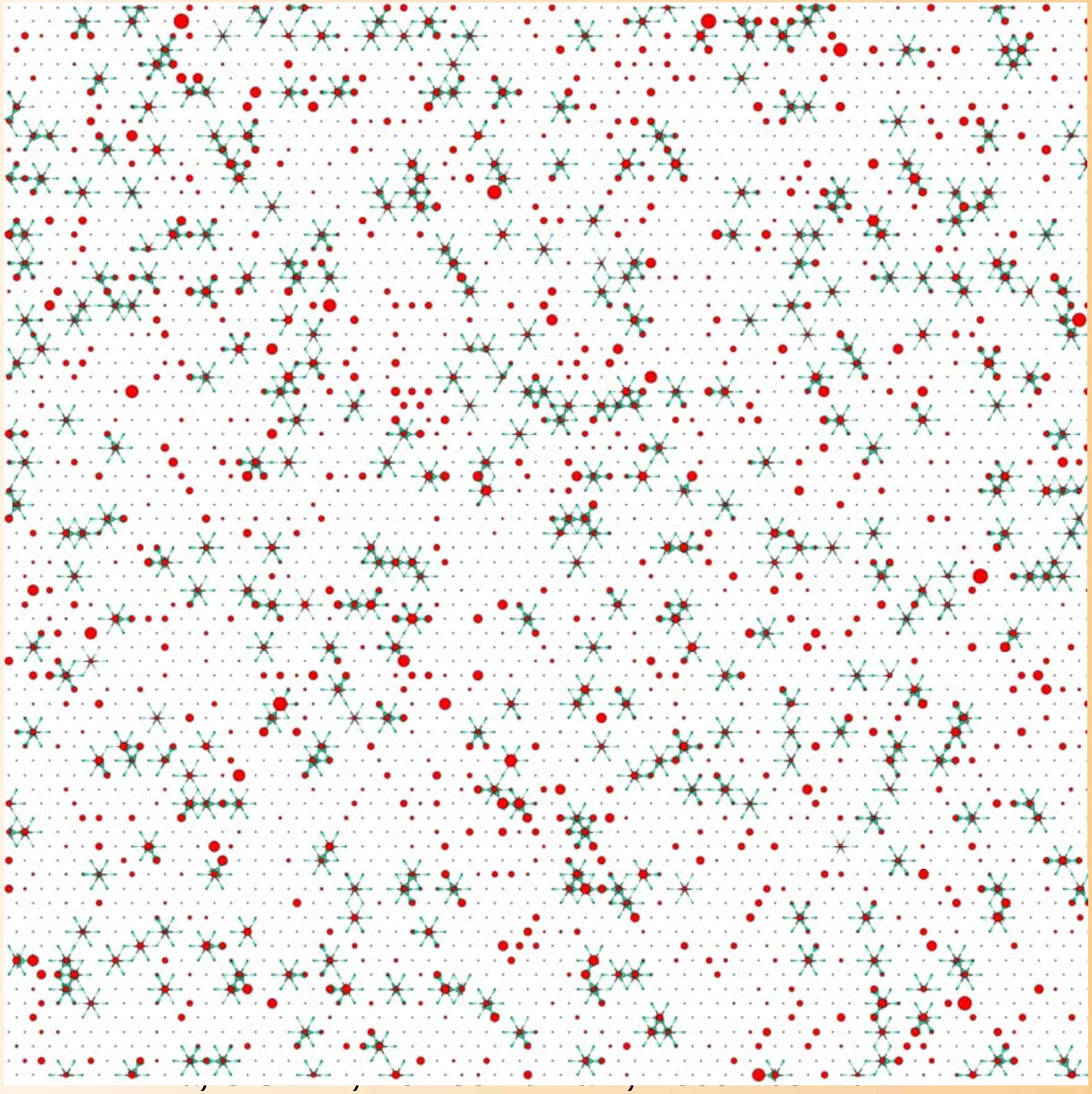
Main variables and parameters

Category	Parameters
State variables	Population, Wealth, Labor force by urban function
Contextual variables (exogenously defined for each urban system)	population and wealth : Mean growth rates Date of emergence of each function Productivity, demand, added value, for each function
Intermediate variables (endogenous)	Unsold goods, Unsatisfied demand Size of the networks
Key parameters (calibrated)	Range of exchanges associated to the different functions Size of exchange networks for specialized cities Attraction level on labor force % of valuable customers Returns from the market on urban growth Barrier effects of boundaries

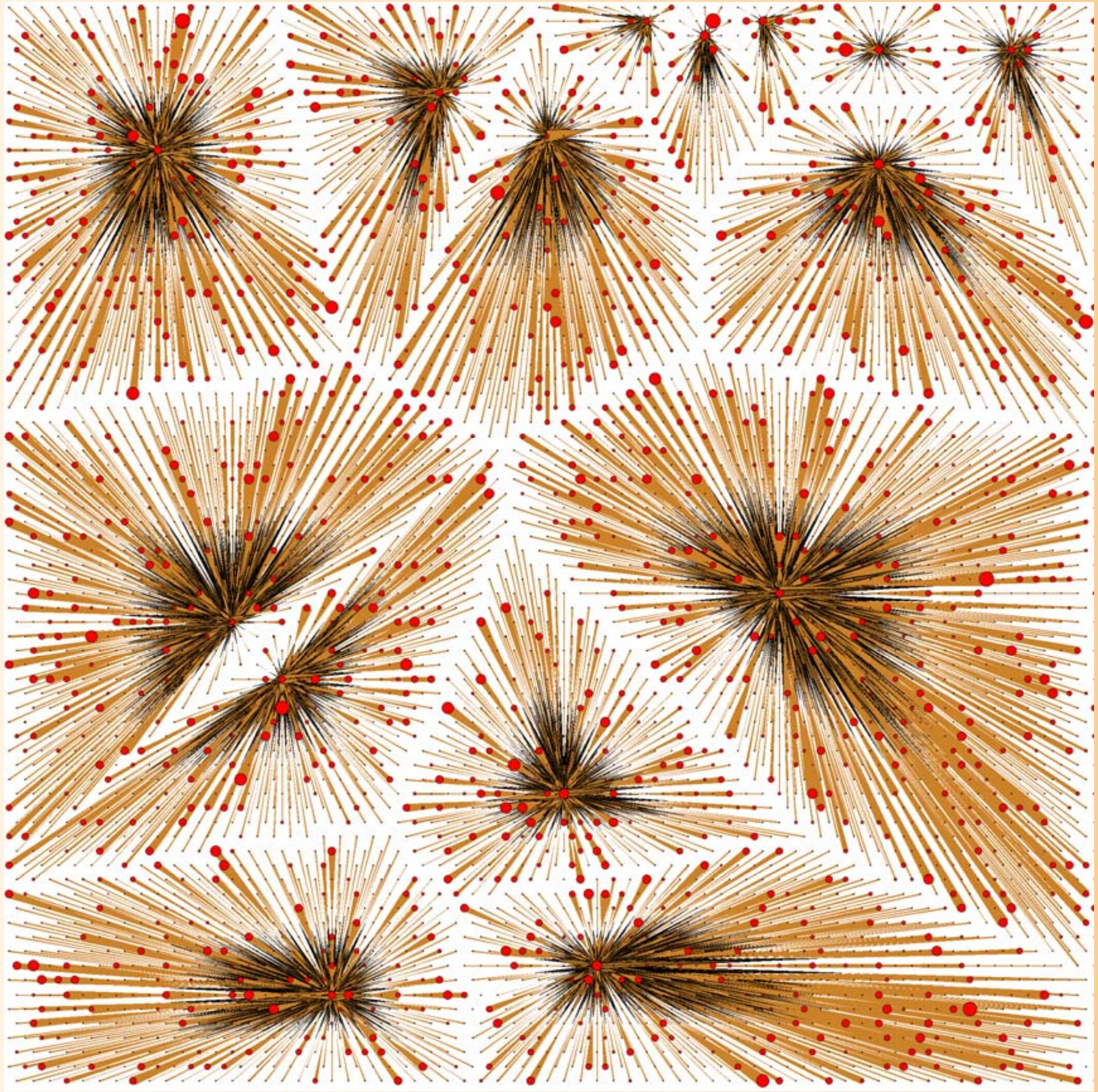
Initial situation
(theoretical pattern, sizes randomly generated)



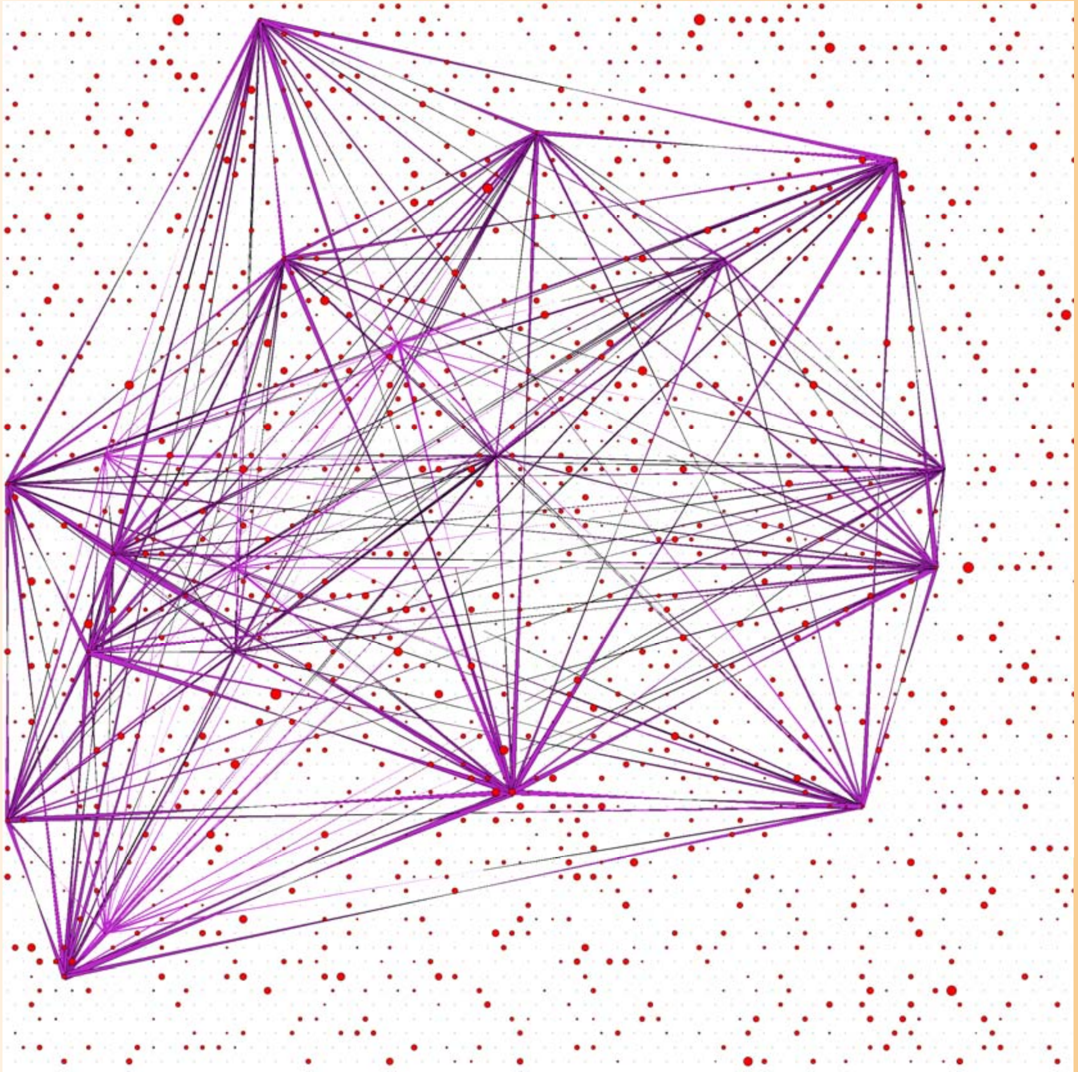
Central functions trade networks (low level)



Central function trade networks (high level)

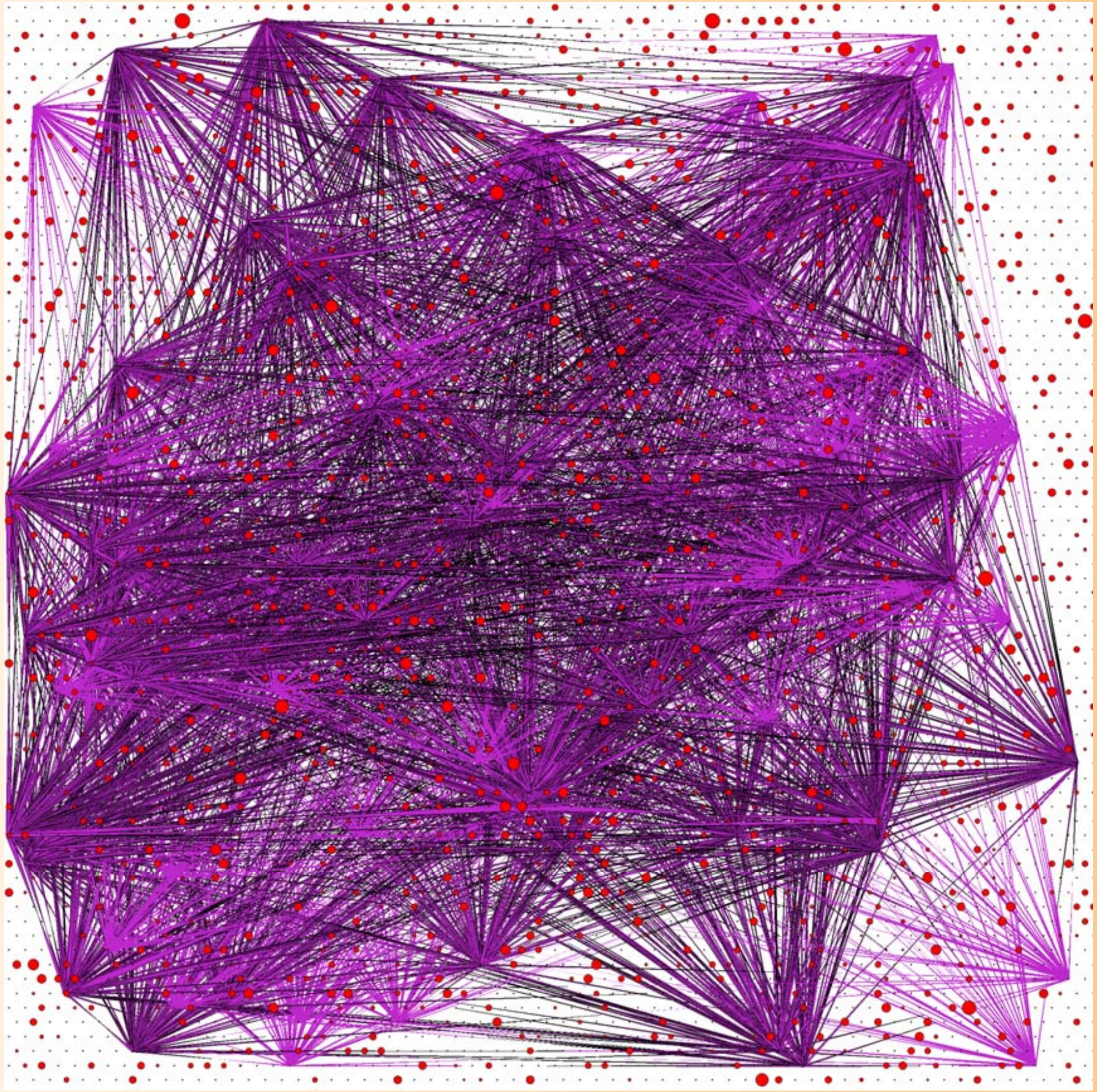


Specialised functional network (1936)



Lima, CISEPA, Denise Pumain, December 2011

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

Discussion: model validation

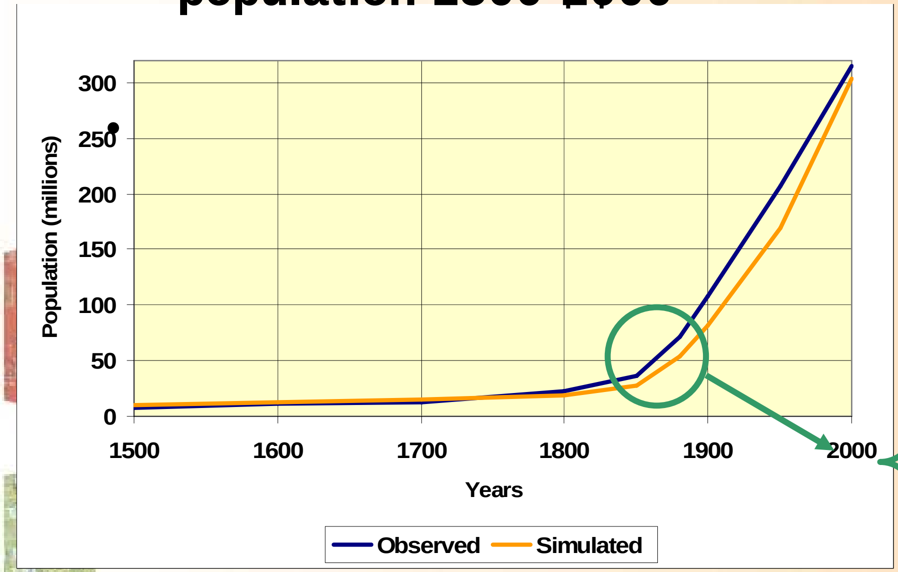
Too many rules and parameters? (as complex systems theoreticians say)

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

➔**Multiscale ‘validation’**

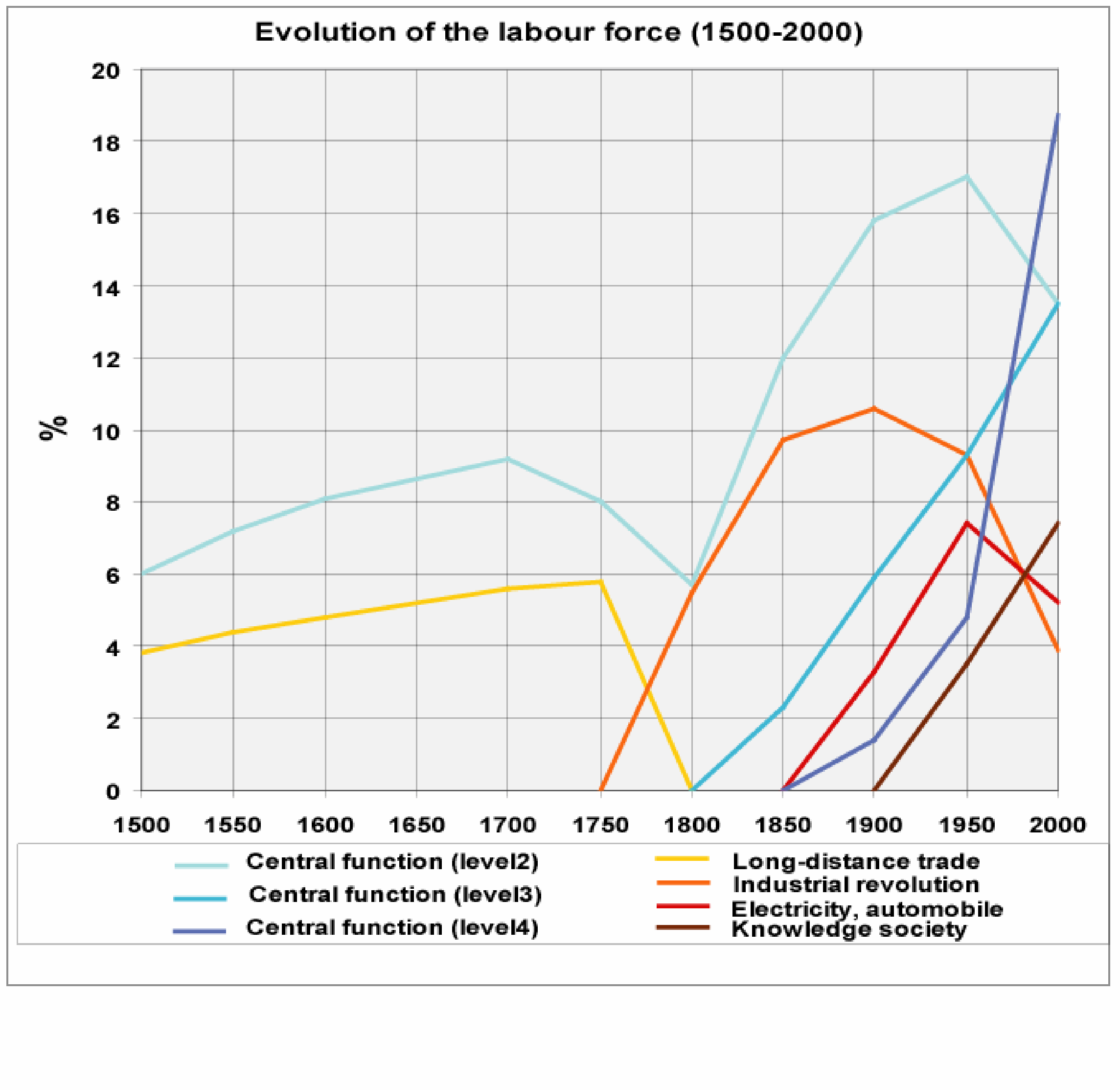
Multi-scale validation
Europe: results of simulation at system's level

- **Evolution of total population 1500-2000**

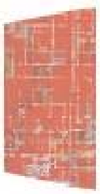


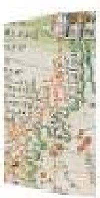
Key parameters	Attraction level (ex. central2)	Market return	Share of exogenous growth
1300-1800	0.5 to 0.8	0.5 to 1	1/3
1800-2000	0.8 to 3	1 to 7	1/3

Multi-scale validation
Europe: results of simulation at system's level



Multi-scale validation: meso level (rank-size slopes)





Europe 1300-2000

	Observed		Simulated	
	Slope	R^2	Slope	R^2
1500	0.72	0.97	0.66	0.98
1600	0.74	0.99	0.70	0.98
1700	0.80	0.99	0.75	0.98
1800	0.69	0.99	0.75	0.98
1850	0.77	0.99	0.78	0.98
1950	0.91	0.99	0.89	0.98
2000	0.94	0.99	0.94	0.98

Multi-scale validation: meso-level

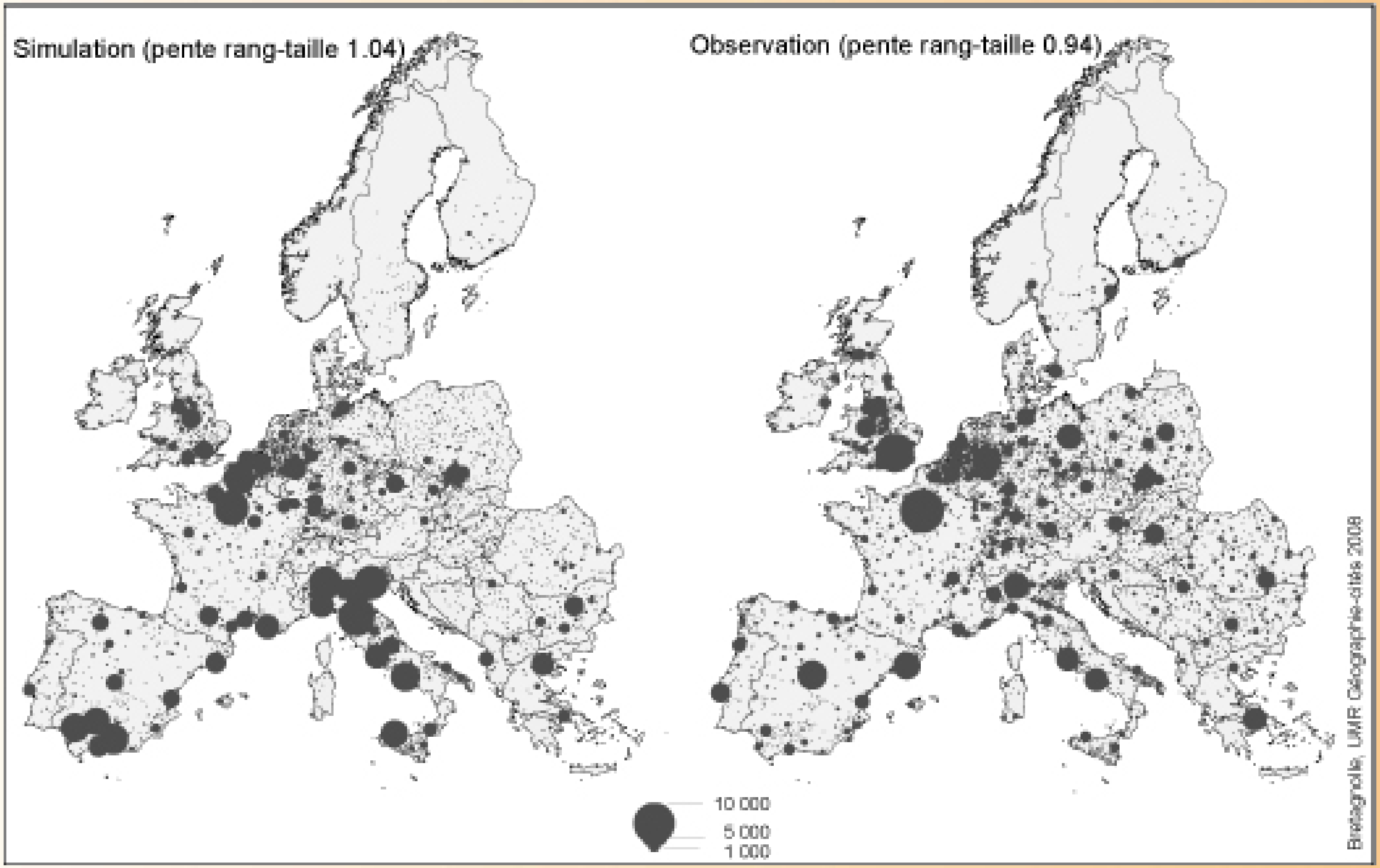
Europe: Number of cities by size class

	1500		1800		2000	
	Obser.	Simul.	Obser.	Simul.	Obser.	Simul.
> 1 million	0	0	0	0	42	45
500- 1000	0	0	3	0	42	50
100-500	4	6	15	20	398	226
50-100	17	16	35	53	541	367
25-50	37	73	83	80	1013	697
10-25	135	230	473	406	3024	3582

Multi-scale validation: micro-level

Individual trajectories of cities

Simulated and observed city sizes in 2000 (initial situation: observed locations in 1300)



Bretagnolle, Pumain, 2008

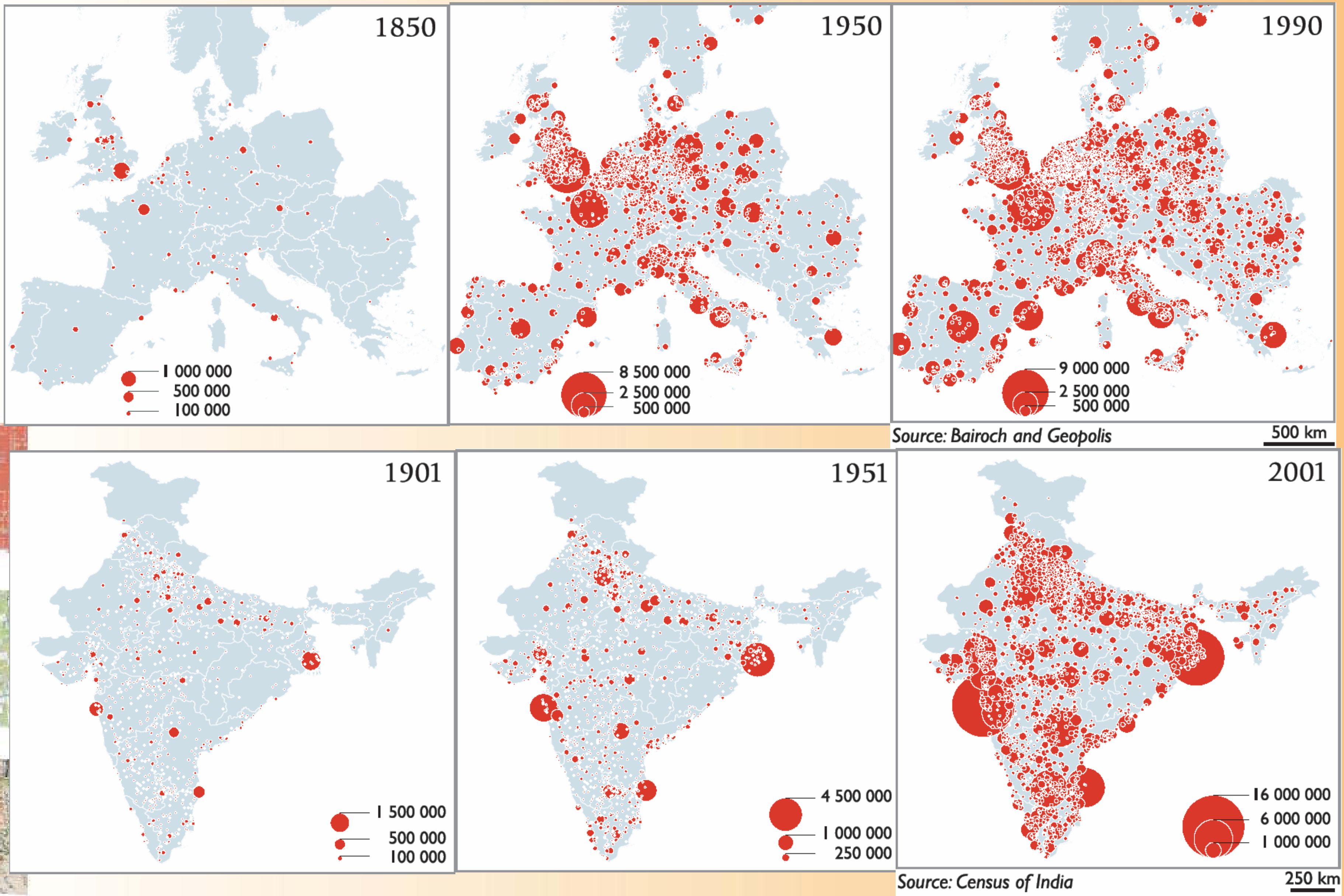
A global city function since Middle Age

Dates	Highest rank of well adjusted cities	Observed data (thousands)	Simulated pop. of largest city
1500	2	Paris, 225	125
1700	3	Paris, 500 Napoli, 300	210 202
1800	3	London, 948 Paris, 550	534 533
1950	5	London, 8900 Paris, 6100 Ruhr, 4000 Berlin, 3500	2780 2650 2630 2510
2000	3	Paris, 10500 London, 9200	7000 6900

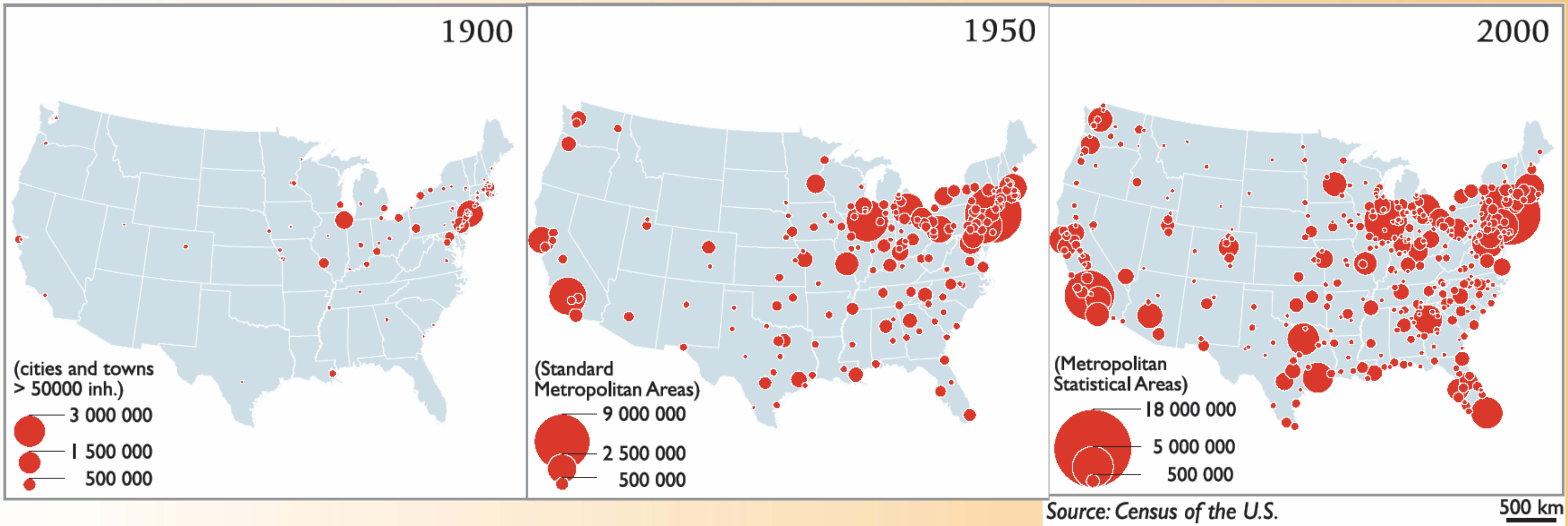
Validation through systems comparison

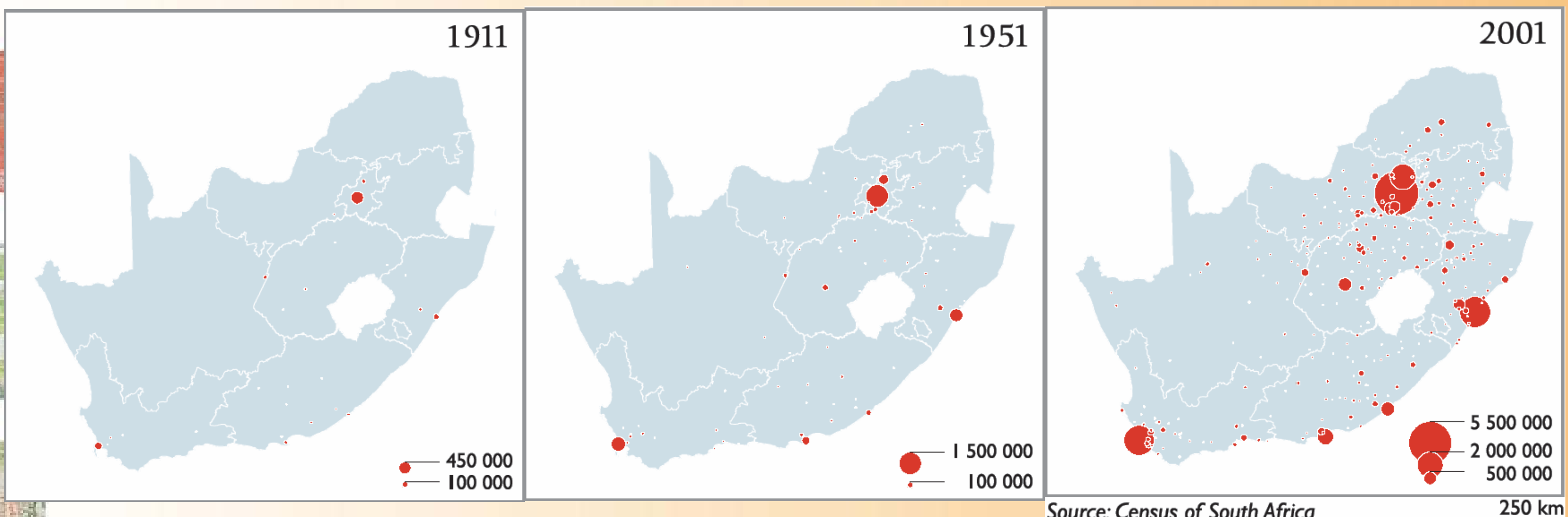
Can the urbanisation processes of the generic SIMPOP2 model simulate both old and recent urban systems?

Old urban systems: path dependence

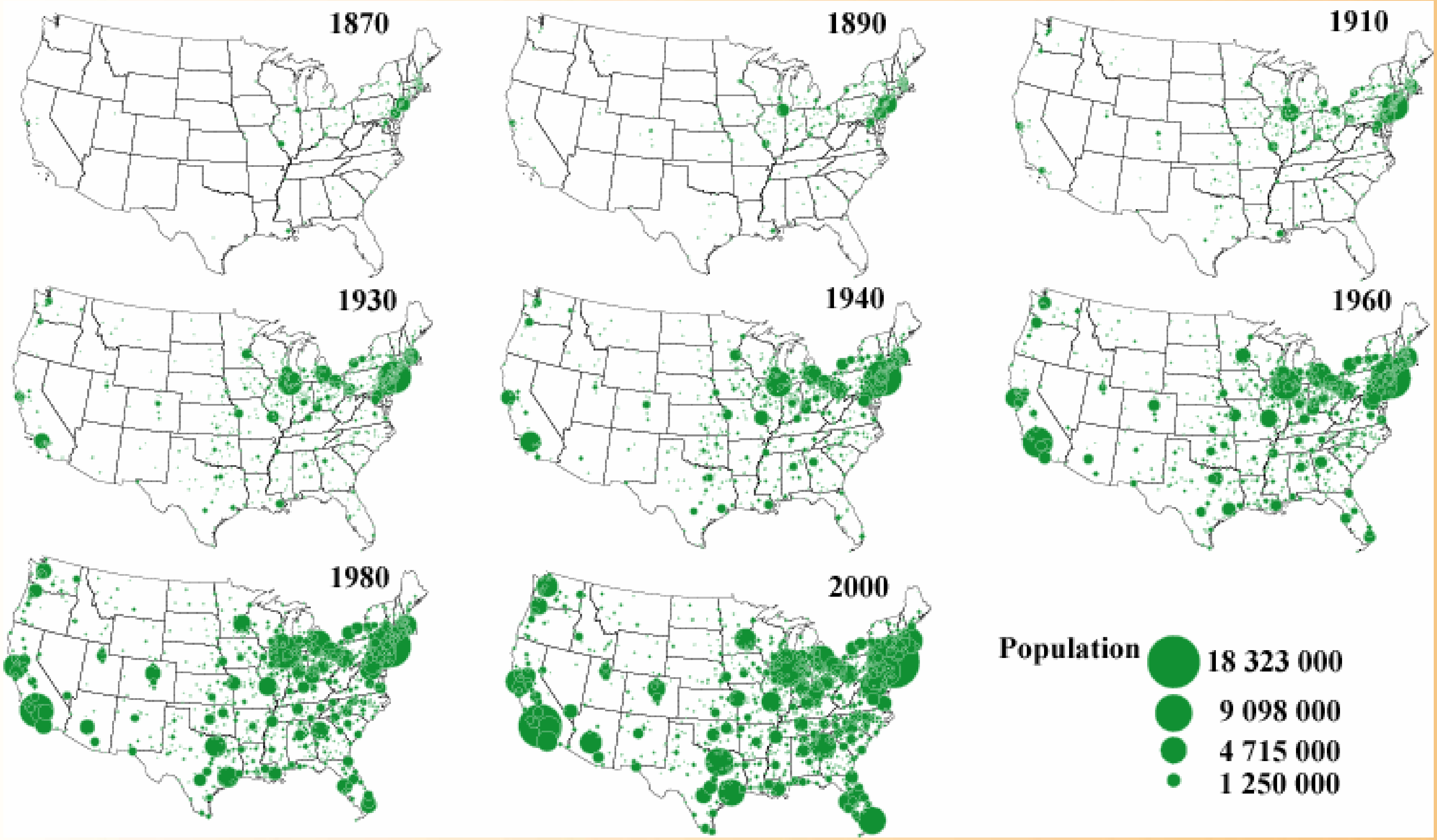


New urban systems: space filling then path dependence





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

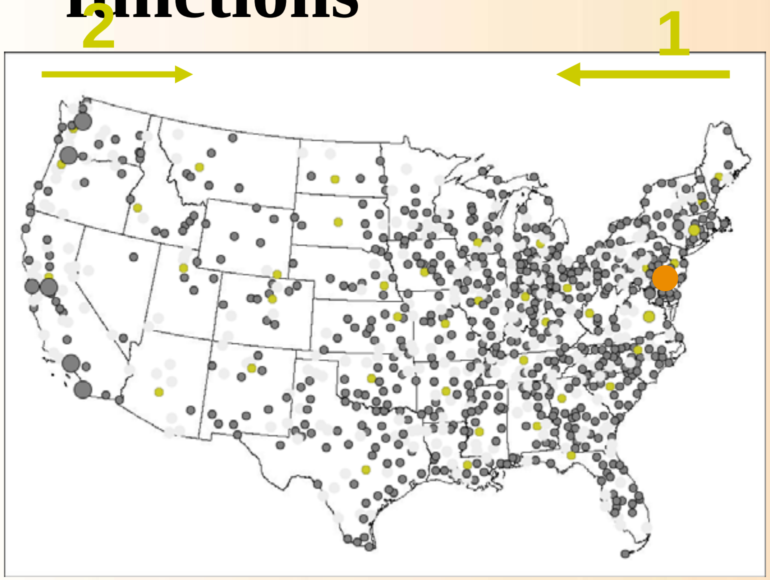
  - decrease in labour force in central and long distance trade functions as early as 1740

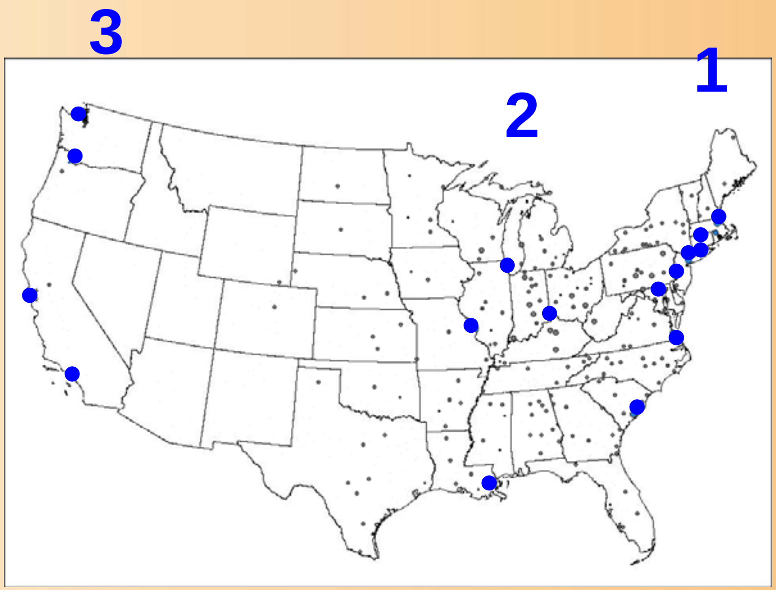
  - stagnation of Western then Southern cities (despite local resources)

  - strong underestimation of the largest cities (New York, Chicago, San Francisco, Los Angeles, Dallas, Miami…)

United States: which adaptations of the generic model are necessary?

- 1 timing the activation of cities with emerging urban functions





Federal Capital (1800)

State Capital (activated between 1800 and 1920)

City acquiring the long distance trade function (between 1740 and 1890)

Source: Bretagnolle, 2007

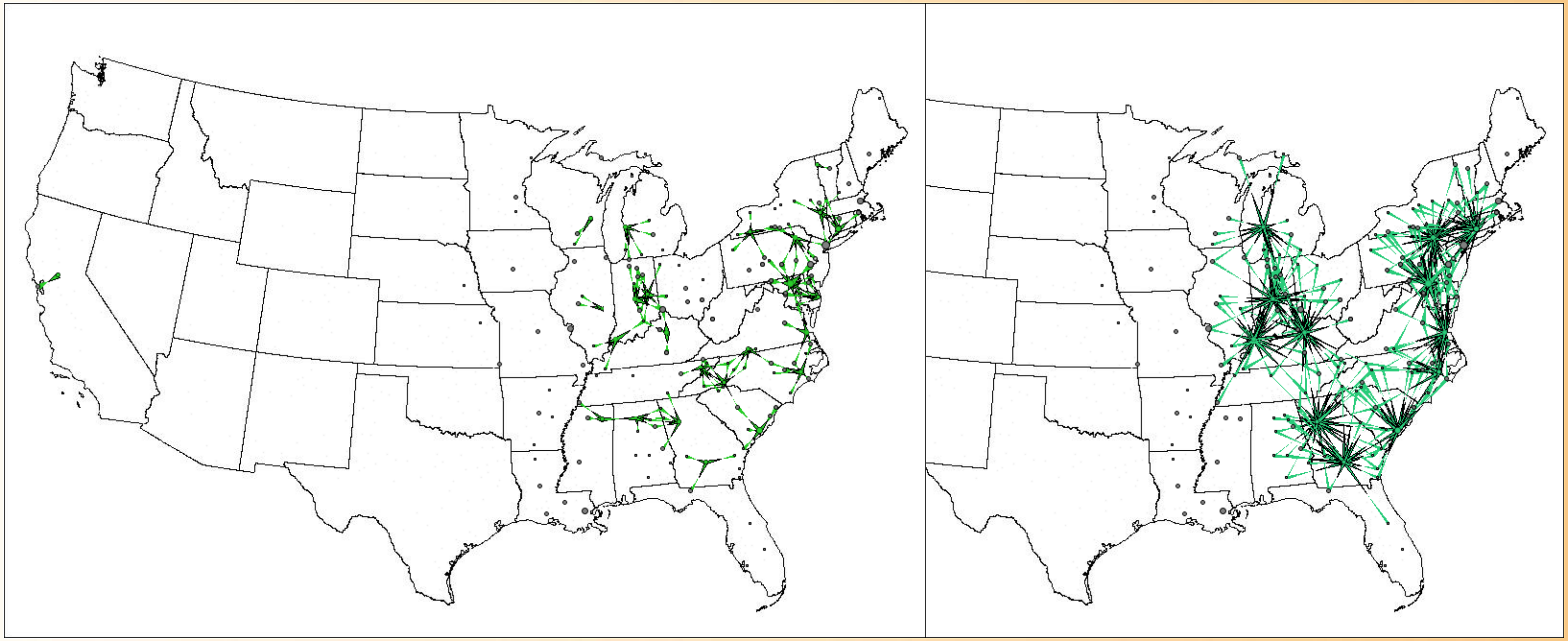
United States: adaptation of the generic model (2)

- **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

United States: adaptation of the generic model (4)

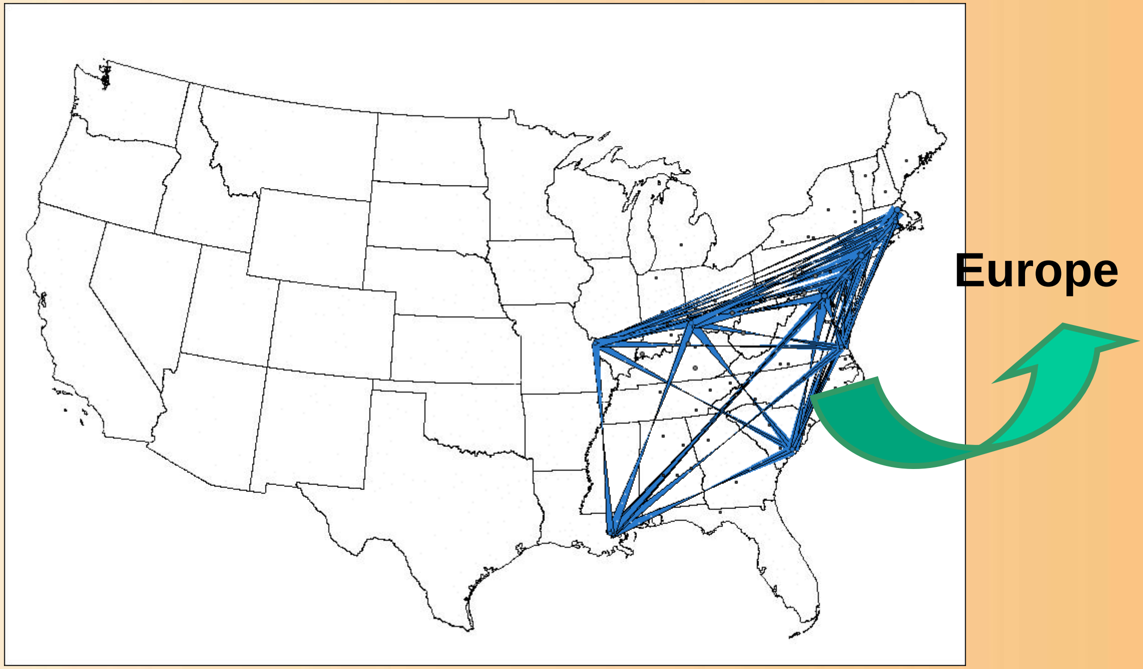
➔ **growth impulses also come from outside (18th-20th century)**

Long distance trade networks in 1840

11 cities

range 2000 km (all cities connected through river and maritime shipping or railways).

Bretagnolle, 2007

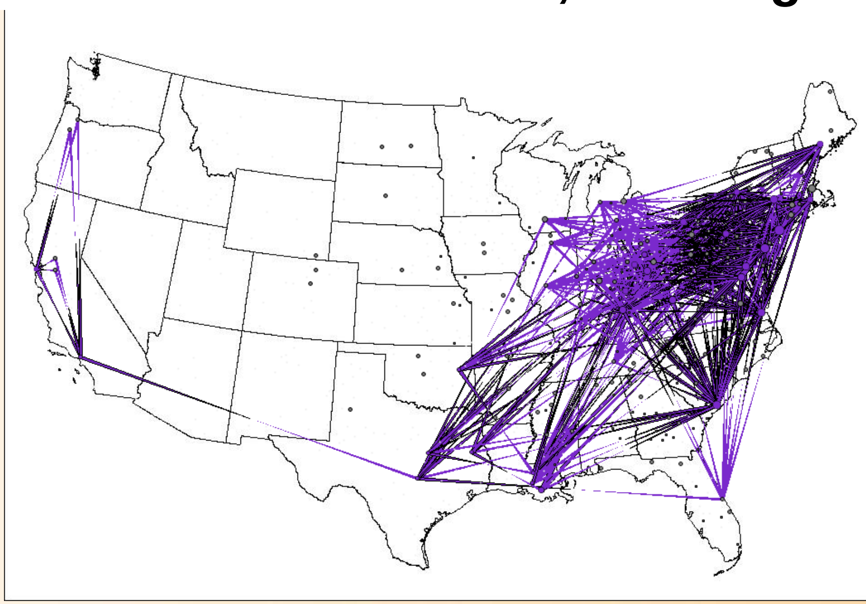


United States: adaptation of the generic model (5)

➔ 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

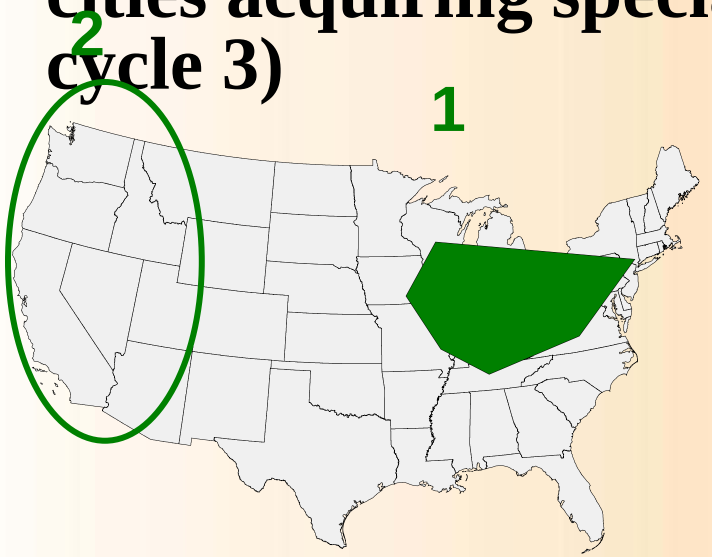


Bretagnolle, 2007

2011

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)

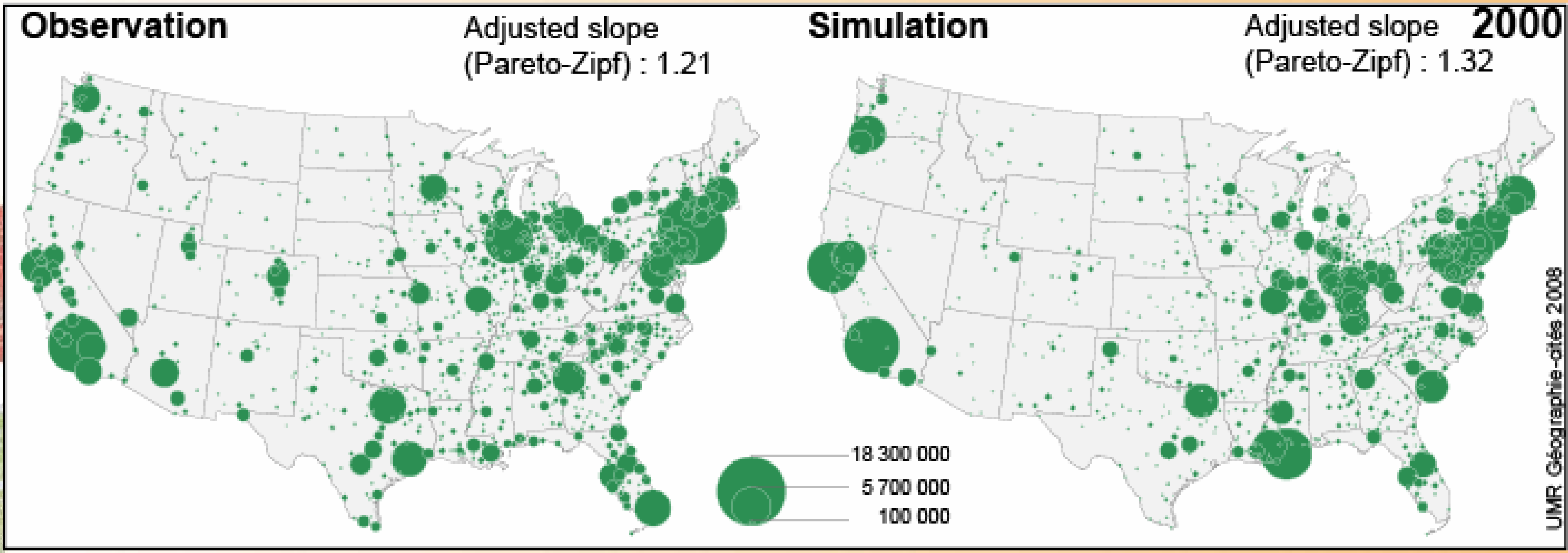
Gold and mineral resources (1870-1890)

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

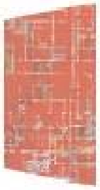
-frontier effect: momentary effect on urban growth (mushroom cities)

-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**

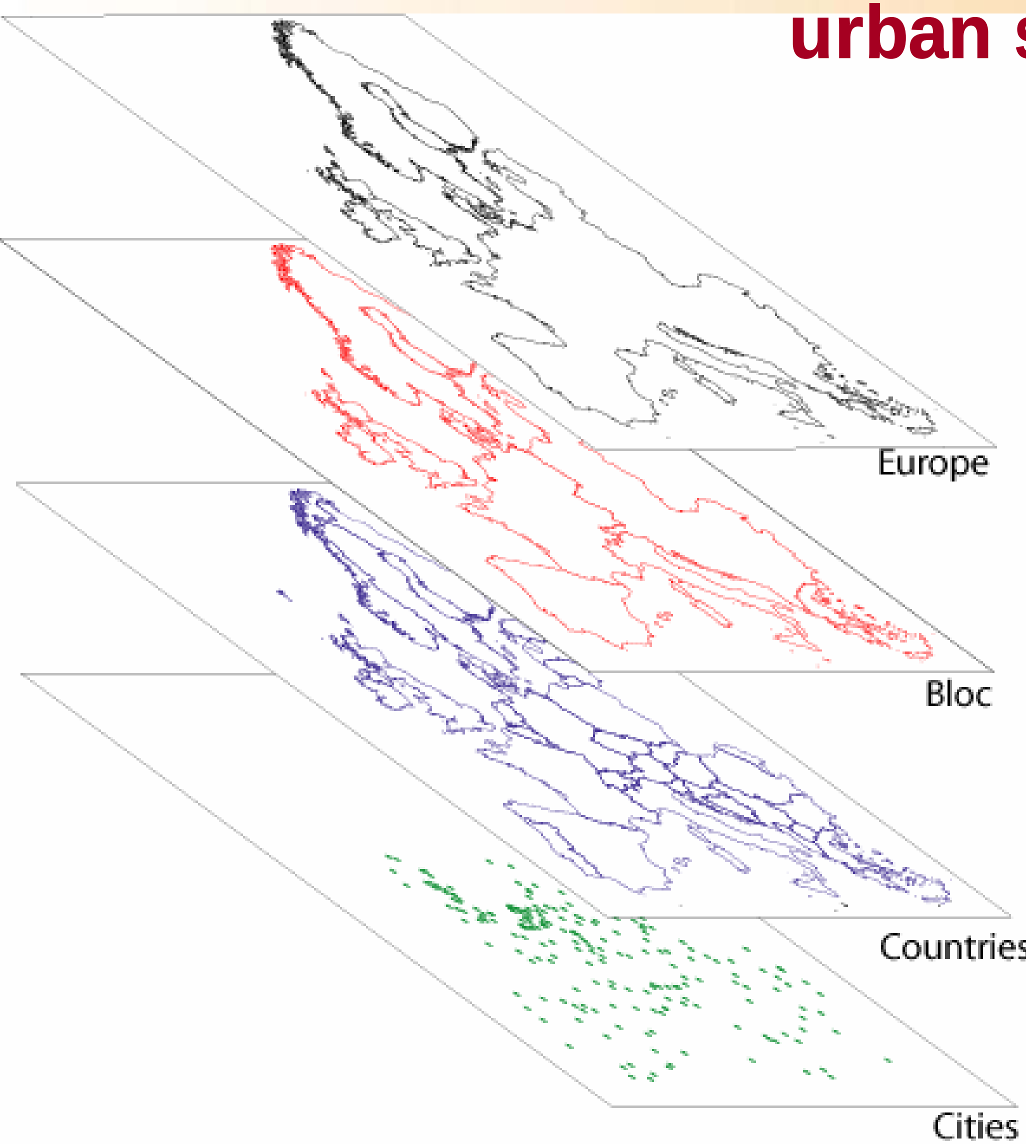


South Africa: **« Frontier » and dual system**

India: **« full world » and dual**

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

EUROSIM: Predicting the future of the European urban system



Lena Sanders, Hélène Mathian, 2006

1-multiscale validation
2- testing scenarios

aggregate trajectories

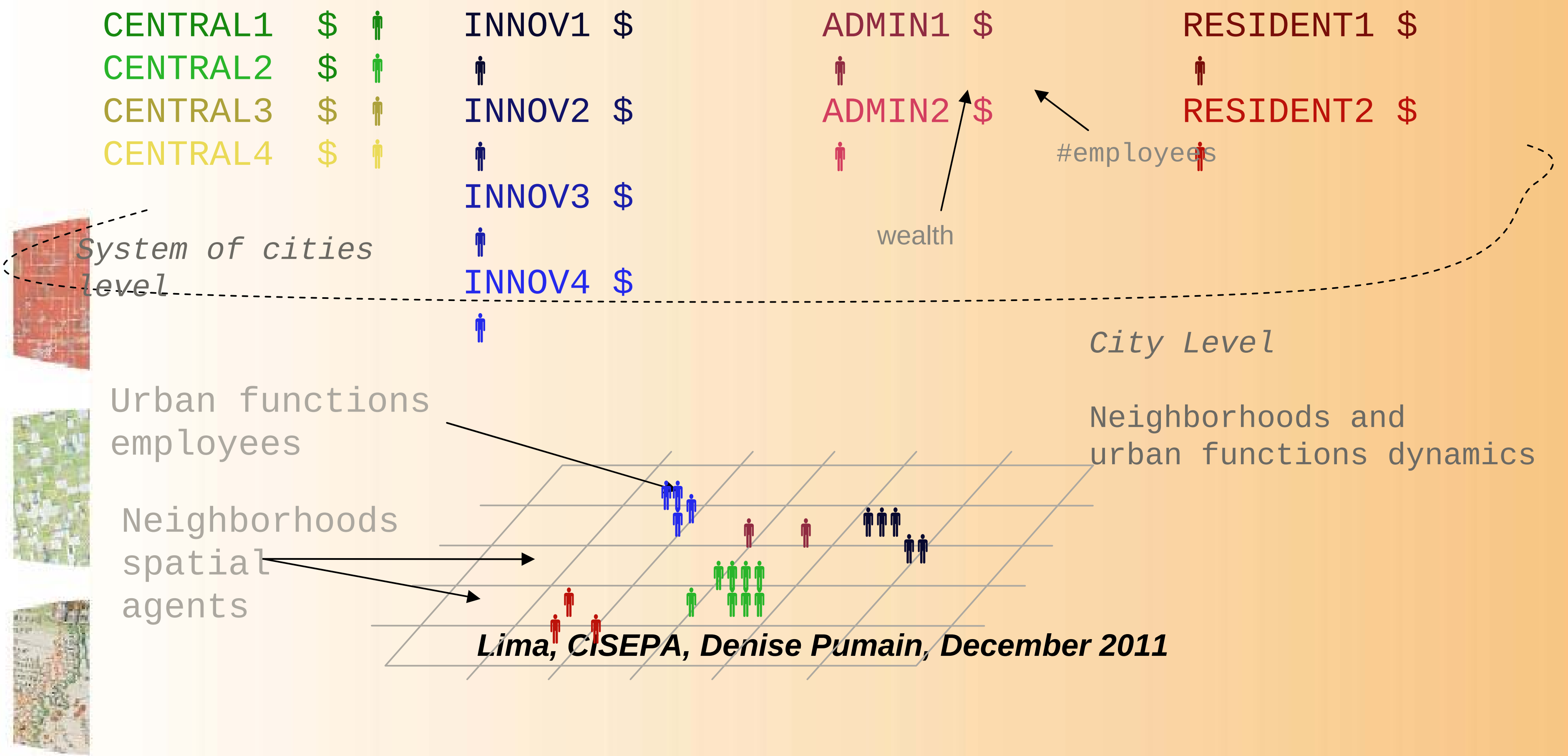
Hierarchical structure analysis (rank-size, primacy)

Concentration analysis

- Trajectories of cities

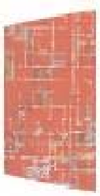
SimpopNano : location of the Simpop2 urban functions agents at intra-city scale

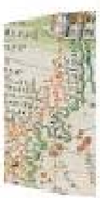
Thomas Louail, PhD, 2010

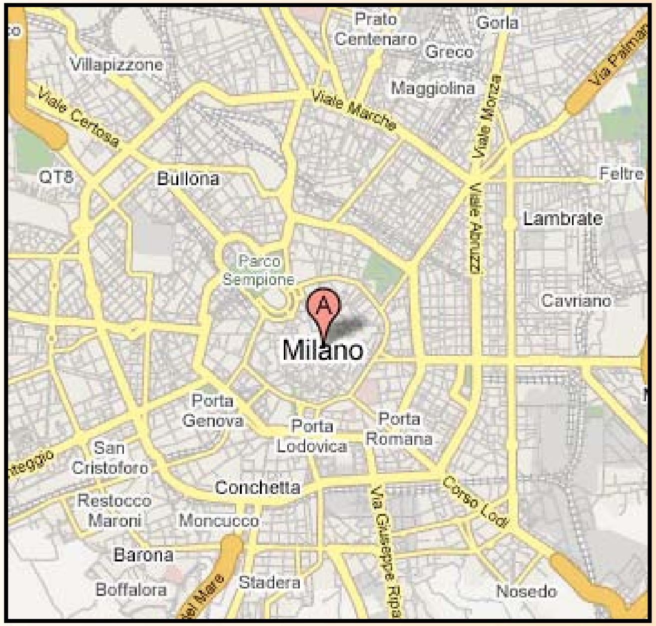


Comparing Urban Dynamics on different spatial patterns

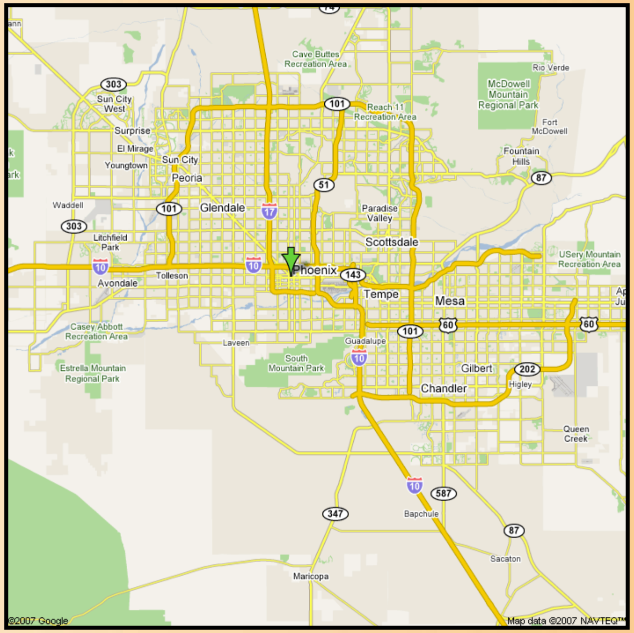
PhD Thomas Louail, 2010
and Bretagnolle, Delisle, 2009



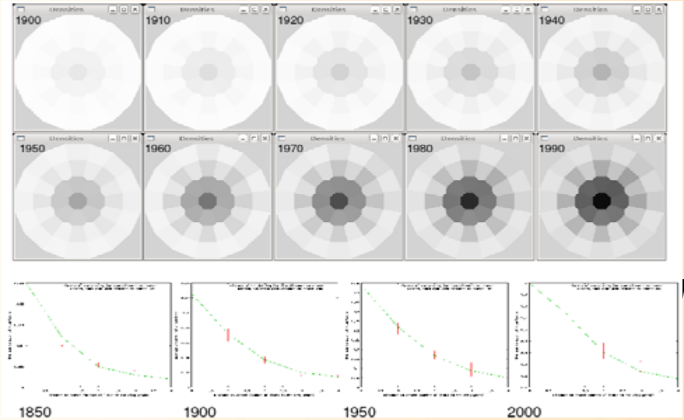




Milano, IT



Phoenix, AZ



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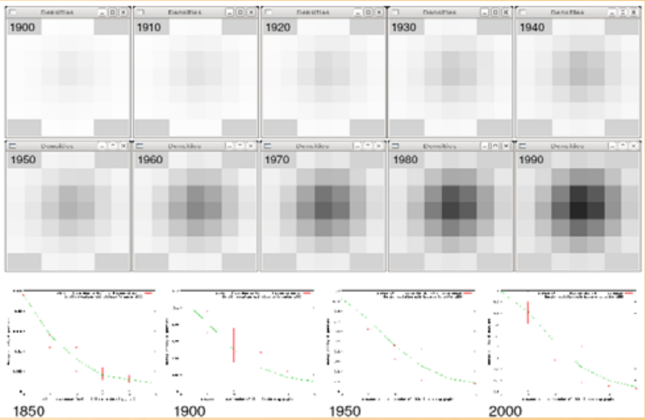


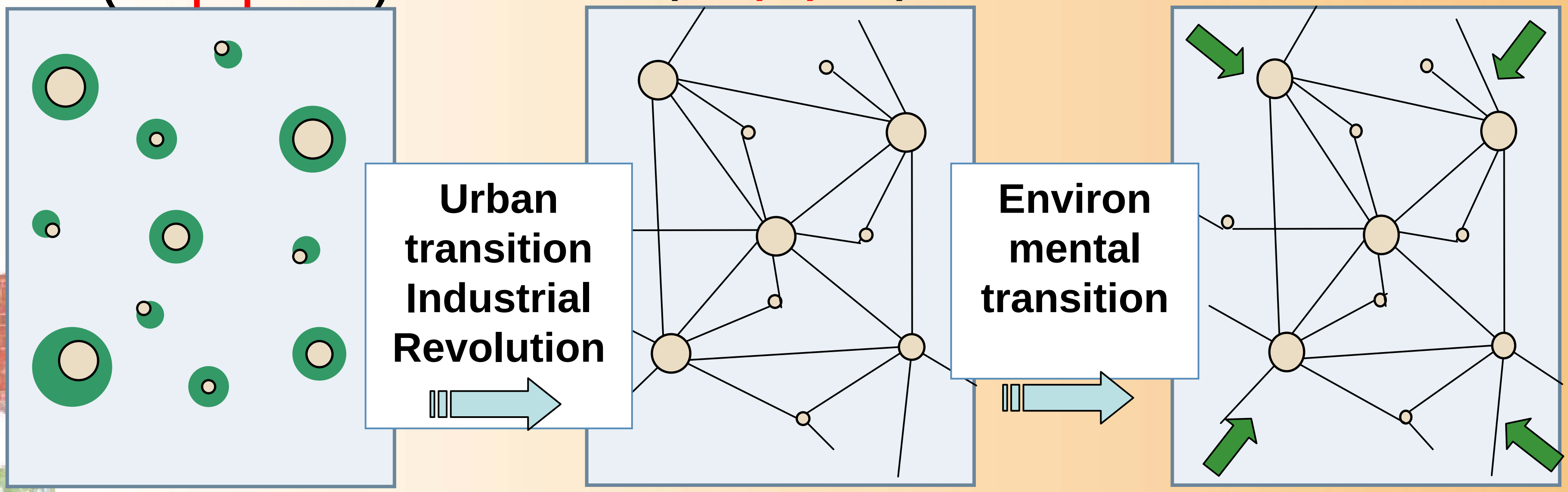
Three stages in urban dynamics for the series of SIMPOP models

Clara Schmitt, Sébastien Rey, PhD

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

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