GEOGRAPHIE-CITES

Urban systems dynamics urban growth and scaling laws

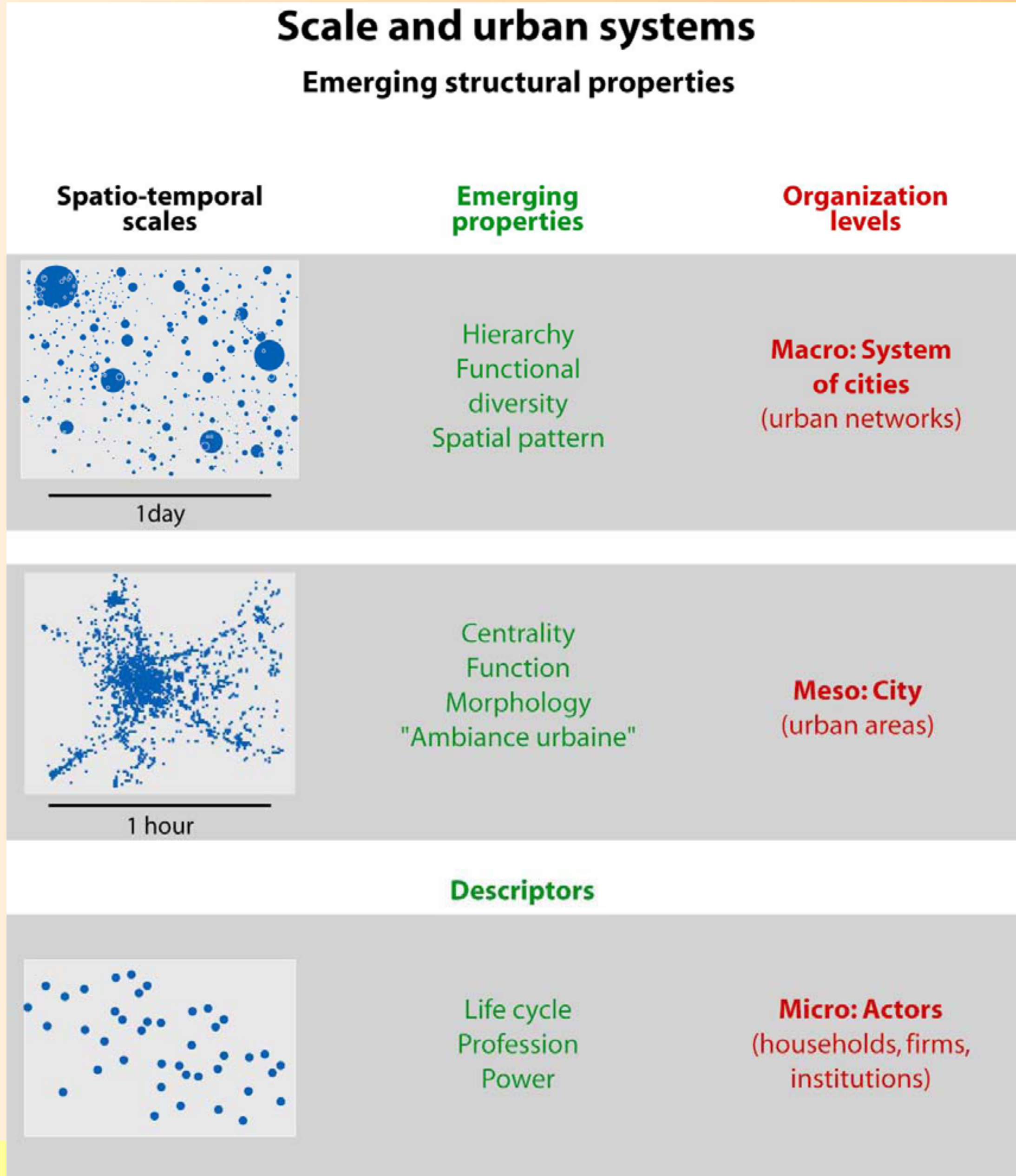
Denise Pumain
Université Panthéon-Sorbonne
Institut Universitaire de France

Lima, CISEPA, December 2011, Denise PUMAIN

Urban systems hierarchical organisation

Two levels: Cities and Systems of cities

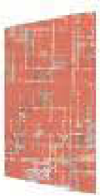
Pumain D. Hierarchy in natural and social sciences, Springer, 2006

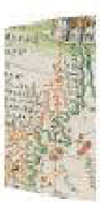


Lima,

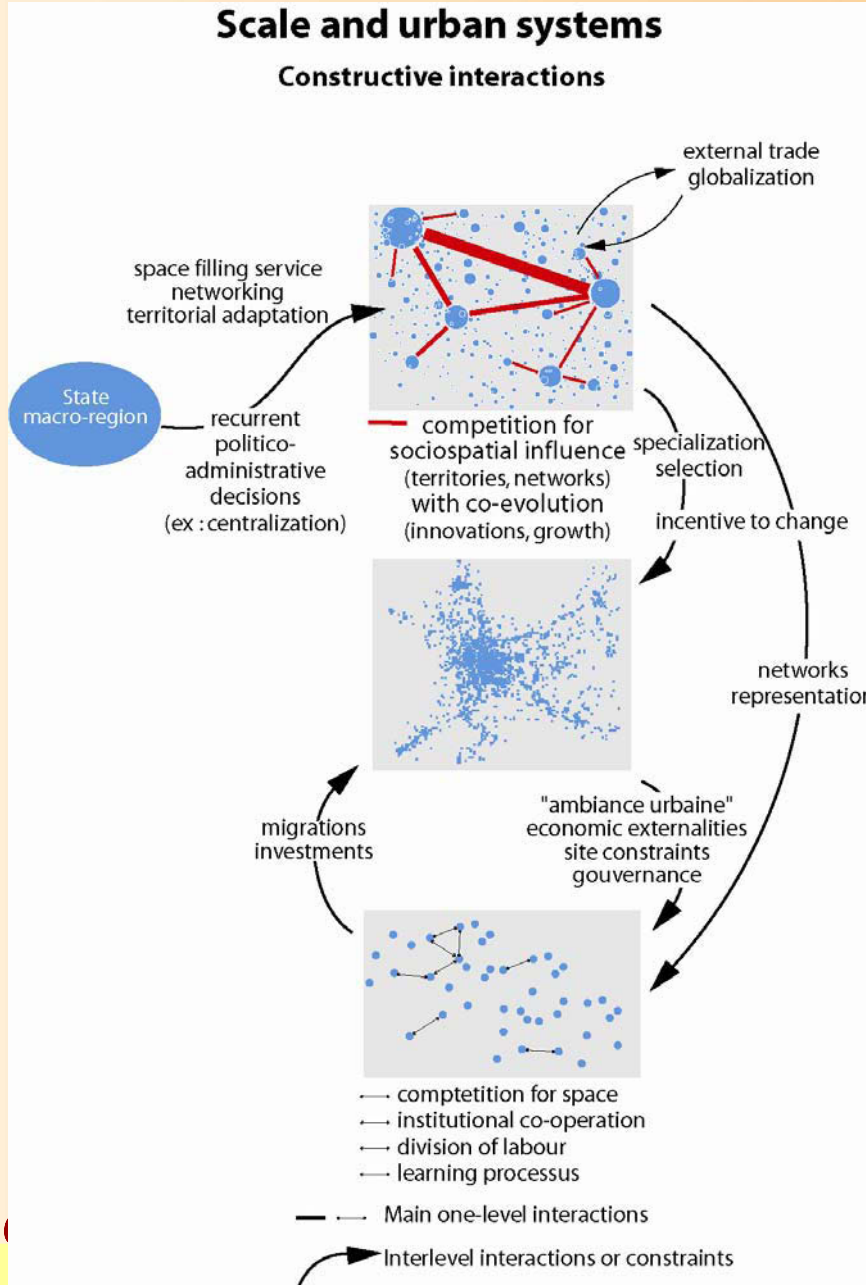
Urban systems emerge from spatial interaction

Multi-levels social interactions





Pumain D. Hierarchy in natural and social sciences, Springer, 2006



Scale, structure and dynamics in urban systems

- Urban systems are complex systems
- Their geographical structure is dynamically produced through societal spatial interactions
- Irreversible historical processes and path dependence ➔ evolutionary theory of urban systems (Pumain, 1997)
- Scaling laws may help to understand urban dynamics and to predict its future

➔ Examples of scaling processes at two levels of observation/organisation

Scaling laws in complex systems

Scaling laws: Non-linear relationship between size of entities and some of their functional attributes ➔ reveal physical constraints on the structure and evolution of complex systems (spatial distribution of energy through fractal networks, theory in biology: West, Brown & Enquist, *Science*, 1997 & 99)

➔ Application to urban systems:

D. Lane, D. Pumain, S. van der Leeuw, G. West: *Complexity perspectives in Innovation and Social change*, Springer, 2009

(FET EU programme: ISCOM (Information Society as a Complex System) 2002-2006

Scaling laws in systems of cities

Linking urban attributes to city size reveals scaling laws that are expressing constraints on the dynamics of complex systems

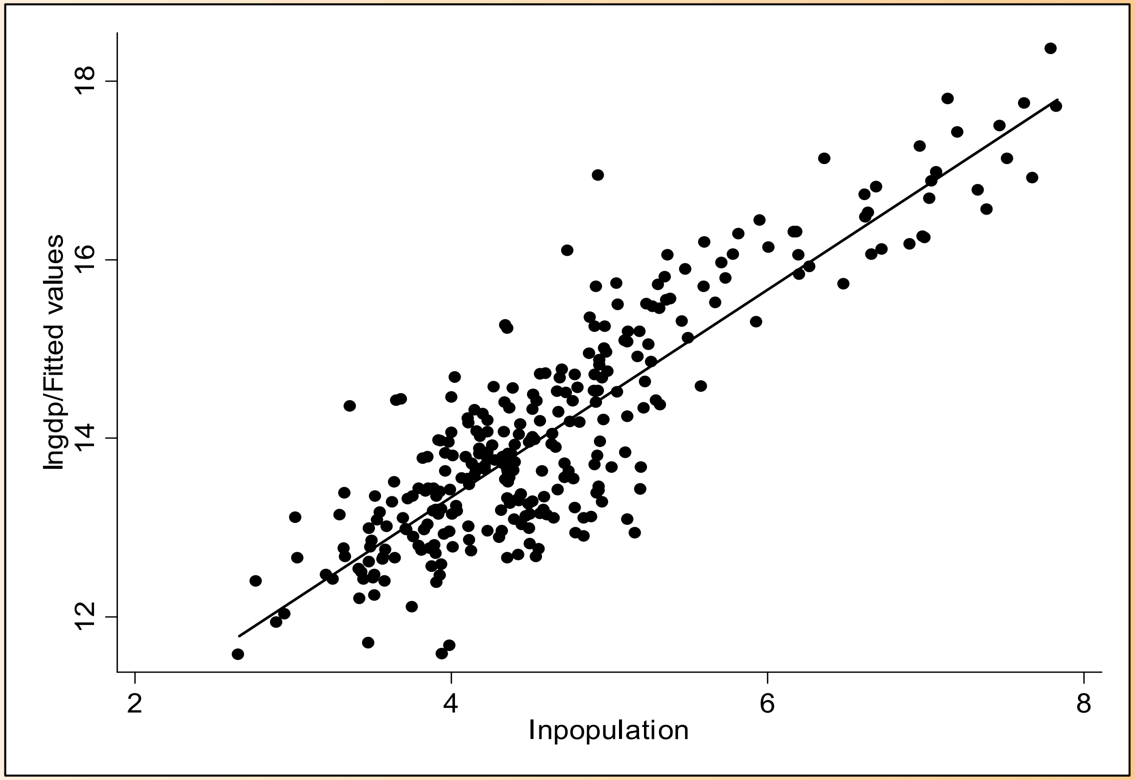
$$x = y^{\beta}$$

(where x is an attribute and y is the size of the city)

A « discovery »: exponents >1

Example of GDP in Chinese cities

β = 1.16
CI= 1.10-1.22



Scaling parameters according to urban attributes

(*Luís M. A. Bettencourt, José Lobo, and Geoffrey B. West, 2009, pp 229-231*)

β <1: gasoline stations, gasoline sales, length of electrical cables, road surface (= scale economies)

β = 1: total establishments, total employment, household power and water consumptions

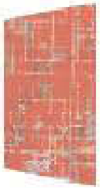
β >1 : wages, GDP, patents, inventors, R&D employment, housing costs, walking speed…

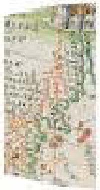
Scaling parameters and growth trajectories

$\beta = 1$ **(linear) =>** $\dfrac{dN}{dtt} = \left(\dfrac{R_1 - R_0}{E_0} \right) N \rightarrow$ **exponential**

$\beta < 1$ **(sublinear) => sigmoidal:** $N(t)^{t \rightarrow \infty} \rightarrow \left(\dfrac{R_1}{R_0} \right)^{\frac{1}{1-\beta}}$

$\beta > 1$ **(superlinear)**: $N^{\beta - 1}(t) = \dfrac{1}{\dfrac{R_1}{R_0} + \left\{ N^{1-\beta}(0) - \dfrac{R_1}{R_0} \right\} e^{\frac{R_0}{E_0}(\beta - 1)t}}$

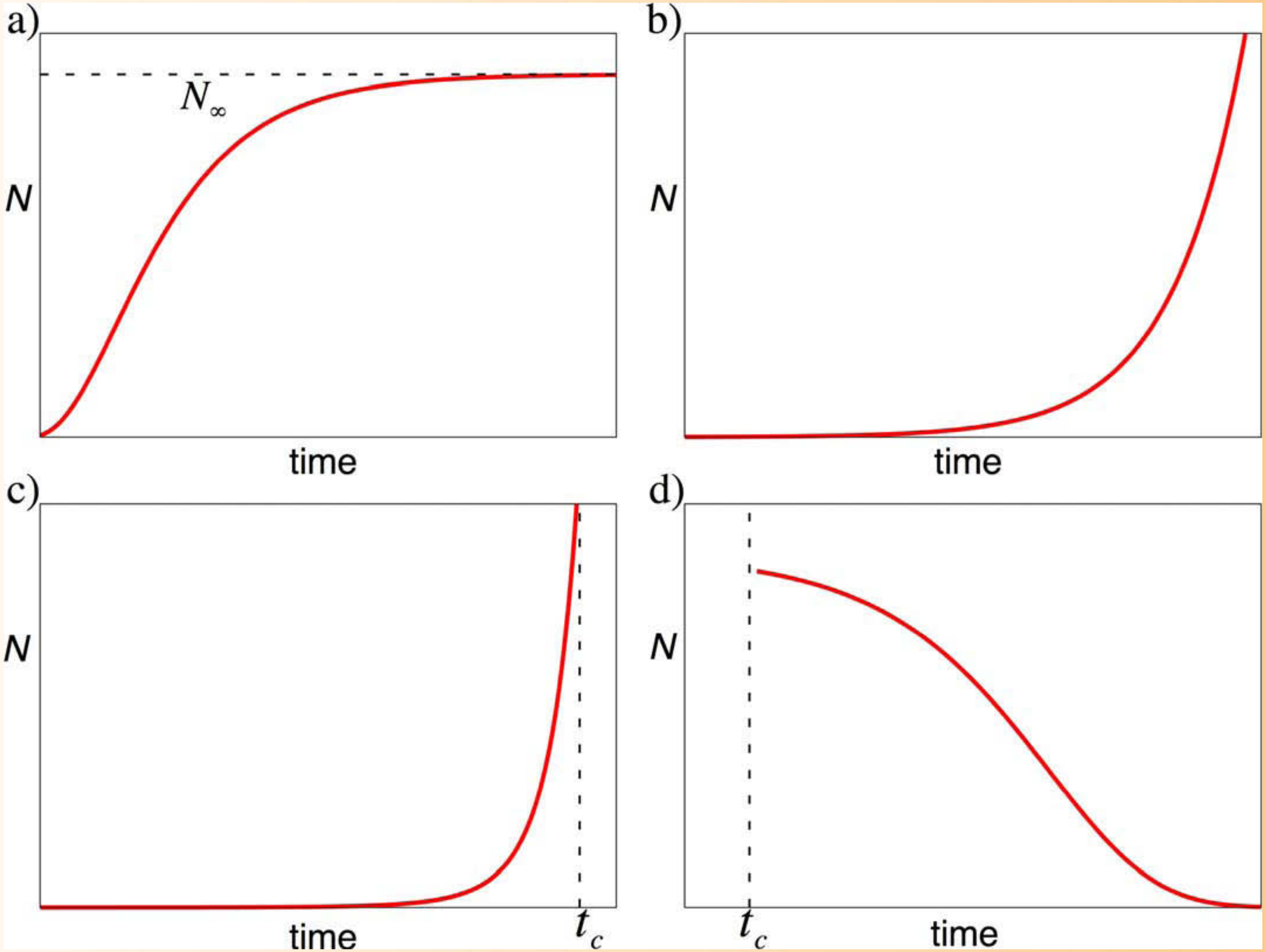




Source: Bettencourt, Lobo, West, 2009

Growth trajectories according to scaling exponent

<1



=1

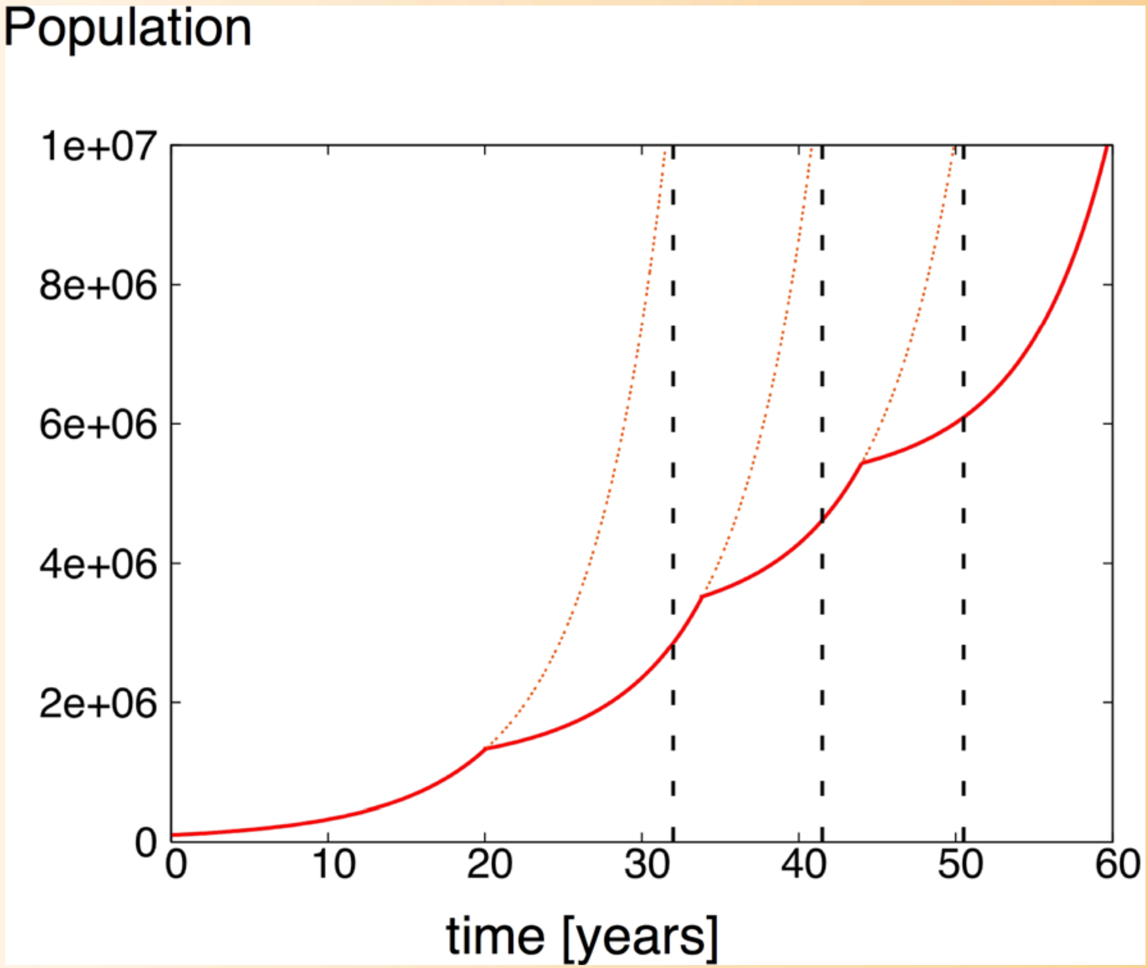
>1

Source: Bettencourt et al., 2009

A « static », « universal physical » interpretation of scaling exponents (Bettencourt et al. 2009)

Scaling Exponent	Driving Force	Organization	Growth
$\beta<1$	Optimization, Efficiency	Biological	Sigmoidal Long term stagnation
$\beta>1$	Creation of Information, Wealth and Resources	Sociological	Boom / Collapse Finite time singularity Increasing acceleration/discontinuities
$\beta=1$	Individual Maintenance	Individual	Exponential

Urban trajectory (Bettencourt et al., 2009)



A « physical » interpretation of urban scaling laws

➔ Values of scaling parameters >1 are a novelty (when comparing urban systems to biological):

Bettencourt, Lobo, Helbing, Kühnert, West, *P.N.A.S.*, 2007, 104

➔ From theoretical considerations linking resource consomption and growth, supralinear scaling laws imply superexponential growth (infinite growth in finite time) and a succession of crisis at shorter and shorter time intervals

➔➔ **accelerating pace of social life** as cities grow larger

The theory crazes the medias!

A Physicist Turns the City Into an Equation - NYTimes.com

A Physicist Solves the City

By JONAH LEHRER

According to the data, whenever a city doubles in size, every measure of economic activity, from construction spending to the amount of bank deposits, *increases* by approximately 15 percent per capita. It doesn't matter how big the city is; the law remains the same. "This remarkable equation is why people move to the big city," West says. "Because you can take the

Scaling laws in social systems

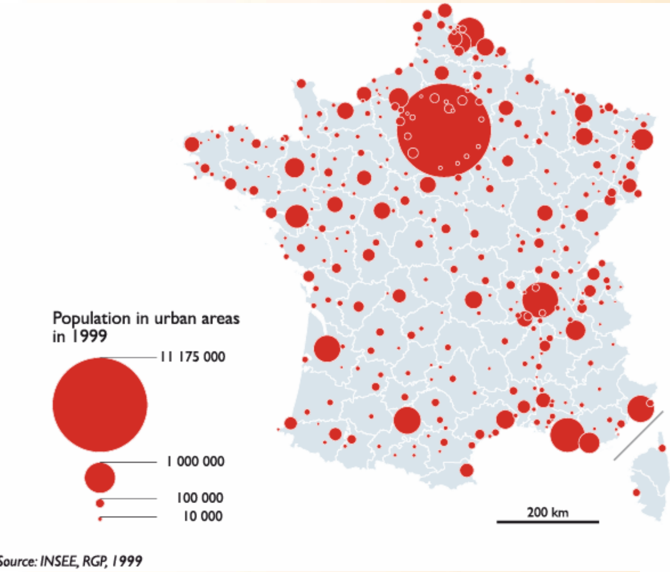
The physical interpretation of scaling laws in terms of growth process is in principle very appealing and challenging,

BUT:

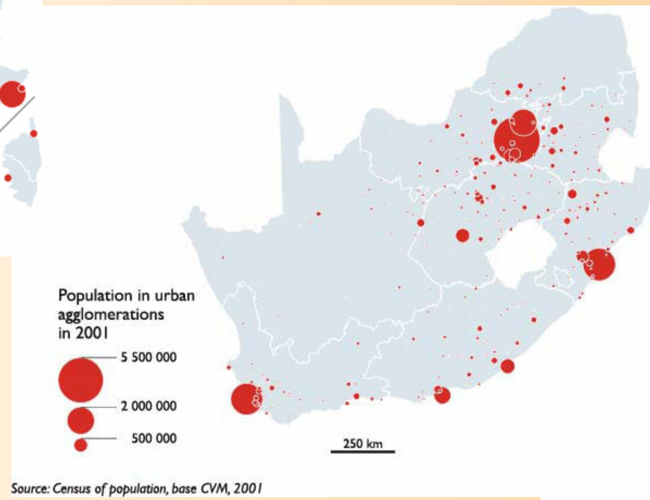
A fundamental (hidden?) hypothesis for deducing the shape of growth curves is that the system is ergodic (any particle can reach any state any time)

➔ Urban systems are not ergodic!

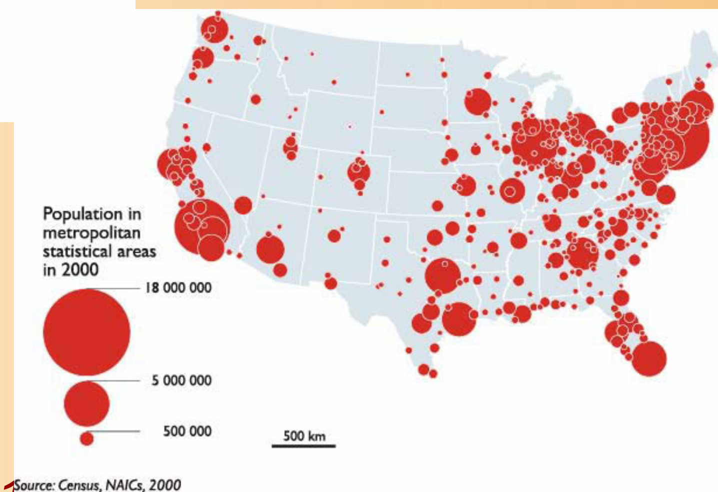
Case studies: 3 types of urban systems

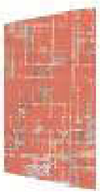


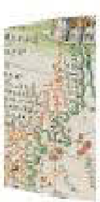
Long standing urbanization
Slow and Regular evolution
Ex : France



New countries
Waves of urban creation
Ex : South Africa, USA







Paulus F. Vacchiani-Marcuzzo C. Pumain, D. Cybergeo 2006

Data for case studies

	France	USA	South Africa
Number of cities *	*276 largest “aires urbaines”*	*276 metropolitan areas*	*276 “urban agglomerations”*
Data for employment	*32 economic sectors (1999, NES)*	*20 economic sectors (2000, NAICS)*	*13 economic sectors (2001, SIC)*

* NB Cities = coherent and comparable spatial entities (daily interactions)
= Urban agglomeration (core) + their periphery delineated according to the intensity of commuting links

Scaling of urban activity sectors

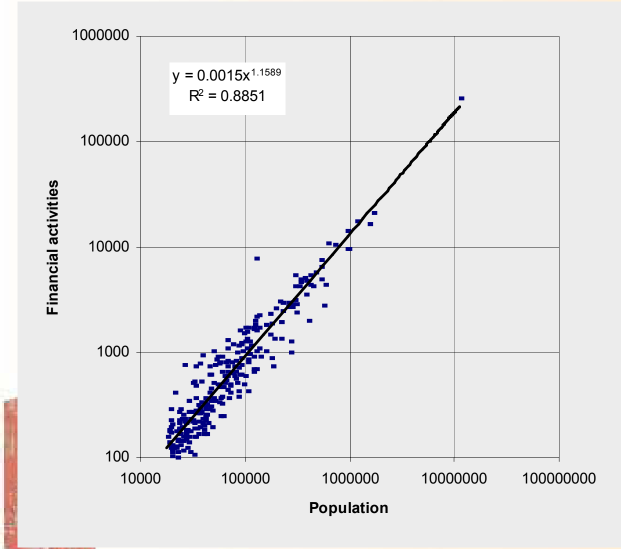
- Estimation of scaling parameters for all economic sectors in each urban system
  - X-axis : Number of inhabitants in cities
  - Y-axis : Number of employees in a given economic activity sector
  - Log-log scatter plots
  - Ordinary least square

Pumain D. Paulus F. Vacchiani-Marcuzzo C. Lobo J., 2006, *Cybergeo*, 343,

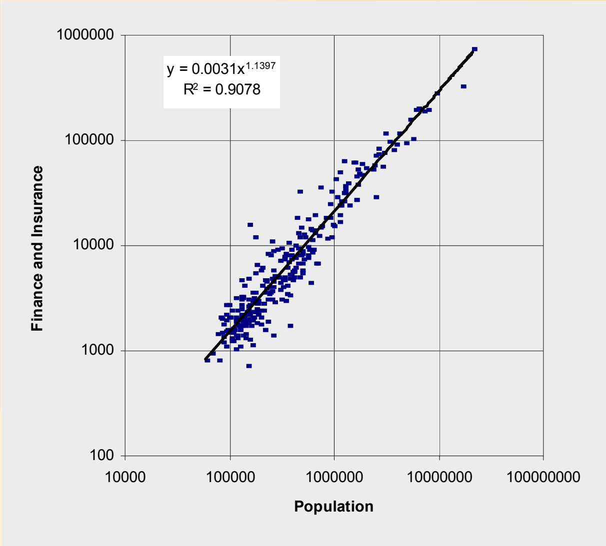
Scaling parameter > 1: leading economic sectors

FIRE (Finance, Insurance, Real Estate)

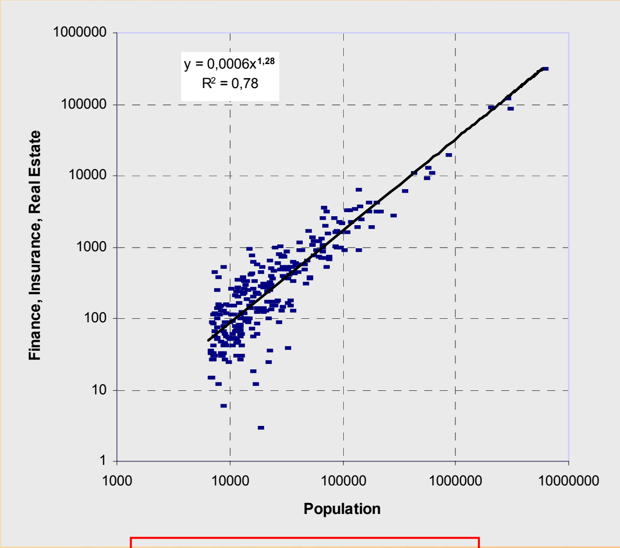
France



USA



South Africa



β = 1.16
95% CL : 1.13-1.19
R^2 = 89 %

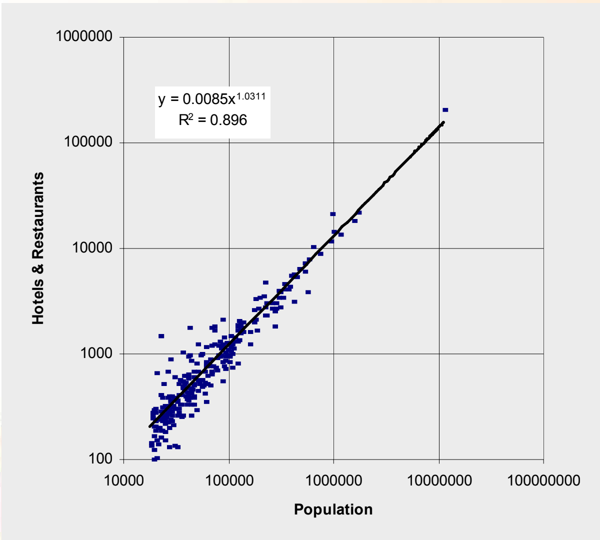
β = 1.14
95% CL : 1.11-1.17
R^2 = 91 %

β = 1.28
95% CL : 1.23-1.33
R^2 = 78%

Scaling parameter ≈ 1: Common Sectors

France

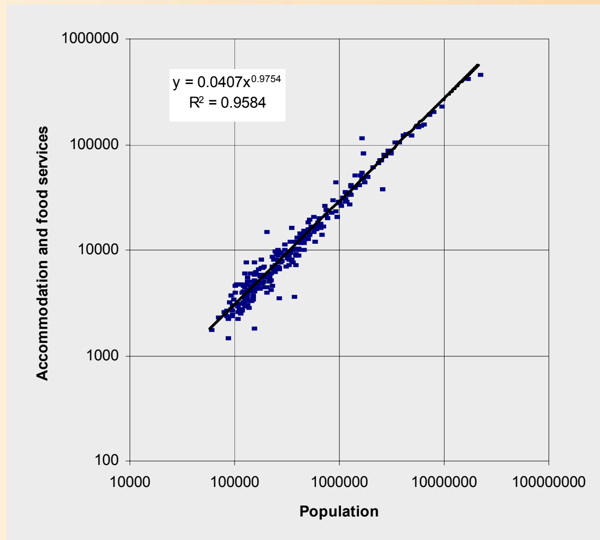
Hotels & Restaurants



$\beta = 1.03$
95% CL : 0.99-1.07
$R^2 = 90$ %

USA

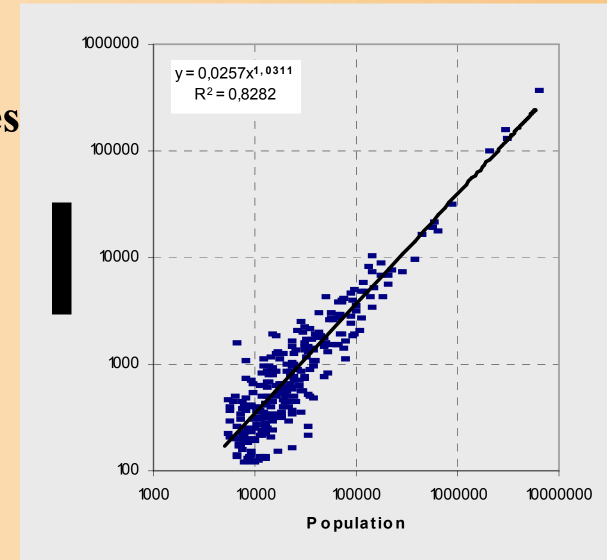
Accomodation & Food services



$\beta = 0.98$
95% CL : 0.96-1.01
$R^2 = 96$ %

South Africa

Retail Trade



$\beta = 1.03$
95% CL : 0.96-1.10
$R^2 = 83$ %

Scaling parameter <1= mature sectors

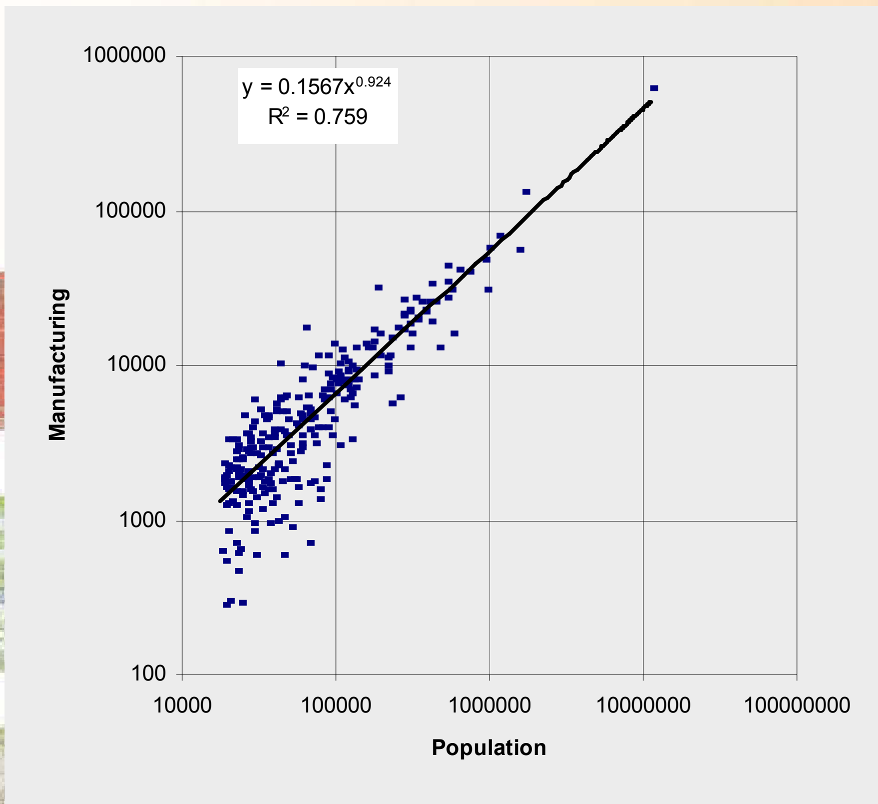
Manufacturing (USA)

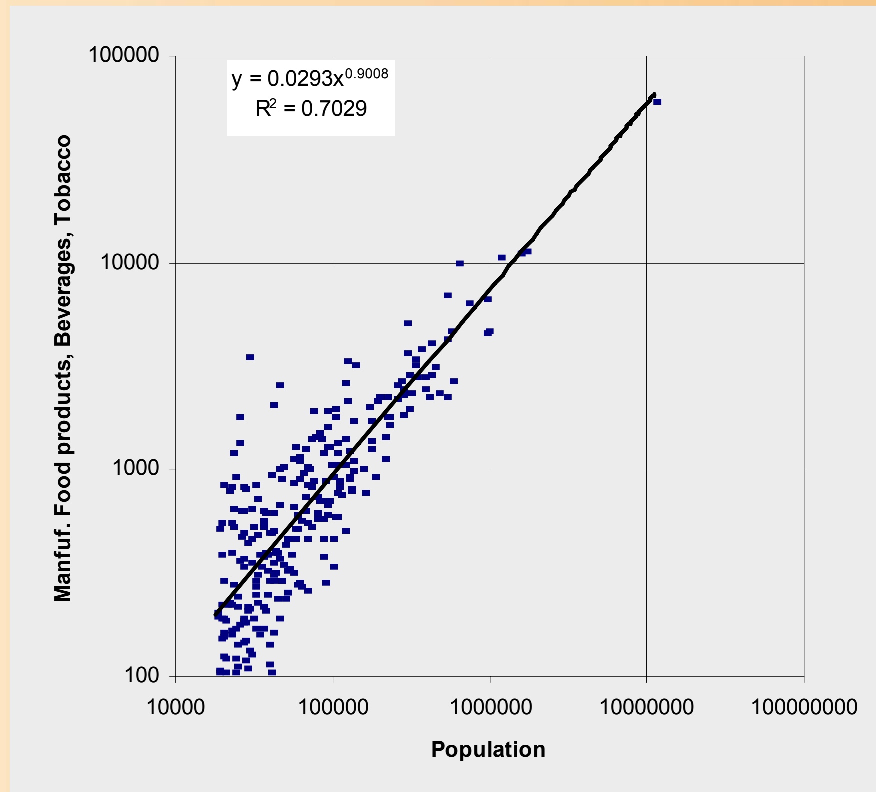
β = 0.92

95% CL : 0.85-0.98
R^2 = 76 %

Manufacture of food products, beverages and tobacco (France)

β = 0.90
95% CL : 0.83-0.97
R^2 = 70 %





Lima, CISEPA, December 2011, Denise PUMAIN

Interpretation: Scaling laws and Innovation cycles

Scaling laws:

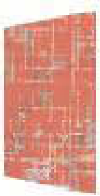
$$x = y^{\beta}$$

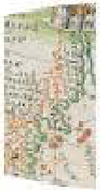
(where *x* is the number of employed in an urban industry and *y* is the size of the city)

Stage in innovation cycles and scaling parameter:

- *Leading, innovative* $\beta > 1$
- *Diffusing* $\beta \approx 1$
- *Mature* $\beta < 1$

A societal interpretation of scaling parameters





Stages in innovation cycle	France	USA	South Africa
Innovative sectors **β > 1**	- Financial activities, Insurance, Real Estate		
	- Research and development - Business services, Consultancy		- Manufacturing
Common sectors **β ≈ 1**	- Hotels and Restaurants - Community, social, personal services		- Retail Trade - Community, social and personal services - Utilities
Mature sectors **β <1**	- Manufacturing	- Retail Trade - Utilities	- Private Households

Paulus et al. in Lane et al., 2009

Theory of innovation in urban systems (1)

Cities as places of innovation

Cities are connecting through their networks a variety of sites, providing complementary resources; they innovate for providing new resources and reducing local and conjonctural uncertainties

➔*social role of innovation*: to reduce uncertainties or local constraints by expanding limits of available (accessible) resources

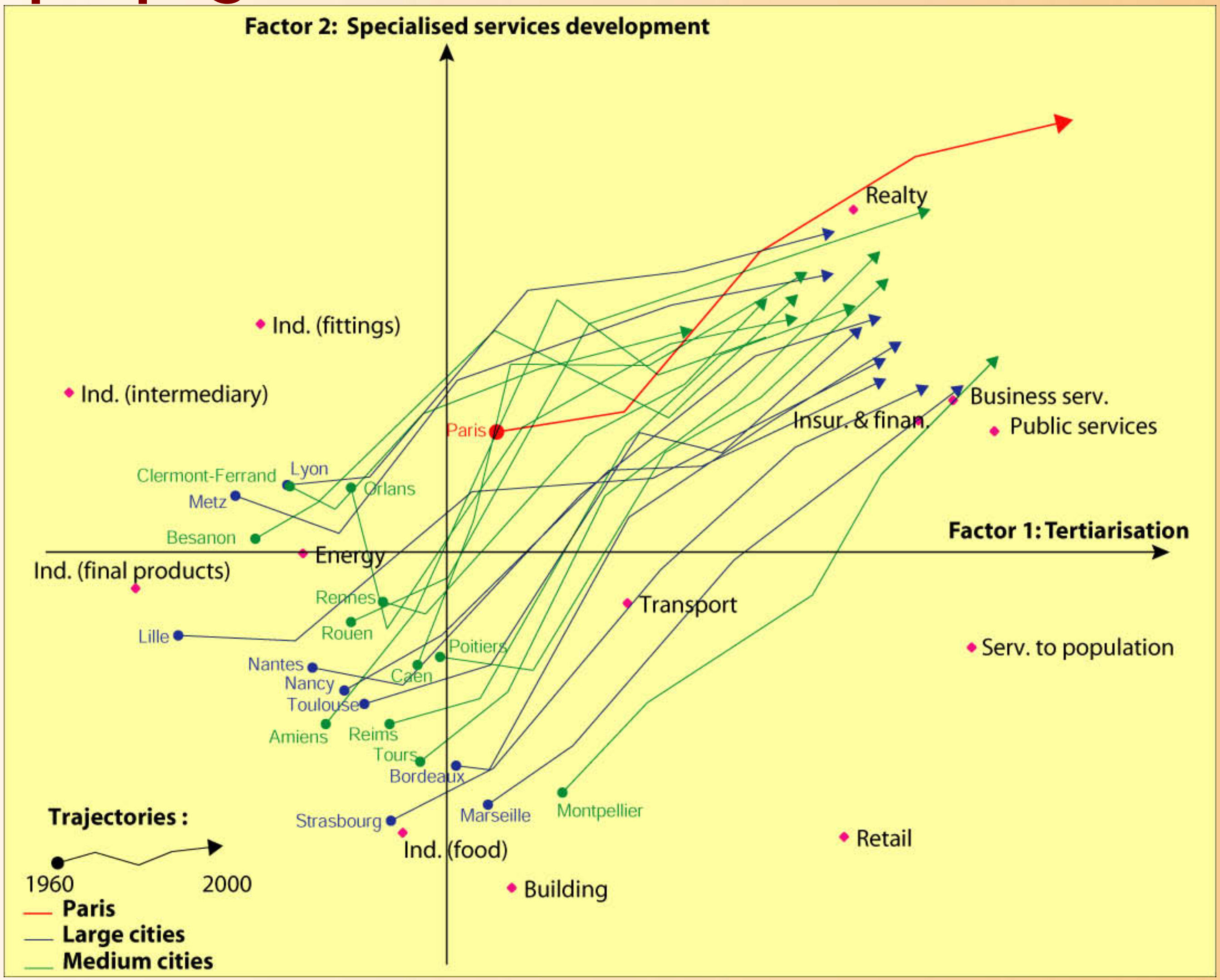
At city level, the innovation process is interacting with the transformation of the system of cities

There is a diffusion of innovation through circulation of information between cities

Diffusion of innovation throughout the system conveys impulses for urban growth (gains from adaptation, attraction of new resources)

Feed back effect from the system: incitation to innovate because of interurban competition

Socio-economic co-évolution
= propagation of societal innovation

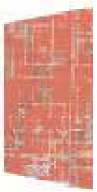


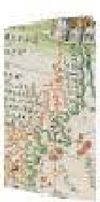
PCA on French cities economic profiles 1960-2000

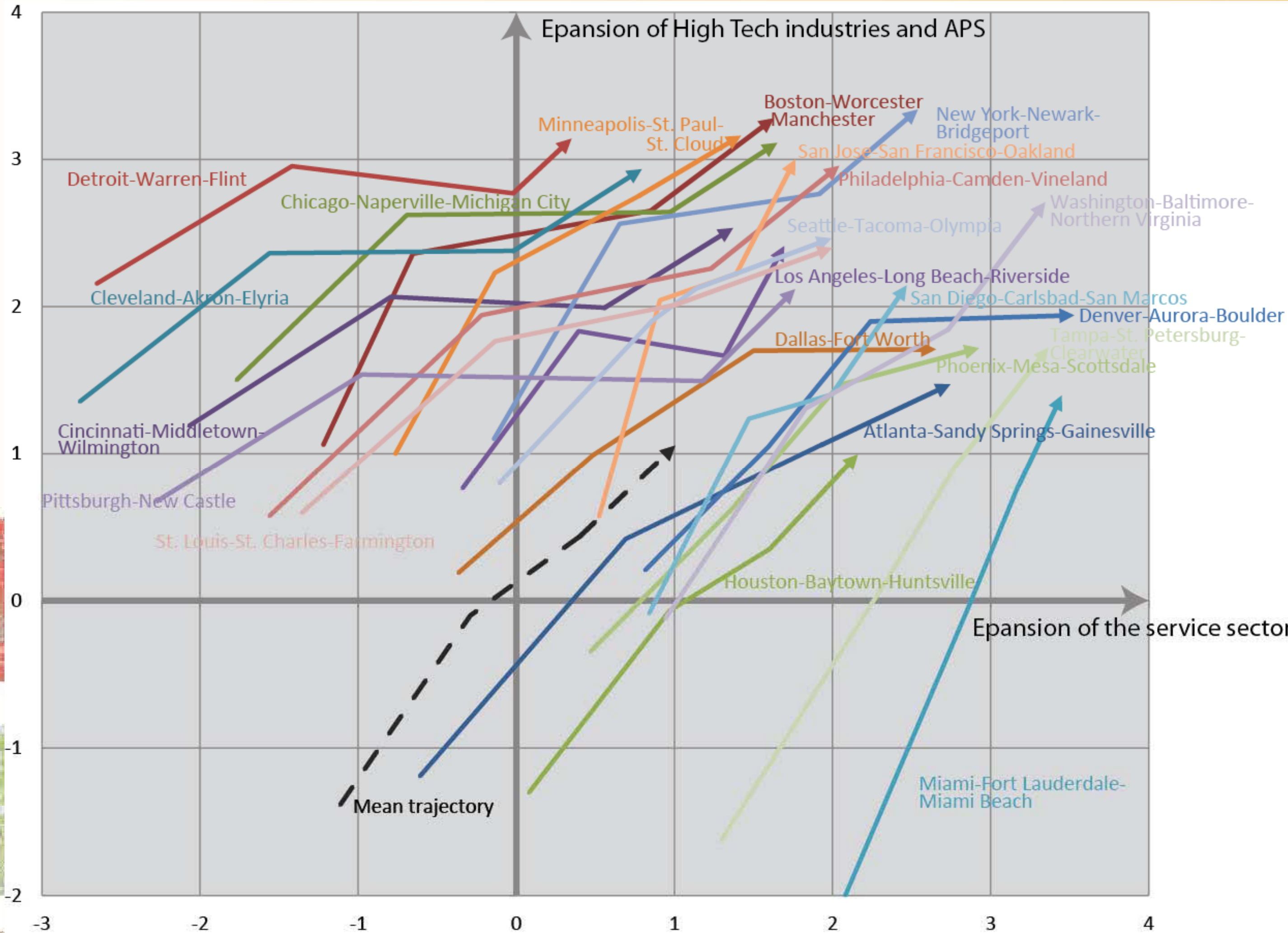
F. Paulus, 2003

Lima, CISEPA, December 2011, Denise PUMAIN

Co-evolution of US cities >2 millions inhab.







F. Paulus
C. Vacchiani-Marcuzzo, 2011

Theory of innovation in urban systems (2)

Most innovations induce a smooth change, without deep structural transformation, some of them emerge in waves of correlated activities.

The innovation cycles induce structural changes:

➔At **city level**:

Growth impulses in largest cities that are first adopters

or *specialisation*, i.e. new urban function in cities of any size

➔At the level of **system of cities**:

Acceleration of the hierarchisation process because of the hierarchical diffusion (*metropolisation*)

Increase in functional diversity (emergence of new types of specialised cities)

Theory of innovation in urban systems (3)

Innovation cycles:

The time period of cycles is reducing over historical times (from thousands to a few tenth of years) but **three main stages** are always noticeable:

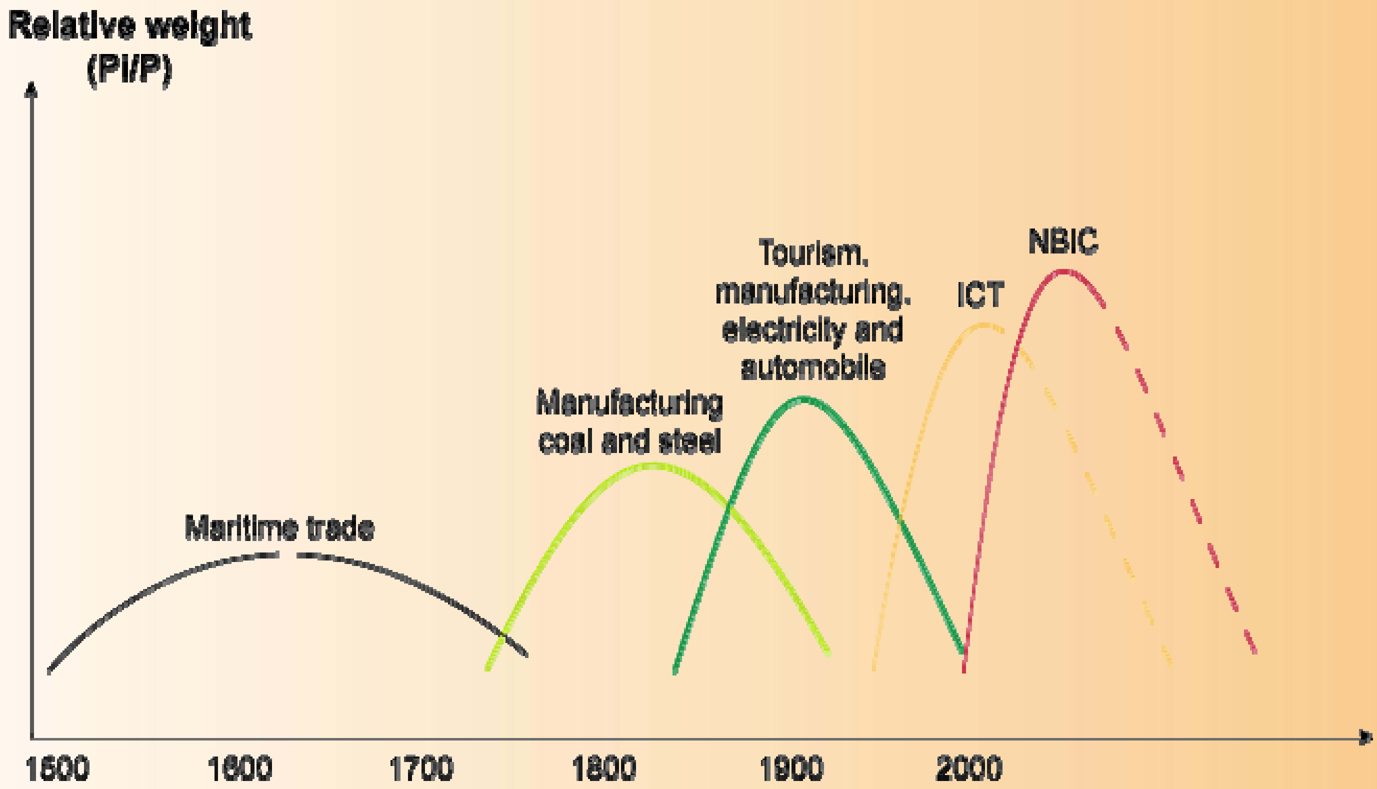
. emergence stage (leading technologies, highly skilled jobs)

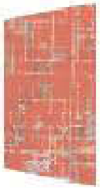
. diffusion stage (mature technologies, skilled jobs)

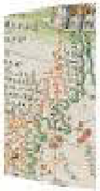
. stage of decay (banalisation and/or substitution by new products (old techniques, unskilled jobs)

Main innovation cycles having generated urban specialisation

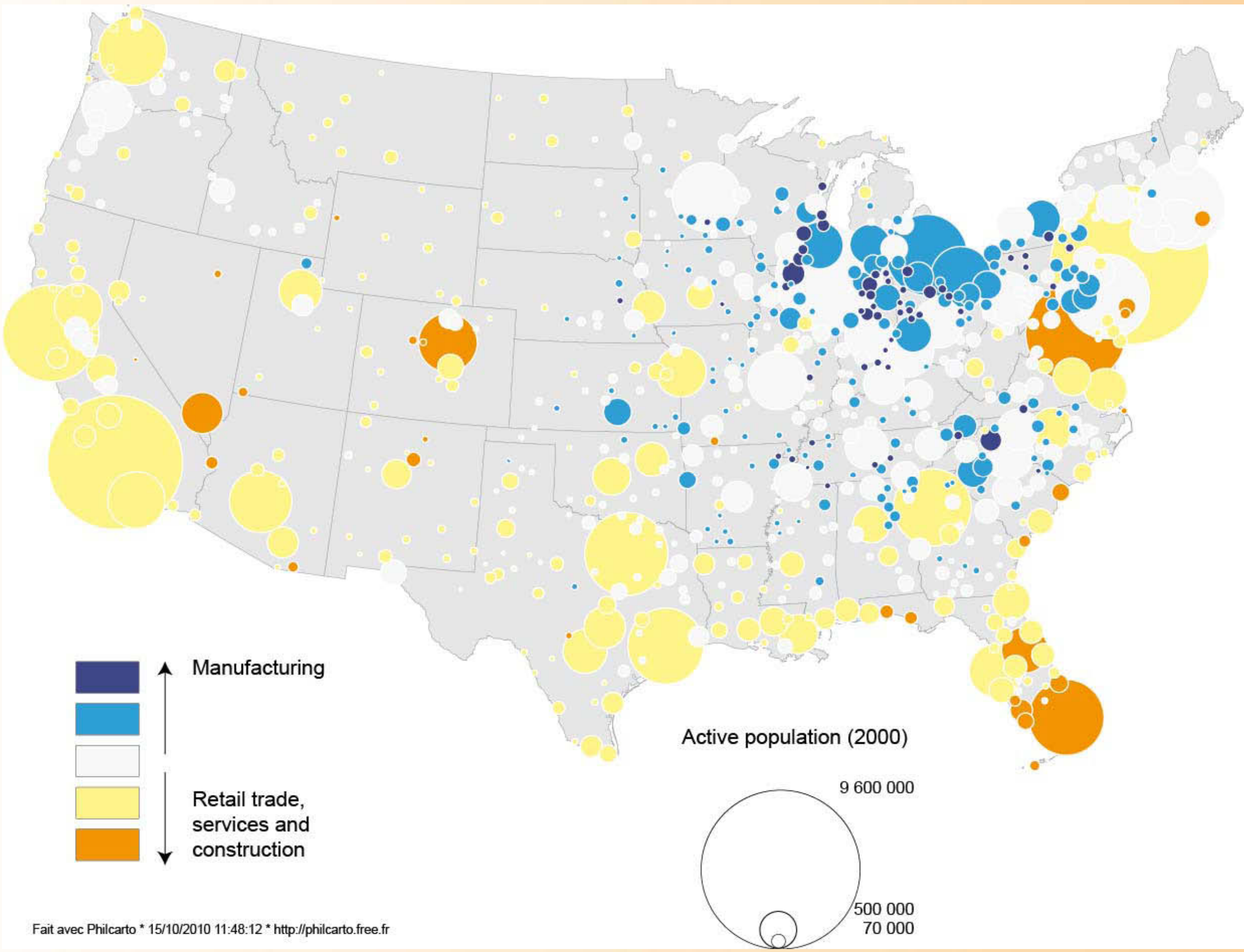
Succession of innovation cycles and urban specialisation in Europe (1500-2000)







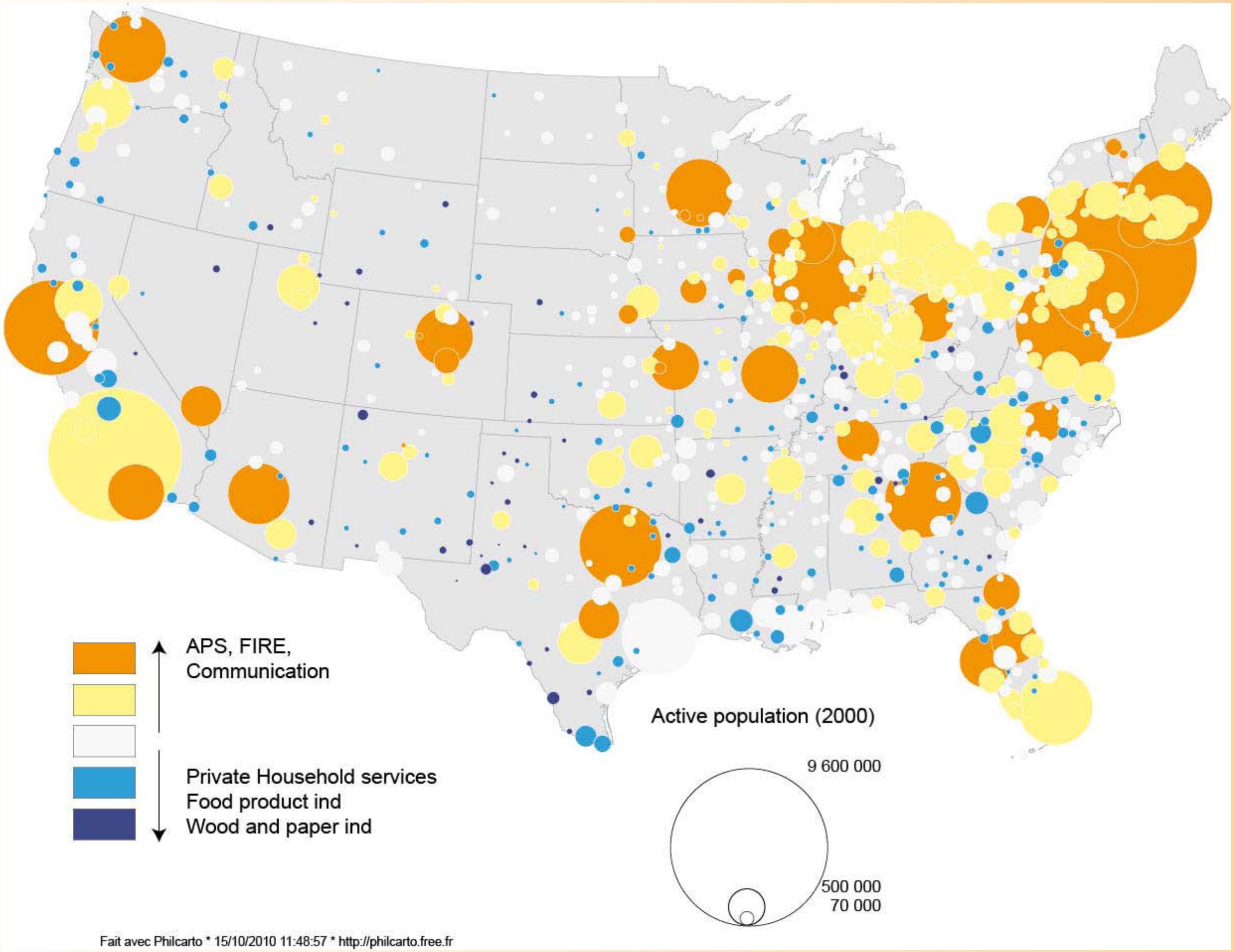
Main economic differentiation of UN cities in 2000 =trace of first industrial revolution innovation wave



1st factor of PCA= manufacturing/ services (differentiation at regional scale)

F. Paulus
C. Vacchiani-Marcuzzo, 2011

Second economic differentiation
= trace of recent economic cycles

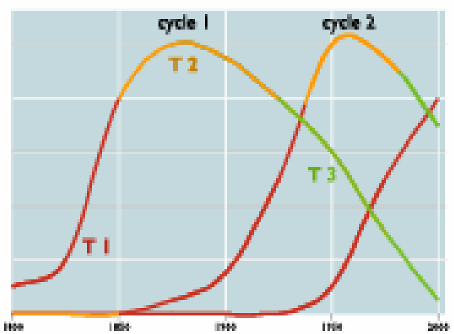


2d factor of PCA = new/old services (hierarchical diffusion)

F. Paulus C. Vacchiani-Marcuzzo, 2011

Stages in innovation cycle

Scaling parameters reflect innovation cycles generating urban growth

	Stages in cycles	Location	Evolution
$\beta > 1$	Innovative (high returns)	Concentration in large cities	
$\beta = 1$	Common place (normal returns)	Diffusion everywhere	
$\beta < 1$	Mature (low returns)	Residual in small towns	

Theory of innovation in urban systems (4)

Each time an innovation emerges, the corresponding activities are located according to available resources under the constraint of expected profits:

-Usually in largest cities because of their social complexity (resources in finance, skill, knowledge, culture…)

-Sometimes in other locations offering specific resources (for industry, tourism, invention…)

Older activities relocate according to the constraint of lowering costs (land rent, wages…)

➔Adaptation process with delays

Connexion with scaling

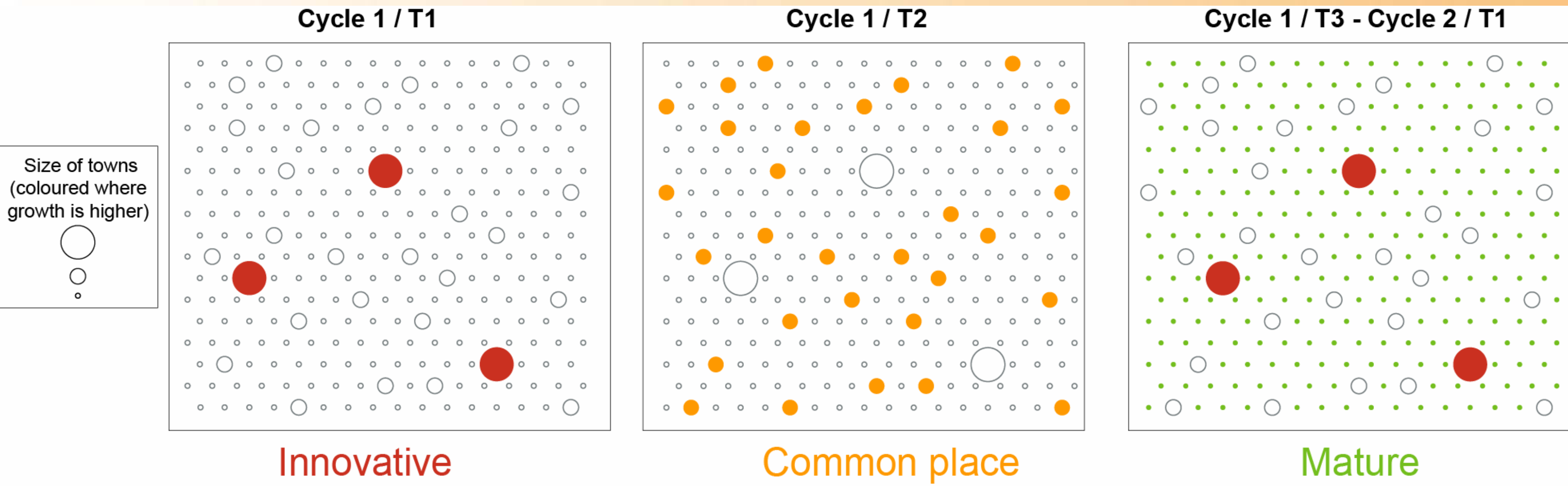
Largest cities became larger because these cities were successful in adopting many successive innovations.

There is a **slow substitution process**

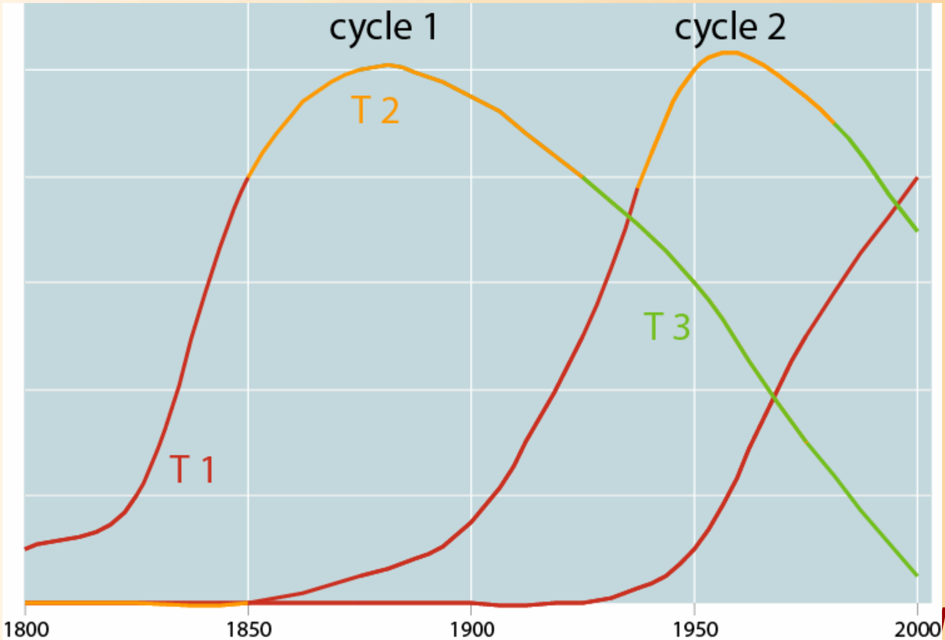
At each time period the activities belonging to a new cycle of innovation remains blocked for a while at that upper level of the urban hierarchy, then diffuse among other cities, then shrink, escaping at first from largest cities

➔Most advanced technologies concentrate in largest cities, current ones are ubiquitous, whereas old ones remain in small towns

Innovation cycles and substitution process



F. Paulus
C. Vacchiani
-Marcuzzo,
Pumain D.
Cybergeo
2006



MAIN

Theory testing 1: Economic diversity and city size

Largest cities become larger because they participated in many innovation cycles over historical time.

They keep a trace of many successive waves of innovation➔ their economic activity should be more diversified than in small towns which captured fewer cycles

Scaling and diversity of urban functions

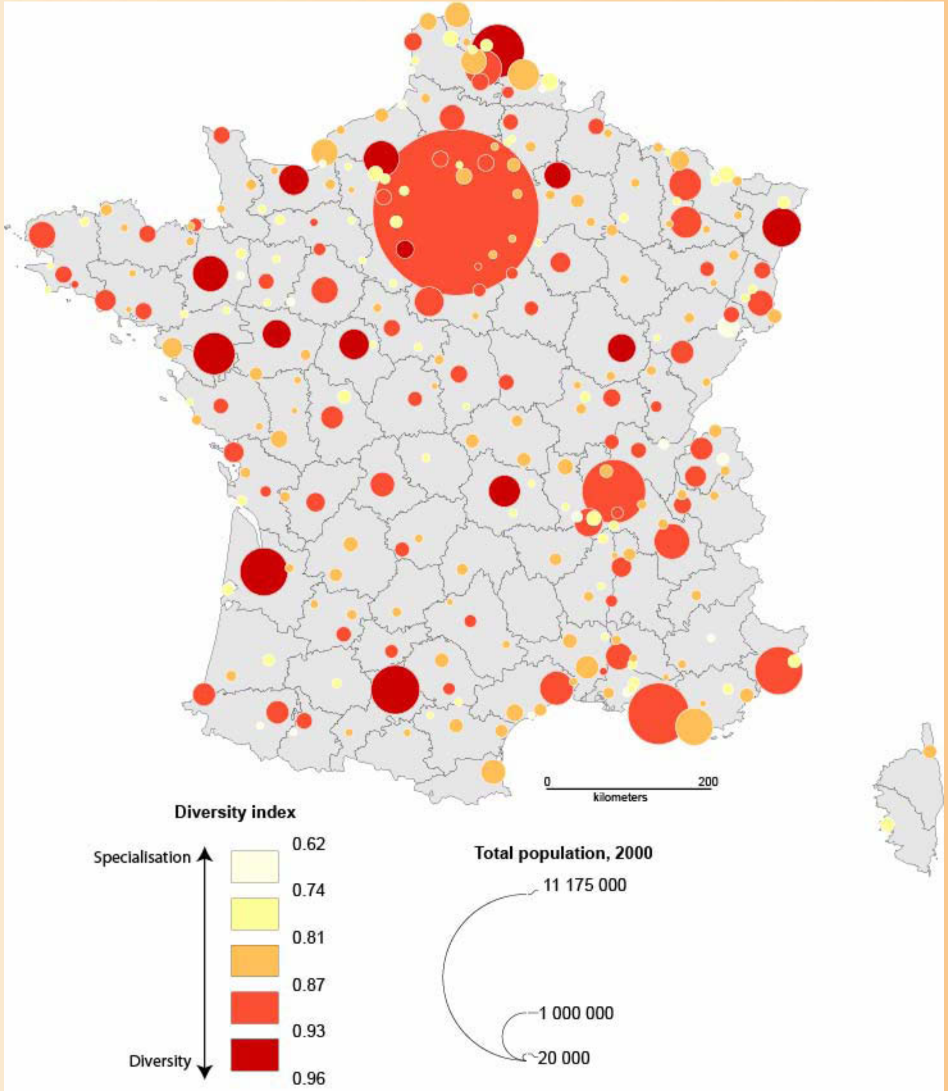
Diversity Index based on Isard's coefficient of specialization :

$$D_i = 1 - \left[\frac{1}{2} \sum_j \left| x_{ij} - \bar{x}_j \right| \right]$$

x_{ij} : share of employees in city i and economic sector j

$\bar{x}_j$: mean of employees in economic sector j

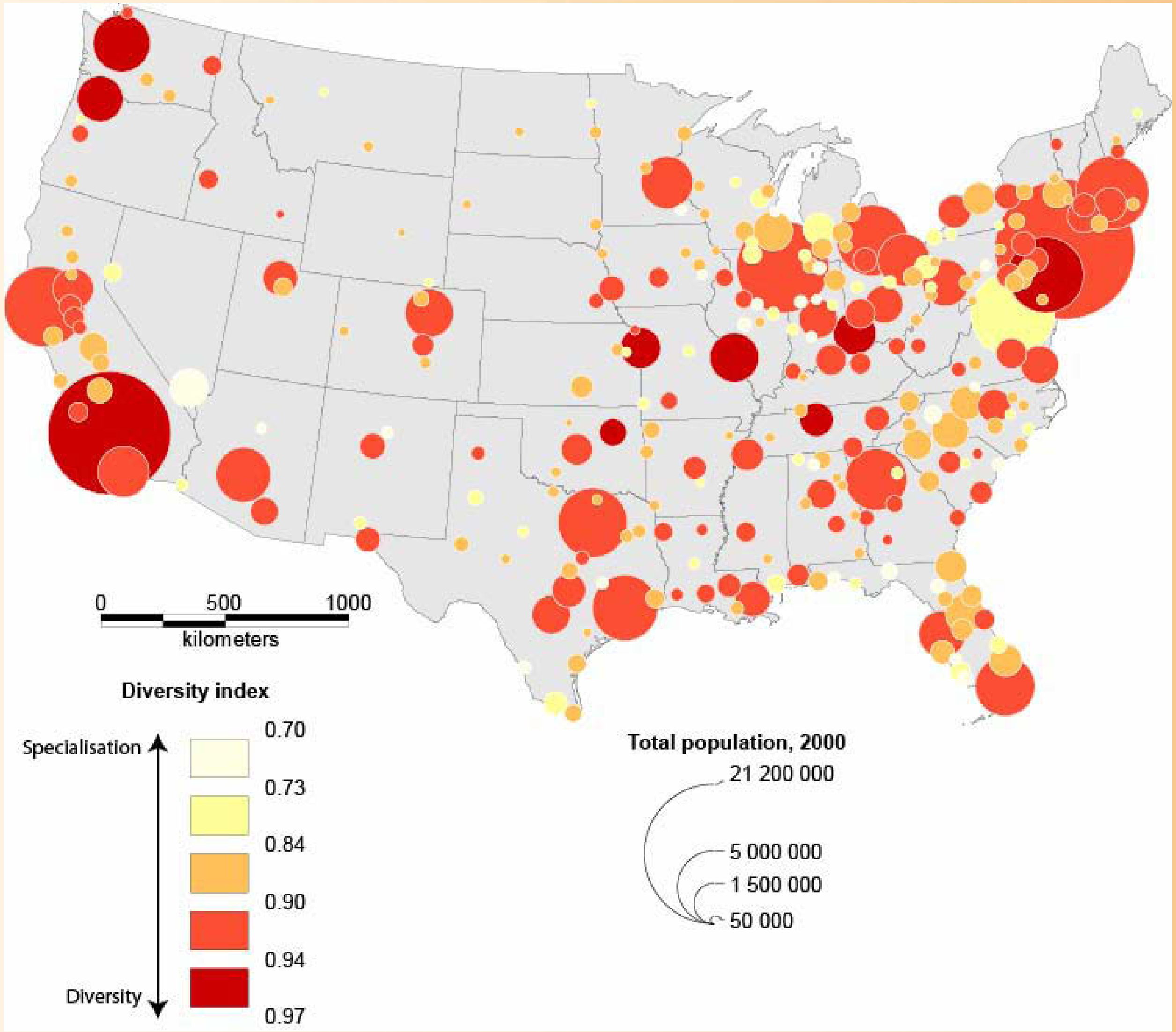
Economic diversity of French "aires urbaines" in 1999



F. Paulus, 2004

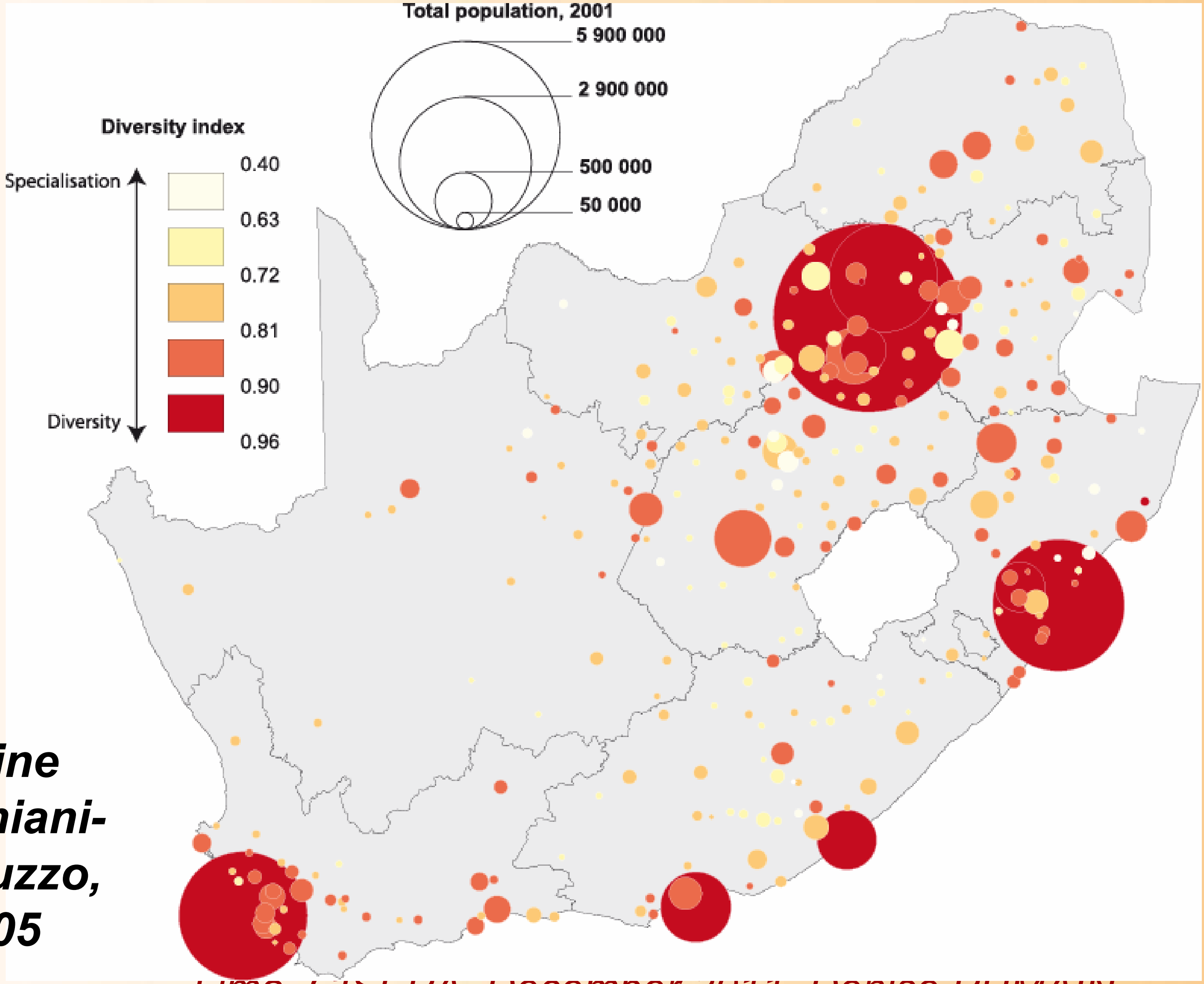
Lima, CISEPA, December 2011, Denise PUMAIN

Economic diversity of US Metropolitan Areas in 2000



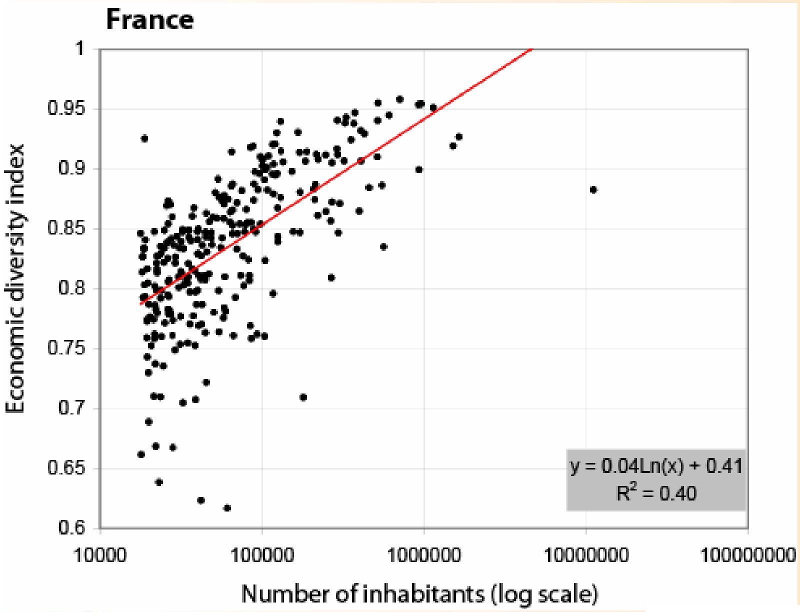
F. Paulus 2008

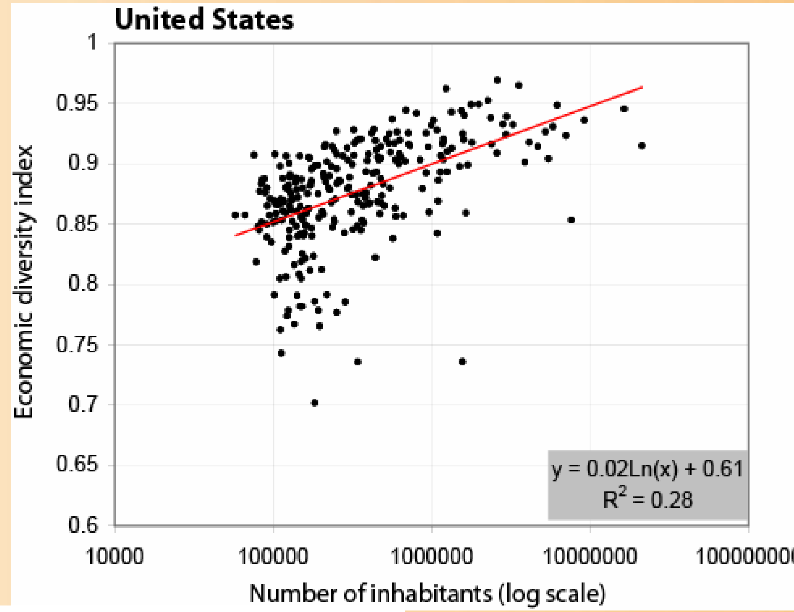
Economic diversity of South African urban agglomerations in 2001

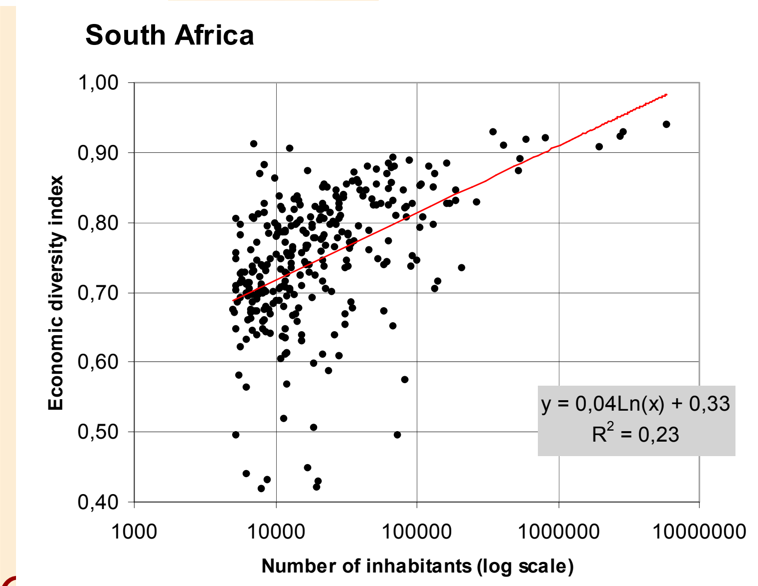


Céline Vacchiani-Marcuzzo, 2005

City size and economic diversity







Lima, C … UMAIN

Theory testing 2: Evolution of scaling parameters

As the hierarchical diffusion and the substitution process are not instantaneous, one should observe an evolution of the value of scaling parameters over time.

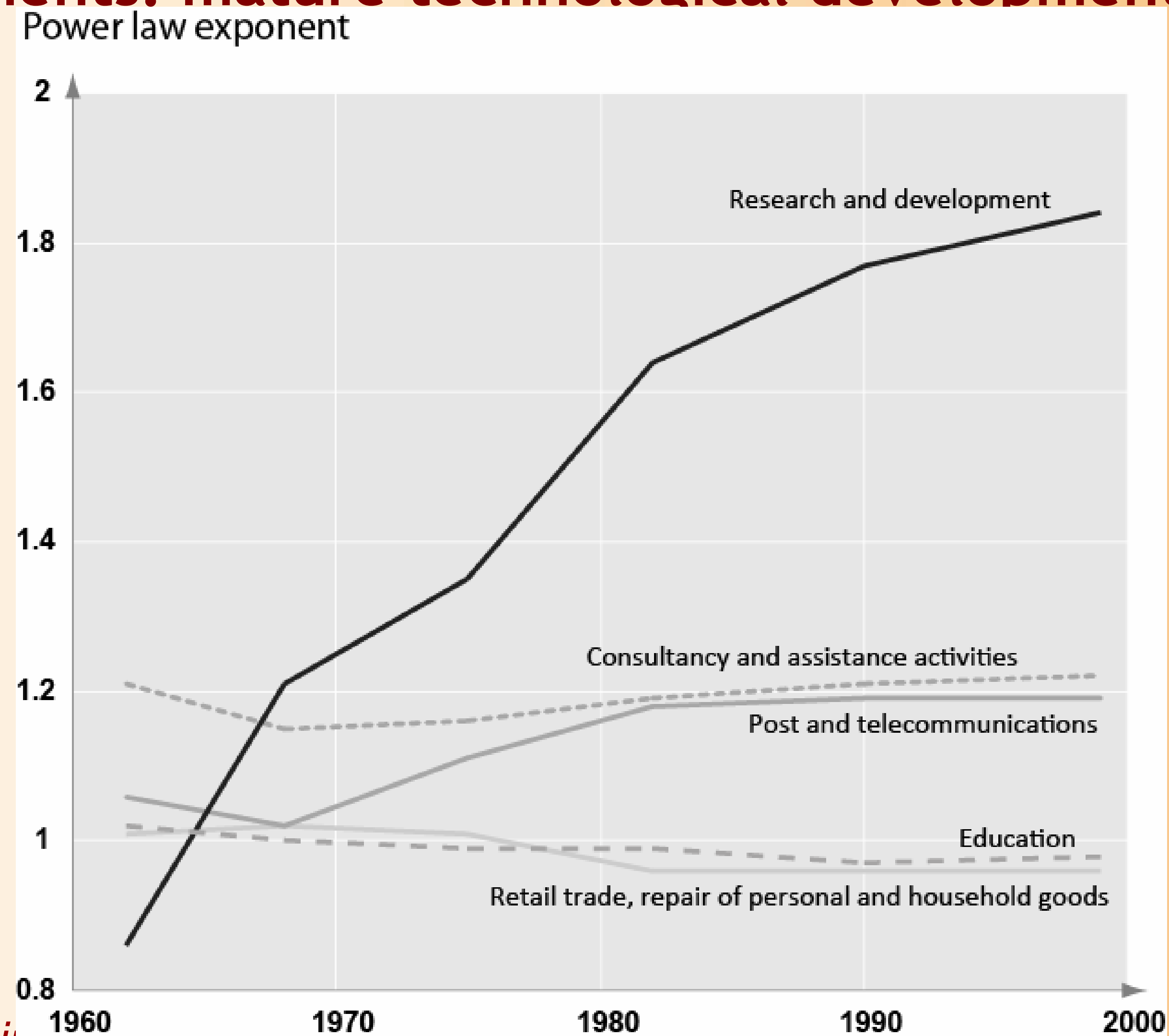
In a first stage, scaling parameter values increase (innovative stage, concentration in large cities), then they become closer to one (banal stage, ubiquity), then lower than one (mature stage, contraction in smaller towns)

→ Historical database on urban activities in French cities, 1962-1999 (*Paulus, 2004*)

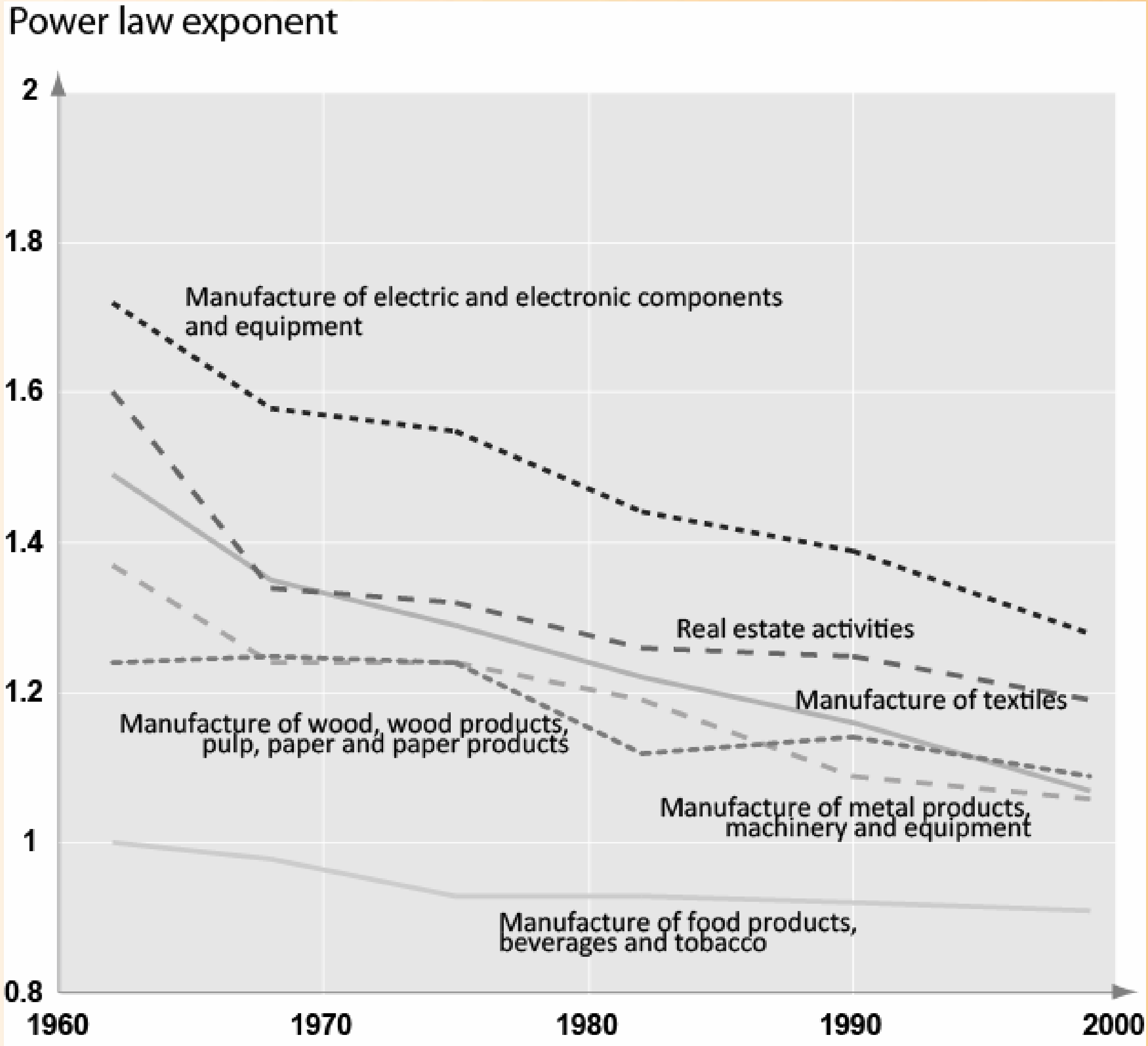
Increasing β exponents over 1: sectors deeply involved in leading technologies
Stable β exponents: mature technological development

French Cities

(Paulus, 2008)



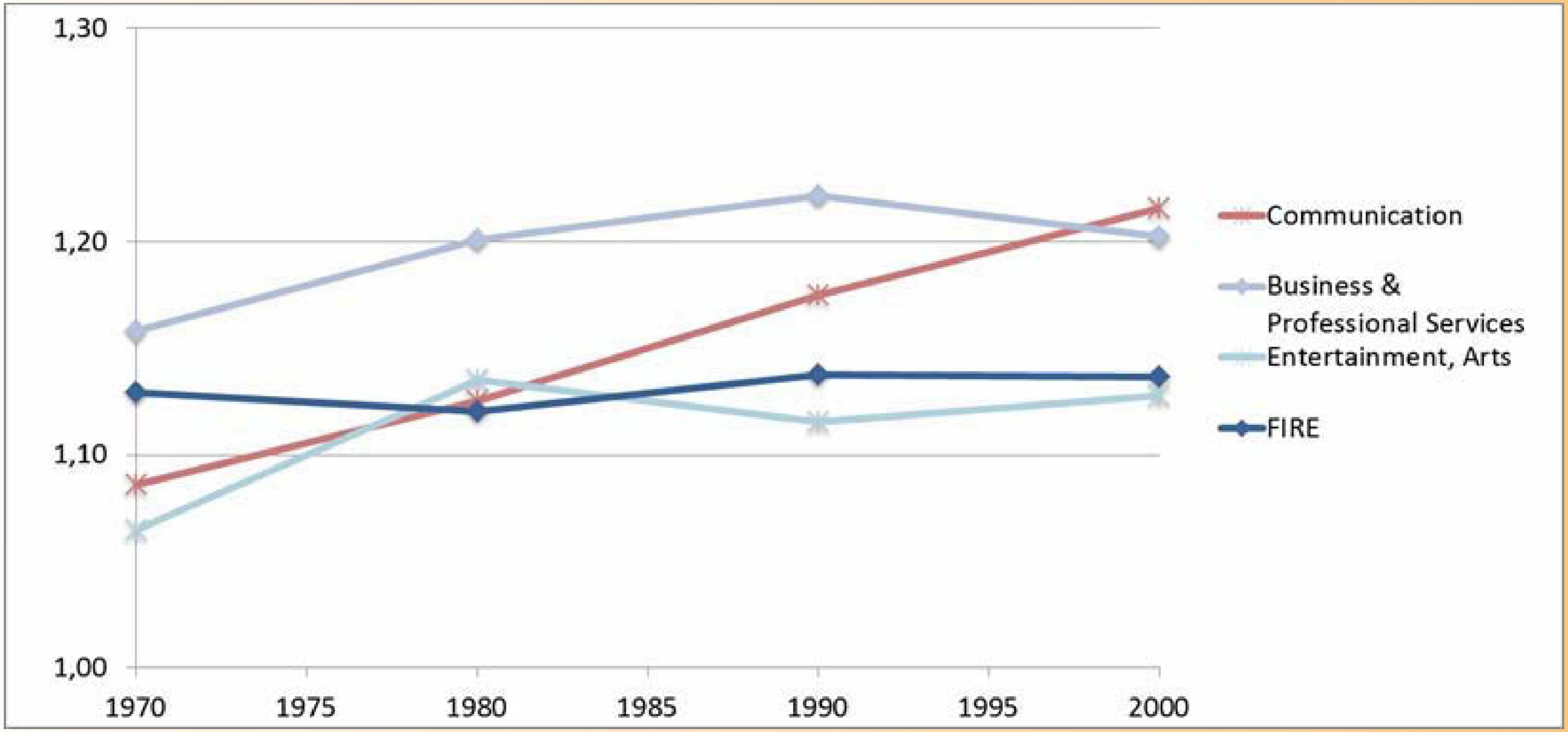
Decreasing β exponents : hierarchical diffusion of innovation



French Cities

(Paulus, 2008)

USA
Increasing β exponents over 1: sectors deeply involved in leading technologies

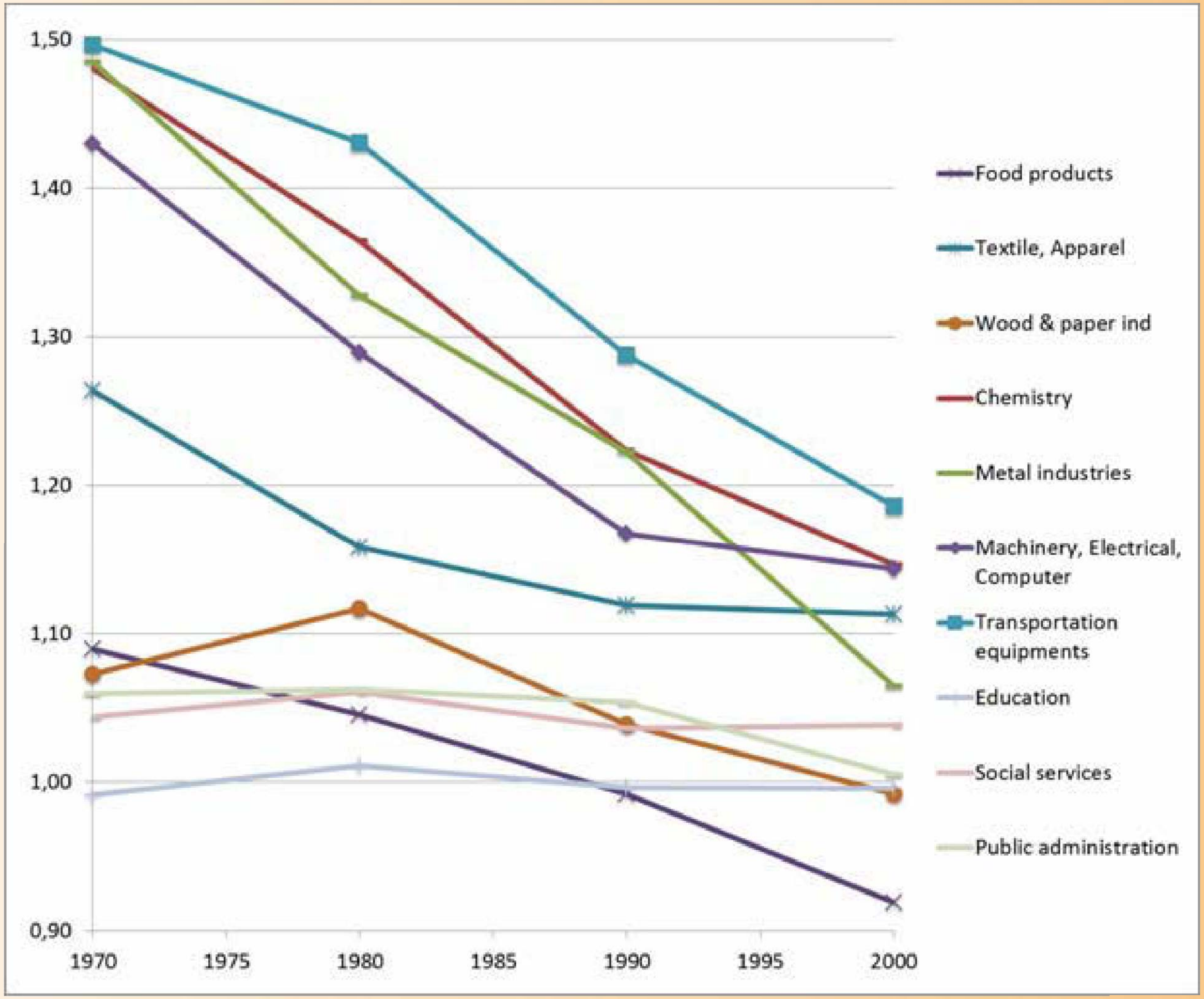


F. Paulus, 2008

USA

Decreasing β exponents : hierarchical diffusion of innovation

Stable β exponents: mature technological development



F. Paulus, 2008

Theory testing 3: Occupational groups

Main problem in empirical testing: official economic nomenclatures are not designed to isolate innovation cycles

➔ Testing through observation of occupational groups

As professions are highly depending upon sectors of activity, one can expect scaling effects for professions as well, of the type:

high skill professions: $\beta > 1$

skilled professions: $\beta = 1$

low or unskilled: $\beta < 1$

French survey: occupational groups

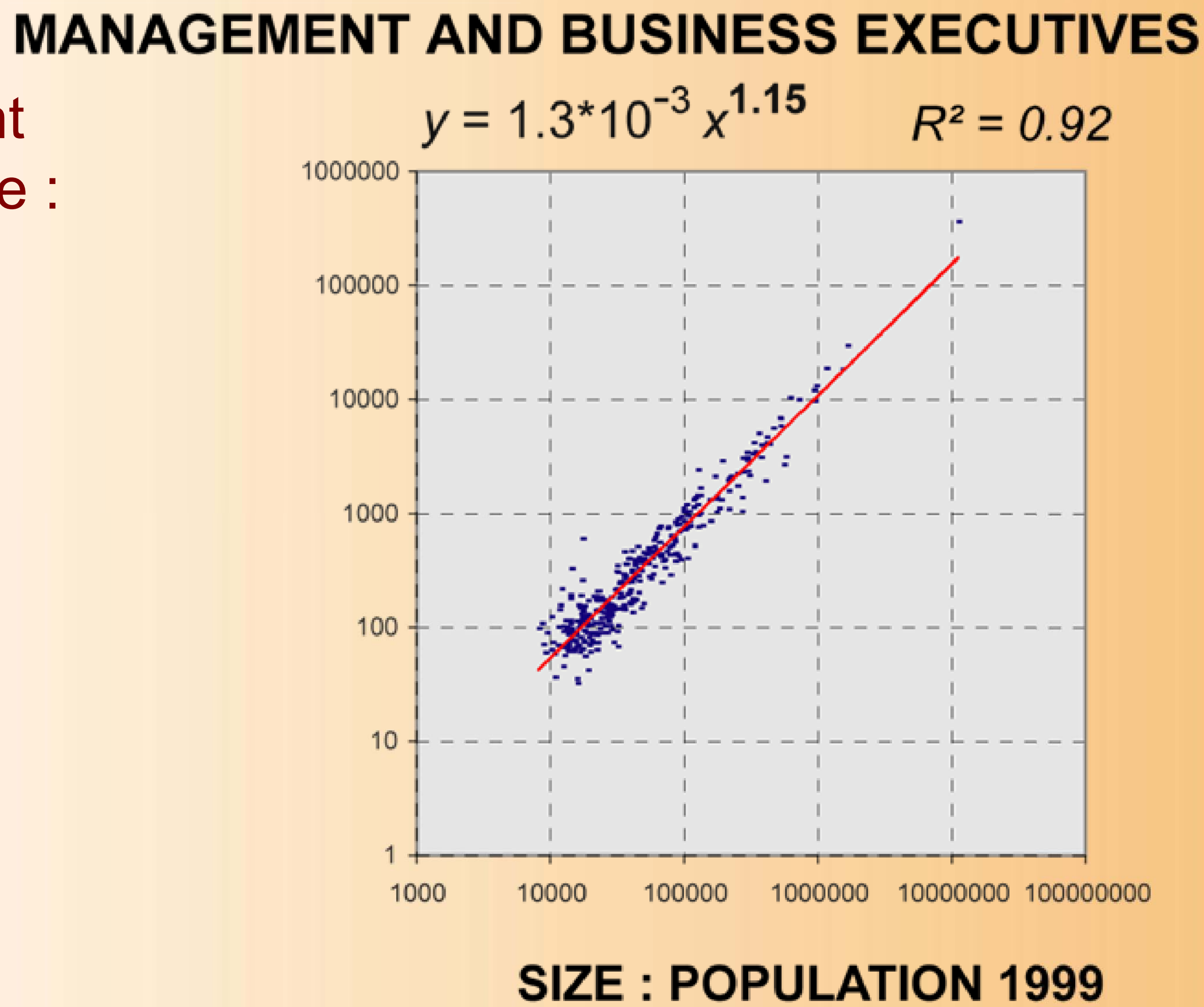
Stage in current innovation cycle :

Highly skilled

β= 1.15

95% CL :

1.11-1.18



French survey: occupational groups

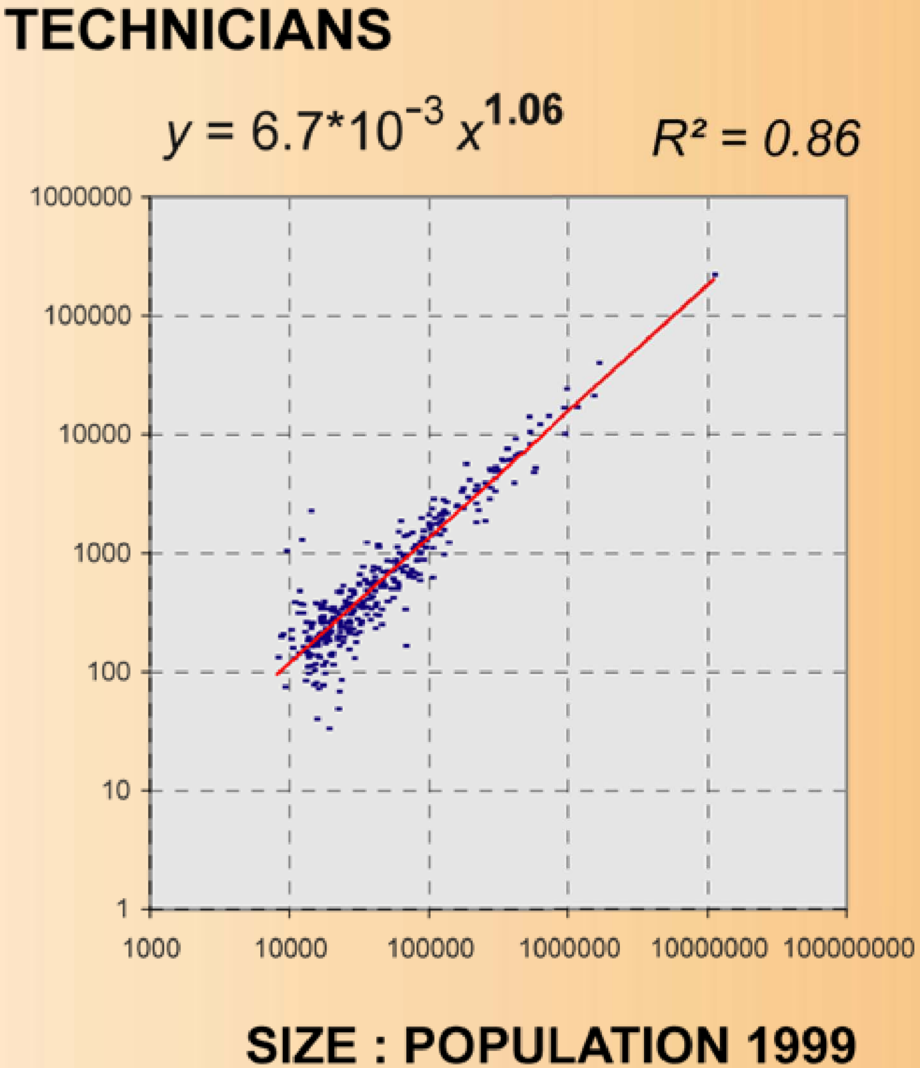
Stage in current innovation cycle :

Skilled

β= 1.06

95% CL :

1.03-1.13



French survey: occupational groups

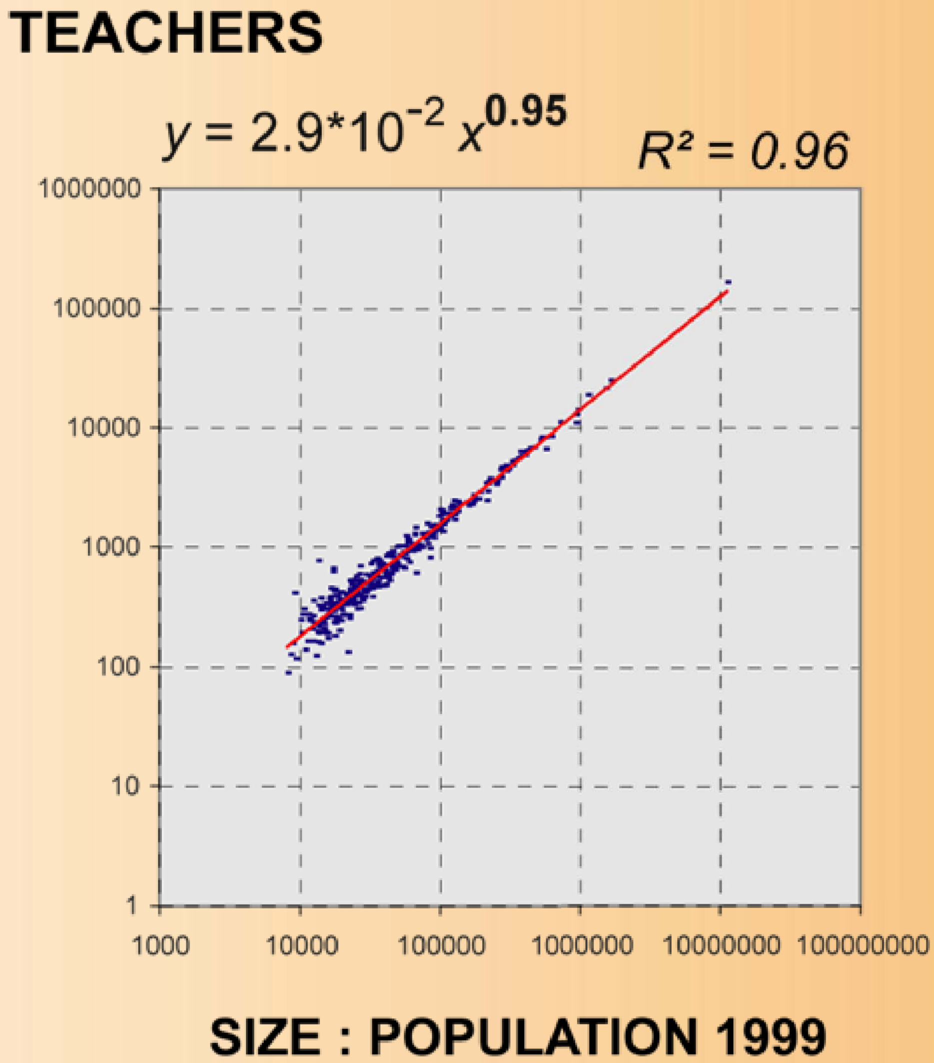
Stage in current innovation cycle :

Skilled

β= 0.95

95% CL :

0.93-0.97

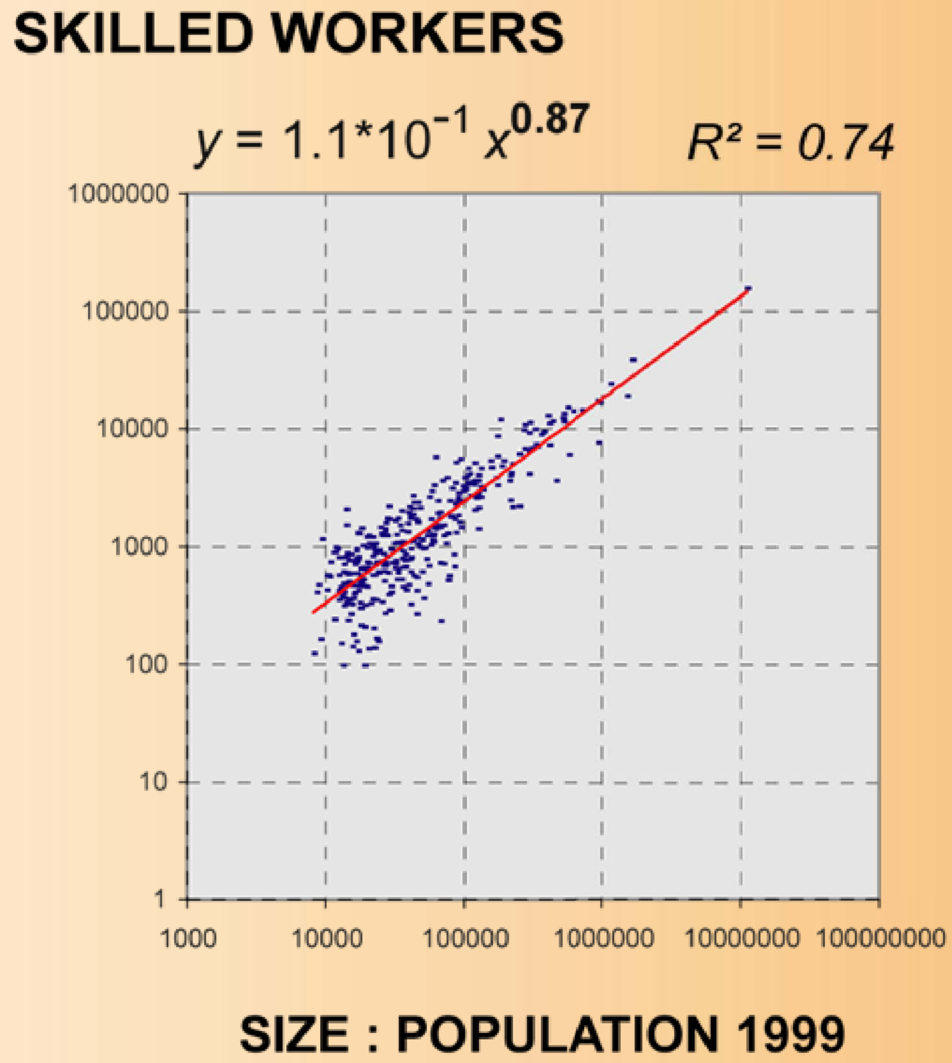


French survey: occupational groups

Stage in current innovation cycle :
Unskilled

β= 0.87

95% CL :
0.82-0.92

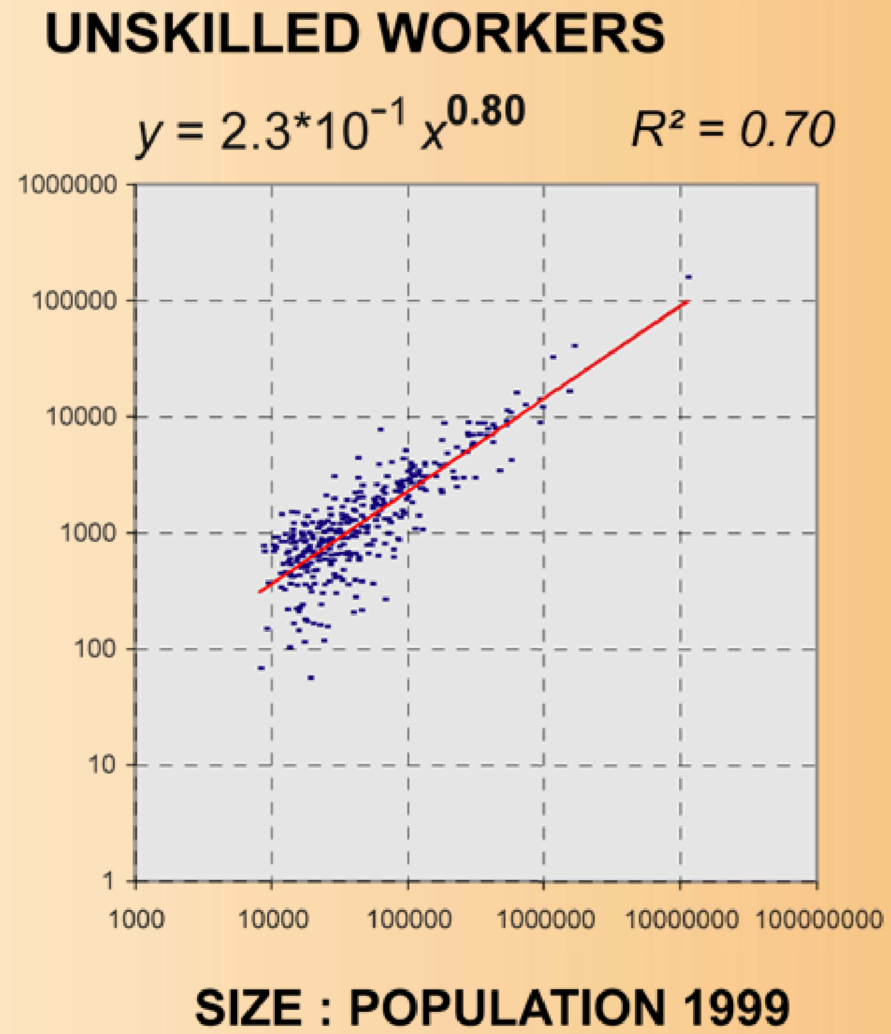


French survey: occupational groups

Stage in current innovation cycle :
Unskilled

β= 0.80

95% CL :
0.75-0.86



US survey: occupational groups

Stage in current innovation cycle :

Highly skilled

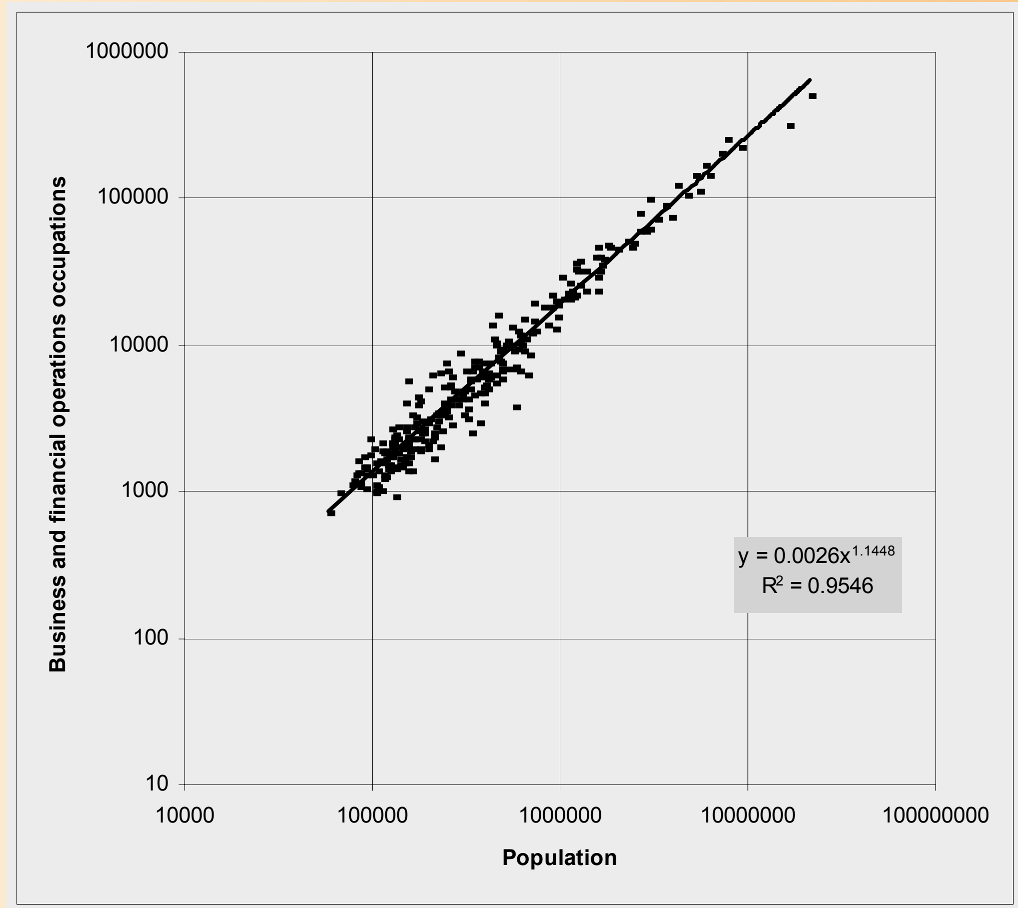
Business and financial operations occupations

β = 1.14

95% CL :

1.11-1.17

R^2 = 95 %



US survey: occupational groups

Stage in current innovation cycle :

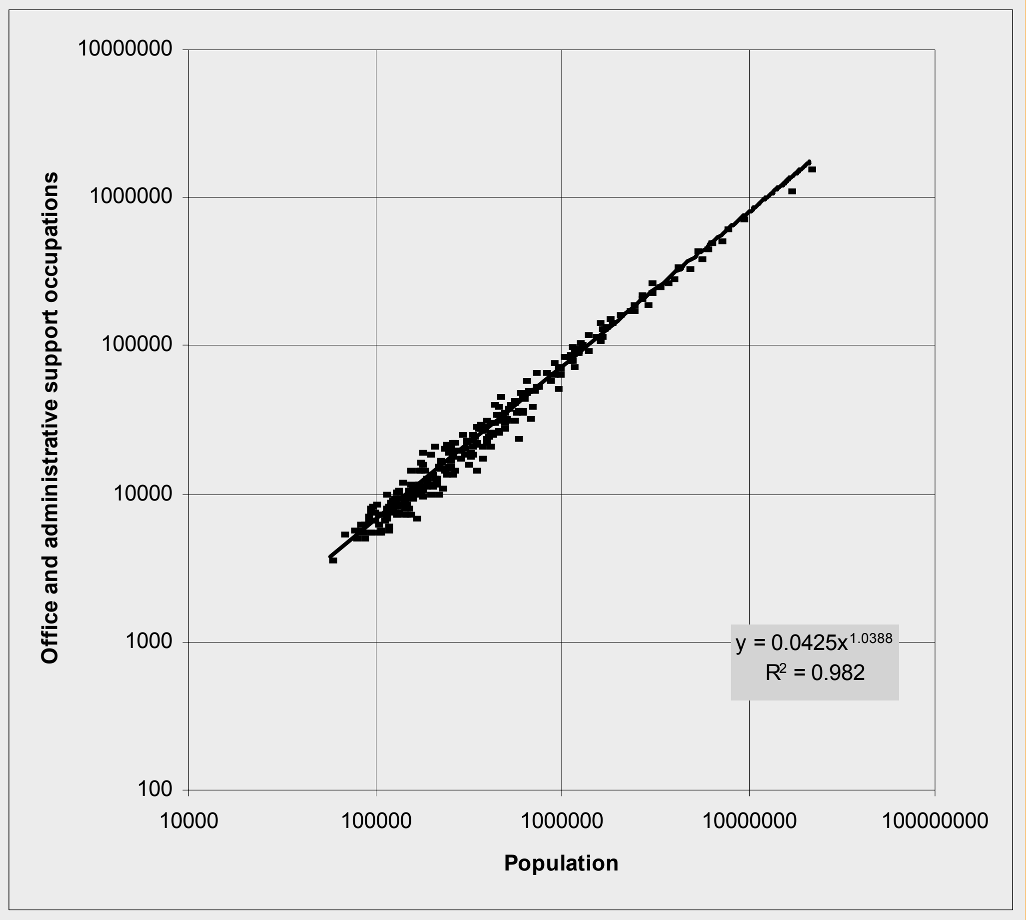
skilled

Office and administrative support

β = 1.04

95% CL :
1.02-1.06

R^2 = 98 %



US survey: occupational groups

Stage in current innovation cycle :

Unskilled

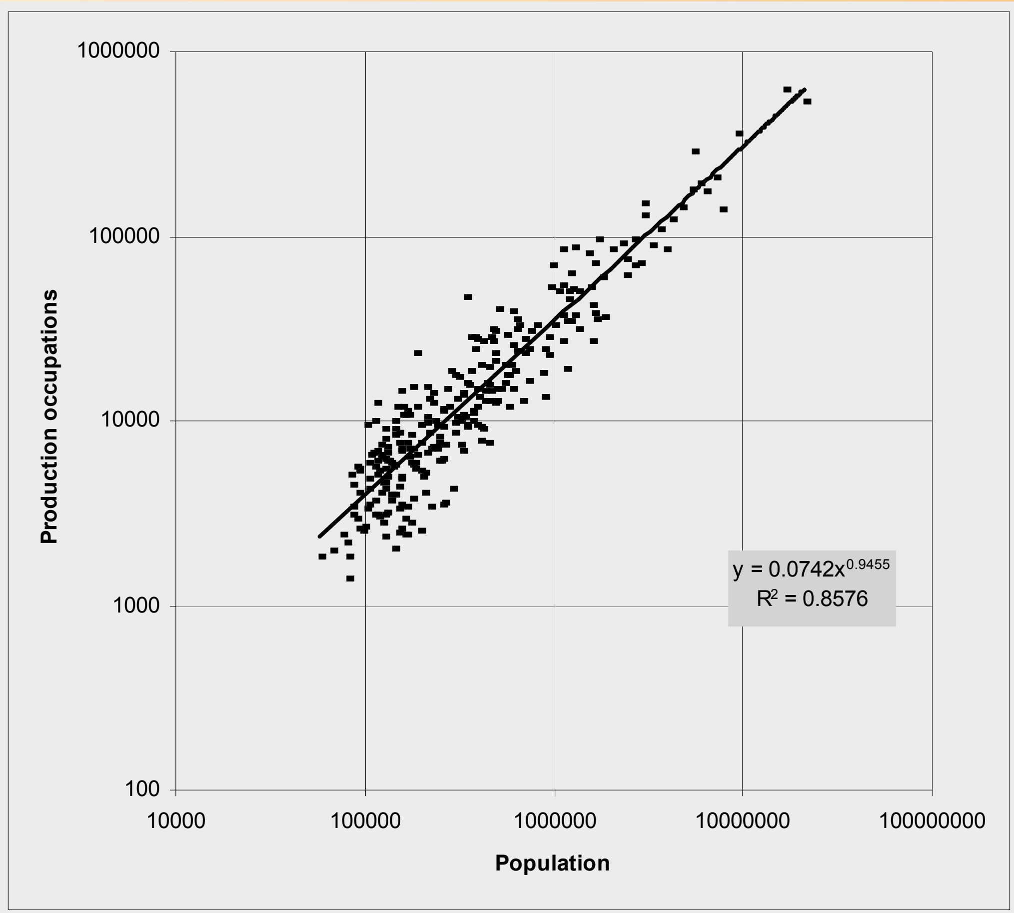
Production occupations

β = 0.95

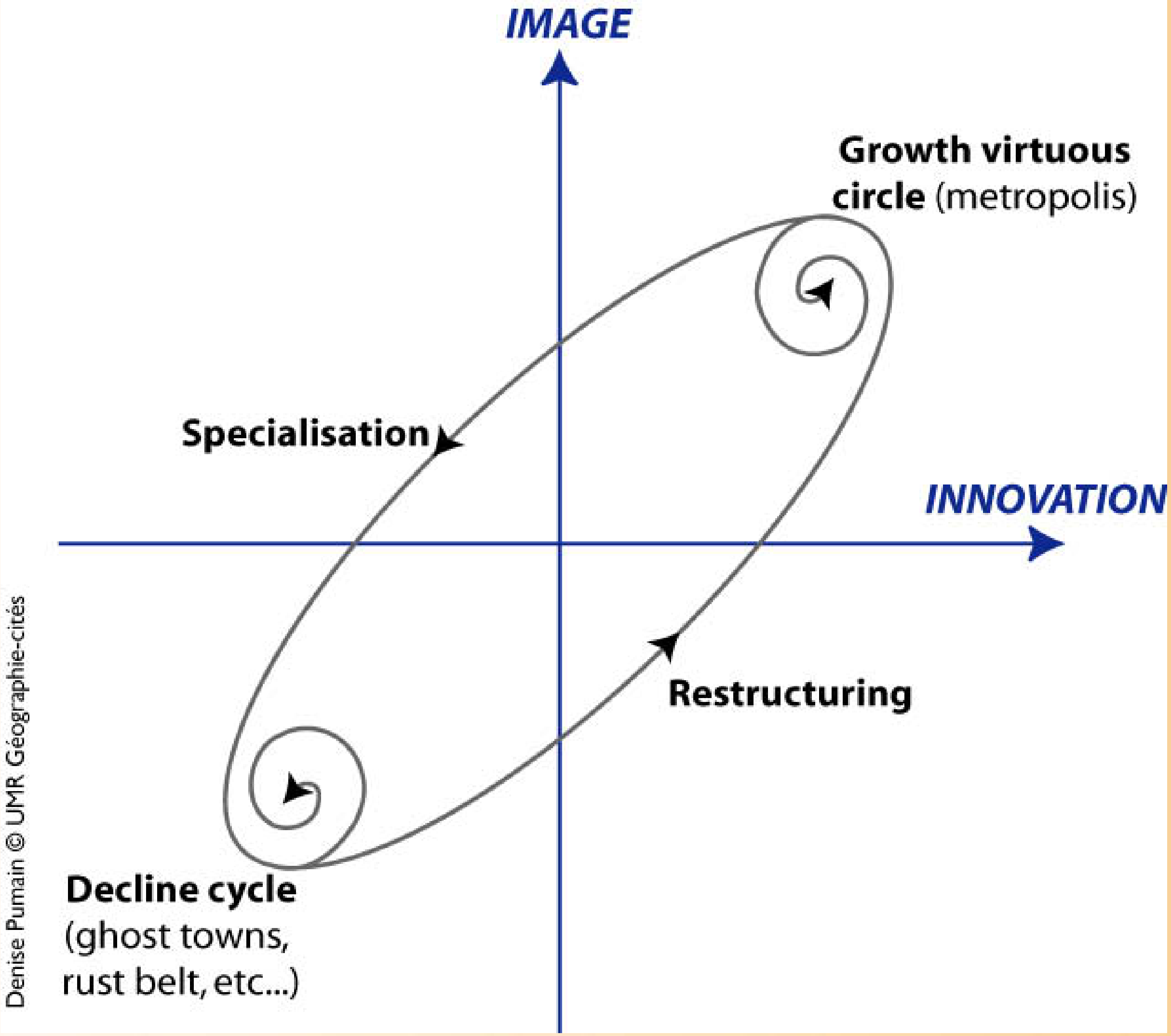
95% CL :

0.90-0.99

R^2 = 86 %

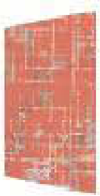


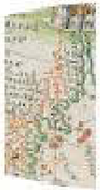
Cities trajectories in innovation space



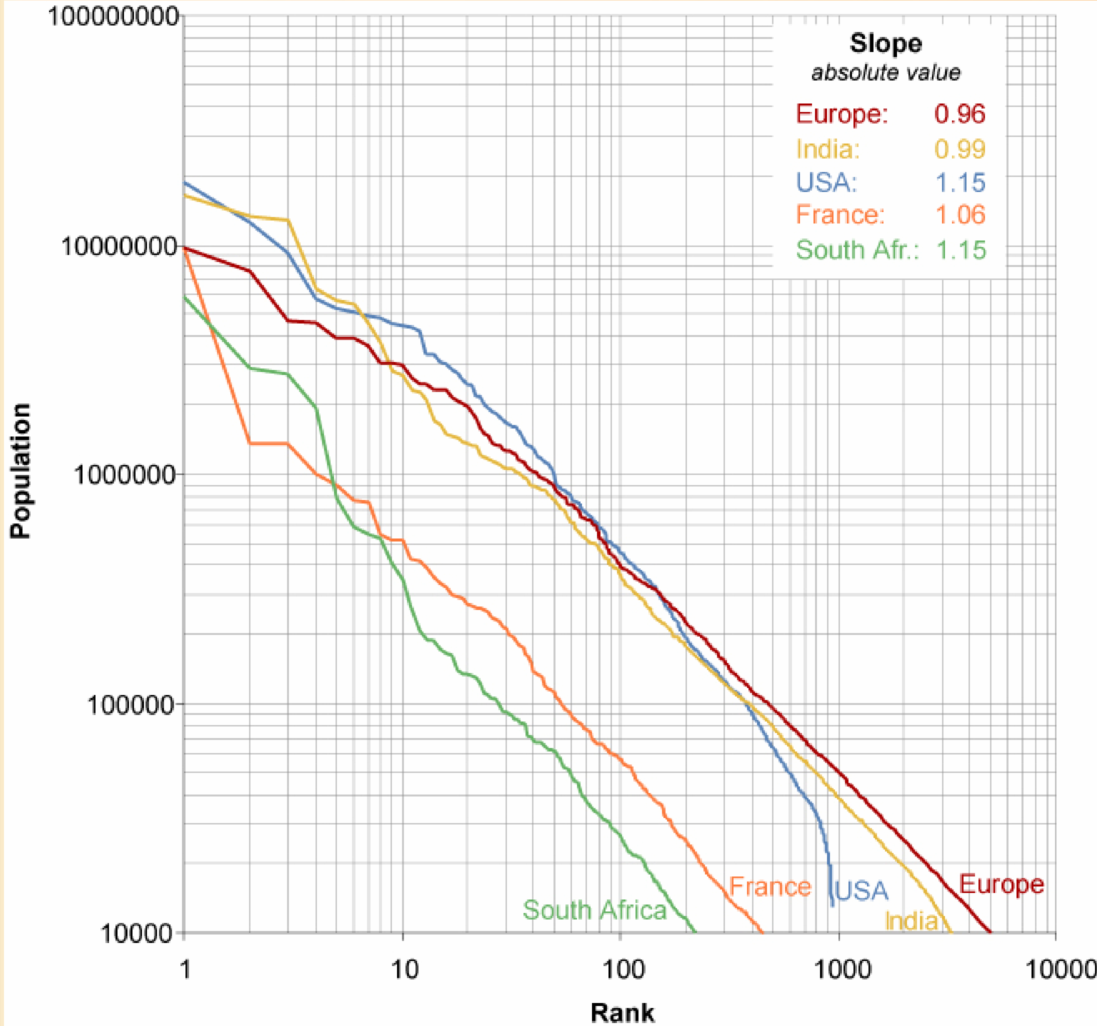
C. Rozenblat
Th. Saint-Julien
F. Paulus
D. Pumain

A universal model of urban settlements





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



Sources : Europe : Moriconi-Ebrard F., 1994, GEOPOLIS / India : Census of India 2001 / USA : United States Census 2000 / France : INSEE, Recensement de la Population 1999 / South Africa : Statistics South Africa, Census 2001, Base CVM

Theory testing 4: urban growth

Three hypothesis in the usual Gibrat's model of urban growth (linking urban growth process to lognormal distribution of city sizes):

• growth is proportional to city size, with random fluctuation

$$r = (P_{it} - P_{i\,t-1}) / P_{it}$$

$$P_{it} = (1+r)\, P_{i\,t-1}$$

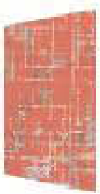
• growth rates are independent from city size

• growth rates of one period are independent from growth rates of the previous period

Defining cities and urban systems for comparison of urban growth processes

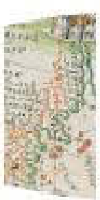
Cities as systems: coherent spatial entities (daily interactions) expanding in space and time

➔Urban agglomerations then metropolitan areas



➔France: data base 1831 to 1999

➔USA: data base 1790 to 2000 (Bretagnolle et al., 2008, *Cybergeo*)



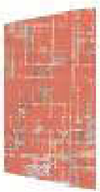
Gibrat's model: a satisfying proxy but some empirical contradiction

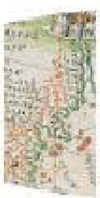
1 The observed distributions of city sizes (actually: settlement sizes including hamlets, villages, towns and SMAs) are lognormal (evidence from Robson, 1973, Pumain, 1982, Eeckhout, 2004, Decker et al, 2007)

2 Gibrat's growth model leads to a lognormal distribution of city sizes

3 but Gibrat's growth model hypothesis are rejected (correlation between growth rates and city size, correlation between successive growth rates)

A geographical model for simulating urban growth





We develop a geographical model of urban growth including:

➔A recurring emergence of clustered new innovations that create growth cycles (Schumpeter)

➔The diffusion of innovations occurs through a dynamic spatial interaction model (Wilson).

➔The diffusion of innovation is a hierarchical process (Hägerstrand) The growth of a city depends on its share of labour force in each innovation cycle = scaling parameter >1

Source: Favaro, 2007

The geographical growth model

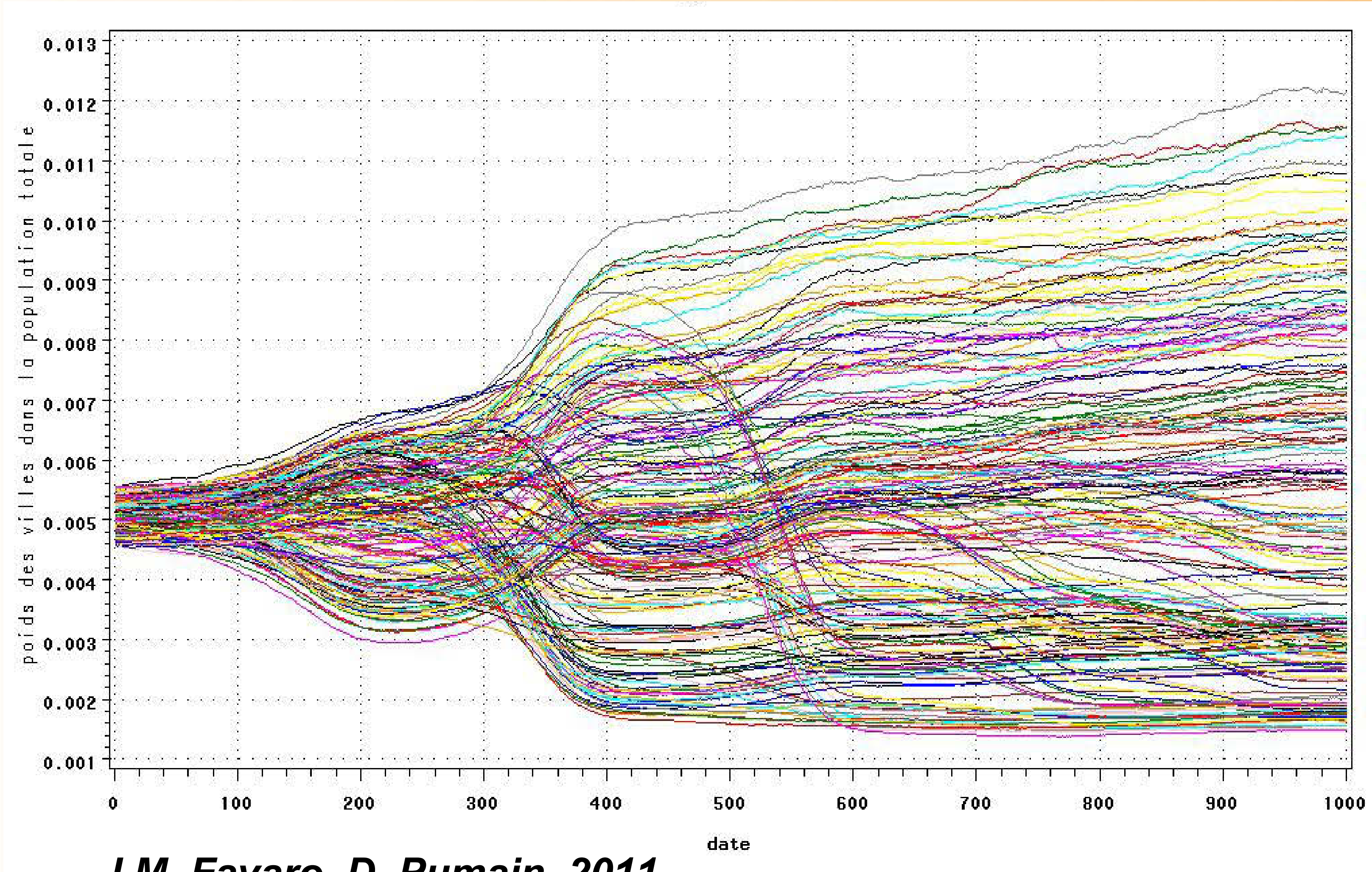
Analytically, the model can be expressed in a form that is very close to Gibrat’s model:

$$\log P_{it} = \alpha + \log P_{it-1} + G_i + u_{it}$$

where G_i holds for the « bias » noticed in estimating Gibrat’s model by MCO (linked with spatial interaction processes)

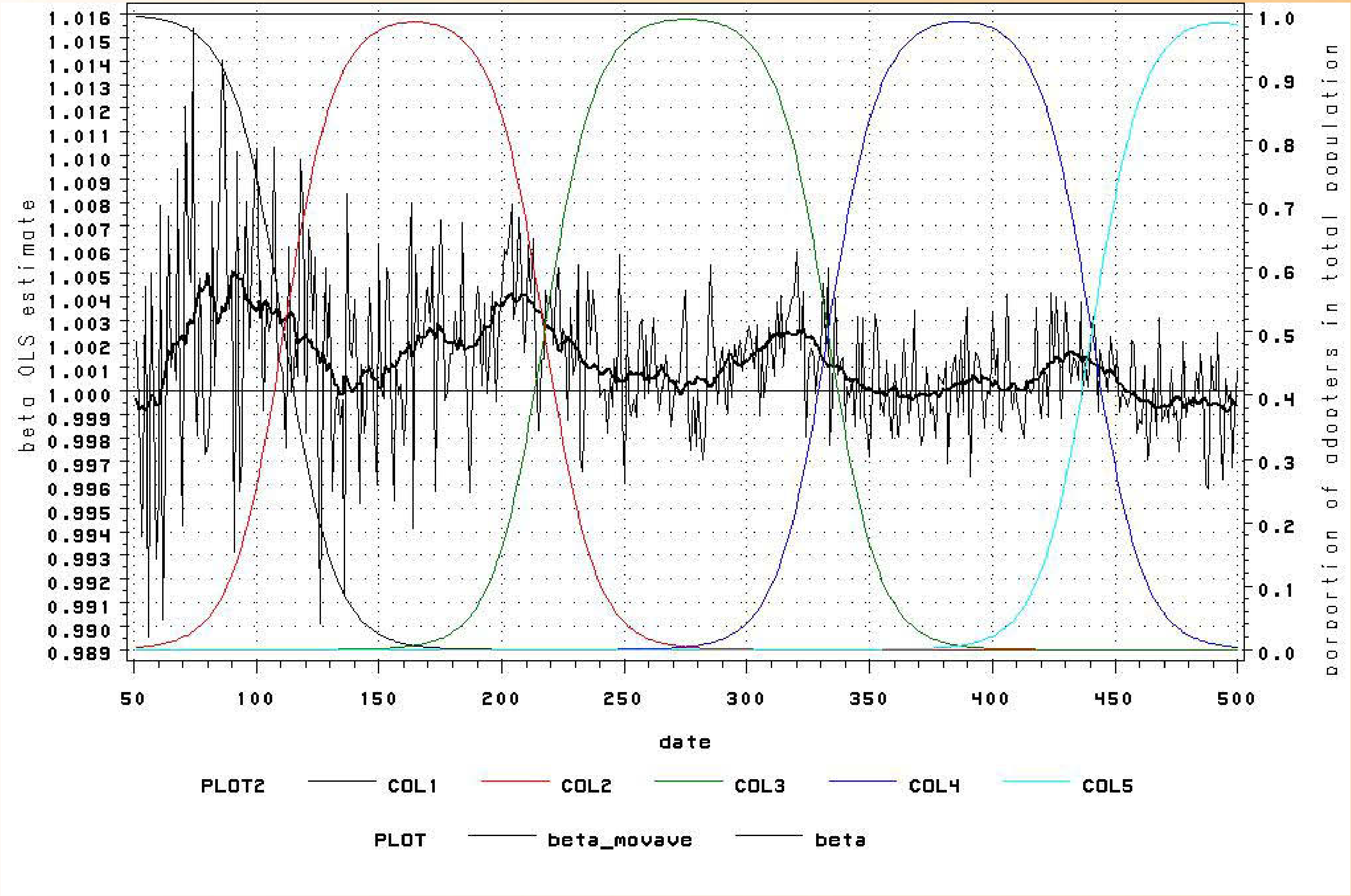
Favaro, Pumain, *Geographical Analysis* (forthcoming)

Simulated trajectories of individual cities (relative weight in the system's of cities total pop)

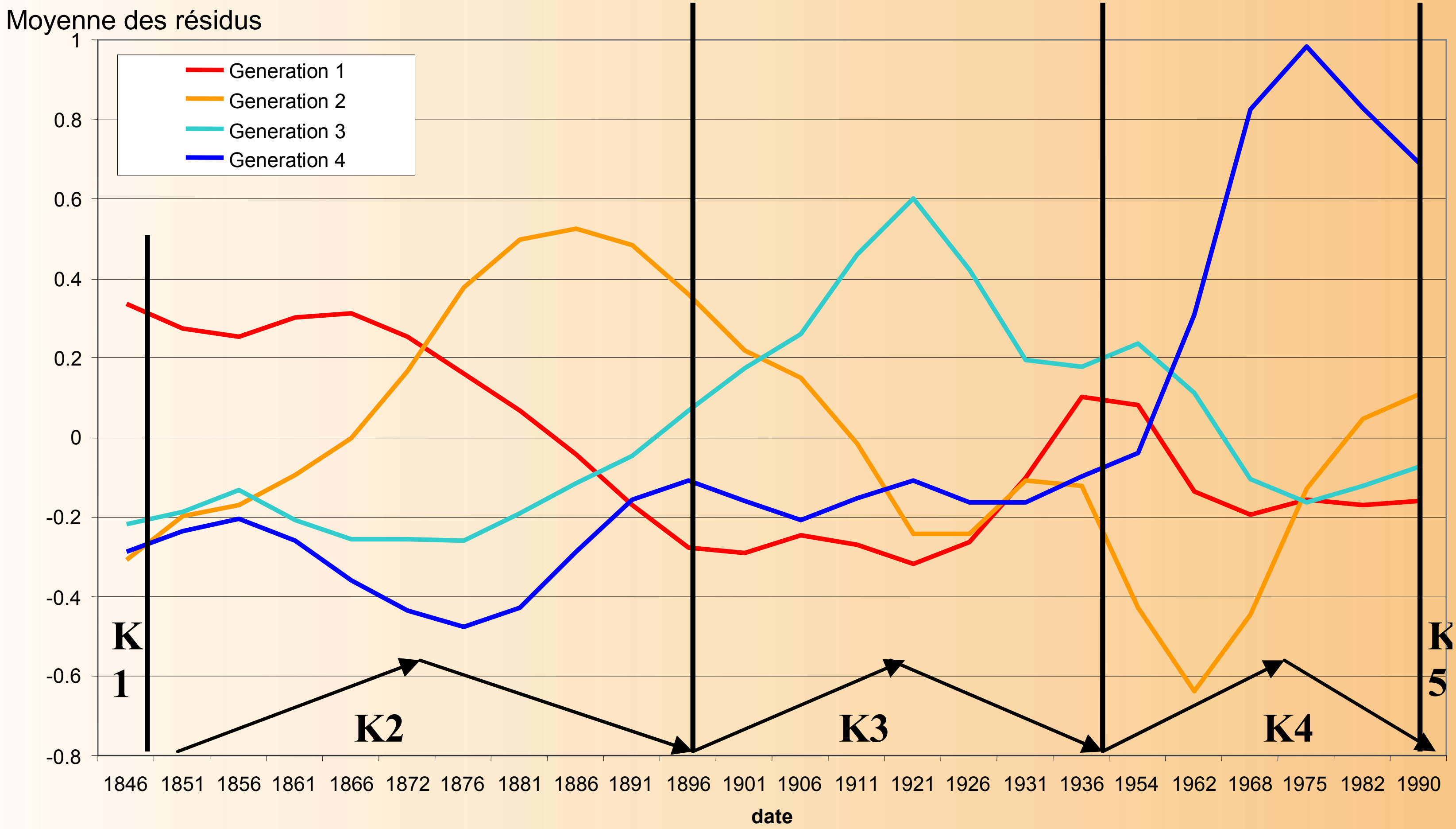


J.M. Favaro, D. Pumain, 2011

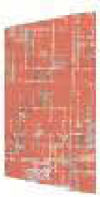
Evolution of beta (size effect, allometric growth) according to innovation cycles

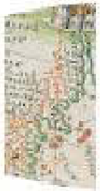


Matching classes of urban growth trajectories and Kondratiev cycles (France)



Freeman & Louça, 2001, Favaro, 2007





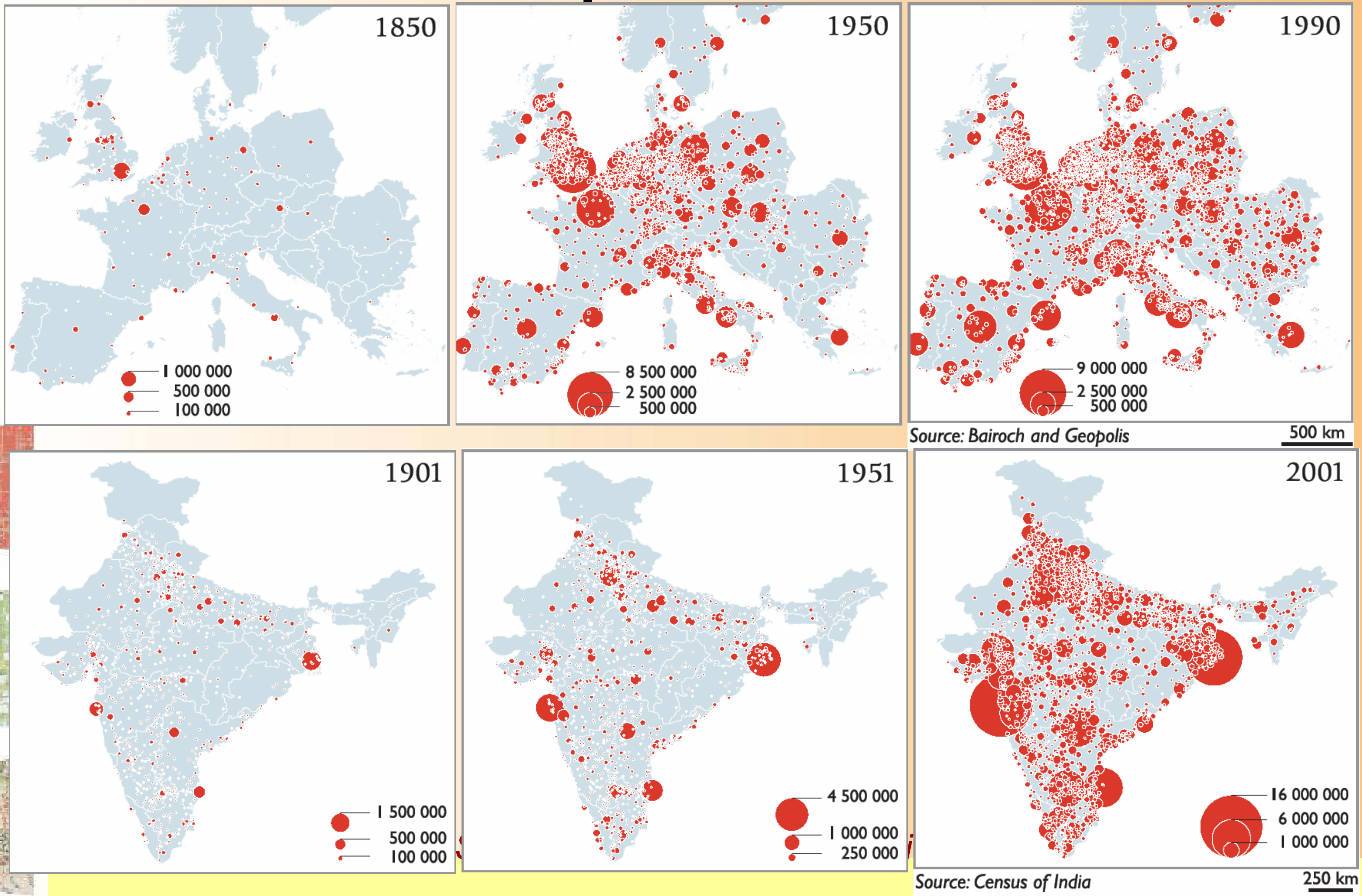
Linking scaling laws to a geographical model of urban growth with spatial interaction and innovation cycles

We suggest to replace a generic statistical model of growing independent entities (Gibrat's urban growth model) by *a model of spatially and temporally interdependent entities* (i.e. the geographical concept of « system of cities » or « settlement system »)

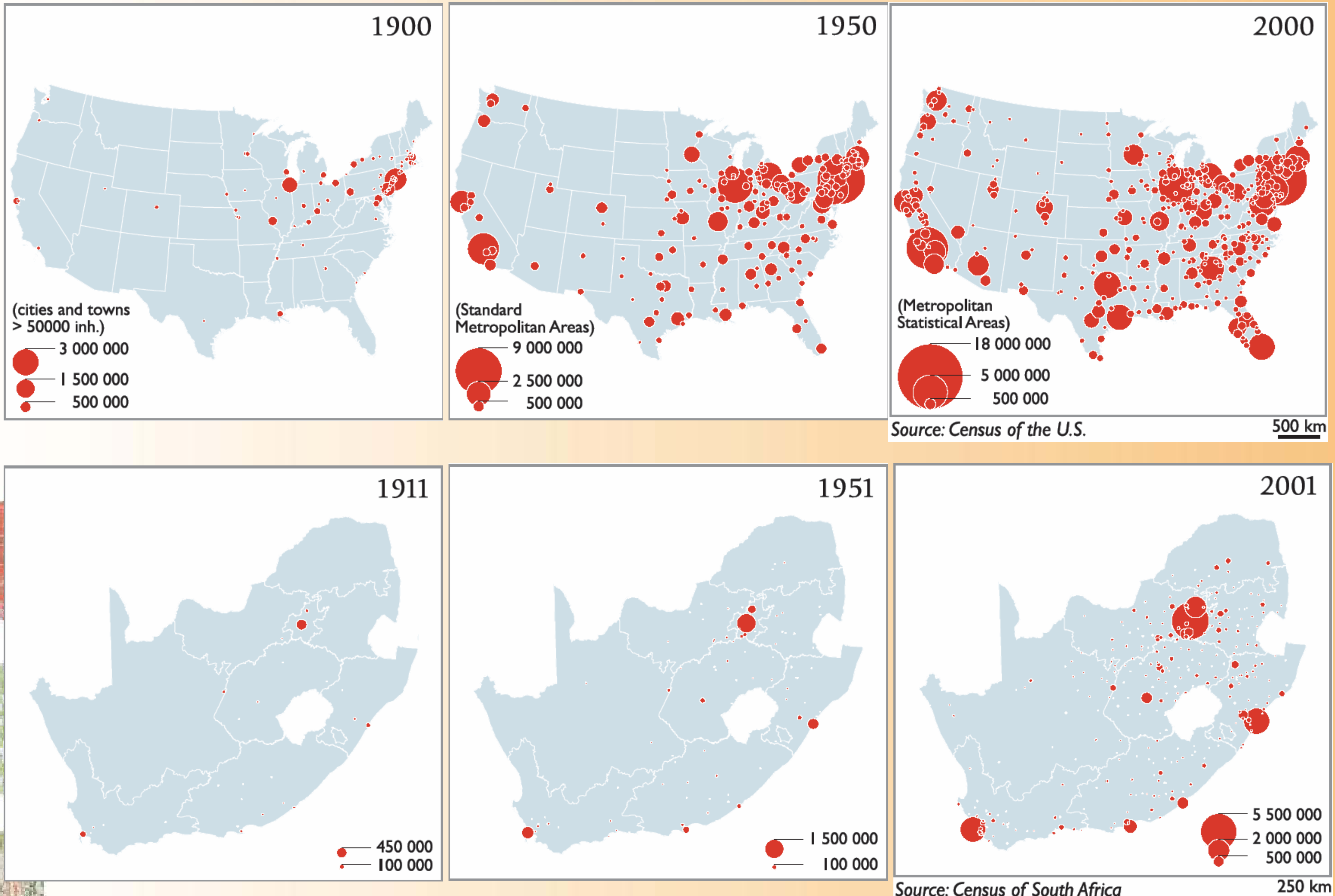
It reproduces the observations on differential scaling parameters for urban activities according to their age in innovation cycles (*Favaro, Pumain, Geographical Analysis, 2011*)

It also makes explicit the multilevel dynamics of interurban competition for capturing innovation, which may itself generate new innovation through interurban emulation, within an evolutionary perspective

Urban evolution in Europe and India



Urban evolution in United States and South Africa



Anne Bretagnolle et Céline Vacchiani-Marcuzzo, 2006

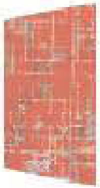
Innovation diffusion and spatial integration of urban systems

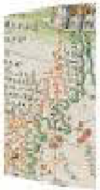
- In new urban systems, as in USA, there is a spatial filling process that occur through waves of urban growth (urban Frontier) corresponding to the diffusion of economic cycles
- In mature urban systems, like in France, the innovations diffusion reaches cities that are not spatially regularly arranged but already experienced other growth periods according to distinct cycles of urban specialisation

Conclusion: why is Gibrat's model « more or less » valid?

The lognormal distibution is an **attractor** for the city size distribution in the long run dynamics of systems of cities.

It corresponds to the Gibrat's model of distributed growth, which is periodically perturbated by the unequal spatio-temporal diffusion in the system of growth impulses brought by each innovation cycle.





Dynamics:creative emulation in urban systems

The model of urban hierarchy is universal because of the long duration of interdependencies between cities competing for resources or sharing common institutions (political, cultural, commercial…)

➔ organisation in coherent urban networks

Scaling processes in systems of cities

Macro-level: system of interacting cities

critical time (length of travel) 1 day (E. Reclus)

high speed networks (x by 40 since 1800)

weak interaction (less frequent)

➔ hierarchy of sizes (Zipf'law, Gibrat's model), spacing and urban functions (Christaller, Lösch…)

➔ scaling laws between size and number of activities (urban functions)

Urban dynamics: from theory to planning

- Innovation (in a broad sense) is a key factor in urban systems dynamics
- The persistance of urban structures is by no means inertia but represents the almost continuous process of adaptation to and creation of social (economic, cultural, technological) innovation

➔ When using urban history or landmarks for city branding, or for anticipating further development, urban planning could not only use traces of the past, their partial collective representation or re-use, but also path dependence in system's dynamics

Evolutionary theory of urban systems

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

Urban modelling tools and resources

Thank you for your attention!

S4 http://s4.parisgeo.cnrs.fr

S4 Spatial Modelling Platform

http://www.spatial-modelling.info/

Cybergeo http://www.cybergeo.eu

CASA www.casa.ucl.ac.uk

CSISS www.csiss.org

CSIS www.csis.u-tokyo.ac.jp