**Handbook on "Entropy, Complexity, and Spatial Dynamics: The Rebirth of Theory?”**

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**Spatial dynamics of complex urban systems within an evolutionary theory frame**

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**Abstract:**

This chapter is about Complexity and Spatial Dynamics in Urban Systems. Strong inequalities in the size of cities and the apparent difficulty of limiting their growth raise practical issues for spatial planning. At a time when new constraints in terms of limited energy and raw material resources or possible catastrophic events such as pandemics are challenging further urban expansion, it is important to consolidate the theories from various scientific disciplines to estimate to what extent the urban dynamics can be modified. While reviewing shortly the contributions to urban theories provided by the new developments in complexity sciences, we first advocate for the soundness of urban theories. Second, we develop our original approach considering spatial interaction and evolutionary path dependence as major features in the general behavior of urban entities. Third, we test these principles grounded in an evolutionary theory of urban systems by experimenting four dynamic models of urban growth calibrated on harmonized empirical data sets with comparisons across the whole world.

**Keywords: spatial dynamics; complex systems; system of cities; evolutionary theory; urban growth; simulation**

**1 Introduction**

The title chosen by Aura Reggiani, Laurie Schintler and Danny Czamanski for this book: “Entropy, Complexity, and Spatial Dynamics: The Rebirth of Theory” is challenging. The problem is twofold: first, it means demonstrating how the insights provided by concepts and models associated with the notion of complexity have contributed to theories on spatial dynamics; second, it questions whether this is a rebirth of the theoretical approach in this field, which would therefore presume that it was relatively abandoned.

This chapter provides answers to these two questions about a particular dimension of spatial dynamics, that of cities and systems of cities. In response to the second question, and considering the progress of research on urban complexity over the last forty years or so, we identify an enrichment and consolidation of existing theories by the principles of complex systems rather than a true renaissance of urban theory. Indeed, contrary to what some scholars claim, the theories developed around the spatial dynamics of urbanization processes and the evolution of settlement systems are far from being obsolete (Brenner and Schmid 2014). Neither are they limited in their application to only one part of the world (Robinson 2016). Scott and Storper (2015) and Wu (2020) rightly criticized both “theories”. We may add that many scholars did not abandon the former urban theories but on contrary tested, revised and completed them during the last four decades (Pumain 1997, 1998, 2003 and 2020; Batty, 2013). The major theoretical challenge of that period was three folds: first, to shift from idiographic postures to nomothetic ones; second, from static views toward dynamic and evolutionary; and third, to really transfer concepts and models from natural sciences to build a socially relevant knowledge. Elements of knowledge from ancient theories can consolidate when situated in their geo-historical contexts, when tests of these theoretical propositions are carried out on subsets of empirical data that are well identified in time and space, and when the means are provided to articulate the observations made at multiple levels of geographic scales.

Starting from such a spiral theoretical conception of the cumulativeness of knowledge (Pumain 2009), we try here to demonstrate how it is possible to construct an evolutionary theory of cities and systems of cities. This theory is abductive in the sense that it is constructed by frequent to-and-fro movements between empirical observations, logical propositions and mathematical and computer models. This theory is not entirely new as it integrates elements of knowledge already well identified by specialists in urban issues, such as geographers, economists, historians and archaeologists, sociologists, town planners and architects. Its originality stems from progress in international comparisons made through using new harmonized databases, methods for validating the results of computer simulation models, and putting these results into the perspective of complex systems theories.

This chapter brings a step forward in the long process of building and testing an evolutionary theory of systems of cities. This theory is based on empirical observations and tested with dynamic models designed for simulating urban development at various spatial and temporal scales. We follow the methodology and results already obtained in the GeoDiverCity project (Pumain et al. 2015, Cura et al. 2015, Pumain, Reuillon 2017), including USA, Europe and BRICS countries, and complete them with new datasets at world scale and other types of models. These models are designed for explaining urban growth and city size distributions with an increasing deepening in the complexity of the implemented processes (Cottineau et al. 2015). They are all conceived for exploring the correspondences between urban trajectories observed at the meso-level of individual cities and the structuring of systems of cities at macro geographical scale. We shall test the validity and representativeness of these four models of complex urban systems and their variations across regions of the world within different spatial frames (Raimbault 2018a, 2018b). Here we use both the GeoDivercity data bases and a new data source that for the first time compares the evolution of cities globally over a period between 1970 and 2015. Eric Denis (2020) already explored the source statistically for comparing urban sprawl trends in the countries of the world. We calibrate four different models of urban growth on both sets of data, across different regions of the world. We analyze their results and assess for each their possible contribution to the theory of urban complex systems.

1. **For a theoretical rearming in urban science**

To clarify our position vis-à-vis urban theories, we propose a first discussion of the diversity of possible meanings attributed to this word among the disciplines that have been interested in explaining the evolution of cities. This discussion is based on a few recent publications, without claiming to be exhaustive within the limits of this chapter. The main question we address is to understand how the disciplines most formerly interested in the scientific object "city" have been able to revise or complete their theoretical statements using the contributions proposed by the natural sciences, which have been advancing interesting concepts and models for thinking about and studying complex systems for some forty years. To begin with, we can start with the definition of complexity as proposed by Aura Reggiani (2014) for whom “the term “complexity” embeds both the assemblage of different units in a system and their intertwined dynamics. In other words, the term “complexity” is strictly related to the concept of networks”. In this definition we would emphasize the physical and societal interactions that are creating and using these networks with a consequence of making the evolution of “different units” strongly interdependent on each other. That leads to a specific deepening in the concept of co-evolution for cities belonging to systems of cities (Paulus 2004; Raimbault 2020a).

Two repeated observations prompted the development of a theory of the evolution of systems of cities. The first, empirical, is the long persistence of urban networks in large integrated territories, which retain, over time, the same spatial configurations of the relative size of cities. This is visible for example on maps representing the population of cities in proportional circles more than a century apart, in Europe, in India, or even in the United States since 1950. The second results of applying to the evolution of these urban population distribution a simple stochastic statistical model formalized by the French statistician Gibrat since 1931. This model states that the growth of urban populations is proportional to the initial size of cities during each short time interval, with fluctuations such as growth rates (amount reported to the population) are statistically independent from the size of the cities and from one time interval to the next. The interest of this model of spatially distributed urban growth in integrated systems of cities is to predict that the result of such a growth process is always a lognormal distribution. Thus, the model provide a first statistical explanation to the "mystery" of the Zipf's law still recently mentioned by the economist Paul Krugman (1996). A huge literature is dedicated to Zipfs law and Pareto distributions that are observed in many natural and social systems, to the extent that these “universal” laws, together with fractal spatial patterns, have been sometimes considered as the “signature” of complexity in different systems. The underlying regularities in the urban spatial dynamics that these models capture have attracted many scientists from various disciplines to propose different theories of urban complexity.

* 1. **Which acceptation of “theory” for complex urban systems?**

A paper posted on Internet in January 2020 (Lobo et al. 2020) deserves a particular attention at first sight for three reasons. First, it announces an “integrated theory”. Second, it covers the full historical period “from the first cities to sustainable metropolises”. Third, 35 names of prominent scholars signed it, which is rather rare among papers dealing with objects of social sciences.

On which propositions do they come all in agreement? A first one is about the necessary multidisciplinary character of “urban science”. A second proposal is about acknowledging the fact that cities are the product of a long but relatively recent and socially driven historical evolution, which should lead to the conclusion that urban theories are part of social sciences dealing with historical objects. However, the paper acknowledges, “a basic tension in current urban science between approaches from the social sciences and those from the natural sciences” (p.3). The authors conclude nevertheless: “the time is ripe for a targeted integration of the social and physical sciences of cities and urbanism” (p.4).

However, when the authors enunciate what the urban theory should be, they suggest Darwinian biology as a model of science to imitate in focusing on processes rather than forms, which we can agree. But they add :” A theoretically grounded science of cities should capture fundamental processes that lie at the core of all human spatial agglomerations, whether these are past or present, agrarian or industrial, in developed economies or developing countries” (p. 11). They clearly tend to think of universal “fundamental principles” that would appear as the core of urban science, while the categories that were elaborated and coined by history or other disciplines of social sciences would be considered as part of a “context”. Should we not require that a “historically grounded” urban science would have processes from societal theories as “fundamental principles”? In other words, the processes leading to the elaboration of concepts such as “agrarian” or “industrial” society or “developing country” may receive at least the same level of attention that the one of “agglomeration” if we want to understand urban evolution and properly integrate the disciplinary points of view.

That is why we are not sure that the “scaling analytic framework” is indeed the first thing to mention of what we have learned from “urban science injected into the study of cities and urbanization” – even if that may appear paradoxical speaking from a geographer’s point of view, always caring about scale! We can nevertheless subscribe to most of the authors’s 13 propositions enabling to converge toward “unified perspectives” –although a few would deserve more discussion. As the authors, we are convinced that there is a need for urban theory and that is it necessarily grounded in history, properly tested with abundant and diverse data compared in space and time. Of course, we agree to consider cities as places of high density, frequent social interaction and mixed activities, knowing that their size is both a cause and consequence of their creativity, acknowledging the universal character of urban hierarchies and the specific role of innovations in their development. However, we could question the list of nine propositions that the authors consider as new insights provided by the new “urban science”. The list of 23 questions to solve in future research is not so new either. We acknowledge that the sciences of complex systems that developed during the second half of 20th century can be granted for having challenged social sciences toward more interest in mathematical and computational formalisms and having provided a series of formalized tools and models and a common vocabulary that established a bridge between researchers in mathematics and physics and social sciences. Nevertheless, the urban theory cannot be reduced to its quantifiable dimensions only.

We may wonder if any “integrated theory” is yet imaginable because at a given moment in science, and in social sciences especially, there are a plurality of theories. Social sciences may deserve a specific definition of complexity that would depend on the number of different disciplines that are required for providing a satisfying explanation or interpretation of a particular object, by borrowing concepts and models from these disciplines, each having investigated a category of complex processes, to make the object intelligible at a particular granularity level. Thus it is likely that while we pretend currently to build an evolutionary theory of urban systems, through integrating as much as possible from accumulated empirical knowledge in geographical, archeological and historical tradition, using statistical and simulation models from the new “urban science”, other fields are not yet satisfied with a theory of urban hierarchy, such as Paul Krugman (1996) for whom it remains a “mystery” that cannot be properly derived from the principles of economic theory.

* 1. **Minimum requirements for a theory of urban complex systems**

When adopting a nomothetic attitude in urban research, we adopt a series of epistemological concepts and practices that are common with other sciences. The starting point is to work with *empirical data that are properly defined before being properly measured*. Taking care for meaningful definitions of cities is not a trivial exercise, because it supposes to enter and to understand the criteria that societies chose for establishing a distinction between rural and urban settlements. It is obvious for any social scientist that such a distinction has a political origin, even if many state governments in the last two centuries decided to objectivize as much as possible their definition through elaborating statistics. For centuries being “urban” was part of a social status, an attribute conveyed to people rather than to places. Most of social scientists are uneasy with attempts at qualifying the urban areas delineated from satellite images as “natural cities” (Jiang et al. 2015). Of course, cities belong to “nature” in using material resources and energy and hosting humans. They may even become greener if they succeed in managing the next ecological transition… However it is social organizations that drive their generative processes, rather than natural features. There are traces of the history of cities as political constructions in the social representations opposing peasants and urban citizens, with sometimes practical and economic consequences on their way of life, if you think for instance of the former Chinese *huku* system (Wu 2020). There are traces as well in the decisions of naming “urban” different places such as India distinguishing “Statutory towns” and “Census towns” (Swerts et al. 2018). Some countries periodically delineate the perimeters of urban areas to follow the spatial expansion of their cities, such as Germany or Russia, whereas other do not.

This did not prevent too many experimented and incidentally prominent scholars to capture “urban data” without any care about their quality, selection, claiming and striking results after crunching them with sophisticated statistical or mathematical models. Such an attitude is detrimental, for instance regarding the endless controversies about the models of city sizes distribution, for building a sound science that accumulate knowledge with reproducible means (Pumain 2012). The resulting cacophony is sometimes disentangled in courageous articles, such as for instance (Cottineau 2017) in a meta-review of hundreds of references, but certainly represents a waste of time and efforts that could be avoided. A recent paper seemed promising in announcing the observation of worldwide trends in urbanization from 1950 to 2030 using some 1857 cities larger than 300 000 inhabitants from 155 countries (Egidi et al. 2020). The paper offers surprising results such as a systematic “inverse relationship” between urban growth and city size in all regions “up to the late 1990s”. At first sight, this could result from mixing countries with opposite urban growth trends, but the authors observe it as well in homogenous sub regions. However, after questioning the authors who kindly accepted to precise the origin of their data, it seems that the selected cities were delineated over time in a way not measuring the spatial expansion of the urban area. This could explain why the results seem in contradiction with those obtained from large parts of the world during the same period with harmonized urban databases (Cura et al 2015). It also reminds about the necessity of starting with a sound conceptual definition of cities for measuring their attributes and controlling the possible effects of the data selection on the results. The urban definition may vary but should be in accordance with concepts and theory, i.e. with the research question and the selection of attributes that are measured for answering them (Rozenblat, 2020).

To specify the fundamentals of our theory we retain a conceptual framework that relies on the long history of social sciences investigating cities and interpreting them (Pumain, Robic, 1996). Thus even if we can integrate insights from complex systems science such as fractals and scaling laws, we do not agree that all fundamentals should stem from “physics for society” (Caldarelli et al. 2018). While maintaining a strong attention to the spatial dimension, our concern with space is neither static nor geometric. It is geographical, and geo-historical. Space is crucial in the definition of cities and systems of cities, it is a social space whose properties are revised and updated with the changing technologies, and it is as well made of transformed natural space in the process of using earth resources and developing political territories. The dimensionality of cities is constrained by the accessible space for face-to-face daily activities, whereas transportation networks enabling less frequent encounters may generate and sustain interdependencies at much longer distances leading to identify systems of cities. At each observation level, those of individuals (persons or institutions), cities and systems of cities, new attributes and new concepts do correspond to emergent phenomena in complex systems that are produced from multiple interactions.

Although the recent development of networks and the accelerating circulation of information seem to blur the three-levels conceptual definition of these geographical objects, we believe that this representation remains useful and relevant for guiding urban research and applications. An interesting contribution by C. Roth (2006) discusses the emergentist view compared to the reductionist and suggests that different modes of access and not only bottom-up interactions could be part of the generative processes of the features constituting one level – which is the view point from statistical mechanics in envisaging self-organizing systems. This rejoins our theory for which urban interactions shaping cities and systems of cities are mostly but not exclusively conceived as emanating from one low level toward the higher level, in societal processes that take a long time, often longer than a human life. Over decades and sometimes centuries, most frequent interactions among urban stakeholders at micro level shape the emerging properties of a city at meso level, and inter-urban interactions generate the hierarchical organization and the functional differentiation of cities within the system of cities at macro-level. However, for instance, a location decision taken by an individual firm (at micro-level) can operate a definite change in the relative specialization of a particular city within the system of cities (at macro level), as well as many policy regulations decided at macro-level may directly change the situation of an individual firm or citizen at micro-level inside a city.

Sociologists such as Michel Grossetti (2020) discuss the ontology of entities that scholars identify in social sciences. A science of cities is possible because cities are remarkably persistent entities, among all societal institutions entities of the meso level, in an intermediary position between individual agents and the territories that embed them. Through their interactions however, they build at a much higher level, comparable to the one of civilizations, spatial organizations that we name systems of cities and maintain their “emerging” properties over much longer durations. The rhythm of relative societal change within cities is much slower than the changes in human life and change in systems of cities is much slower than change in individual cities. Our theory of cities as complex social systems embedded within systems of cities and territories is *evolutionary*. However, the historical evolution is different from biological, of course because its processes are social, meaning they are guided with human intentions (even if that causality is not always directly effective) and they proceed much more rapidly than changes in biology.

While trying to identify major processes guiding the evolution of cities within system of cities, we stressed the role of information and innovation (Lane et al, 1999). Innovation when defined as a socially accepted invention may represent a form of social organization or a belief or a practice as well as a technological device or a new service. We shall develop further in the models presented below how innovation and its more or less always hierarchical diffusion among cities within systems of cities appears as a major dynamic process for explaining the expansion of urbanization and the persistency of cities’ relative situation in urban systems.

**1.3 How to make models and theory dialogue? Juste**

Tested with models including progress in technologies for simulating and validating with evolutionary algorithms and distributed computing = a scientific breakthrough for SHS (à developer en début ou fin de cette section)

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All models includes the well-established fact that the urban hierarchy receives a relevant statistical explanation from the Gibrat’s model of urban growth. This very simple model is only a proxy whose results mimic relatively well the spatial distribution of urban growth. It helps to implement models and to check their ability to produce relevant results. However, Gibrat’s model is a statistical abstraction, not an explanation, of the actual processes that occur during interurban interactions. Its exact mathematical solutions derives from a fundamental hypothesis that urban units are independent of each other, which they are not. On the opposite, cities are interdependent through a multitude of interactions at micro level between their stakeholders. One know and presuppose the existence of these interactions but cannot observe them in detail when studying at meso or macro scale the evolution of urban systems. They occur in very large numbers at micro scales of time and their aggregation, for instance at census intervals for a large set of cities within a system of cities, are translated into an apparent absence of correlation between urban growth rate and city size and with previous growth rates.

However, this random mathematical model has at its core a hypothesis that makes it little credible to found a theory of cities, since it assumes that all cities (elements of the statistical distribution) are independent of each other, as well as the random events that lead to their growth. Such a hypothesis enters in conflict with the definition, the functioning of cities and the processes of their emergence and their evolution. which organizes them into systems of co-evolution, counteract these simplifying assumptions a priori. In fact, the slight deviations noted in relation to the hypotheses of the model have led to the completion of other hypotheses that adapt this simple model, powerful but too general, to different historical and geographical contexts.

1. **A simple model of urban evolution**

This first model implement in a most simple way the major conceptual process that we think is at the core of the spatial dynamics: urban evolution based on innovation diffusion (Raimbault 2020b). The evolution of the sizes of cities in a system of cities is represented in a muti-agent system where cities are interacting agents. The model is experimented on synthetic data for a first exploration of its capabilities. Two processes induce change in urban population over time; the first one is a transformation of urban activities and capabilities that represents in an abstract and aggregated way a multidimensional innovation process (equivalent to DNA mutations in biological evolution, or changes in the *meme* concept in cultural evolution). The second is a transmission process of innovation between cities that couples two models of spatial interaction for representing innovation diffusion.

Cities are characterized by their size in terms of population, and city size evolve following a spatial interaction model in which city attractivity is included. This attractivity is determined by how innovative cities are. Transformation processes are included as mutations, when random innovation appear in cities. Transmission processes (spatial crossover) are included by diffusing innovations between cities.

Each city has an innovation profile that represents the proportion of its population engaged in the innovation it has adopted. The city profile is also described by a diversity parameter reflecting the number of innovations that it successfully adopted and ranked according to their utility. Innovations are randomly characterized with a utility parameter that controls the speed of their diffusion in the system. Aggregated indicators of averaged utility and diversity are computed over all cities and are related to the corresponding urban hierarchies.

Peut-être insérer ici figure 3 du preprint avec son commentaire?

Model exploration yield complex behavior while multi-objective optimization shows the potentiality for the model to produce compromises between utility and diversity in the system of cities. It also introduced the possibility of technical co-evolution niches (expliciter)

1. **A model developing urban hierarchy with transportation network**
2. **A model linking urban growth with innovation as spatial diffusion process**

Thus, Favaro and Pumain (2011) proposed to link this model to that of the hierarchical diffusion of innovations realized by Torsten Hägerstrand.

1. **A model explaining urban growth with economic and environmental processes**

Simulation models: Marius, Cottineau, Raimbault

**Conclusion**

À revoir

We investigate models of urban growth at different scales and on different urban systems: a model of urban morphogenesis at the metropolitan scale which we calibrate dynamically using the diachronic population grid on largest urban clusters, and interaction models for systems of cities at the macroscopic scale on main systems of cities across the world. We also suggest research directions towards the coupling of these models into a multi-scale model of urban growth.

We use among others a new unique source correlating population and build-up footprint at world scale: the Global Human Settlement built-up areas (GHS-BU). The dataset is available at different dates between 1975 and 2015. In 2015 the source delineates precisely some 13 000 urban agglomerations between 50000 and tens of million inhabitants in the world. These data help in further empirical testing to the hypotheses of the evolutionary theory of urban systems and partially revising them.

: complex systems’ dynamics is in principle unpredictable, but Contextualizing regarding demographic, income and resource components may help in minimizing the forecasting errors

Reliquats de textes éventuellement réutilisables

**3 Simulation des croissances et reconstruction des trajectoires**

Nous avons réalisé le test des six modèles à l’aide de la plateforme OpenMOLE. En entrée du modèle nous utilisons les populations des villes en 1970 de GHS et nous calculons la population qu’elles auraient en 2015 en fonction des hypothèses de chaque modèle. Un choix important est alors celui de la mesure de l’adéquation de des résultats avec les observations. Utiliser un seul critère comme par exemple la pente de la loi rang-taille serait trop réducteur. Nous avons décidé de mesurer l’ensemble des écarts de population constatés pour chaque ville. Compte tenu de la forme très dissymétrique des distributions les écarts sont mesurés sur les logarithmes des populations. Deux calculs sont alors considérés pour mesurer la qualité des ajustements : le premier est une mesure classique de la fitness qui est la somme des carrés des écarts entre populations observées et populations simulées, le second est la somme des logarithmes de ces écarts. En effet, la première mesure attribue un poids très important aux plus grandes villes dans le calcul, tandis que la seconde permet de mieux caler le modèle sur l’évolution des plus petites villes, en queue de distribution.

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