Chapter **1**

Hierarchy and co-evolution processes

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1.1. Introduction

1.1.1. *Complexity and hierarchy*

Complex systems with emergent properties through self-organization processes are also most of the time exhibiting some kind of hierarchical structure. Although the term of hierarchy has several different definitions and uses in very different disciplines, ranging from political science (Crumley 1987) to physics (Mones *et al*. 2012), it seems to be intrinsically linked with complexity. Lane (2006) classifies four frequent uses of the term hierarchy, namely (i) order hierarchy corresponding to the existence of an order relation for a set of elements, (ii) inclusion hierarchy which is a recursive inclusion of elements within each other, (iii) control hierarchy which is the "common sense" use of the term as ranked entities controlling other entities with lower rank, and (iv) level hierarchy which captures the multi-scale nature of complex systems as ontologically distinct levels (or scales). For the particular study of social systems, he concludes that hierarchical levels may be entangled, that upward and downward causations are both essential, and that at least three levels (micro, meso, macro) are generally needed to capture the complexity of such systems. In a more philosophical account of complexity, Morin (1980-2005) constructs a hierarchical method of interdisciplinary knowledge, insists on the tension between dependancy and interdependency or between opening and closing (rejoining ideas from Holland

(2012)), and develops an implicit hierarchy of social systems when hypothesizing the emergence of third-type societies (swarm intelligence between humans).

Different types of complexity may be related to different types of hierarchy as Raimbault (2019*a*) proposes, and hierarchy would indeed be endogenous to theories of complexity. Allen *et al*. (2017) develop a multiscale information theory in which the information profile across scales, or hierarchical levels, allows quantifying the complexity of a system. The complex adaptive system theory of Holland (2012) considers complex systems as systems of boundaries that filter signals, implying an inclusion and scale hierarchy between boundaries. Theories of scaling as the one synthesized by West (2017) rely on the quantification of hierarchy in certain dimensions of systems, captured by exponents of scaling laws. Hierarchy may be endogenous to complexity, or to knowledge of the complex itself, since for example Fanelli and Glänzel (2013) provides empirical evidence of a “hierarchy of sciences”, in the sense of possibility to reach theoretical and methodological consensus. This corresponds in some sense to the “ontological complexity” of Pumain (2003), which relies on the number of viewpoints needed to grasp a system, or the number of perspectives in an applied perspectivism framework (Raimbault 2018*c*). Wether linked to systems themselves or to models and theories of them, hierarchy appears to be tightly linked to complexity.

1.1.2. *Territorial systems and hierarchy*

Pumain (2004) scaling laws and urban systems (although vary by definition of cities Cottineau *et al*. (2017))

Batty (2006) shows that hierarchies are inherent to urban systems, as fat tail distribution of settlement size are already produced by simple models of urban growth, and suggests also that urban design processes imply underlying overlapping hierarchies.

Pumain (2006*a*) links hierarchical selection and hierarchical diffusion of innovation across cities to the long-term dynamics of urban systems.

Urban systems Pumain (2006*c*)

Pumain (2019)

Jiang (2009) transportation flows

1.1.3. *Co-evolution and hierarchy*

Hierarchy in complex systems is furthermore intrinsically linked to the concept of co-evolution. Following Lane (2006), the approach to complex adaptive systems proposed by Holland (2012) integrates levels and nested hierarchies, since it considers complex systems as ensembles of boundaries that filter signals.

Volberda and Lewin (2003) economic geography, coevol of firms: genealogical hierarchy vs ecological hierarchy

1.1.4. *Proposed approach*

Pumain (2006*b*) methodological questions: how are hierarchies produced? How do hierarchies evolve?

Our contribution brings new elements of answer to these two questions, in the particular case of co-evolution of transportation networks and territories. More precisely, we systematically explore a macroscopic co-evolution model and study its properties regarding both hierarchies of cities and networks, in terms of final hierarchy produced but also in terms of dynamics of hierarchies.

1.2. Co-evolution model

1.2.1. *Context and rationale*

The issue of interactions between transportation networks and territories remains an open question for which different approaches have been proposed Offner (1993), Offner *et al*. (2014). Raimbault (2018*a*) has explored a co-evolution approach, in the sense that both dynamics have circular causal relationships. More precisely, Raimbault (2019*b*) introduces a definition of co-evolution in that particular context, based on co-evolution niches Holland (2012)

Raimbault (2019*c*)

1.2.2. *Model description*

The co-evolution model for cities and transportation networks at the macroscopic scale extends the spatial interaction model introduced by Raimbault (2018*b*) by adding dynamical speeds to network links. More precisely, (i)

1.2.3. *Quantifying hierarchy in systems of cities*

1.2.3.1. *Static quantification of hierarchy*

A simple way to quantify hierarchy is to use Zipf rank-size law, or more generally scaling laws. Let Y_i the variable for which the hierarchy is estimated. Assuming i

is ordered in decreasing order, the OLS estimation of $\log(Y_i) \sim \log(i)$ gives an estimation of the rank-size slope which is a proxy of hierarchy.

The correlation between two hierarchies informs how two dimensions correspond in terms of ranks, and is computed with $r_s[X_i, Y_i]$ for two variables X_i, Y_i with r_s an estimator of Spearman rank correlation.

1.2.4. *Dynamical indicators*

The rank correlation between initial and final distribution of a variable will measure how much an ordering hierarchy was modified, which is different from the variation of hierarchy given the variations of previous indicators such as the rank-size slope.

Dynamical hierarchy regimes are defined the following way:

1.2.5. *Spatialized indicators*

A spatial non-stationary version of a scaling law would write $Y_i(\vec{x}) \sim \left(\frac{X_i(\vec{x})}{X_0(\vec{x})}\right)^{\alpha(\vec{x})}$, where $\vec{x}$ is the spatial position and assuming that samples can be defined at each point in space. In practice, a discrete version could be more relevant, for which $\vec{x}_k$ center point are defined, samples consist of points within Thiessen polygons of centers and the exponents are estimated for each center $\alpha(\vec{x}_k)$.

1.3. Results

1.3.1. *Implementation*

The model is implemented in NetLogo Tisue and Wilensky (2004), which is a good compromise between performance and interactivity, the former being necessary with a model with such a spatialized network.

1.3.2. *Hierarchy patterns*

1.3.3. *Hierarchy regimes*

1.4. Discussion

1.5. Bibliography

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