Are Cities Complex?

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Summary

The question of whether cities are complex or not is surprisingly difficult to answer. This paper discusses three defining criteria of complex systems relevant to urban structure: hierarchy and scale, discontiniuties and path dependence, and emergence and causality. Evidence is reviewed for the complexity of cities in relation to these criteria, concluding that cities are likely hierarchically structured, and manifest both spatial and temporal discontinuities, yet that evidence for emergence and complex, circular causality within urban systems is largely lacking. This paper provides a very preliminary roadmap for the incipient science of cities as complex systems.

KEYWORDS: complexity, cities, spatial structure, hierarchy, path dependence

1 Introduction

The overwhelming majority of urban science to date has not treated cities as complex systems. It has been argued that urban systems are simply *too* complex to be studied within the framework of complex systems (Stewart, 2001). Methods and models from the science of complex systems are, however, likely to offer great advances for understanding urban structure, and this paper accordingly surveys a few domains in which cities are demonstrably complex, or in which methods and models from complexity science are likely to yield fruitful insight into urban structure and dynamics.

This paper examines three properties of complex systems, and how these might relate to the structure of cities (Samet, 2013): (i) Hierarchy and Scale, (ii) Discontinuities and Path Dependence, and (iii) Emergence and Causality. Where extant, evidence in each case is presented from both mathematical and simulation models, with due acknowledgement that simulation models can only demonstrate mechanistic plausibility, and can rarely provide *general* insight into how cities (dynamically) behave or (statically) manifest the properties of complex systems (O'Sullivan, 2009).

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2 Properties of Complex (Urban) Systems

2.1 Hierarchy and Scale

An etymological interpretation of hierarchy requires complexity to arise through the interactions of multiple constituent parts (Levin, 2003) arranged in a hierarchical manner (Allen and Starr, 1982; Holling, 1992). A second, contrasting interpretation neglects the requirement of distinct components, and relies on the lesser requirement of processes acting, or patterns emerging, across wide ranges of scales (Bak et al., 1987, 1988; Song et al., 2005). Although this kind of self-similarity appears to be a general property of urban systems (Makse et al., 1998; Batty et al., 1989; Bettencourt et al., 2007, 2008; Bettencourt, 2013; Cohen, 1981; Friedmann, 1986; Batty, 2006, 2008), it implies that the same processes are responsible for observed patterns across all scales (Taylor, 1997). This interpretation is rejected here, because complex systems are asserted to require different processes at different scales (Wu, 1999).

Hierarchies within urban systems have generally only been examined as exogenous phenomena, primarily in simulation models (Sanders et al., 1997; Pumain, 2008). Exogenous hierarchies can not reveal how hierarchical differences might emerge, and whether or not properties or processes at different scales are distinct or distinguishable from mere (linear) aggregation. Models have been developed to describe the spontaneous formation of hierarchically-arranged groups, yet these generally require pre-specifying numbers of hierarchical levels (Gil-Quijano et al., 2007), although advances have been made toward modelling formation of an arbitrary number of groups at specified levels (Gil-Quijano et al., 2012; Caillou and Gil-Quijano, 2012; Vo et al., 2013).

The requirement of discernible hierarchical distinctions implies that processes as well as patterns must change across scales (Manson and OSullivan, 2006). Changes in process across hierarchical levels have been incorporated in spatial interaction models (Clayton, 1982; Fotheringham, 1986; Fotheringham et al., 2001; Fik et al., 1992), although resultant models are merely hierarchical and devoid of any necessary complexity. A promising alternative, which has been successfully applied to the simulation of urban sprawl (Zou et al., 2012; Torrens et al., 2013), is to construct ensembles of fine-scaled simulations in order to characterise their temporal development in aggregate, and to use that to construct a temporally coarser simulation which is used in place of otherwise unknown macroscopic equations governing a system's state (Kevrekidis et al., 2003, 2004).

Processes defining the dynamics of groups at different hierarchical levels will differ whenever and wherever the effects of agglomeration are non-linear—a strikingly simple requirement that nevertheless appears not to have been considered in any urban studies to date. Both theoretical models and empirical data have described processes of agglomeration into single centres (Leonardi and Casti, 1986; Weidlich and Haag, 1987), while agglomeration into multiple centres (Leonardi and Casti, 1986; Krugman, 1993; Fujita and Thisse, 1996), as well as the emergence of structured hierarchical relationships (Rosser, 1994; Postiglione and Hewings, 2008), have been studied only within specifically economic systems.

Hierarchy is generally conceived of as emerging from processes of agglomeration (Flack, 2012), yet any agglomeration must also be presumed capable of fragmenting (Zachary, 1977; Bonabeau et al., 1999), including entire cities (Fujita and Mori, 1997). Complex hierarchies will thus be necessarily dynamic structures that themselves change and evolve, and must therefore be assumed to be transitory rather than reflective of stable states (Phelps, 2004), requiring both dynamic models and methods of analysing dynamic systems.

Finally, there are strong reasons to suspect that hierarchies composed of distinguishable yet likely multiply–confounded levels (Simon, 1962; Goldstein, 2002) can not emerge from local recursion rules typical of simulation models, primarily because these fail to generate the kind of novelty necessary for hierarchical distinctness. It nevertheless remains highly uncertain what kind of simulation or other systems might be capable of generating such emergent hierarchies. Moreover, general techniques for discerning and analysing hierarchical structure (Wikle, 2003; Chen et al., 2007) have yet to be applied beyond the domains in which they were developed (respectively ecology and network theory).

2.2 Discontinuities and Path Dependence

Discontinuities within complex systems are often conceived of as primarily temporal manifestations of irreversible processes, leading to systematic dependence on historical developmental trajectories or, in short, *path dependence*, which is also a defining property of urban systems (Arthur, 1988; Straussfogel, 1991). What has until now been almost entirely overlooked in complex social systems is that path dependence in any spatially distributed system must also imply *place dependence* (but see O'Sullivan, 2009). If any one part of a system can undergo a phase transition (Solé et al., 1996), or some equivalently irreversible, bifurcating process, then other parts can presumably follow different trajectories, producing discontinuities that ought to leave lasting spatial traces. The classic complex systems manifesting such place-dependent traces are magnetic domains, yet place dependence as a manifestation of complex discontinuities has yet to be considered in urban realms. Spatial discontinuities must nevertheless emerge within complex systems through dynamic processes, and discontiniuties are thus directly related to the following further defining criterion of complex systems, that of emergence.

The path dependence of urban systems has long been hypothesised, and models have convincingly demonstrated how urban systems develop their own unique historical trajectories which act to constrain future developmental trajectories (Allen and Sanglier, 1978; Straussfogel, 1991; Markusen, 1996). While such path dependence may be presumed to imply some form of temporal discontinuity, this has neither been explicitly examined nor demonstrated (although again, such issues have been given extensive consideration within economics, Rosser, 2003). Models demonstrating path dependence may be devoid of discontinuity if the full space of possible states is in fact reachable from any point, and it is very difficult to formally demonstrate whether path dependence necessarily implies discontinuity.

Discontinuities have been observed for urban systems in the form of localised 'clumping' in distributions of city sizes (Bessey, 2002; Garmestani et al., 2005, 2007, 2008, 2009), although quantitative models of the processes leading to such clumping have yet to be developed. Quantitative models that produce discontinuities have been developed in models of urban economies (Haag and Dendrinos, 1983; Zhang, 1994), which are capable of generating aperiodic, chaotic oscillations. Such oscillations not only demonstrate path dependence, but can readily produce discontinuities as oscillations at different frequencies become entrained in a hierarchical coupling (Rosser, 1994). While this provides compelling evidence of complex behaviour, these models are again not amenable to generalisation beyond their exclusively economic formulation.

2.3 Emergence and Causality

The above definition of hierarchy resolves one difficulty in defining complex systems, that of defining emergence (Rastetter and Vallino, 2015). Hierarchical levels may serve as appropriate structures or processes to judge as emergent, yet hierarchical levels are nevertheless unlikely to emerge through distinct processes, rather new levels are more likely to emerge from an entangled soup (or 'gel', Sheller, 2004) that is irretrievably 'confounded' with the lower level from which it emerges (Goldstein, 2002). Importantly, such 'confoundedness' will generally render impossible any formal distinction of levels.

Observations of discontinuities will thus never be demonstrable without uncertainty. Moreover, this confoundedness both of hierarchical structure and emergence must translate into a concomitant confounding of causal paths. Unlike in classical Newtonian-like systems in which causality operates unidirectionally, causality in complex systems must always be considered circular. Particularly important in complex systems is the causal constraint of higher hierarchical levels on lower levels (O'Sullivan, 2009)—usefully referred to as 'downward causation' (Ulanowicz, 2004).

Hypothetical models of complex systems will thus not be generally verifiable in terms of demonstrated causality, rather they must be corroborated through more sophisticated means including the generation of a range of observable phenomena. Urban systems will also manifest complex webs of horizontal or mutual causality between components at the same hierarchical level (Galster, 2001), and satisfactory models or hypotheses must extricate to some degree these complex causal webs, and provide explanations of how such extrication can be translated into empirically observable phenomena.

Finally, emergent hierarchical structures will impose top-down causality (Campbell, 1974; Ulanowicz, 2004) that can not necessarily be anticipated in advance. Even absent this kind of top-down causation, causality may be impossible to preempt when aggregative processes are non-linear—as required for hierarchical systems—because a group may cause an effect on another group that is not understandable in terms of any linear scaling of individual properties between those groups. This may apply as much to horizontal relationships among non-hierarchically structured groups as to hierarchical relationships.

3 Concluding Comments

There is significant theoretical understanding of hierarchy in urban systems, yet comparably little empirical evidence to date, although analytical techniques from other domains are likely to be directly applicable. Discontinuities have been observed in urban systems, and indubitably exist in spatial delineations between neighbourhoods, yet future work must confront the difficult task of developing dynamic models for the generation and dynamic maintenance of spatial discontinuities. Understanding emergence in urban systems is likely to be the most difficult of the properties discussed here, requiring models and analytic techniques for circular causality between ill-defined components. Although there is surprisingly little evidence to date that cities are, or may be modelled as, complex systems, future developments are likely to indeed reveal the complexity of urban spaces.

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5 Biography

Mark Padgham researches ecological and urban systems, applying and developing mathematical tools to describe and understand dynamic processes in complex spatial systems. His current research focusses on the structure and dynamics of intra-urban spaces.

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