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Urban transitions: scaling complex cities down to human size

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ABSTRACT

Complexity science has become prominent in studying cities as concepts like "smart city" and "big data" indicate. In particular network analysis has allowed to studying various aspects of cities in new ways. As such these analyses are often disconnected and subsequent business models often remain disembedded. However, complexity science can also compare various patterns extending over different scales (scaling) if they belong to the same entity (allometry). Such relationships pertain to cities too suggesting that buildings, infrastructure and traffic amongst other things develop interdependently and, that across specific city systems scaling phenomena can be compared according to cities' population size. The article argues that while many scaling phenomena of physical and social networks can indeed inform urban transition research the proposed central role of cities' population size is highly ambivalent. This is particularly true for economic indicators like GDP, which do not reflect the need for sustainability. Still, network and scaling analysis of the built environment can contribute to transition theory if explanatory social mechanisms relating human behaviours *and* social institutions to existing scaling phenomena are provided.

1. Introduction

We like to think of cities as unique places, which we may associate with night life (Bangkok), coffee (Vienna), or art (New York). Yet cities manifest remarkably universal features that render them quantitatively comparable. The spatial sciences have come a long way to arrive at such methodologies for spatial analysis (Batty, 2012). In this article we will outline the analysis of scaling phenomena as a means to progress transition theory with respect to cities and urbanisation. Scaling refers to regularities across different hierarchical levels of the same entity.

Typically, indicators of city development are treated independently: indicator X measures x and indicator Y measures y. Both establish causal relationships in statistical terms and both are considered to be independent of each other (Economist Intelligence Unit, 2009). This is for instance expressed in indicators that measure quantities per capita e.g. the number of schools per 1000 habitants or the unemployment rate of a city. The implicit assumption of per capita indicators is that an average increase of a given characteristic is linear proportional to the increase in population size. However, scaling stands for non-linear relationships: the per capita measurement systematically increases or decreases faster or slower than population size (Bettencourt, 2013).

Scaling analyses have shown a variety of such statistical relationships. Ultimately, knowledge of such regularities may lead to better management of cities with some writers proposing even predictive theories for the social realm with an air of self-enforcement (Anderson, 2008). Yet, the research agenda has shortcomings: so far these relationships have only been shown for some phenomena while ignoring others. For example, a key research gap relates to diseconomies of cities and the quest for sustainability. In order to move beyond these limitations the article will address end-use technologies that closely relate to final energy consumption to present a more complete picture of cities' future.

Although scaling patterns are being analysed structurally in great detail, the social processes bringing these patterns about are not well understood. This is particularly true for those phenomena that are reproduced by conglomerations of interdependent social institutions (Conte et al., 2012). Perhaps surprisingly, such analysis can have immediate influence as for instance the applied concepts of smart cities and big data show. Complexity science has rarely provided theory *explaining* social self-organisation (for an exception see Pumain, 2006) but it has influenced evolutionary theorising in several disciplines working towards explanatory theories, e.g. in economics, geography and transition management. This article argues for explanations since we need socially robust

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theorising to manage the transition of cities (Nowotny, 2005). In this regard, transition theory offers a theoretical framework capable of integrating the methods of complexity science and bringing it in line with democratic decision-making. Particularly, the article proposes to elucidate social mechanisms for transition management. Identifying and specifying social mechanisms that can be associated with sustainable or unsustainable pathways promises the added value of envisioning possible and implementing concrete futures with stakeholders.

The next section will introduce the analysis of urban scaling phenomena and summarise the key insights of this research strand. The discussion will particularly focus on the work of Bettencourt who has – as an exception to the general observation – proposed a theory of urban scaling. He suggests that cities show similar growth properties as found in nature. Thereafter the article will look in more detail at diseconomies of cities already analysed by sustainability and complexity science. To bring complexity science closer to application the following section will make an argument for developing complexity scientific questions within transition theory. The article argues that complexity science can help to establish the built environment as a fourth field of transition theory but that it is necessary to develop mechanistic explanations (Section 4). This is due to ever-present immergence pressures in the social realm. A discussion of the findings and a conclusion follow.

2. Cities on a scale

In the past decades or so network analysis has made tremendous progress in analysing network typology and evolution. Scientific progress has not been restricted to the domain of nature but has been applied to society and its artefacts too (Andersson et al., 2006). Complexity science has studied the properties of networks across all domains not least in cities. By contrast, most network research in the social sciences has focused on *institutionalised* networks (Powell, 1990). Instrumental to progress has been mathematical graph theory (Caldarelli and Vespignani, 2007).

Complexity science's analyses have primarily focused on the structure and secondly on the evolution of networks. Key to analysis is the degree distribution that is the number of links of individual nodes to other nodes. Some networks show a normal-distribution while others have a logarithmic distribution: The latter's degree distribution shows an invariant relationship between one factor and a second variable signified by a power law (see Appendix). These networks are called scale-free since the same structure prevails across all hierarchical levels. Their median reveals little about their behaviour. Instead nodes above the median influence the system disproportionally. There are two more particularities associated with scale-free networks: they may scale in different directions according to different power-laws, a phenomenon that is called self-affinity, whereas networks are self-similar if their scaling pattern follows the same power law in all directions. In natural systems scaling relationships allow prediction of how changes of one variable will impact on a second in the network's evolution. In the social sciences such correlation-derived prediction may amount to a natural fallacy. Nevertheless, scaling has been observed in social artefacts and social structures too.

From a complexity science perspective the independent examination of urban indicators is considered inadequate for analysing and comparing cities since it ignores for instance emergent agglomeration effects. It has been shown that characteristics such as economic growth and mobility vary systematically with population size (Bettencourt et al., 2007; Batty, 2008). This concerns the changes of cities' attributes relative to their size. It is a remarkable feature that increases of population size show the same statistical relationships for a range of phenomena, across large sets of cities. These relationships follow power-laws as various studies show: physical infrastructure studied so far grows less than proportionally with city size, e.g. road networks (Lämmer et al., 2006; Jiang and Claramunt, 2004; Samaniego and Moses, 2008), subways or train networks (Roth et al., 2012; Louf et al., 2014). This might also apply to other systems of provision (Kühnert et al., 2006). These are instances of sub-linear scaling and the power in this case is smaller than 1 standing for negative allometry. Other factors scale more than proportionally with population size such as innovations, GDP and income (Bettencourt et al., 2007, 2010; Bettencourt and West, 2010; Lobo et al., 2013). In contrast to the previous scaling behaviour the power is greater than 1. Thus, they scale super-linearly indicating positive allometry.[1] These long-term relationships are not necessarily static but may change over time. In an analysis of French cities Pumain et al. (2006) show for instance how the scaling relationship of various professions changed over time also falling below 1.

In conjunction with in- or decreasing returns explanations (cf. Arthur, 1994) the group of analytical relationships scaling super- and sub-linearly provide explanations for a variety of phenomena in cities. Increasing returns have been applied to the dynamics and organisation of the socio-economic networks not least in cities (e.g. Louf et al., 2013). The main characteristics are: socio-economic activities become faster and lead to higher productivity, they also increasingly diversify while they become more interdependent (Bettencourt and West, 2010). The super-linear scaling of GDP and innovations relate to the diversification of the socio-economic processes with cumulative effects over time (Bettencourt et al., 2014), i.e. economics of scale and scope and agglomeration effects emerge (Pumain et al., 2006). However, we also find decreasing returns for other phenomena such as diseconomies from high land prices, congestion of infrastructure, increasing emissions or higher infection rates.

The study of increasing and decreasing returns to scale has been pursued by several schools of evolutionary theorising in different disciplines, including, amongst others, evolutionary economics (Nelson and Winter, 1982), new economic geography (Krugman, 1991), evolutionary economic geography (Boschma and Lambooy, 1999), ecological economics (van den Bergh, 2007) and evolutionary transition theory (Foxon, 2011). Within their disciplinary contexts these theories show how increasing and decreasing returns explain economic and urban growth and explain it.

Bettencourt (2013) has consolidated much research in urban complexity science and radicalised some of the aforementioned evolutionary theories by proposing an endogenous theory of urban growth and shrinking: cities emerge as diseconomies from transport and social interaction are overcome by social and physical networks transporting goods, people and information. These are more efficient than direct, unstructured paths enabling increasing returns in socio-economic activity (super-linear scaling) and exploitation of the economies of scale in urban infrastructure (sub-linear scaling but faster than city area). Accordingly, urban form and social networks feed-back on each other and we find geographic and social characteristics of cities aligned in the theory. Furthermore, the theory proposes a threshold where cities are most productive. Beyond this threshold social costs overcome benefits and cities decline, e.g. their GDP may shrink and the maintenance of infrastructure may become increasingly difficult. Despite the theoretical openness to diseconomies of urbanisation complexity science has scarcely engaged in the study of such diseconomies or thresholds.

[1] Allometry designates the relative growth of a part in relation to the whole entity. It was originally developed for the taxonomy of biological organisms.