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Emergence and self-organization in urban structures

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Abstract

Research on urban growth divides into two strands that barely come together. The first strand is aligned to the view that an understanding of cities as socio-spatial phenomena is indispensable for any sensible modelling approach. The second strand is established on assumption-based computational modelling with the perspective that without testing our understanding by reconstructing the phenomena we cannot verify our theoretical propositions about it. It is clear to our understanding that by bridging these two strands we can subject the explanatory models of cities to experimental testing. We acknowledge however the need to explain urban dynamics as a process rather than as an end product for us to base our assumptions on solid evidence. In search for evidence on laws that capture urban dynamics we outline invariants in the historical evolution of two urban structures. The invariants indicate to two processes that govern city growth; a generative process that contributes to structural differentiation and a process of self-organisation that is seen to resemble reaction-diffusion systems famously known in chemistry and biology. At this stage, we cannot verify whether these invariants constitute spatial laws in themselves or whether these invariants are a side effect of another more implicit process. Nonetheless, we assume that the presence of these invariants is conditional for a grid structure to be admitted to the class of natural urban systems. In that, the invariants serve as measures for the characterisation of urban pattern recognition.

Keywords: self-organisation, reaction-diffusion, Space Syntax, travelling waves, generative structure, city growth.

1 Introduction

Research in certain branches of urban geography has been immersed in building computational models to simulate urban growth. Mostly driven by the assumption that cities are complex systems, the simulation models have been essentially based on mechanisms that characterise natural and biological systems rather than the actual spatial dynamics that give rise to their existence. Some of the analogies made in this approach were perceived to be effective in producing city-like patterns on the aggregate level. On a higher resolution, however we have sensed the necessity to look for clues in the spatial growth of urban structure.

Early models in urban geography were based on the principle of self-similarity that is seen to mark the overall spatial arrangements in cities. Based on this principle, simulation models were devised to reproduce fractals of block arrangements [1, 2]. In spite of the significant move towards modelling fractal patterns in cities, there was no apparent insight on how to characterise self-similarity in urban structures. A reference to that characterisation was made recently by tracking the historical dynamics of angular structure within a radius of 500 meters [3]. Structures within this metric distance were seen to be preserved throughout growth. This allowed for the hypothesis that if we are to consider a unit for self-similarity that is inherent in the urban structure then this unit can be captured within five minutes walkable distance from each segment element in the street network. Findings in this research indicate that the depth properties of this unit were proven to aggregate forming a log normal distribution when the aggregate depth properties of the whole would typically fall within a normal distribution. This might be suggestive of a degree of scalability between the parts and the whole. The findings seem to agree with recent trends in urban research that point towards scalability and allometry in the distribution of urban systems [4], [5], [6], [7]. To further develop on this approach, there is a need to outline the spatial laws that give rise to these aggregate properties of the system. This is not to say that space can be isolated from other socio-economic processes in cities, but to start from the perspective that space is the physical imprint of these processes. We admit with this auxiliary hypothesis that the physics of space is much simpler to quantify and track compared to the socio-economic processes that make streets alive. With this perspective we investigate how metric and geometric configurations of the grid work together to plot the aggregate patterns we see in growing urban systems. For that we need to investigate the self-generative mechanisms in the grid by scrutinising the patterns conserved during the period of growth. Our guess is that these mechanisms derive from the local configurational structure of the grid although they might have some higher order control mechanisms that fit these dynamics to a hierarchical model. This idea is driven by the observation that local dynamics operate on the spatial and micro economic state of street structures that are themselves influenced by the increase in accessibility to the global network [8]. While it is difficult to verify the control hierarchy that govern growth in cities, it may be possible to infer its mechanism by outlining the structural invariants that are preserved in the constantly transforming structure of street networks. Considering different scales, we need to examine how patterns that are recognised as self-similar emerge on the local and global scales of a topo-geometric urban network and how they connect on the global level representing a parts-whole superstructure. Beyond that, and considering the dynamics of time, there is a need to expose the chain of events and the order in which self-similarity emerges as an effect of structural transformations and permutations in cities.

In modelling growth dynamics, Batty implemented reaction-diffusion models to direct Agent-CA simulations [9]. This has led to the establishment of an analogy between chemical processes and city growth. The approach that has interestingly produced city-like aggregate patterns, has not made clear the structural properties that make this methods effective. For this reason and to elucidate on the finer-grained dynamics, an attempt here is made to track the processes that led to these formations by disaggregating the geometric transformations in cities. Taking a structural approach towards identifying spatial dynamics, we establish our investigation on Space Syntax theory [10, 11]. Yet, we differ to that by asynchronising the process hence going beyond the reading of space as a synchronic frame in time. Space Syntax is recognised as an explanatory theory of cities. It stands on the view that cities are socio-spatial objects and by doing that it constructs a fundamental argument to any scientific reading of city architecture. In that sense, a science of cities cannot ignore the contribution of this theory to the field of city modelling. However, lacking the element of time, it is hard to see how the synchronous representation of Space Syntax can capture the evolutionary dynamics of urban systems. This might be seen as the main obstacle in engaging Space Syntax into dynamic modelling of city growth. Attempts towards engaging a structural description of space into an agent-modelling approach have been made [12]. In these attempts, no clear validations for the assumptions were made to establish them on real case evidence. Instead, the attempts were more likely to follow the line established in urban geography that focuses on producing simulation models for urban growth. These types of approaches would have benefited from an evidence-based understanding of the structural processes in spatial systems. In an attempt to attain this understanding, we make the move from the static description of Space Syntax theory to a dynamic description of urban processes. In this paper, we argue that the abstract values of space-time as a dual dimension play a key role as generators of city systems. Hence, we explore the driving forces that help reproduce growing spatial networks and yet preserve their structural properties. For that, it is seen that a new reading of spatial structure is inevitable for urban processes to be modelled. This new reading would entail tracking the changes in the measures that capture the configurational structure of cities. While this method is needed to expose the generative properties of the network, additional observations on the repetitive patterns that are conserved throughout growth might also be indicative of the process that led to such side-effects. These observations might lead to constructive assumptions about the spatial laws that control growth. Considering that an empirical testing of these laws is needed before making any speculations about their role in growth, we suggest the use of these invariants in recognising urban patterns.

1 A generative syntax in city structures

In this section, we present our observations on the configurational changes of urban street networks. To represent urban street network we use Space Syntax representation of axial street structure that reduces streets to the longest and fewest lines. The representation is manually constructed as a vector layer on top of a map. We then use the higher resolution segment map (street interjunctions) to calculate metric and geometric properties of the network using UCL Depthmap [13]. Considering two case studies; Manhattan and Barcelona, synchronic states of the growing systems were analysed. The states are separated by a short radius of time provided the availability of historical map data. By observing regularities in the transformation of urban systems, we identify two processes that direct urban growth; an evolutionary process and a self-organisation process. Both processes are based on the spatio-temporal properties of urban structure. Yet, they both operate on two levels; an atomic level that has to do with the configurations of a segment element in the spatial structure and a molecular level at which patches of segment elements operate as composite molecules. The evolutionary process -we assume- is a composite of two layers. The first layer is identified by topological and angular properties that outline the shortest angular path uniquely termed by Space Syntax as *choice*; measuring the shortest putative journeys across the street network [14]. These journeys appear in the foreground as a continuous network that links the city as a whole. The second layer is a background structure that is more likely to be defined by metric properties [15]. For the background layer, angular properties are what define its structural patterns. The molecules we describe can be defined by both metric properties and angular properties. The angular structural properties of the atoms (the segment street elements) and the metric formations of the molecules (the patches) can be recognised to have self-similar patterns given different radii. The type of self-similarity is identified by the constructs of measurement whether structural or metric. The structural and metric attributes are calculated by measuring geometric and metric *depth* in the segment street network. Mainly angular integration and metric mean depth (MMD) are used to capture angular and physical depth from every single segment element to its adjacent neighbours in the graph network of streets. Patterns that are marked by metric depth can also be identified in the relationship between two metrically-defined radii of angular integration; thus revealing synergies between the parts and the whole [16]. Both types of patches need to be treated with care as they represent different properties.

2.1 Evolution and differentiation in street structures

An evolutionary process in urban structures can be read in the tendency for street elements to reproduce or disappear subject to their spatio-temporal configurational properties. Elements that are part of well-connected and accessible structures are more likely to survive. Elements that are identified within weak local structures are more likely to disappear. The

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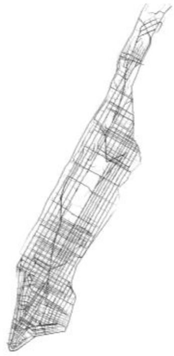
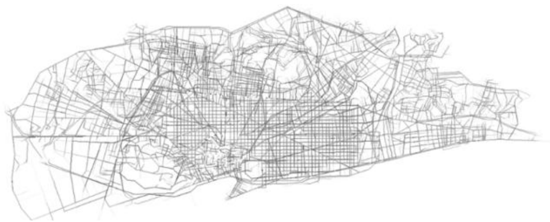
addition and disappearance of street elements are assumed to be products of the angular relationship between these elements and their neighbours. In previous research, generative and pruning mechanisms were outlined through a comparative analysis between transformations that occur between two states in a historical growth and states that follow these transformations [8]. The generative mechanism prevails in periods of expansion. Within these periods a positive feedback process operates and takes the form of exponential addition of elements. The emergence of patches in vacant areas follows high gains of *choice* (an angular measurement of mathematical *betweeness*). The process is also applicable to areas where uniform grid exists to deform order and allow for the differentiation of structure. Locally, new elements are added to the edges of areas that have previously witnessed a gain in angular integration. These generative mechanisms of choice and integration are continuously updated throughout growth. An observation into the long-term time dimensionality would indicate to a change in the trend of the system as it reaches its maximum boundary. Following this change another process of reinforcing feedback is observed. That process involves the pruning of poorly integrated elements. Both generative and pruning mechanisms contribute to structural differentiation in the network. Once, we plot the cumulative changes in choice we can highlight an embedded structure that might be considered as the stem from which cities grow. The properties of this structure might outline the generative structure of growth that represents the origin of cities (figure 1). The structure representing the cumulative transformation of centrality in the urban system outlines a semi-continuous branching network of streets. Centrality is the tendency of structure to fall within the shortest angular path. The structure that represents cumulative centrality holds the angular memory of the system. It matches by large the overall angular properties of the elements in the system. It is expected however that this generative structure has some innate unique properties that distinguish it from the system and characterise it as the genetic material from which the whole system inherit its properties. The map outlining cumulative transformations highlights certain elements to have more important role in terms of gaining choice values hence a more evident generative functionality in the overall growth process. In Barcelona, the freeways that historically connected the old city to the organic patches of grid in the region record along with the organic patches recurrent gain in choice values. In Manhattan, the Broadway along with its parallel diagonal line in uptown Manhattan and a selection of diagonal lines in the downtown area are predominantly recording increasing change in choice values. They highlight a primary structure of diagonal lines that persist throughout the grid and interrupt the uniform order. It appears to branch and connect throughout the spatial structure of Manhattan. These two structures are representative of the permutation in the system. Most of these roads are known to be in concurrent terms highly significant roads that afford dense movement and high economic activity. These observations cast a light on the process of evolutionary structural generation itself, its drivers and the directional vectors it is likely to follow. The revealed generative and pruning processes yield that even at events of large scale planning interventions; cities adapt the local configurations of the new uniform parts to deform in such a way as to reproduce natural growth.

Figure 1. The generative structure of growth representing cumulative changes in angular choice. Darker lines represent higher change in choice recorded over the period of growth.

Manhattan



Barcelona



2.2 Structural self-organisation

Considering the generative dynamics involved in evolving city structures, it is may be hard to believe that the local generative rules can lead to the observed emergent organised patterns which persist in the overall network. This may pave the ground for the suggestion that there is a higher order process which ensures through a mechanism of self-organisation the maintenance of a part-whole structural unity. By visualising changes along with conservative properties in the two city structures understudy, we observe two phenomena that are indicative of a process of self-organisation. These phenomena are known to be common features of reaction-diffusion systems. They appear in the dual tendencies of the urban system to change and to persist to change. The phenomena outlined are namely; the travelling waves and the self-replicating spots as a form of *dissipative solitons*. The presence of travelling waves and self-replicating spots indicates to an analogy of some sort between the mechanisms of local reactions and spreading of urban systems and those comparable in chemistry and biology.

2.2.1 Travelling waves of change

By applying the methods explained in the previous section, we map changes in local integration. Volumetric modelling of these changes would highlight wave-like patterns that appear to transfer throughout the system from the core towards the edges and bounce back into the system (figure 2).

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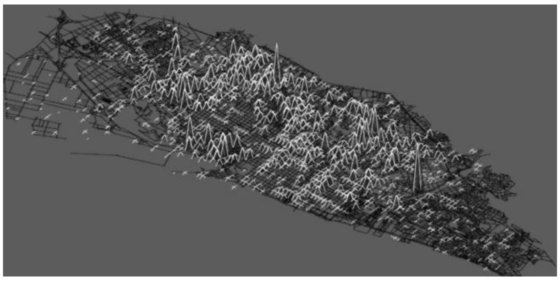
Figure 2. Wave-like patterns representing change in segment integration (radius 500 meters) [13]



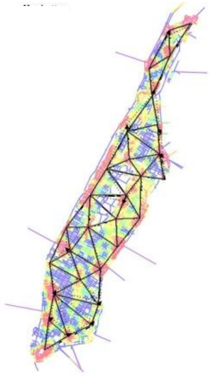
2.2.2 The self-replicating patches

The second phenomena; namely self-replicating spots is highlighted using a different measure. By only observing the patterns that are rendered through calculating MMD in the urban structure, it is noticed that molecular patterns that appear like patchworks will roughly conserve a fixed distance in-between. This phenomenon is observed throughout the evolutionary process of growth in Manhattan and Barcelona. The overall distance between patches approximates one and half the radius that defines them (in this case radius 1000 meters). The distance is measured between the centres of the patches in an XY plane is not very different from the distance between the peaks themselves. Arrows representing the difference in coordinates between the centres of the patches and the peaks might be considered to be directions in which patches are likely to expand or connect (figure 3). They might be defined therefore, as drift vectors of a metric patch. The structure connecting the centres of the patches is a triangular mesh that seems to preserve the edge length throughout growth (figure 4). Although this structure seem to plot a similar pattern to that recognised in Christaller's Central Place Theory [17], it is early to tell whether the structurally and metrically-defined patches correspond to vital economic centres within the city region. In his theory, Christaller identified a triangular/hexagonal lattice structure to plot the pattern in which cities are placed in a region to be central in relation to agricultural resources. A reconsideration of that model on the scale of a city is difficult to be made given that in the post-industrial city vital economic centres are more likely to be aligned to more accessible street elements in the network [11].

The patches themselves are defined by considering certain thresholds to outline the area that defines the patches boundary. The peaks are less likely to be affected by this threshold. While some of these patches seem to be bigger than others and some tend to have two peaks than one, it is assumed that the properties of the patches are subject to the molecular dynamics of the system. The dynamics can be prescribed in the process of self-replication where patches merge or replicate given certain spatio-temporal conditions. The predominantly subtle pattern of these patches might be a clue to a reaction-diffusion process in cities, where metric patches render out the steady state effect of this process.

Figure 3. Patches identified in Manhattan and Barcelona by calculating MMD (radius 1000 metric) [13]. The lattice structures links the peak points or the central points in the patches. The difference between both is a drift vector that might be indicative of the overall directionality of growth.

Manhattan



Barcelona

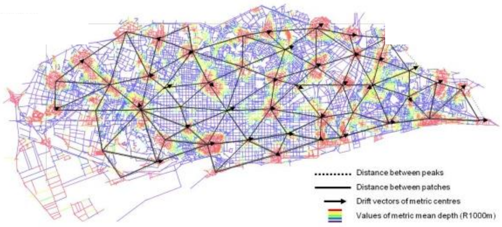
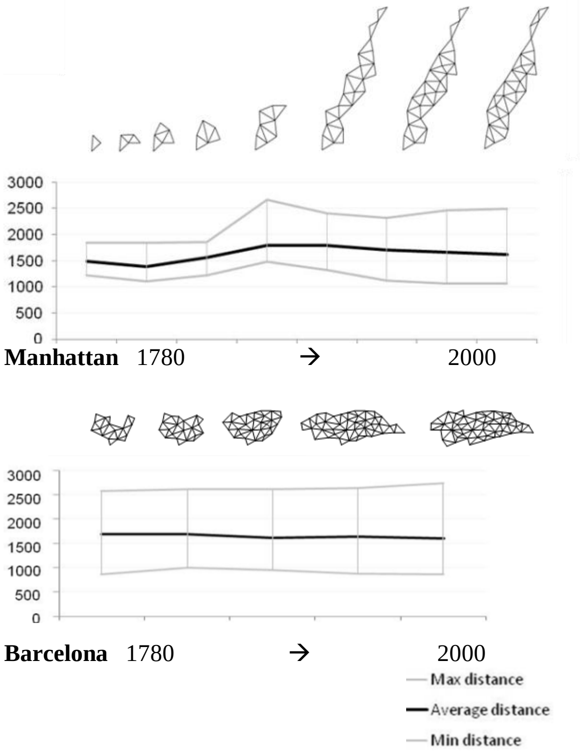


Figure 4. Conserved distance between self-replicating patches throughout growth. The lattice structure connects the patches' peaks with the highest MMD R 1000 values



3 Towards modelling structural dynamics

Over the last decades, the emergence of urban form was found to be appealing to researchers and modellers; however no evidence was given for such process in historical growth. The contribution we made in these regards is to elucidate the evidence on this process. The invariants outlined in this paper are indicative of certain mechanisms that operate on the lower order of elementary segment components of the grid and higher order of the parts. While these invariants might help recognising the image of a city, it is difficult to ascertain the mechanisms that give rise to them without building empirical models that account for structural properties of street network. In search for evidence that support assumptions made on growth dynamics, we identified invariants that are indicative of the laws of structural generation, differentiation and self-organisation that distinguish urban form.

We outline a structure that records the structural differentiation in time through visualising cumulative changes in choice over the period of growth. Further to that, we follow our intuition that a higher order self-organisation process plays a role in controlling the overall organisation of the parts-whole superstructure. We realise that this process repeats a fractal structure that has certain metric proximity within itself and between its parts. This realisation together with wave patterns of structural change justifies the analogy between urban and chemical processes as reaction-diffusion systems. The patches formation appears to have a latent order in the sequential process of generative growth. It is a resultant pattern of an emergent activity that goes through a continuously updated state of equilibrium. The metric patches or fractals multiply leaving similar distances in-between and repeat that pattern throughout the growth process. The phenomenal effect appears along a process of grid differentiation that deforms the symmetry of the uniform parts to match the structural attributes of organic grids.

At the moment, there is a need to distinguish between invariants that are indicative of a generative process and those that represent a side effect of this process. It is difficult to rule out the order at which these processes appear by simply observing their patterns. There is a caveat not to rush into conclusions before verifying the assumptions made on generative, pruning and reaction-diffusion mechanisms. It would have been easy for example to fall into the trap of claiming that the self-replicating patches we identified are generative rules in themselves. Assumptions made on reaction-diffusion were only made after putting together our observations on wave-like patterns of structural changes and analogies previously made between urban systems and chemical processes. This has led to the realisation that the replicate patterns of patches are a side-effect of another less explicit reaction-diffusion process. With all that in mind caution is yet needed as we interpret these results. Assumptions made on structural emergence and reaction-diffusion mechanisms need yet to be validated by further testing. The invariants we outline in this paper will help recognising urban patterns in the process of modelling and testing hence will pave the ground for further research.

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