Decoding the urban grid: or why cities are neither trees nor perfect grids

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Abstract

In a previous paper (Figueiredo and Amorim, 2005), we introduced the continuity lines, a compressed description that encapsulates topological and geometrical properties of urban grids. In this paper, we applied this technique to a large database of maps that included cities of 22 countries. We explore how this representation encodes into networks universal features of urban grids and, at the same time, retrieves differences that reflect classes of cities. Then, we propose an emergent taxonomy for urban grids.

Keywords: urban morphology; space syntax; taxonomy; hierarchical clustering; continuity lines; street networks;

Reference

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Introduction

One of the key characteristics of recent studies on urban morphology is the use of networks to describe the built environment. In this perspective, the city is not seen as a collection of building blocks that may have geometrical regularities, ultimately architectural styles, but a network of interconnected open spaces created by those blocks – the urban grid (Martin, 1967; Hillier and Hanson, 1984). Such studies unfolded cities in their underlying spatial organisation, tracing a connection between space and society, and revealing that the urban grid itself contains an imprint of society (Holanda, 2002).

The main descriptive technique applied to the built environment has been the decomposition of the urban grid into axial lines. The axial map is the minimal set of the longest straight lines of unobstructed movement that crosses and interconnects all open spaces in the system (Hillier and Hanson, 1984). It creates a graph where nodes are lines and edges are intersections between lines. A number of topological measures can be extracted from this graph in order to quantify characteristics of the spatial configuration of the urban grid. Most of these measures are based on topological distances, i.e. the number of steps (edges) between two nodes. The axial map has been proven useful for a wide range of applications, including the study of movement patterns (Hillier et al, 1993).

However, recent studies pointed out a number of inconsistencies in the axial technique. In particular, the use of straight lines is oversensitive to small deformations in the grid, which leads to noticeably different graphs for systems that should have similar configurational properties (Ratti, 2004). In real cases, this creates an artificial differentiation between straight and curved or sinuous paths that have the same importance in the system. Long straight paths, represented as a single line, are overvalued compared to curved or sinuous paths as they are broken into a number of axial lines (Figueiredo and Amorim, 2005). To overcome such limitations, two new techniques have arisen: the angular-segment maps (Dalton et al, 2003; Hillier and Iida, 2005) and the continuity maps (Figueiredo, 2004; Figueiredo and Amorim, 2004, 2005).

The angular-segment model focuses on cognitive aspects by investigating if individuals navigate in the built environment using the geometry of the urban grid. In the graph, nodes are no longer lines but segments and the distance between two segments is the least angular changes of direction (Hillier and Iida, 2005). This representation returns to the classic idea that the network is a skeleton for an external model, i.e. the configuration of the system is not captured by the structure of the network but it is highlighted as a result of the angular analysis. On the opposite direction, the continuity maps were designed to improve the axial representation without challenging its fundaments (Figueiredo, 2004; Figueiredo and Amorim, 2005). Therefore, it keeps the idea that the nodes (lines) should have an individual meaning and that the hierarchy and geometry of the system can be, to a large extent, encapsulated in the structure of the graph – the network itself is the tool of analysis.

A continuity line arises from the aggregation of axial lines, in axial maps, or line strings between junctions, in standard road-centre line data. This process of generalisation is known in cartography (Thomson and Brooks, 2002) and the rules for aggregating lines can be based in a number of different properties, such as street names (Jiang and Claramunt, 2004; Rosvall et al, 2005) or the angle between two lines (Figueiredo and Amorim, 2004, 2005; Porta et al, 2006). Although different criteria could be combined to built continuity maps, the use of angles is a purely geometrical criterion and therefore more appropriate for cross-cultural morphological studies. In this case, two lines are aggregated if the angle of continuity (Figueiredo and Amorim, 2005), i.e. the angle between the linear continuation of the first line and the second line, is less than or equal to a predefined threshold. If more than one continuation is available, the line that forms the smaller angle is chosen.

Figure 1: (Left) The continuity map of Brasília, Brazil (Holanda, 2002), using an angle of 45°. (Right) The underlying graph created by the continuity map (Figueiredo, 2004) where lines are nodes and intersections between lines are edges. The darker lines and nodes are the ones with high degree value. The degree or connectivity of a line is the number of lines that intersect that line. The degree defines the primary importance of a line in the system or, as cities are grids, the number of neighbours up to two steps.

The subsequent encoding into a network is the same as in the axial map; nodes are lines and edges are intersections between lines (Figure 1). However, while axial lines are hard to recognise in real systems, a continuity line can be associated to two-way traffic flow through a sequence of continuous streets, where the intersecting streets, or optionally the streets up two changes of direction[1], potentially feed or distribute traffic from that flow. Therefore, the continuity map is a generalisation of the urban grid that encodes into a network a hierarchy of line lengths, i.e. the hierarchy of the street network is ultimately simplified in the degree distribution of the system (Figure 2). This representation focuses on the potential created by the morphology of the grid instead of the actual physical or traffic constraints of the real system.

Hillier (2002) and later Carvalho and Penn (2004) had already showed that the distribution of line lengths in axial maps present universal features "which seem to go across cultures and even across scales of settlements" (Hillier, 2002). In any axial map, there are a large number of short lines and a small number of very long lines. In the Figure 2, we see that the line length distribution also presents this behaviour in continuity maps (left) and that it is also reflected in the degree distribution (right). It is commonly argued that the tail of this type of distribution (from the point where the curve starts to resemble a straight line) follows a power-law with a decay exponent a (Newman, 2005), i.e. $P(X \geq x) \sim x^{-(a-1)}$ and $P(X = x) \sim x^{-a}$. However, despite having similar behaviours, the relation between line length and degree becomes clearer in continuity maps because curved and sinuous lines are reconstituted and correctly placed in the hierarchy of line lengths (Figueiredo and Amorim, 2005).

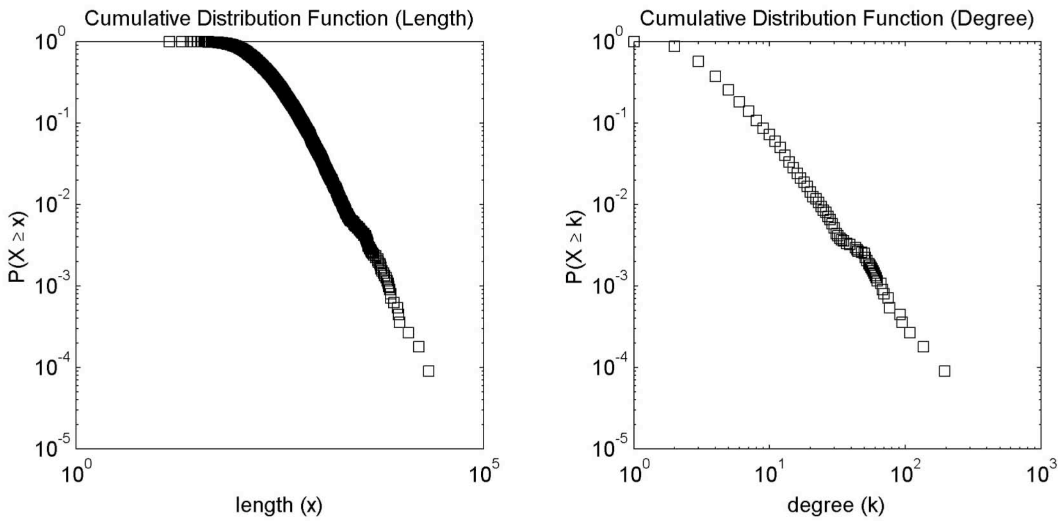

Figure 2: (Left) The line length distribution of the continuity map of Recife, Brazil, using an angle of 45°. The plot is a cumulative distribution function in a logarithmic scale. The horizontal axis is the length of the line and the vertical axis is the probability of finding a line that has a length longer than or equal to x. (Right) The same plot for the degree distribution. It shows how the topology simplifies the line length distribution. In fact, the correlation (R) between line length and degree in this map is 0.9064.

Due to this descriptive consistency, several researchers have adopted this type of representation in order to explore structural properties of street and road networks (Rosvall et al, 2005; Porta et al, 2006; Karapala et al, 2006). They argue that these networks exhibit small-world and scale-free properties (Porta et al, 2006) as numerous other natural and man-made systems when represented as networks (Barabasi, 2003). The small-world phenomenon occurs when the average topological distance between any pair of nodes in the system, i.e. the average path length (L), is small regardless the size of the system. This is due to the presence of “hubs”, highly connected nodes that create shortcuts between different parts of the network. These networks also have a high degree of clustering at the local level, i.e. groups of interconnected nodes. The scale-free behaviour means that the degree distribution in these networks exhibit fractal properties, following a power-law (Figure 2). These studies are still in preliminary stage and restricted to a small number of maps. In addition, the meaning of such abstract properties in real cities has yet to be discussed, with the notable exception of Rosvall and colleagues (2005).

In this paper, we applied our previous definition of continuity lines (Figueiredo and Amorim, 2005) to 101 axial maps of cities (Table 1) from 22 countries using a maximum angle of continuity of 45°. The continuity maps used in this study were created from three databases or axial maps built or collected for the doctoral thesis Urbis Brasiliae[2] (Medeiros, 2006). We used a wide threshold for aggregating lines in order to overcome differences in the construction of axial maps from different data sources and reflect a directional system, in which 45° stands between a straight continuation and a 90° turn left or right. The aim of this paper is to unfold morphological and configurational properties of cities through continuity maps. We explore how this representation encodes into networks universal features of urban grids and, at the same time, retrieves differences that reflect classes of cities. We propose, then, a new taxonomy for urban grids based on quantitative methods that avoid any type of pre-classification.

Decoding the urban grid

As argued before, continuity maps are based on the simple idea that longer lines are more important in the system. As long lines usually have more connections, the line length tends to be reflected in all topological measures applied to this representation. In fact, the average correlation (R) between line length and degree in our set of 101 continuity maps is 0.8371, compared to 0.7413 in the original set of axial maps. In this context, if the impact of the line length on the topology of continuity maps increases in relation to axial maps, one can expect an overall increase in the interdependence of other variables. The intelligibility index (Hillier et al, 1987) demonstrates this. It evaluates how global properties reflect local properties in the system. However, the original definition suffers of size effects[3]. Instead, we used the correlation between degree and betweenness centrality (Freeman, 1979) as an intelligibility index. Betweenness, or choice (Hillier et al, 1987), captures how often a node is used in journeys from all spaces to all other spaces in the system. It highlights not only highly connected nodes, but also strategic connectors that are between subsystems, such as a bridge. The average correlation (R) between degree and betweenness is 0.6597 in the continuity maps, compared to 0.4781 in the axial ones. These differences are usually higher in “organic” or “deformed” grids, confirming that the continuity maps improve the axial representation by reconstituting curved or sinuous paths.

From another point of view, continuity maps enables the comparison between the urban grid and other networked systems, in particular small-world and scale-free networks. At the first sight, the small-world phenomenon seems to be an abstraction that has no meaning in spatially embedded systems such as cities. Topological distances do not ensure shortest paths in terms of metric distances, and two streets can be located kilometres apart. However, previous studies using axial maps and topological distances (Hillier et al, 1993) have shown that movement flows throughout the city are strongly affected by the urban grid, which naturally creates a system in which journeys tend to pass through the most accessible locations. In such studies, the shortest path between two locations is interpreted as the least number of "changes of direction" between them.

Although axial and continuity maps seem to be similar in this aspect, in the second one changes of directions are no longer bound to the concept of axial line. A change of direction can be roughly associated to an instruction "left" or "right" if we assume that the built environment provides enough information to discover where we should make the turn by, for instance, counting a sequence of streets or finding a street name. Therefore, in a continuity map, the shortest path between two nodes is any path that requires a minimum number of instructions "left" or "right", assuming that the journey starts in the correct direction. The encoding of cities into this representation confirmed that the average path length (L) is indeed small (Table 1), regardless the size of the system. Even large urban grids such as São Paulo (52826 nodes) or Tokyo (53116 nodes) have average path lengths of 13.11 and 7.45 steps respectively. In our perspective, these results suggest that cities retain a reasonable degree of navigability regardless their size, as we can describe most paths using a small number of directions. In addition, this confirms the key role of long lines in these systems, which connect entire subsets of interconnected short lines (Figueiredo and Amorim, 2005, Rosvall et al, 2005; Karapala et al, 2006).

In fact, the encoding of cities into continuity maps seems to reveal an underlying structure of the urban grid. If cities were perfect grids they would be non-hierarchical systems. All lines would have the same length and number of connections. In addition, the average path length of any system would be smaller than two, as any pair of nodes would dist up two steps. This would create a highly accessible system that provides multiple routes between any pair of locations. On the opposite direction, if cities were purely hierarchical systems, such as a tree, the average path length would tend to be higher than in a grid of the same size due to the existence of isolated branches[4]. This would create a segregated system that provides a single route between any pair of locations. The figure 3 illustrates these ideas. Imagine that we have to describe the simplest route between the location 1 to the location 2 in both maps (a) and (b). In the first case, we can describe five routes using two left-right directions. In the second case, there is only one route of four directions.

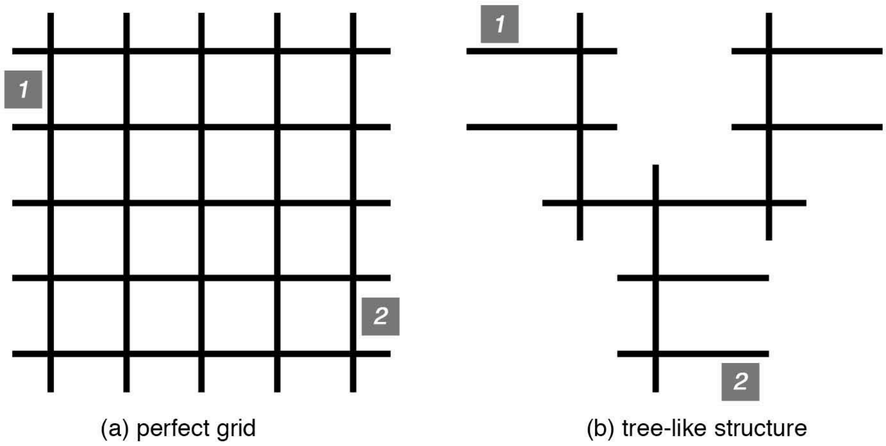

Figure 3: (a) The perfect grid is non-hierarchical system that provides multiple routes between two locations. If we have to describe only the simplest routes between 1 and 2, we have five short descriptions that use two directions. This means that there is a degree of uncertainty about which route would be effectively used. (b) In the tree-like layout, there is only a single route that can be described using four directions. A perfect hierarchy means no uncertainty. Cities are neither trees nor perfect grids. They retain a clear hierarchy as tree while enabling short descriptions as a grid.

One may argue that pure grid systems are easy to navigate due to this high accessibility and to the existence of multiple paths between any pair of locations (Rosvall et al, 2005). However, if we assume that such routes are equally probable[5], we see that morphology of the perfect grid does not differentiate main spaces and movement tend to be dispersed everywhere. The tree, on the other hand, clearly has a main space that connects all branches and controls movement between them. This kind of geometrical order seems to reflect ideals of equality and freedom or hierarchy and control. It creates either systems of short descriptions and high randomness, i.e. disorder in their underlying spatial organisation, or systems of long descriptions and no randomness (Hillier and Hanson, 1984). Real cities seem to be a result of a process of negotiation, through which the paradigms of equality-freedom and hierarchy-control generate a structure of a different kind. The urban grid minimises descriptions as long as possible while maintaining enough differentiation to establish a clear hierarchy. It is this differentiation, characteristic of traditional systems, that creates a well-defined underlying structure (Hanson, 1989) in which journeys converge into set of key locations (Hillier et al, 1993). Therefore, cities are neither trees (Alexander, 1969) nor perfect grids, but a combination of these structures that emerge from a myriad of social and constructive processes.

This hierarchy of lines has a signature. Our findings confirmed that the line length and degree distributions in continuity maps have a shape that could be described as a scale-free behaviour (Carvalho and Penn, 2004). The same power-law tails illustrated in the Figure 2 in both distributions were found in a large number of maps, mainly in maps of relevant size. However, irregular shapes and faster decays in the tails, which would characterise scale-dependent distributions, were also found. At this stage, we can only point reasons that would lead to irregular or scale-dependent distributions. In the mapping and descriptive procedures, inadequate choices to determine the boundary of the maps or flaws in the aggregation process can damage the representation of very long lines. In the real systems, topographical or geographical factors can limit path lengths in several cases, such as in an island. In addition, long lines often cross peripheral or non-urban areas, where the number of potential connections is noticeably reduced.

Figure 4: The continuity map of Nicosia, Cyprus, using an angle of 45°. The Figure has two types of visualisation (Figueiredo, 2004). In the left, the multilayer structure of the supergrid is highlighted. The darker lines roughly correspond to the 5% longest lines. In the right, "neighbourhoods" are highlighted by finding clusters of lines with similar line length. The intensities of grey are based on the average line length of the cluster. Note that the two parts of the Old Nicosia (centre) have slightly different intensities of grey. The map is a courtesy of the Space Syntax Laboratory (Konstantinos Kypris).

We have found that the continuity map decomposes the urban grid into a multilayer main core that interconnects a number of clusters, which roughly correspond to "morphologically defined neighbourhoods". Examining the Figure 2 again, we see that the line length distribution starts with a horizontal sequence of short lines followed by an abrupt decay – the power-law tail. However, it may be not obvious that roughly 75% of the lines are "short" and thus concentrated right before the tail. On their turn, the long lines that form the tail are also present in a higher or smaller degree in the top values of most measures applied to this type of map[6]. We have found that this phenomenon is universal in continuity maps and, as the interdependence of variables is higher in this type of map, the core is better defined than previously observed in axial maps (Peponis et al, 1989; Read, 1997). The main core or "the supergrid" (Read, 1997) is a system itself. It starts with few very long lines that are complemented by shorter and shorter lines that create several "grids" in a multilayer structure, when it is finally completed by clusters of short lines (Figure 4). In some extent, it is the relation between the main core and the clusters that defines the underlying structure of the urban grid. There are cases in which the "neighbourhoods" are attached to the main grid, creating "tree-like" structures, or embodied by long lines that define a sort of boundary. In other cases, the supergrid pervades the clusters blurring the frontier between local and global. Finally, there are cases that core creates "super neighbourhoods", i.e. the long lines are clustered as in Eixample district in Barcelona (Spain).

Finally, we quantified some morphological and topological characteristics of our set of maps. We have shown that the aggregation degree (Figueiredo and Amorim, 2005), i.e. the percentage of axial lines that are aggregated, measures how "organic" or "deformed" is a grid. In addition, there is a "descriptive improvement" that can be measured as an increase in the correlation between line length and degree. However, we are also interested in determining where a particular urban grid stands between a tree-like structure and a perfect grid. As mentioned before, small-world networks are also characterised by a high degree of clustering at local level. It is possible to measure if lines are clustered as a grid[7] using the "grid coefficient" (Caldarelli et al., 2004). The definition we adopted is based on the number of cycles of four steps that include a two-steps neighbour. The grid coefficient of a line is the sum of all existing cycles of four steps between that line and its second neighbours over the maximum number that could exist if all its first and second neighbours were clustered as a grid (Figure 5). Therefore, the average grid coefficient summarises this underlying grid structure even if it is not immediately obvious in the geometry of the urban grid. The values of aggregation degree, "descriptive improvement" and average grid coefficient for our set of 101 continuity maps are listed in the Table 1.

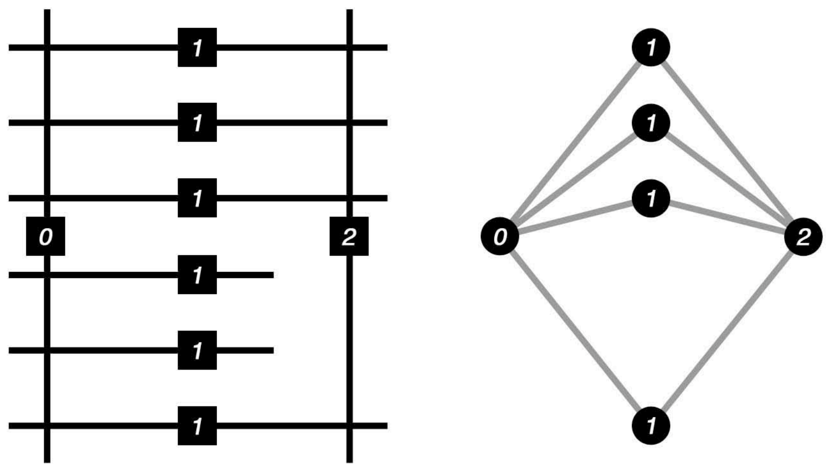

Figure 5: (Left) On the left, the line "0" has six first neighbours labelled as "1". However, only four of them are also connected to the two-steps neighbour "2". (Right) If we take in consideration the number n of common neighbours between the two lines "0" and "2", the number of existing cycles of four steps that start and end in the line "0" using the line "2" is n (n – 1) / 2. The grid coefficient of a line is the sum of all existing cycles between that line and its second neighbours over the maximum number that could exist if all the first (1st) and second (2nd) neighbours of that line were clustered as a grid, i.e. 2nd * (1st (1st – 1)) / 2.

Families of cities

The urban grid is an imprint of the history of the city, containing traces of different growing, planning and social processes. Each grid tell us a particular history, that might include the accelerated growing of Latin America cities or the deep medieval roots of some European cities. In this sense, these objects invite us to reconstitute their ontology. We have shown that continuity maps provide an important insight into the morphology of urban grids, capturing geometrical and topological properties of such objects. In this section, we introduce new analytical procedures that match certain similarities between urban grids and reveal an emergent taxonomy.

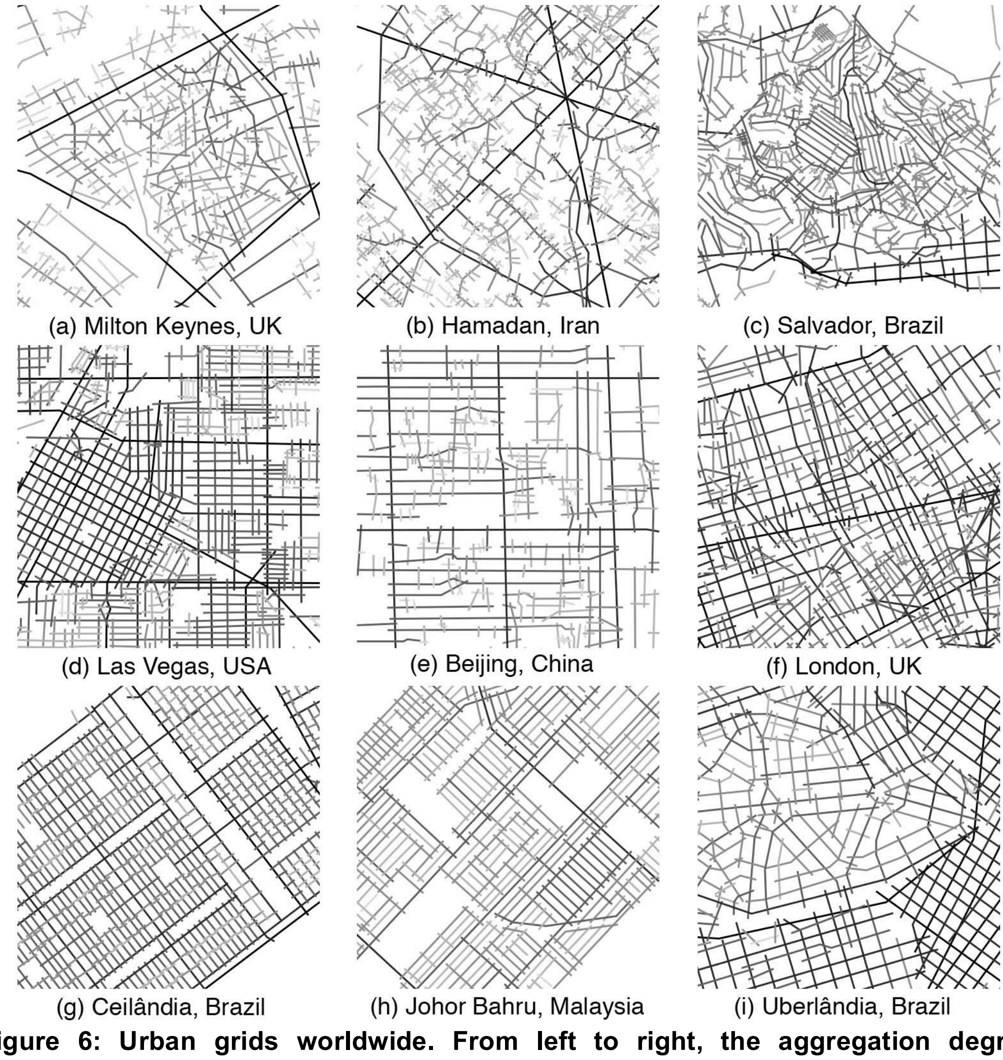

Figure 6: Urban grids worldwide. From left to right, the aggregation degree increases, i.e. the range could be described as "regular – irregular". From top to bottom, the grid coefficient increases, i.e. the range could be described as "tree – grid". The maps are courtesy of Space Syntax Laboratory (a, b – Kayvan Karimi, d – Mark David Major, f); Valério A. S. de Medeiros and DIMPU UnB (c, g, i); Tao Yang (e); and Loon Wai Chau (h).

We start by examining the problem of classification within space syntax. Previous comparative studies do not use syntactic tools to classify cities. Instead, they adopt other classifications, such as cultural or geographical criteria, and then apply analytical tools to characterise the existing groups in morphological terms (Major, 1997; Karimi, 1997; Hillier, 2002, Kubat et all, 2001, Medeiros, 2006). Therefore, the categories and their components precede the analysis. A second and more elegant approach is to propose objectives or paradigms (Holanda, 2002) and use the analytical tools to identify cities of each category. Although the classification itself is a result of the analysis, the categories are bound to the argument of the investigator and still precede the analysis. Recent studies inverted this sequence and avoid predefined categories (Medeiros and Holanda, 2005; Figueiredo and Amorim, 2005). Instead, groups are interpreted as a result of the analysis. Figure 6 illustrates this approach. From left to right, the aggregation degree increases, creating an “irregular – regular” scale. From top to bottom, the grid coefficient increases, creating a “tree – grid” scale. However, even in this case the categories are based on the argument of the investigator, who ultimately decides the boundaries and thus the elements of each group.

There are alternatives. Methods for automatic classification or grouping, broadly termed “hierarchical clustering”, are known in disciplines such as Biology (Sneath and Sokal, 1973) or Geospatial Analysis (de Smith, 2007). The general idea behind the hierarchical clustering is that elements of any set have similarities and differences that can be mapped as distances in an n-dimensional space in which each characteristic (variable) is an axis. Then, clusters are created by grouping isolated elements or subgroups or, alternatively, splitting the set into smaller groups, according to the distance between them. Although the researcher can still select the variables, neither the groups nor the components precede the analysis – an important step towards a non-discursive or “numerical” taxonomy (Sneath and Sokal, 1973). As an exploratory experiment, we apply the “average linkage” method to our set of maps. The average linkage clustering starts by considering the elements as isolated groups. Then, step-by-step, two groups are merged if the average distance between their components is the smallest in relation to all other group combinations. We used three variables presented before (Table 1): aggregation degree, descriptive improvement and average grid coefficient, which are relatively independent as the maximum correlation (R) between them is 0.5084. They were standardised between zero and one and the distance or similarity between two cities was defined as the sum of the absolute difference between each measure[8]. The result is presented in form of a dendrogram (Figure 7). Indentations in the tree indicate when the groups were clustered. As we see, in the beginning, pairs of elements are usually grouped. Then, isolated elements are added to an existing group or two subgroups are merged together until the whole tree is built. We can obtain the final groups by cutting vertically the dendrogram or selecting branches. Finally, this method has known limitations. Isolated cases tend to be added to bigger clusters, as the selected variables may not be sufficient to characterise them or other samples of the same type are needed. In addition, the use of the average distance in each step leads to a loss of information (Ward, 1963), i.e. later groupings are less meaningful because the average distance between large groups may not be a representative value.

Despite these limitations, the results were satisfactory as we found meaningful branches in the tree. In the top, we have cities with an exceptionally high average grid clustering, e.g., Gama, Ceilândia-Taguatinga (planned cities in Brazil) e Johor Bahru (Malaysia). The second group is mainly composed of English and European cities, along Brazilian ones with a strong Portuguese influence, e.g., Canterbury (UK), Lisbon (Portugal) and São Luís (Brazil). These cities have high aggregation degree and descriptive improvement. If we ignore Penang (Malaysia), an odd case, we have two large branches of "grid" and "tree" cities. The "tree" branch (in the bottom) and is mainly composed of Iranian and planned cities such as Brasília (Brazil) and Milton Keynes (UK), characterised by low aggregation degree and low grid clustering. Seattle (USA) is also grouped to this branch because the map includes large sprawl areas. Finally the "grid" branch has two main subdivisions. The "regular" grid branch is mainly composed of Brazilian and American cities, e.g., Fortaleza (Brazil) and Chicago (USA). This branch has relatively low aggregation degree and low descriptive improvement. These results are consistent with Medeiros' (2006) original study. By comparing 44 Brazilian cities to cities worldwide he revealed that, on average, they are predominantly regular and composed of distinct grid patterns resembling a patchwork. Finally, the "deformed" or "mixed" branch is the largest group and includes cities that have medium values of the selected variables. Not surprisingly, several minor branches are mainly composed of cities of the same country, revealing the trace of similar growing, planning and social processes. Even when they challenged our common sense, we found that the branches revealed similarities that would remain hidden if we had used any type of pre-classification.

Conclusions and future developments

In this paper, we have shown that the continuity lines are a powerful tool for the representation and analysis of the urban grid. This descriptive technique is fully embedded in the recent developments on network science, drawing contributions from fields such as the statistical mechanics and biology. We explored only few of these innovative tools on a large database of continuity maps that included cities of 22 countries. The results unfolded striking properties of such objects. We have found that the underlying spatial organisation of the urban grid retains a clear hierarchy as a tree while enabling short descriptions as a grid. We have also shown that although being composed of a set of pieces that follows universal laws, such pieces are arranged in countless ways, reflecting the particular history of each city. We characterised such arrangements and proposed an emergent taxonomy for urban grids.

The challenge is still to fully understand the rules that govern and generate these spatial and networked structures. In particular, we need to characterise the supergrid and its relation with the neighbourhoods. Our next efforts include the use of innovative clustering methods (Newman, 2004) not only to identify and extract this supergrid and the morphologically defined neighbourhoods, but also to create new powerful taxonomic procedures. Finally, we expect that the methods and results presented here to shed some light on the complex urban phenomena.

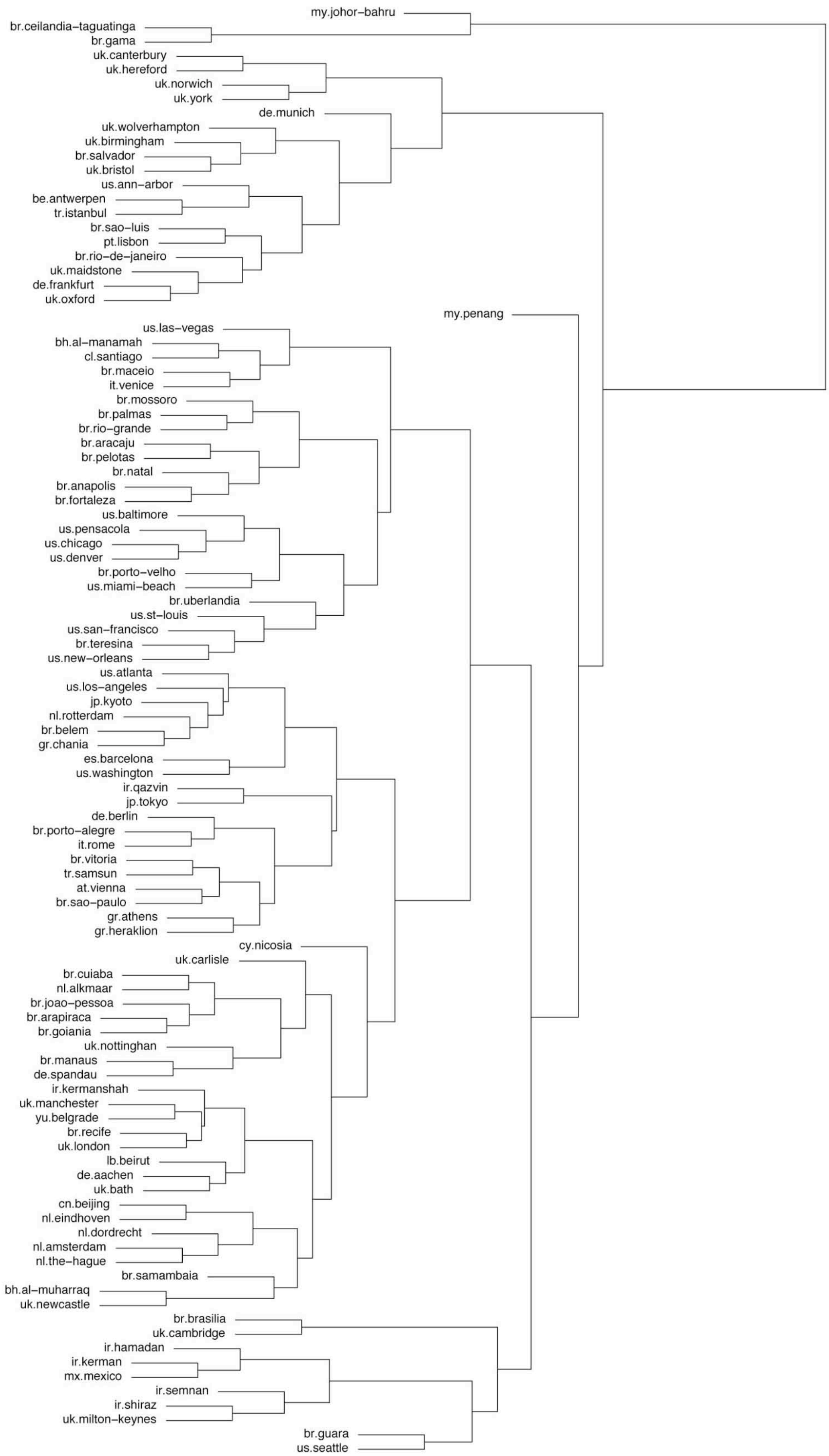

Figure 7: The cluster dendrogram created by the average linkage method. It shows the similarity between the cities taking in account three variables: aggregation degree, descriptive improvement and average grid coefficient.

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[1] Several classical studies used "Radius 3" measures, i.e. "up two three steps", to capture local properties of urban areas (Hillier et al, 1993). However, they used a software called "Axman", written by Nick Dalton, in which the distance from a node to itself is one instead of zero. Therefore, "Radius 3" should be read as "Radius 2" in these studies.

[2] The first database is composed of Brazilian cities. It is georeferenced and was mainly created by Valério A. S. de Medeiros (2006), with contributions of several Brazilian research centres, in particular the DIMPU UnB and MUsA UFRN. The second database of world cities was built by researchers and students of the Space Syntax Laboratory and the Bartlett School of Graduate Studies. Finally, the third database contains individual contributions of several researchers worldwide.

[3] The original index is the correlation between connectivity (degree) and integration (Hillier and Hanson, 1984), a normalised version of closeness (Freeman, 1979). Integration highlights a central core, which becomes "over concentrated" as the size of the system increases. This measure is also sensible to discontinuous systems (two or more subsystems connected by few lines) and boundary conditions, the "edge effect" (Ratti, 2004).

[4] The exception would be long linear trees with shallow branches attached.

[5] We can use information theory to formalise this argument. If the probability of choosing a route between 1 and 2 (Figure 3) is p, the entropy (or uncertainty) of this system is $H = -\sum p \log_2 p$. Therefore, the perfect grid (3a) has maximum entropy if the routes are equally probable while the tree (3b) has no entropy as $\log_2 1 \cong 0$. Note that we can encode an instruction of the type left (0) or right (1) into a single bit.

[6] With the exception of integration (or closeness) measures due to the already mentioned "edge effect" (Ratti, 2004).

[7] See also "grid axiality" (Hillier and Hanson, 1984) and "n-clustering coefficient" (Jiang and Claramunt, 2004).

[8] This similarity distance is also known as "Manhattan" or "city-block" distance in the literature (Sneath and Sokal, 1973).

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Table 1: The set of 101 continuity maps used in this study.

Map	Nodes	L	Aggregation Degree	Average Grid Coefficient	Descriptive Improvement
at.vienna	1448	5.5105	0.4824	0.1588	0.0823
be.antwerpen	2565	5.9915	0.4965	0.1602	0.1442
bh.al-manamah	3216	6.4670	0.2597	0.1825	0.0884
bh.al-muharraq	3311	8.8694	0.3207	0.1827	0.1281
br.anapolis	2445	6.2126	0.3340	0.2060	0.0697
br.aracaju	6387	9.8427	0.3392	0.2309	0.0796
br.arapiraca	1246	6.7345	0.4454	0.1932	0.0786
br.belem	8366	8.4576	0.3734	0.1634	0.0559
br.brasilia	1683	7.9037	0.1979	0.1594	0.1592
br.ceilandia-taguatinga	3799	6.8773	0.1331	0.2690	0.0032
br.cuiaba	5423	7.7533	0.4744	0.2001	0.1052
br.fortaleza	8914	7.7566	0.3270	0.2106	0.0540
br.gama	1029	6.2170	0.0752	0.2718	0.0044
br.goiania	14231	9.1693	0.4533	0.1976	0.0807
br.guara	845	8.0221	0.0957	0.1547	0.0939
br.joao-pessoa	7290	9.2646	0.4610	0.1921	0.0937
br.maceio	2434	7.9107	0.2130	0.2052	0.0690
br.manaus	16439	10.7051	0.4539	0.1892	0.1298
br.mossoro	1735	6.0583	0.2590	0.2337	0.0481
br.natal	8555	9.3514	0.3176	0.2118	0.0273
br.palmas	2301	6.6380	0.3220	0.2368	0.0581
br.pelotas	1808	5.8663	0.3611	0.2175	0.0757
br.porto-alegre	7697	10.0371	0.4458	0.1633	0.0906

Map	Nodes	L	Aggregation Degree	Average Grid Coefficient	Descriptive Improvement
br.porto-velho	1852	5.4499	0.2796	0.2201	0.0013
br.recife	11149	8.6658	0.4048	0.1712	0.1189
br.rio-de-janeiro	10133	11.1423	0.5405	0.1984	0.1869
br.rio-grande	708	4.9412	0.2994	0.2580	0.0583
br.salvador	28635	14.6388	0.5558	0.1564	0.2046
br.samambaia	2150	7.0888	0.2759	0.2103	0.1181
br.sao-luis	7480	8.4450	0.5621	0.1919	0.1312
br.sao-paulo	52826	13.1077	0.5157	0.1528	0.0776
br.teresina	4939	8.0636	0.3733	0.2080	0.0310
br.uberlandia	3871	6.2623	0.4695	0.2040	-0.0166
br.vitoria	1890	9.2564	0.5319	0.1621	0.0820
cl.santiago	24918	6.5827	0.2661	0.1897	0.0616
cn.beijing	15539	6.6508	0.3682	0.1904	0.1169
cy.nicosia	4468	7.8600	0.4005	0.2027	0.1780
de.aachen	1375	6.0019	0.3769	0.1664	0.1235
de.berlin	3198	5.6401	0.4583	0.1469	0.0933
de.frankfurt	761	6.7410	0.5066	0.1867	0.1768
de.munich	623	4.4762	0.6070	0.1353	0.1611
de.spandau	1270	5.4284	0.4341	0.1902	0.1341
es.barcelona	3934	5.4847	0.4705	0.1600	0.0326
gr.athens	15954	7.7715	0.5104	0.1421	0.0492
gr.chania	824	5.4778	0.3835	0.1608	0.0581
gr.heraklion	1618	6.2055	0.5091	0.1418	0.0979
ir.hamadan	3051	6.3474	0.3341	0.1099	0.0676
ir.kerman	3489	6.2047	0.3317	0.1276	0.0586
ir.kermanshah	1428	5.6465	0.3909	0.1649	0.0971
ir.qazvin	2741	6.3276	0.4155	0.1333	0.1199
ir.semnan	1632	6.2923	0.3009	0.1120	0.1017
ir.shiraz	6982	7.0439	0.2187	0.1279	0.0794
it.rome	7340	9.6702	0.4612	0.1689	0.1000
it.venice	2262	16.1509	0.1976	0.1811	0.0702
jp.kyoto	16056	7.9960	0.4086	0.1705	0.0507
jp.tokyo	53116	7.4553	0.4275	0.1336	0.0715
lb.beirut	2278	5.7071	0.3613	0.1485	0.1265
mx.mexico	3833	4.9572	0.3168	0.1342	0.0469
my.johor-bahru	20167	10.1633	0.2983	0.2964	0.0343
my.penang	5491	10.4150	0.3517	0.2575	0.1462
nl.alkmaar	1748	7.7153	0.4407	0.2023	0.1020
nl.amsterdam	7744	7.6875	0.3378	0.1895	0.0580
nl.dordrecht	2906	8.4895	0.3493	0.1862	0.0926
nl.eindhoven	4485	8.8638	0.3666	0.1996	0.1084
nl.rotterdam	1000	6.2330	0.3830	0.1691	0.0692
nl.the-hague	2603	5.5370	0.3606	0.1895	0.0673
pt.lisbon	5016	12.6716	0.5263	0.1853	0.1462
tr.istanbul	15094	12.3082	0.4922	0.1660	0.1340
tr.samsun	741	4.5580	0.5393	0.1652	0.0634
uk.bath	2328	7.8847	0.4058	0.1602	0.1345
uk.birmingham	1621	5.8063	0.4827	0.1579	0.1920
uk.bristol	4656	9.3853	0.5191	0.1492	0.2103
uk.cambridge	1224	6.7960	0.2962	0.1585	0.1904

Map	Nodes	L	Aggregation Degree	Average Grid Coefficient	Descriptive Improvement
uk.canterbury	486	5.5351	0.5237	0.2227	0.2694
uk.carlisle	778	6.4889	0.4360	0.2272	0.1266
uk.hereford	551	5.8106	0.5422	0.2004	0.2789
uk.london	11764	8.2174	0.4171	0.1701	0.1033
uk.maidstone	1060	7.5043	0.4791	0.1918	0.1618
uk.manchester	2501	5.7407	0.3923	0.1795	0.1061
uk.milton-keynes	4848	7.5431	0.2055	0.1167	0.1037
uk.newcastle	4875	10.6000	0.3046	0.1832	0.1248
uk.norwich	1484	6.4108	0.4606	0.1927	0.2349
uk.nottinghan	3313	7.5155	0.3833	0.1880	0.1452
uk.oxford	1103	6.6285	0.5049	0.1916	0.1701
uk.wolverhampton	3498	7.2239	0.5390	0.1745	0.2264
uk.york	1231	6.3779	0.4805	0.1750	0.2760
us.ann-arbor	2447	6.6169	0.5568	0.1595	0.1571
us.atlanta	2425	5.6055	0.3969	0.1574	0.0348
us.baltimore	9696	7.7910	0.2818	0.1793	0.0294
us.chicago	25086	6.4504	0.2925	0.1914	-0.0032
us.denver	1703	4.5301	0.3112	0.1893	0.0029
us.las-vegas	7434	5.9278	0.1914	0.1855	0.0278
us.los-angeles	745	3.7598	0.3779	0.1453	0.0575
us.miami-beach	1439	4.8032	0.2340	0.2014	0.0062
us.new-orleans	3598	6.3614	0.3917	0.2042	0.0109
us.pensacola	3458	6.2584	0.3254	0.1901	0.0200
us.san-francisco	1673	5.5510	0.3814	0.1838	0.0157
us.seattle	17953	8.4808	0.1941	0.1530	-0.0032
us.st-louis	3805	6.4821	0.4333	0.1974	0.0410
us.washington	2503	6.0345	0.4357	0.1679	0.0168
yu.belgrade	1930	7.0204	0.3786	0.1750	0.1092