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FINDING THE SECRET FORMULA

How can we quantitatively understand cities' growth, based on their street network structure?

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ABSTRACT

Cities are complex, perhaps one of the most complex kinds of structure created by humans. Some cities have been planned top-down to a large extent while others have grown organically on their own. The outcome of these planning and growth processes are the various morphological building and street patterns seen in cities. There are strong reasons to believe that the street system in a city has a crucial effect on land use and building development (Hillier, 1996). It is therefore essential to understand the complex street networks in our cities. This is not only to categorize cities but also to be able to switch-over our transport system towards a higher degree of sustainability.

Despite extensive research in the fields of urban planning and urban history, there are still very few consistent ways of quantitatively describing and classifying cities. The perspectives used in research so far have mainly categorized them based on visual judgements of their morphology (Kostof & Tobias, 1991). It is problematic that classifications are mainly based on subjective judgement and lack a quantitative measure. To understand cities and their characteristics, it is necessary to find methods and measures that can describe these characteristics and also be suitable for comparisons between cities.

By using space syntax methods, it is possible to find measures and properties of the cities' street networks, which sometimes seems to exhibit patterns with scale free properties (Jiang, 2007). Thanks to recent progress in the field of complexity studies, it is now also possible to test if and to which degree a network has scale free properties. One commonly used approach is to test whether the distribution of a certain property in a collection of elements fit a power law distribution(Clauset et al., 2009).

The results of this study show that the degree distribution for a city's street network seems to fit a power law for cities grown organically. On the other hand, cities that are planned to a large extent do not have that good fit. This result seems sound, since a distribution that fits a power law is a signature of a multiplicative growth processes. Another interesting finding following this result, is that this way of quantitatively classifying cities seems to correlate well with earlier attempts of qualitative morphological classification.

KEYWORDS

Space syntax, power law, organic growth, spatial morphology, degree distribution

1. INTRODUCTION

Cities have been a very important part of the human civilization since agriculture based society emerged. They have been built independently from each other in different parts of the world in varying cultures. A very basic dichotomy's way of classifying cities is by their growth and resulting morphological pattern: organic cities have grown gradually, versus planned cities that have grown from larger planning interventions (Hillier, 1996) . Some cities are entirely planned in one sweep, while others have mainly grown organically, and often, these processes have alternated back and forth over time (Kostof & Tobias, 1991).

Although this is not a distinct dichotomy, but rather a question of more or less planning resulting in different patterns in different areas (Kostof & Tobias, 1991), it is still used as a predominant description of cities. Another way of describing this dichotomy is using the concepts of bottom up growth (organic) versus top-down growth (planned) (Batty, 2013). A peculiar aspect is that these organic patterns have been seen as desirable in cities, and therefore efforts to mimic them have often been used in planning (Kostof & Tobias, 1991). Despite research on the topic, there are still few consistent ways of quantitatively classifying and describing these properties and characteristics of morphologic patterns (Volchenkov & Blanchard, 2008). Since cities are such an important part of society and this dichotomy's categorization – organic versus planned - is often used as fundamental explanation, it is problematic that there are still few consistent ways to quantify it.

2. BACKGROUND

Urban areas have been studied as an academic discipline for a long time, but is has often been done in qualitative studies based on perceived patterns (Kostof & Tobias, 1991). Around the 1980's a new methodology for quantitative analysis of city structures was developed, are called space syntax (Hillier & Hanson, 1984). As the name indicates it is about the analysis of the configuration of spaces: architectural, urban streets or open spaces. Spatial configuration is best explained as how spaces, or in the case of cities usually streets, are related to and connected with each other (Hillier, 1996; Marshall, 2015). A basic concept of space syntax is that it analyses the topology of the street network, and therefore leaves out metric information (Hillier, 1999).

Parallel to this research, other research groups started in the 1990's to analyse cities by growth simulations, often using cellular automata (Batty & Longley, 1994). In this field, cities are often claimed to be fractal, which means that certain measures have scale free properties. This is claimed to be the result of a bottom up growth, which mean that organic cities might by analogy be called fractal.

During the last ten to fifteen years, parallel to the growth of space syntax as a research field, another important field of research that has been rapidly evolving is network science (Watts, 2004). As computers have become more powerful, new methods appeared for calculating network properties in large networks, such as small world network properties and scale free properties. Those properties are based on new theories and methods (Watts & Strogatz, 1998) discovered during the past twenty years. Topological analysis is the fundamental model for this new scientific paradigm of network science, where many kinds of networks are studied, including city street networks (Barthélemy, 2011) (Watts, 2004). This offers the possibility to study cities from an entire new perspective.

Based on this progress on complex network analysis in general, new theories and methods for analysing road and street network patterns have been developed within the research field of space syntax (Jiang et al., 1999; Porta, S. et al., 2006; Jiang, 2007). These methods use the results from a space syntax analysis and thereafter analyse various properties, both individual measures and statistical distributions (Jiang, 2007; Volchenkov & Blanchard, 2008; Shpuza, 2017). These elaborations of the space syntax research field, thanks to the network science field in general, might enable the quantification of cities in a better way.

2.1 EARLIER WORK

Some efforts to find properties for cities as a whole have been made (Crucitti, P. et al., 2006; Porta, S. et al., 2006; Porta, Sergio et al., 2006; Jiang, 2007; Volchenkov & Blanchard, 2008; Shpuza, 2014), although many of these studies were done on a small sample area or on few cities that make the results harder to use for general conclusions. The results are also diverging and sometimes incompatible. It has been shown in some studies that various network measures like degree, betweenness and other centrality measures, reveal a scale free behaviour in many cities (Porta, Sergio et al., 2006; Jiang, 2007; Volchenkov & Blanchard, 2008). Other studies refute this and have shown that there are differences and exceptions from these patterns (Jiang & Claramunt, 2004; Crucitti, Paolo et al., 2006; Porta, S. et al., 2006). To further support or refute these claims, a more extensive analysis is needed. The results of this earlier work can be discussed with the results from the present study, even though the preconditions and methods are not identical.

2.2 AIM

The aim of this study is to uncover measures calculated from the street network's topology in a number of cities to find out whether there are universal patterns as claimed in earlier studies, or if they vary as other studies (referred to in 1.2) suggest. That could explain the contradictory results claimed in these studies.

The hypothesis is that these patterns are not universal, but rather depend on whether the cities are organic or planned. If that holds true, then these measures might be used for further analysis and categorization of cities, as well as used to evaluate plans and extend our understanding of cities in general.

3. THEORETICAL FRAMEWORK AND LIMITATIONS

3.1 NETWORK ANALYSIS METHOD

When the space syntax research field started in the 1980's, the main element of analysis of street configuration was the axial line (Hillier & Hanson, 1984). An axial line is an unobstructed line of sight. To analyze an area or a city an axial map is created, made of the fewest and longest unobstructed lines of sight, which are the axial lines (Hillier, 1996). This method has been dominating the research field until early 2000's, when efforts were made to integrate space syntax in ordinary GIS research and make it possible to utilize the more common road centerline maps (Jiang et al., 1999; Thomson, 2003; Turner, 2007). Axial line analysis requires the manual digitising of the streets (Hillier, 1996), which would be too time consuming for this extensive quantitative analysis. Therefore the use of a method based on readily available road centerlines is necessary. To analyse the degree centrality of the street network, it is necessary to use a method that renders a discrete result for each street. That rules out the street segment based angular analysis models widely used today (Turner, 2007).

One of the methods developed in this effort to replace axial lines as the basic spatial element when using road centerline maps is the concept of Natural Roads (Jiang et al., 2008), similar to strokes (Thomson, 2003) and continuity lines (Figueiredo & Amorim, 2005). These concepts are based on the Gestalt principle of good continuation (Jiang, 2007). Over the years, steps have been taken to elaborate this method, in order to improve it in revealing the structure of the city (Jiang & Liu, 2009). It has a consistent response to boundary effects (Gil, 2016). Its correlation with pedestrian and vehicular movement is on par with the other major methods in the space syntax research field, such as angular segment analysis and axial lines (Jiang, 2009; Jiang & Liu, 2009), which also supports its validity. All together this makes the Natural Roads method the most suitable for this study.

3.2 DEGREE DISTRIBUTION AND POWER LAW FITTING

The most basic measure obtained in space syntax calculations is called connectivity, i.e. the number, per street, of connections with other streets, also called degree centrality in network science studies. When studying the distribution of degree, often a certain pattern occurs. This pattern sometimes seems to follow a power law distribution, which has scale free properties (Porta, Sergio et al., 2006; Jiang, 2007). In other fields of network research, such as sociological studies of connections between people, flight connections or power grid structures, the same pattern occurs, namely that there are far more low connected elements than highly connected ones (Barabasi & Albert, 1999; Clauset et al., 2009). This aspect of urban studies has not been extensively researched, and seems interesting and enables the possibility of new discoveries.

3.3 ASSUMPTIONS IN THIS STUDY

Many studies in network science rely on degree centrality as the single measure of distribution to test for power law fitting (Clauset et al., 2009) (Barabasi & Albert, 1999; Volchenkov & Blanchard, 2008). There is a large variety of other centrality measures that can be calculated. They offer a possible direction of investigation in future studies, but to make the results of this study easily comparable with other studies, also from other network research fields, only degree will be used. It is a question of not getting stuck in complicated results, where there are too many variables involved to reach clear conclusions.

A parameter that has to be taken into consideration is the extent of the studied areas. It could be argued that larger study areas are better due to the larger amount of analyzed data. On the other hand, many cities with organic patterns are often small or their areas with organic patterns are small (since these are often the oldest areas). In this study, the main goal is to capture the structure of the city that is the result of its historical growth to get an indication of whether the hypothesis might be true. This means that this study does not require large amounts of data to reveal interesting results. Therefore, a circular sample area with a radius of 8 km has been used, also to make cities with different sizes more comparable. These are centered (where applicable) on the historical starting point of the city, like Île de la Cité in Paris. In some cases, one can argue that this delimitation is arbitrary, while in other cases, like Venice, the city limits are very clear.

Having more cities in the study could be beneficial, but since the aim is not to reach a conclusive answer, but rather open up the path for new theories, the number of cities chosen (10) can be considered sufficient. This selection should be seen as a starting point for further and deeper studies of both large cities and smaller neighborhoods. Studying parameters of cities over time as done by (Shpuza, 2014, 2017) could maybe also reveal interesting results. I seems unlikely that the studied properties are constant over time.

4. DATASETS AND METHODS

4.1 STUDY OBJECTS

There are no standardised and consistent ways of describing cities, therefore the selection will be somewhat arbitrary and subject of discussion. Since the aim of this study is to find patterns depending mostly on growth processes, the selection is mainly based on earlier attempts of classifying cities (Kostof & Tobias, 1991; Batty & Longley, 1994; Hillier, 1996). The other criteria for the selection have been chosen in order to have variations, to try to confirm or refute the existence of universal patterns.

The first and foremost criterion is degree of planning or self-organization, in order to have a somewhat balanced collection between organic and planned cities. As second criterion, the dominant culture that has shaped the city morphology is chosen. Different cultures may play a large role in the cities' street network structure (Hillier, 1996). This is probably because of different ways of social structure and organization (Kostof & Tobias, 1991). In various cultures, there have been different ways of living the daily life and performing social interactions. Then, geographic location is chosen as third criterion, since the preconditions differ considerably in different parts of the world, namely the geology, climate, building materials supply and cost. Intuitively, this should affect the structure of the street network. The cities in this study are chosen from different continents or continental areas. Finally, age of the city can also play a role in that organic city evolution takes long time whereas building a planned city can be done quite fast in comparison.

Based on these criteria, ten cities have been chosen for this study (Table 1). Excerpts of their street network are shown in figure 1.

City	Degree of planning	Shaped by culture and religion	Location	Age	Geographical characteristics
Rio de Janeiro	Many self-organized favelas	Catholic South American	Brazil	Modern (60's	Coastal city
Venice	Self-organized villages grown together	Catholic European	Europe	Middle age	Several islands
Damascus	Old roman city organically, reshaped when under Arab government	Originally roman, later Arabic/Islamic	Middle east	Roman age	Desert/plain
London	Low, self-organizing	Anglo-Saxon, Lutheran	Europe	Middle age	River city
Tokyo	Low, self-organizing	Japanese all the time, although became capital later	Eastern Asia	Middle age	Coastal city
Beijing	High, since it became capital	Chinese all the time, although it became capital later	Eastern Asia	Antiquity	Topographical constraints
Moscow	High, as an expression of power	Russian Orthodox, capital all the time	Russia	Middle ages	River city
New York	High, the original grid is virtually unchanged	American all the time.	North America	About 1600.	Several islands
Brasilia	Very high, entire city planned at once	Very new, built as Capital	Brazil	60's	Exploited jungle
Paris	High, since both the Baroque planning and Haussmann's boulevards.	Catholic European	Europe	Middle age	River city

Table 1 - Summary of properties for the studied cities

4.2 SOURCE OF STREET NETWORK DATA

The street network of the studied cities is the main study object. Therefore, it is essential to use a reliable data source. To make such a worldwide comparison, it is essential for such a common data source to have the same kind of data classification and collection process. Publication restrictions and copyright issues make usage of official land surveys or proprietary navigational street data (e.g. TomTom, Navteq, Google) hard. Instead, Open Street Map (OSM) was used as source for the street networks (© OpenStreetMap contributors). OSM is an initiative to create public domain map data. It is open for anyone to edit and create new features in the map. It has a worldwide coverage, although the level of detail might differ between different areas.

There has been some debate about OSM regarding its data quality, since anyone can edit it. Research has suggested that the errors in this map are on par with those in other maps from authoritative sources (Haklay, 2010; Dhanani et al., 2012). Therefore, the benefits of being able to use a common map source for all the cities in this study, without copyright or other legal restrictions, outweigh the possible data quality drawbacks of using OSM.

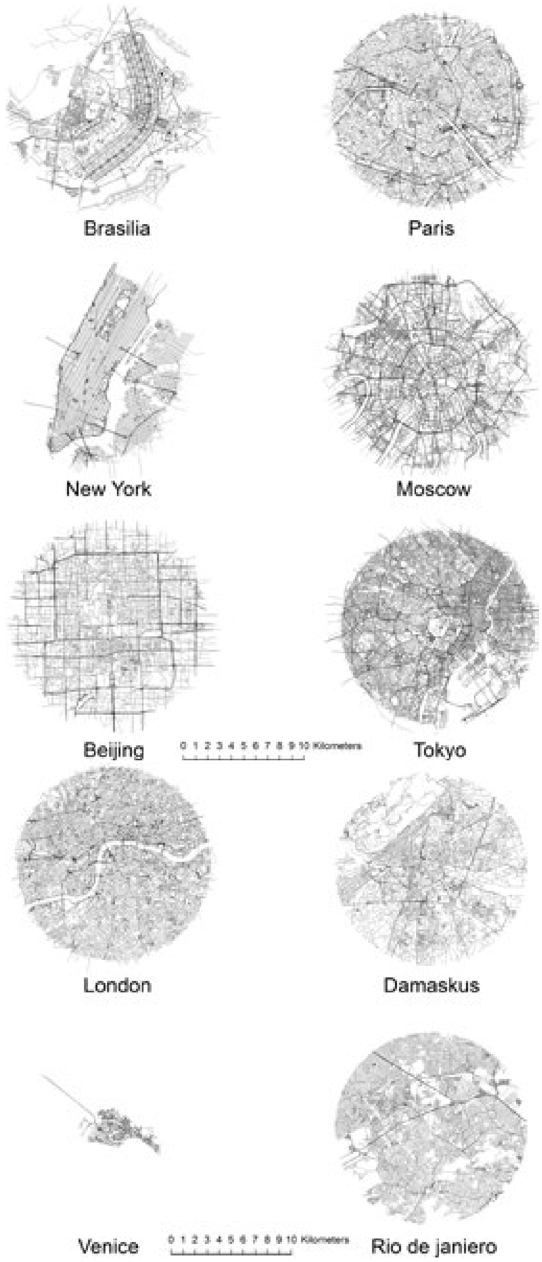

Figure 1 - The street networks of the studied cities

4.3 SOFTWARE USED IN THE ANALYSIS

To do an automated data validation and analysis, several pieces of software are needed. Firstly, the FME[1] software is used for cleaning and validating the data. Then, the software Axwoman (Jiang, 2015) for ArcGIS is used to create natural roads and calculate degree centrality. The degree distribution of the streets (from ArcGIS[2]) is processed in MATLAB (MathWorks, 2014) for each city. This analysis uses the additional software package "Power-law Distributions in Empirical Data" (Clauset, 2007) in MATLAB. Further tests are carried out using the poweRlaw package in R (Gillespie, 2015), which is also based on the work by Clauset. Finally, Microsoft Excel is used to collect and visualize the statistical results. The use of several pieces of software has been necessary to reach the desired results, although it would be a simpler process if a single application with all the capabilities existed.

4.4 METHODOLOGICAL PROCESS

The analysis method starts with the download of OSM data in shape file format from the internet site www.geofabrik.de. After the data download, a series of extraction, cleaning and validation operations are performed in FME to enable further processing of the data set with Axwoman. Clipping is the first step, in order to extract the streets in the 8km study area and discard all other streets in the data set. The next step is to project the map with a projected coordinate system. In this study the WGS84 World Mercator projection is used. The next cleaning step is to break all the street lines at every intersection. This is because some street segments are continuous across intersections, which renders it impossible to make the natural streets interconnection algorithm to work. Finally, any isolated single streets or "islands" of streets are identified and deleted. This is necessary, as the network has to be a single connected component for this analysis to work. When this data validation step is completed, the next step is the analysis.

The next step is to generate the natural roads. This is done by joining the street segments at the intersections according to the "every best fit" algorithm in Axwoman with the threshold angle of 45 degrees (Jiang et al., 2008). The result is a network of natural roads that can be seen in figure 2. Once the natural roads have been created, Axwoman is used to calculate degree centrality, which is then exported for the final statistical analysis.

The degree centrality results of natural roads are imported into MATLAB for statistical analysis with "Power-law Distributions in Empirical Data" (Clauset, 2007). The analysis checks if the degree distribution seems to fit a power law distribution. The first step is to do a power law fit, where a possible x-min and alpha values are calculated. The next step is to test whether the data can fit a power law doing a Smirnoff-Kolmogorov test. This test generates many samples based on an ideal power law distribution with the x-min and alpha values derived from the distribution under test. Then, these samples are compared to the distribution being tested and a regression analysis is done to derive a significance test. If the resulting p-value is above 0.1, the distribution has a large probability of being a power law. The results of these tests (the p-value, x-min and alpha) are then used in the final analysis and judgement.

When all these measures are extracted, it is time to do a qualitative comparison between the cities to see if their quantitative properties have some relation to their qualitative morphological characteristics.

1 FME software package, https://www.safe.com/fme/fme-desktop/

2 Environmental Systems Research Institute (ESRI). (2012). ArcGIS Release 10.2. Redlands, CA.

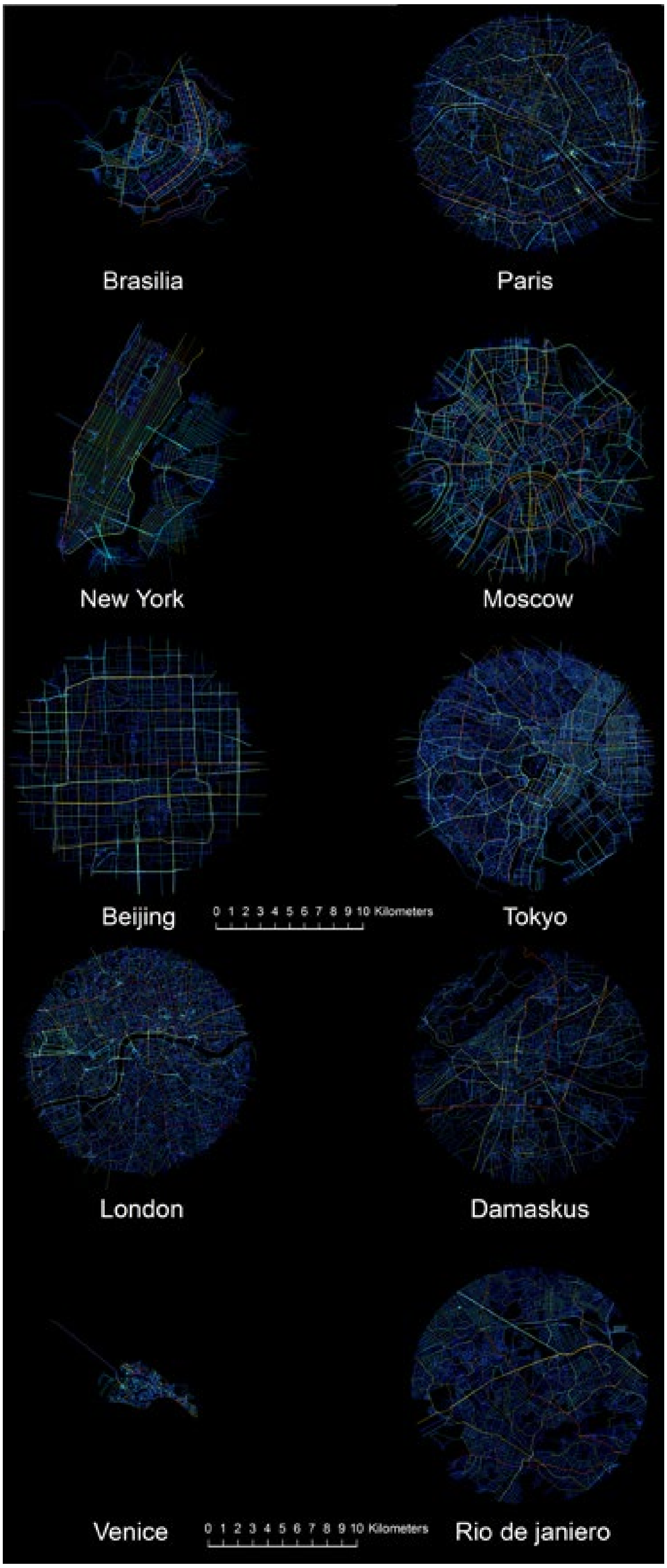

Figure 2 - The cities' dual graph network coloured after degree distribution, red is high.

5. RESULTS

5.1 DERIVED PARAMETERS OF DEGREE DISTRIBUTION

The final results of the geographical, topological and statistical calculations for each city are shown below in table 2. The table is sorted on the p-value in ascending order, since it is the most important test in this study. That is because this value is a good way to find out the probability if it does follow a power law or not. The next parameter is Alpha, which is the slope of the hypothetical power law. Following that is X-min, which is the starting value from where the distribution can fit a power law. Finally, the number of vertices and their mean degree value are in the last two columns.

The p-value is a value derived from a statistical test, the Kolmogorov-Smirnov test. It indicates the probability of the degree distribution following a power law (Clauset et al., 2009). Even though a lot of empirical data looks like it follows a power law distribution, it is not always the case. If the p-value is larger than 0.1 it is probable, but not certain, that the data follows a power law.

It seems likely that the results can be grouped into two rather distinct categories, those with a $p < 0.1$ and those with $p > 0.1$. This means that approximately half of the cities' street network degree distribution does not fit a power law, while the other half has a decent probability to do that. This finding is interesting since a statistical distribution can tell something about the growth process that has created it. If we identify what differs in the two categories according to section 1.3, there is one main factor that differs: top-down planning or governing during city growth, versus organic growth.

City	P-value	Alpha	X-min	#Vertices	Mean	Growth process
Brasilia	0,00	2,60	3	7646	3,566	Entirely planned from start
Paris	0,00	2,44	4	13043	4,822	Planned to a large extent
New York	0,01	2,32	6	3449	6,590	Entirely planned grid
Moscow	0,03	2,52	3	14471	4,354	Planned to express power
Beijing	0,11	2,49	4	4862	4,736	Planned
Tokyo	0,29	2,55	7	19007	4,934	Organically grown
London	0,39	2,73	6	16786	3,832	Organically grown
Damascus	0,40	3,09	8	6337	3,765	Organically grown on Roman grid
Venice	0,46	3,50	8	2145	3,425	Several cities organically grown together
Rio de Janeiro	0,88	3,13	9	8240	4,021	Many organically grown favelas

Table 2 - Results of the calculations on the cities

The cities with a p-value below 0.1 have all been subject to rigorous planning and structuring, even though the purpose, time and type of planning vary (Kostof & Tobias, 1991). The other cities that have a larger p-value are all to a varying extent what is called organic grown cities (Kostof & Tobias, 1991; Batty & Longley, 1994; Hillier, 1996), or cities with large areas of organic patterns. These so called organic cities are those where the city to a large extent has slowly grown over a long time and have not been not subject to any comprehensive planning effort. There is a city on the edge of the p-value limit, Beijing. The value means that it cannot be ruled out that it fits a power law, although it is just 0.01 above the limit. It is unclear why this is the case, but it would be surprising if all data could perfectly fit the dichotomy of way of growth.

The next parameter is alpha. It tells us the scaling factor in the distribution. Even though the differences are not as striking as for the p-values, they can also be divided into two categories with significant different mean. Alpha values are generally higher in the group of organic cities than the planned ones. The alpha values tell us that the organic cities have relatively fewer roads with high degree compared to the number of low degree roads. This might be explained by the process behind city evolution: in organic cities, the preferential attachment process results in that new roads strive to attach to the existing roads with high degree, while few new roads with high degree are built from the start. That means that the growth process in organic cities results in the evolution of the fine-grained background network, while the high degree foreground network is more stationary. In planned cities, a common measure is to create many high degree streets like highways, boulevards and main streets. This has various reasons, mainly political ones or ways to handle traffic. More high degree roads means more arterial roads that can handle larger amounts of traffic.

The x-min also seems to somewhat correlate with the division into organic versus planned cities and the alpha value. The reason behind this finding is unknown, but correlation with alpha values are often found (Gillespie, 2015). It can be interpreted that all cities might share a universal pattern for low degree streets up to around a degree value of ten. Since the slope of this part seems pretty flat, it fits a lower alpha better.

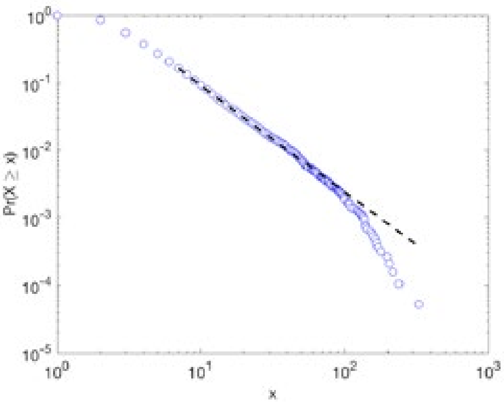

Figure 3 - Degree distribution of Rio de Janeiro, with a good probability to fit a power law.

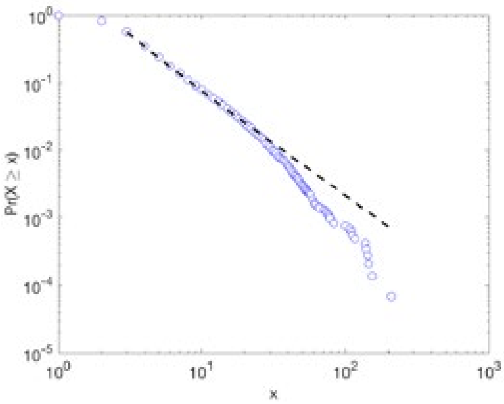

Figure 4 - Degree distribution of Moscow, which is unlikely to fit a power law.

It seems that, based on these measures, whether the degree distribution fits a power law tells something about the level of planning in a city. This result can be explained by considering the city as a self-organized scale-free network (Barabasi & Albert, 1999). If a city is not subject of large scale planning, it tends to organize itself according to the principle of preferential attachment (Volchenkov & Blanchard, 2008) which is a kind of multiplicative growth (Batty & Longley, 1994) that results in a scale free network. That explanation is also in line with previous research (Jiang, 2007; Volchenkov & Blanchard, 2008). What the result in this study indicates, is that not all cities can be explained in this way; there seems to be a dividing line between planning and self-organization.

These results are interesting because they can give a good explanation to the earlier, sometimes contradictory, results from (Crucitti, P. et al., 2006; Porta, S. et al., 2006; Jiang, 2007; Volchenkov & Blanchard, 2008), where some results adhered to a power law while others did not. The steeper slope found in the organic cities can give a deeper explanation to the growth process behind them. Since there are mainly local bottom up forces that shape the city, relatively few primary high connected streets are built, because they require more central initiatives and large amount of resources. The higher proportion of the less connected streets is simply explained that they are necessary for the developing bottom up forces to connect to the street network. That makes sense since it is a more effective use of land (less proportion of roads) which is logical in the perspective that the forces behind bottom up-growth (often residential and firms) are acting economically.

6. CONCLUSIONS

This study has revealed similarities and differences in the degree distribution of the street network among cities with varying cultural, topographical, geographical or societal organizational circumstances. The factor that seems to explain the striking differences found in the degree distributions is the way of growth, organic bottom up or top-down planned. It seems that cities with an organic pattern likely follow a power law in their degree distribution. One the other hand, the extensively planned cities do not follow a power law.

These results can be useful in several ways. Firstly, they offer an explanation for the disparate results from other studies mentioned earlier, which have tried to find universal patterns in cities, often power law distributions. The answer to the question whether a universal pattern exists is: no, because it depends on the growth process of the city. Rather, it seems that there are at least two kinds of patterns.

Secondly, they elegantly verify the categorization and judgment that urban planning historians and theorists such as Kostof and Tobias have done on a qualitative basis, through visual analysis of the morphology. This opens up the possibility for urban planning historians, theorists and morphologists to support their work with quantitative analysis on a larger scale than the, usual qualitative, judgements allow.

Thirdly, for a long time there have been attempts to plan cities or neighbourhoods with an organic morphology. These attempts have often been unsuccessful or failed to produce the kind of urban fabric that was intended. The insights following this study might help these attempts, opening up a possibility to test various designs. The result can be used to see if they have the same properties as the organically grown cities that serve as models.

Although this study is too small to draw conclusive lessons, it provides clues and starting points for further studies. It also raises the question of whether there is some differentiated universal pattern in cities. It has shown that one measure of the street network can reveal such patterns and relations that seem to depend on the city's history of growth and planning.

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