

Article

Living Structure as an Empirical Measurement of City Morphology

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Abstract: Human actions and interactions are shaped in part by our direct environment. The studies of Christopher Alexander show that objects and structures can inhibit natural properties and characteristics; this is measured in living structure. He also found that we have better connection and feeling with more natural structures, as they more closely resemble ourselves. These theories are applied in this study to analyze and compare the urban morphology within different cities. The main aim of the study is to measure the living structure in cities. By identifying the living structure within cities, comparisons can be made between different types of cities, artificial and historical, and an estimation of what kind of effect this has on our wellbeing can be made. To do this, natural cities and natural streets are identified following a bottom-up data-driven methodology based on the underlying structures present in OpenStreetMap (OSM) road data. The naturally defined city edges (natural cities) based on intersection density and naturally occurring connected roads (natural streets) based on good continuity between road segments in the road data are extracted and then analyzed together. Thereafter, historical cities are compared with artificial cities to investigate the differences in living structure; it is found that historical cities generally consist of far more living structure than artificial cities. This research finds that the current usage of concrete, steel, and glass combined with very fast development speeds is detrimental to the living structure within cities. Newer city developments should be performed in symbiosis with older city structures as a whole, and the structure of the development should inhibit scaling as well as the buildings themselves.

Keywords: head/tail breaks; scaling; living structure; wholeness; natural streets; natural cities; urban morphology

1. Introduction

The cities and direct environments we live in are designed, shaped, built, and structured by ourselves, and we have to abide by the rules these structures provide. In the past, the motivations for and speeds of city development differed from the current situation [1]. The necessity of restoring buildings in Europe after World War II and abundance of resources such as concrete and steel led to architecture based on predominantly using these resources to this day [2]. This is in contrast to historical developments before this time. Resources were limited and construction took longer. This meant that developments were often much more thought out and also designed to not only be functional but also beautiful at the same time. This attracted more people to cities, allowing them to grow naturally over time at a natural pace [3]. The difference in development between now and the past is that the

structure of cities are becoming less natural. Houses all look alike, and often lunchbox-like buildings are created as they are cheap, fast, and easy to build. This leads to people having difficulty navigating, neighborhoods being avoided, and city structures which adversely support the city itself.

People traverse through cities via its constructed pathways—roads, footpaths, bike paths, and corridors. To analyze the structure of a city, the street networks can be used. These are essentially the arteries of the city and, when taken together as a whole, are crucial in determining the city's inner structure. Christopher Alexander has developed a theory on how to measure beauty or life within objects and structures. Based on his theory of centers and fifteen different principles, we perceive the quality of life within objects in differing amounts [4,5]. This living structure can be measured in cities by looking at the city as a complex network [6]. The characteristics of features, objects, and the city as a whole allow a comparison between different cities. By looking at cities as objects, we are able to quantifiably measure differences between cities' living structures.

Currently, cities are losing their meticulously built-up natural structure as developments outpace the natural speed of evolution. This means that the inner structural cohesion of cities will be lost over time, but also the cohesion between different cities as a whole will weaken. With the upcoming and current challenges regarding population growth and climate change, this is not desirable. Cities need to become stronger and inhabitants should all be able to feel at home. Cities need to be able to support their inhabitants so that the inhabitants can support the city. This study tries to identify key aspects of improvement for cities or key developments which either improve or weaken cities' underlying structure. By using known examples of attractive and repelling cities, it is possible to identify differences between them.

When the living structure within cities can be measured and compared, areas can be given a relative score of how living they are. Following this, further research can be conducted to identify the effects on human health—not only on short-term happiness, but especially on long and lasting happiness. This may also support governments with troublesome neighborhoods by explaining why they are troublesome, and at the same time offer a solution. This makes this analysis very powerful and important for all living environments. By using a concept discovered by Alexander [4] which is further expanded upon by Jiang [6], this research is able to undertake this kind of analysis.

Based on the concept of living structure captured by Alexander's work [4], this study identifies a city's structure as a whole and evaluates it based on its underlying structure. By doing this for multiple cities and countries, comparisons can be made between cities and historically within cities. For this, further research carried out on this concept by Jiang [6,7] allows a novel usage of geographic information systems (GIS), with which it becomes able to perform this type of analysis. This study is essentially a case study of these proposed theories to see if living structure, or beauty, can be measured empirically. This study will have three main goals to answer this question. Firstly, the study investigates if cities can be characterized using the concept of natural streets and natural cities. Secondly, different types of cities are identified and compared with each other to capture the degree of livingness or the amount of living structure. Thirdly, individual cities are compared temporally to look at the evolution of living structure within these cities to get an idea of how living structure is formed.

This paper is structured as follows: In the next section, the structural analysis of urban morphology is explained together with the key concepts of living structure, natural streets, natural cities, and scaling law. Thereafter, Section 3 indicates the methodology, and then Section 4 describes the results. Finally, Section 5 discusses the outcomes of this research, and the final section concludes the paper.

2. Analyzing Urban Morphology Empirically by Its Structure

Cities are very complex things; to be able to understand their complexity and solve the problems arising from said complexity, cities cannot be treated as simple problems. Because of their complexity, it becomes very hard to understand all the effects of decisions made. Jane Jacobs [8] developed her theory of organized complexity to approach the problems cities provided. At the time, she did not agree with practices of city planning and rebuilding, as they are “a foundation of nonsense” [8].

Modernist architecture, which started around the 1950–1960s, was criticized as it had no scientific base [6]. Next to Jacobs, who analyzed cities as a web to understand how everything was connected, Kevin Lynch analyzed how people perceive cities. He found out that people were able to understand their surroundings by forming mental maps where several main identifiers played a major role. Paths, edges, districts, nodes, and landmarks are needed to be able for a person to navigate through a city. These elements form the image of the city [9].

The works of Jacobs and Lynch supplement each other. Cities can differ from each other in their organized complexity, which will lead to a different human view of the city. The interesting notion here is that each individual has a different view of a city through the five elements Lynch discovered; however, each city also has only one main structure which determines these individual views [8,9]. This shows that it is very important to study cities as a whole instead of focusing only on newer development areas or districts, as the whole is greater than the sum of its parts. There has been more research based on organized complexity, and one of the most influential which affects this study considerably is the well-known work of Mandelbrot [10,11]. Fractal geometry is used to describe these complex structures by using recursivity across different scales. By analyzing spatial phenomena from a fractal perspective, the structure they contain is much easier to understand, as they show patterns where there are much more smaller things than large ones [12,13]. The fractal patterns in cities can also help in explaining the development patterns they exhibit, especially with the current pace they are growing at [14].

Additionally, Christopher Alexander developed the concept of wholeness to measure the order in things. Greater wholeness indicates a structure that is more natural, or living. This natural structure is indicated by the appearance of many more small things than large ones [4]. Everything within a city is built in such a way that it adds something to the city and increases its usefulness. Each part of the city belongs to each other, which is then part of a greater whole. These sets of the city and their hierarchies form a recursive structure [15]. Different cities are not the same in this way; different decisions and characteristics create differences in the underlying structure of cities. This means that every different city exhibits different amounts of wholeness. When a city shows greater amounts of wholeness, it indicates that a city is more living or more natural [7]. Alexander believes that the world is separated into two parts—the external world and the internal experience. Because they are a part of each other, they should also reflect each other. This means that a city which expresses greater wholeness, or a better living structure, is closer to our natural inner self and thus more sustainable. He uses pattern theory in an attempt to bring these two parts together so that beauty can be scientifically measured [16].

Our internal experience changes and evolves over time. Just like other observable natural things, it grows. This is one of the key things in nature; over time, it is able to change, adapt, and become stronger. For the external world to reach the greatest potential in reaching greater wholeness, it too must be able to change over time. A living structure which does not change over time can still be living—a dead tree still shows its living structure of a couple of big branches and many more smaller forks [6]. Buildings or paintings, however, are only living if they follow this structure. Because they are not subject to the time dimension, as after they are finished they remain—they are not able to evolve and reach a greater wholeness. For structures which already exhibit living structures this is fine, as they will feel good intrinsically. For structures which do not follow this living structure, however, it becomes difficult to connect to them, as the external world and internal experience are separated.

Many modernist buildings and developments do not abide by these ideas. This, in turn, means that we cannot connect and bad spaces are formed [17–19]. There are differences in goodness between spaces, and on top of that goodness can change over time. One of the main points Alexander makes regarding the goodness of space is that it is not subjective. Even though it feels like a subjective matter, there is no denying that it affects humans unnoticeably [20]. By using wholeness as a tool, urban areas can be developed or redeveloped so that they become better for humans [21,22].

For an object to be considered living, its structure cannot be one dimensional, and it must be able to show scaling law properties across multiple scales [6]. The following Figure 1 shows a structure—the

Saint Peter's basilica in the Holy See—which can be considered as living as there are multiple scales where scaling law can be detected. This building invites you in and there is no question as to where the entrance is located. There are already architectural movements focusing on restoring aspects of older architecture in modern buildings. Thousands of years of architectural work should not have been done for it to be ignored now. There is a reason for the shapes and structures made in history. By analyzing these kind of structures empirically, a direct reason might be attributed.

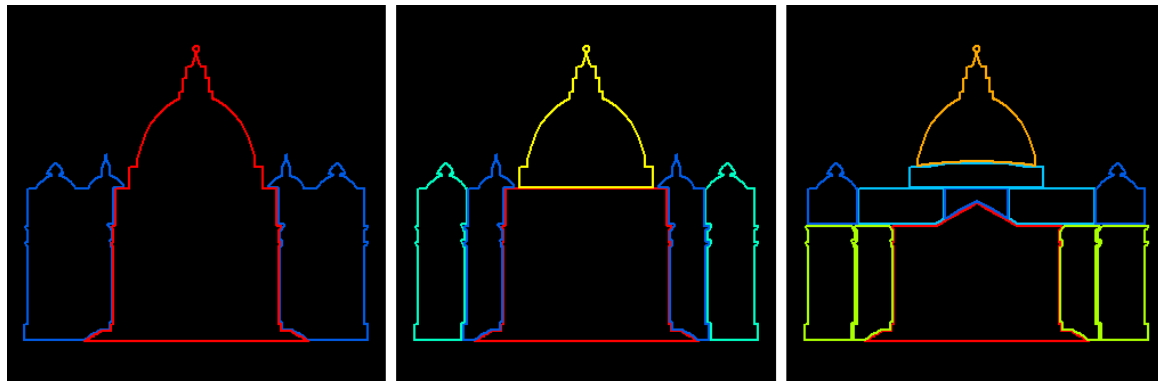


Figure 1. Facade of the St Peter's basilica with scaling patterns across multiple scales. Large areas are denoted by warm colors, while smaller and more numerous areas are denoted by colder colors [23].

Using common methods of visualizing data is not sufficient, as they are bound by the Euclidian way of thinking. The classification of data has a large impact on the overall visualization, and for this reason it has to be changed to conform to a fractal way of thinking. Jiang [24] has done just that by developing a classification method that is able to show the underlying long-tailed distribution inherently visible within spatial data. This method is called head/tail breaks, and it works by dividing the data into two parts over and over again (recursively) around the mean. By recursively dividing the data into a larger set (the tail) and a smaller set (the head), a classification is built which naturally follows this long-tailed distribution. Getting back to the organized complexity from Jacobs [8], this means that head/tail breaks allow different parts of the web to be visualized. This also fits into the theory of centers Alexander advocates [4]. By being able to identify these centers with classification, visualization and empirical measurement should become possible.

People's movement within urban areas is bound by their structure, and this structure is reflected in either building outlines or more specifically roads, as they are used directly as transportation routes. When navigating, the shapes of the streets do not matter, but rather to which streets they are connected. The connections between streets have been measured by drawing axial maps [25]. As a successor to axial maps, Jiang and his colleagues [26] developed natural streets. By determining the connectivity between roads in a city with a bottom-up approach, the structure of the road networks within a city can be analyzed. Next to natural streets, another bottom-up approach is followed to analyze and define cities. This paper uses natural cities [27] to define cities where possible based on road network data. This is a method which is, compared to the use of a grid-based approach or a kernel density analysis, a good estimator [28]. By determining the borders of a city based on naturally occurring structural characteristics such as the road system, there is a consistent way of determining where the borders of the city are. Additionally, when certain city parts are not within this border, there must be an explanation of why this would be the case. Note that this is a different definition of natural cities defined by Alexander [15] as he defines natural cities as naturally occurring cities, as opposed to naturally defined city edges.

Additionally, when data contain many more small points than large ones, it is expected to follow a powerlaw distribution. Many natural, social, and physical phenomena can be described by the powerlaw distribution [29–31]. The implication is that the data which follow the powerlaw

distribution better are seemingly also more natural. Therefore, analyzing the powerlaw distribution in topological data can be used as an additional measurement to verify the measurement of living structure. Altogether, living structure can be measured by looking at a combination of natural cities and natural streets, where especially the hierarchy within natural cities and natural streets indicates the livingness complemented by the powerlaw statistics.

3. Measuring Living Structure in Cities Comparatively and Temporally

Within this research, only one main data source is used, which, combined with GIS techniques, leads to our results. Raw OpenStreetMap (OSM) data obtained from geofabrik.de are used as a basis for all further analyses. OSM data are particularly useful because, as volunteered geographic information, the general accuracy within urban areas is good [32]. The geometric accuracy of volunteered geographic data can be less good; however, because of the nature of this research, geometric accuracy is not important, but rather topological accuracy is. The length and position of road segments have little effect on the analysis, and the connectivity between different segments is what is crucial [25]. Because of how we usually navigate ourselves, junction to junction, these are often represented accurately. Even though this research focuses on city morphology, it is important to obtain data from a whole country because cities are part of the wholeness of a country. City boundaries are therefore determined based on the road dataset of an entire country. Table 1 indicates the chosen countries and cities which are analyzed, the determined city type is dependent on the historical background and age of the city.

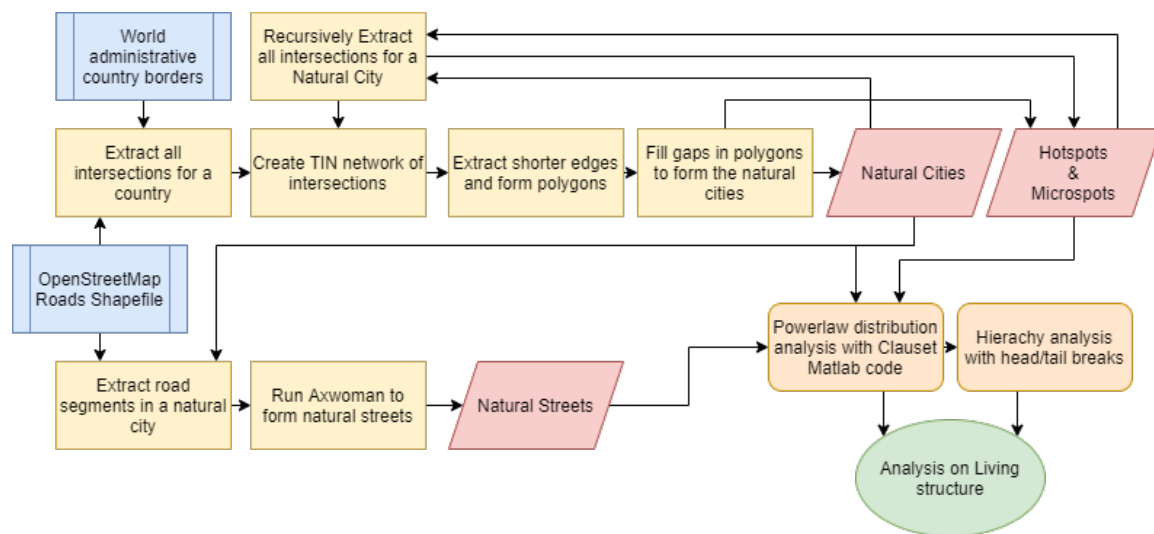
Table 1. Chosen cities and study areas within this case study.

COUNTRY	CITY	CITY TYPE
Netherlands	Amsterdam	Historical
Italy	Rome	Historical
	Genoa	Historical
United states	Levittown	Artificial
India	Chandigarh	Artificial
Brazil	Brasilia	Artificial

To be able to analyze and compare the six different cities with and to each other, firstly the cities need to be defined. This is done by generating the natural cities of each country [27,33], which identifies cities based on a bottom-up approach where a pre-existing structure determines the city borders. This is instead of arbitrarily defined municipal borders, which may cover more area than the actual city or vice versa. It is important to identify the city correctly, because living structure is measured according to the whole city, where it is important that the start and end of the city according to existing physical information is measured correctly. For the generation of natural cities, the road network is therefore taken as input information. Cities are identified based on the distance between intersections. If an area contains many intersections, the assumption is made that there is a city there, while areas with few intersections are considered to be rural. Scheme 1 illustrates this methodology, which is followed schematically.

A triangulated irregular network (TIN) is created from all intersections within a country derived from all road classes in the OSM roads. Connections between intersections and isolated by extracting the individual lines between points from the TIN. Then, the distances between each intersection are calculated. The obtained distances per country are analyzed with head/tail breaks to separate long-distance rural intersections from short-distance urban intersections. There are differences between countries; for countries with a relatively uniform road network, like the Netherlands, only one separation is made to obtain natural cities. In larger countries with a greater difference between urban and rural areas, such as Italy and Brazil, there are several more iterations of head/tail breaks because the first break only separates the mountains in Italy or rainforest in Brazil. A second break is needed to

subsequently separate the rural areas from cities. Figure 2 shows the process of generating natural cities for the area of West-Friesland in the Netherlands.



Scheme 1. The GIS operations and methods used to obtain the results. Blue (rectangle with lines) indicates outside input data, yellow (rectangle) indicates GIS operations, red (parallelogram) indicates main results, orange (rounded rectangle) indicates data analysis, and green (ellipse) indicates the final result.

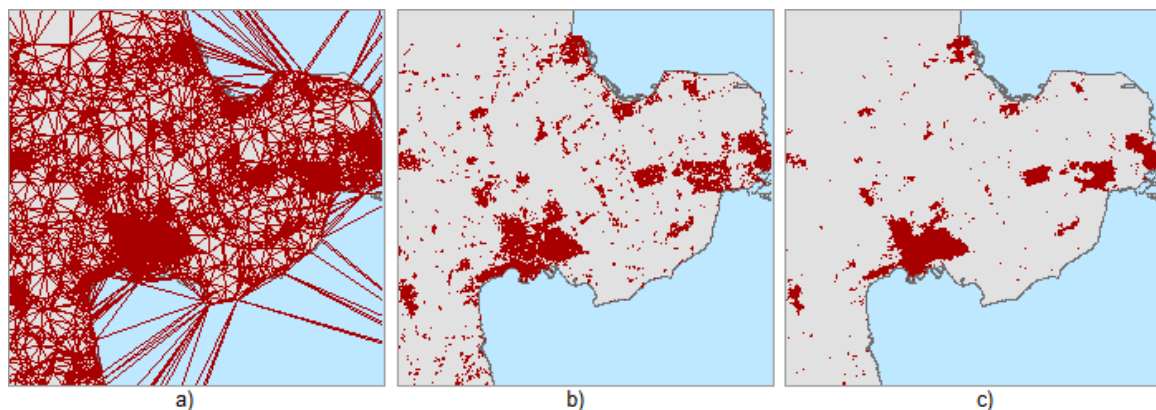


Figure 2. Generating natural cities from road intersections. Panel (a) shows the constructed TIN lines connecting each intersection to each other based on proximity. Panel (b) shows the same dataset, however the longer distances determined by head/tail breaks have been removed. The final panel (c) shows the natural cities derived from the input OSM roads [23].

After cities are identified, now the inner city structure can be analyzed. To determine the center of the city, the streets and its connections to other streets are used. Areas with streets which have a relatively low street connectivity are calm and, vice versa, streets which have a high connectivity indicate many routes using that street, thus it is located in a busy and central area. To be able to determine the connectivity of roads, natural streets are used [26]. The generation of natural streets is calculated with the Axwman software [34]. This software considers roads to be self-organized, and based on the Gestalt principle of good continuity individual road segments are connected to form the natural streets. After the creation of the natural streets for each city, they are classified with head/tail breaks from their connectivity. This process visualizes where the most well-connected streets are located within a city. It also shows the underlying structure of the road network by highlighting the busiest roads and the quietest areas.

Differences between historical cities and artificial cities are looked at by analyzing the structures present in the natural cities of the countries and the natural streets of the cities themselves. In addition, hotspots within cities are identified using the natural city approach recursively for inner city structures. A hotspot is essentially a set of natural cities (inner city structure) for the selected natural city (city borders). The largest hotspot can then be analyzed in the same way to identify microspots, which are the densest areas within the hotspot. Classifying the different hotspots and microspots according to head/tail breaks visualizes the inner city structure based on its density. By looking at the natural cities, hotspots, microspots, and natural streets, an approximation of how living they are can be made by looking at the scaling patterns and ht-index—i.e., the amount of classes in the head/tail breaks classification [13]. Finally, their powerlaw statistics are looked into. Powerlaw statistics are obtained using the MATLAB code developed by Clauset and his colleagues [29], and the parameters are calculated using a maximum likelihood ratio test.

To support this methodology and to indicate a more natural growth pattern, the historical cities are also analyzed temporally. Using historical maps, the size and developments of a city can be discovered. Amsterdam is chosen to show historical development over time, as this city has a lot of detailed information about its past. The road patterns in Amsterdam are analyzed by taking the current OSM roads and clipping them by the size of the historical city taken from historical maps, which are georeferenced. Thereafter, natural streets are generated from these and presented with a head/tail breaks classification.

4. Analyzing Living Structure within Cities through Its Road Network

4.1. Measuring Living Structure

Living structure is recursive in nature; this means that a good living structure shows this recursivity more. Using these characteristics, it is possible to look at individual city districts and compare them. In the case of natural streets, a few larger roads need to be supported by many more small roads, and these smaller roads need to be supported by many even smaller roads for a good living structure. We compare two city districts of Brasilia and Amsterdam, which are shown in Figure 3. The natural streets indicate that, structurally, Brasilia is much less interconnected compared to Amsterdam. Brasilia has four large individual arms which are not interconnected, while Amsterdam is much more wrapped around itself and tiered, leading to a higher structural cohesion.

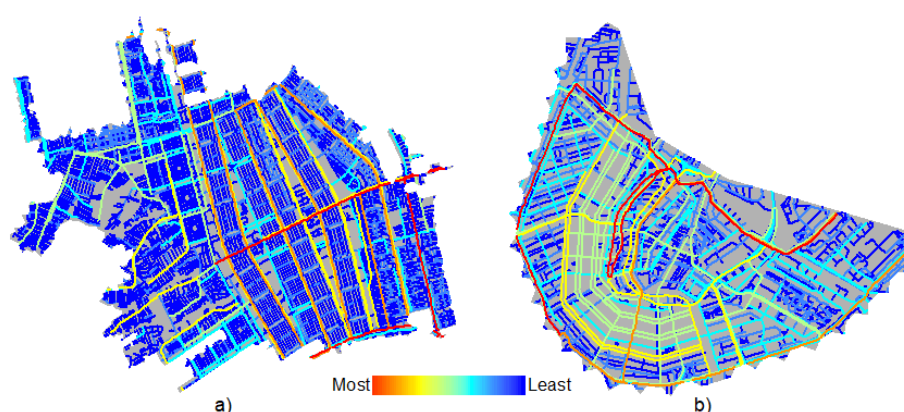


Figure 3. Natural Streets compared in neighborhoods. Warmer colors (red) indicate high connectivity, while colder colors indicate a lower connectivity (blue) Panel (a) shows the northwestern worker district of Brasilia and panel (b) shows the residential area around the city center of Amsterdam. It is shown that the roads in Brasilia are not very connected as a whole; there are 4 disjointed geometric arms in the middle running from north to south crossed by the red (highest connectivity) street which have no support from each other, while Amsterdam shows interconnectivity within the city center, with an onion-like support.

Complementary to a city's natural streets, hotspots and microspots are analyzed. Living structure supports itself at different scales, therefore structures which have greater wholeness will show scaling law soundly across all scales. Amsterdam, Rome, and Brasilia are compared, where the largest hotspot in the city center is selected for a microspot analysis. In Figure 4, the hotspots and microspots are shown classified according to their size in head/tail breaks. The hotspots in Rome show the best natural structure—there is a clear center with supporting hotspots around them; subsequently, this pattern continues within the city center. This pattern is less clearly defined in Amsterdam because of its rapid expansion after the Second World War. The overall structure of Brasilia is already disconnected because of its disconnected natural city, which results in its hotspots also being very large and unnatural. Because of the elongated shape of its largest hotspot, the edges of this hotspot seem to have very little support, and also the biggest microspots are all located in the center, leaving the different scales of microspots disconnected from each other and reducing the support they can provide to each other. This, therefore, violates the prerequisites for good living structure, as the support across all scales is lacking.

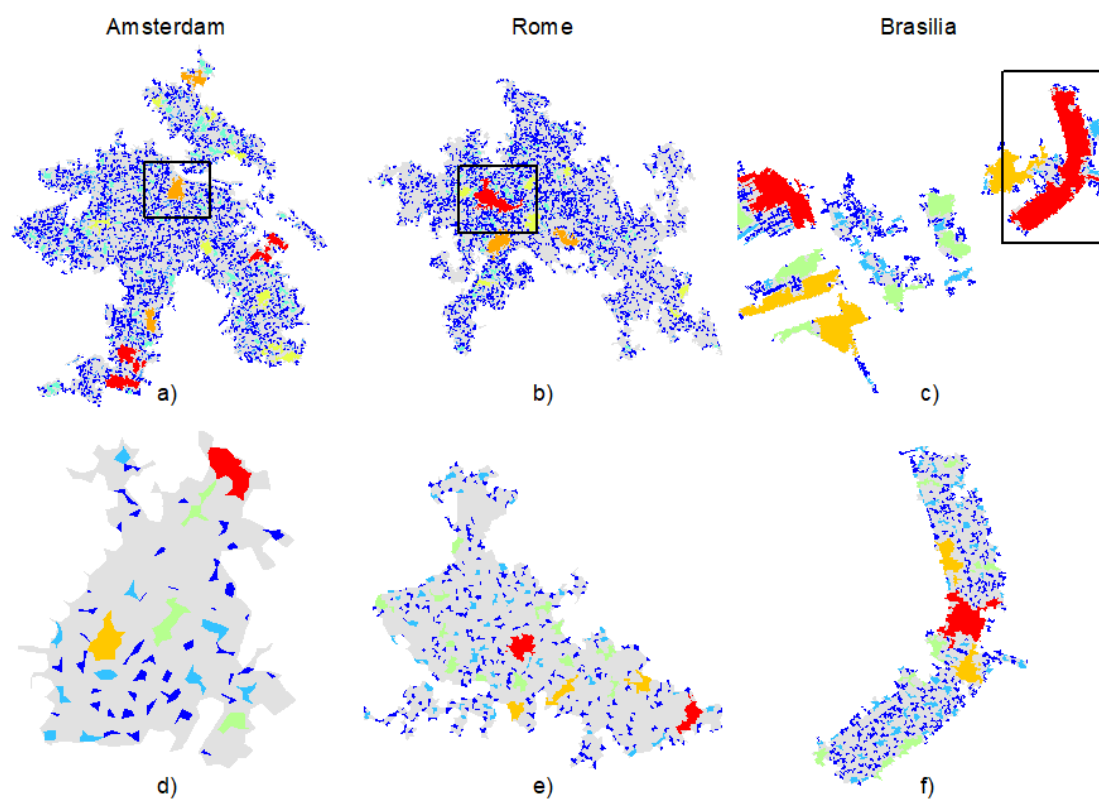


Figure 4. Recursive natural city analysis. In panels (a–c), the natural cities of Amsterdam, Rome, and Brasilia are shown with their hotspots. In panels (d–f), the microspots in their main hotspots are chosen. For Rome and Brasilia, they match the biggest hotspot. In Amsterdam, the hotspot laying over the center is chosen instead of the largest one, as denoted by the black boxes in the first three panels.

Looking in further detail at the microspots, Rome lacks a well-defined center, which is indicated by the fact that there are two largest centers (indicated in red in Figure 4). This can be explained because of the location of the Termini train station, which is the western large microspot. This is a very dense area on the edge of the central area in Rome. Amsterdam's biggest microspot is also located at its central train station. The microspots within the main city area of Brasilia show a better structure than the hotspots, however there are still issues. The difference between the largest microspot and the second largest microspot, for example, is very large. In Amsterdam and Rome, these differences are more gradual. It is more difficult to support a large structure with two far smaller structures; moreover, they are also located right next to the largest microspot. This does not represent a self-supporting

structure. Even though the scaling within Brasilia's microspots seems correct, with far more small than large areas, the distribution is completely off, making its structure not very living relative to Rome and Amsterdam.

4.2. Comparing City Types

The difference in livingness within cities can be attributed to the way the cities are developed. In this section, two city types are analyzed in further detail. Historical cities, which are developed over a long period of time and have a registered history, and artificial cities, which are mainly planned in full before the city exists, are compared to each other by looking at their natural streets and their hotspots, as these indicate differences in livingness. Amsterdam, Rome, and Genoa are selected as historical cities, and Chandigarh, Levittown, and Brasilia are selected as artificial cities. These cities are similar in size and population to each other, except for the smaller population of Levittown.

In Figure 5, the differences between the hotspots of the six analyzed cities are shown. We observe that the scaling pattern is much better defined in the historical cities compared to the artificial cities. Even though the ht-index is similar, the different classes are much better defined in the historical cities. Especially Rome shows a good self-supporting structure. The biggest difference which can be observed is that, for the artificial cities, most of the hotspots are in the (invisible) first class of smallest hotspots, while this is far better divided across the next classes. This indicates that the artificial cities have far fewer centers which support the underlying classes, which in turn indicates a lower level of livingness.

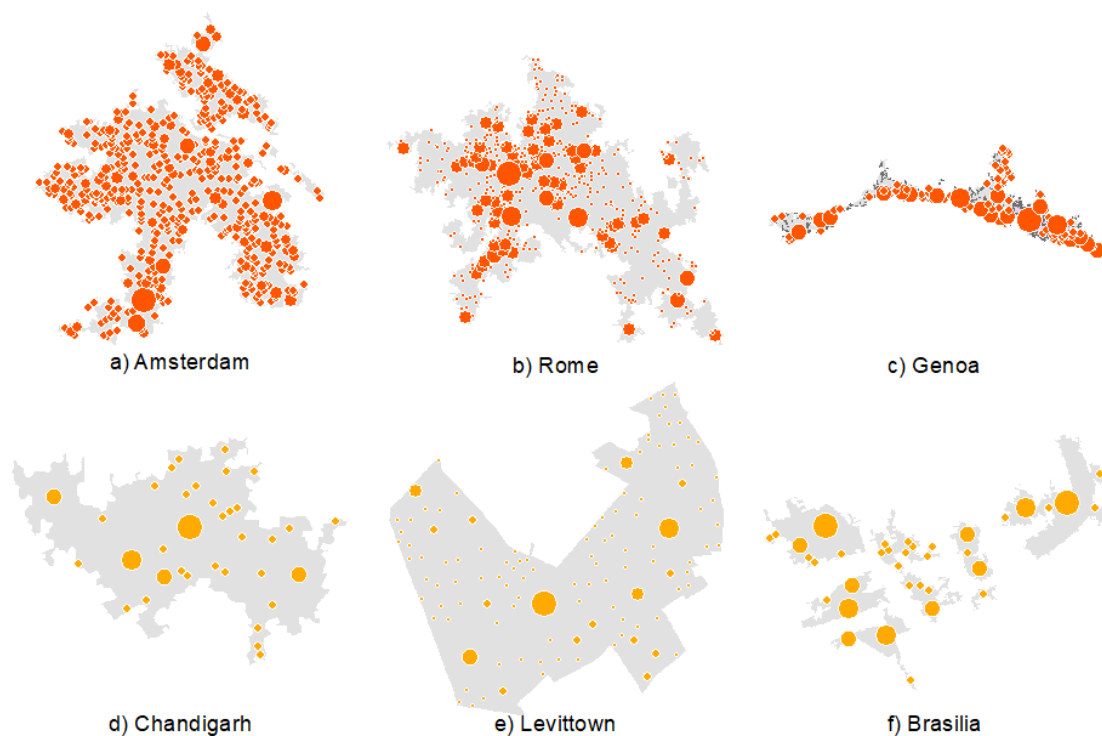


Figure 5. Hotspot comparison between artificial and historic cities. Each city shows its hotspots within its borders. Hotspots are classified according to head/tail breaks. In red, the historical cities are shown (a–c), and the artificial cities are shown in orange (d–f). For visualization, the lowest classes within the head/tail breaks 2.0 are not shown except for Levittown, which shows all classes. Larger hotspots are shown by the larger circles, and the smaller hotspots are shown in smaller circles, classified according to head/tail breaks.

Complementary to this are the statistics in Table 2; the average size of the hotspots is a good indicator of this phenomena. The hotspots are far smaller on average in the historical cities, which highlights

a much more intricate inner structure due to the differences in observed density. Because of this, there are also relatively fewer hotspots in the artificial cities because there are no clear borders or differences in density; lots of areas form together because they are so similar, and thus non-living. Finally, the ht-index is, on average, slightly higher in the historical cities regarding the hotspots, so not only are there more hotspots, but they are also structurally more recursive in size.

Table 2. Comparison of statistics between the six analyzed cities.

	Amsterdam	Rome	Genoa	Chandigarh	Levittown	Brasilia
Size	119	303	64	266	27	218
Population	850.000	2.500.000	580.000	1.000.000	50.000	2.500.000
Hotspots total amount	3.647	4.174	1.223	804	116	1.091
Average Hotspot Size	5.366	7.828	11.137	109.344	52.384	122.216
Hotspot ht-index	8	6	5	5	6	5
Hotspot α (Powerlaw fit)	1.99	2.02	1.76	1.77	1.86	1.56
Hotspot p (Powerlaw fit)	0.93	0.92	0.93	0	0.81	0.09
Hotspot x-min (Powerlaw fit)	4941	6378	1415	13243	16547	2097
Natural Streets total amount	23.787	34.378	12.789	12.687	1.079	26.876
Avg (max) Natural Streets Connections	5 (386)	4 (184)	3 (419)	4 (68)	4 (145)	4 (389)
Natural Streets ht-index	9	11	8	11	7	10
Natural Streets α (Powerlaw fit)	2.59	2.63	2.63	3.46	3.46	2.79
Natural Streets p (Powerlaw fit)	0	0.03	0.02	0.64	0.64	0.65
Natural Streets x-min (Powerlaw fit)	7	4	3	9	9	11

The hotspots of the cities indicate that the three historical cities are more living and thus more whole compared to the three artificial cities. Complementary to this, the natural streets are also compared. In Figure 6, the natural streets of the six cities are compared and there are clear differences between the two city types but similarities within. From the structure of the natural streets, we observe that Amsterdam can be considered, in terms of natural streets, the most living because it follows the expectation of a whole structure the best. The most well-connected street is in and around the city center, while the other well-connected streets diverge from and connect to the largest street. The most well-connected streets in Rome are directed towards the center, indicating that the city center is probably the main destination for many travelers here. Genoa shows through its elongated shape a living network where the most well-connected streets are located along the coast, which then branches out through the rest of the city.

Contrary to the higher degree of life of the historical cities, the artificial cities show a lack thereof. Chandigarh has its most well-connected road on the edge of the city, and there is no support from other roads. There are smaller structures visible which indicate the square city districts, but they are disconnected from each other, and the second most and third most well-connected streets are disjointed and only connect to the ends of the other well-connected roads instead of around their centers. Levittown shows a similar structure, where the main roads, in terms of connectivity, are not in the center. The major road is expected to be along the horizontal axis to cover the area. Here, the different areas within the area are singular structures which are loose, and lots of the support is from the second smallest roads. Lastly, Brasilia's natural streets are located along the axis of the district, which is good, however they themselves are not connected to each other and, without support from the underlying classes of roads, the degree of life is much smaller.

The natural streets seem to be similar for all cities if only the statistics (Table 2) are taken into account, however this is incomplete. Even though in the ht-index the amount of natural streets and the average and maximum connections are comparable, the way the natural streets are laid out is very important in interpreting the degree of life. Similar to the hotspots, the spatial location of natural streets can greatly affect wholeness. Although a structure exists over multiple scales, the support each scale receives from each other is instrumental in determining the degree of life.

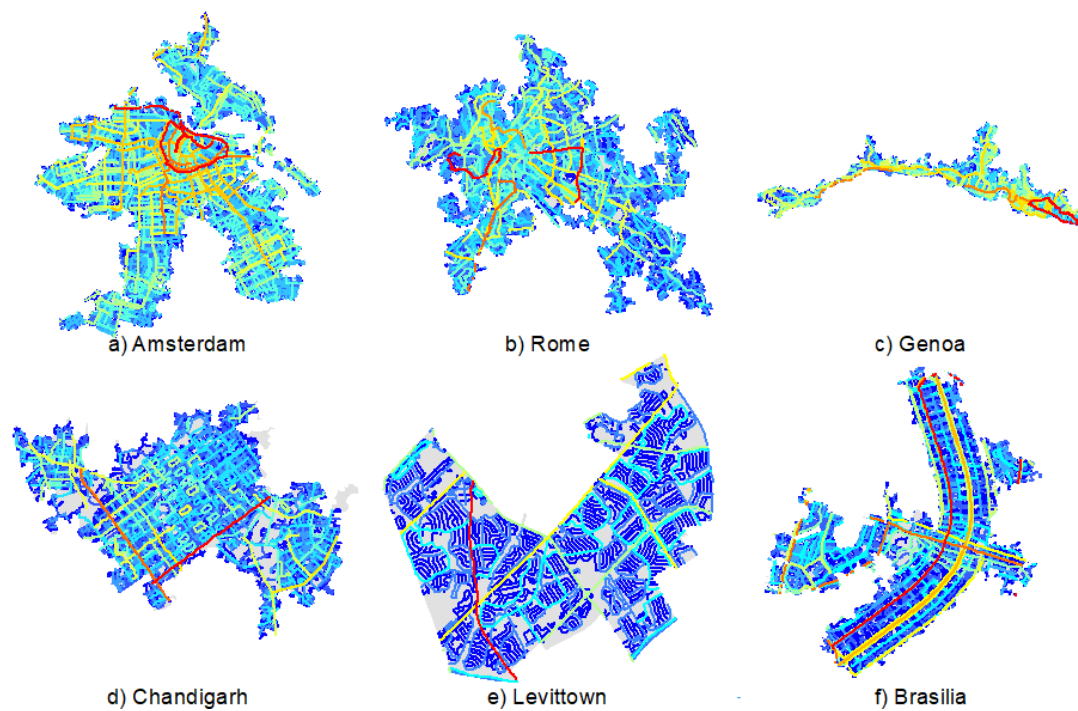


Figure 6. Natural street comparison between the artificial and historical cities. In warmer colors (red), the most well-connected natural streets are shown, with colder colors (blue) showing less connected streets. The top panels (a–c) show historical cities and the bottom panels (d–f) show artificial ones. The natural streets are classified according to head/tail breaks, and more details can be found in Table 2.

By analyzing the powerlaw plots seen in Figure 7, it becomes clear that all cities for both the natural streets connections and their hotspots are fairly well powerlaw-distributed for large parts of the distributions. For the natural streets, only the artificial cities are statistically powerlaw-distributed (see Table 2), however the alpha value corresponding to that fit is very high (>3) [29]. Additionally, the best fits for the artificial cities have a relatively high x-min, therefore a lot of the less well-connected streets are omitted in the best fit. For the hotspots, only the historical cities and Levittown have a significant powerlaw fit, and from the graphs we see that the historical cities have generally smaller hotspot sizes, with better support from the smaller hotspots. Levittown is still fairly well balanced, however it does not have many smaller hotspots, thus they lack the first level of basic support from the theoretically smallest hotspots.

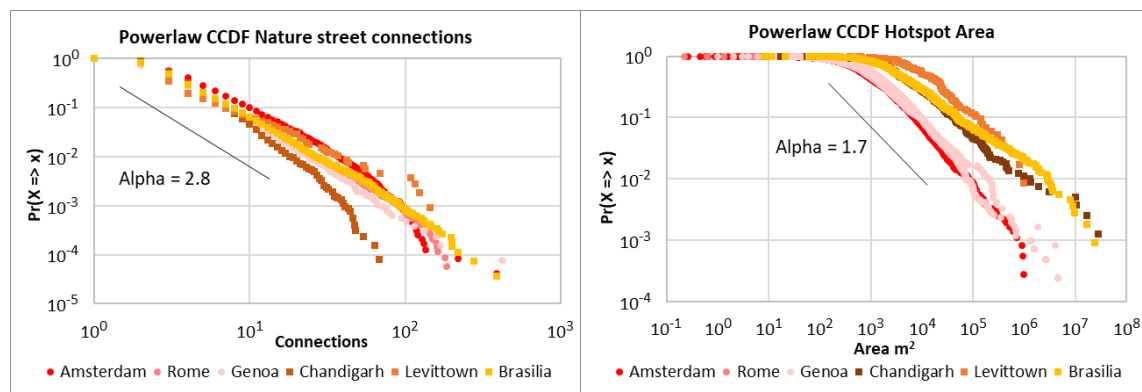


Figure 7. Powerlaw plots of the natural street connections and hotspot areas.

4.3. Temporal Analysis

To understand the reason why historical cities exhibit more wholeness compared to artificial cities, the historical development of Amsterdam is further looked at. Figure 8 shows Amsterdam's development over time. This figure shows a very natural development path; the city is expanded while the city's structure remains intact. The most well-connected roads show little change and only increase in size when the city grows. Because the current city center is based around this structure and because it remains intact to this day, modern Amsterdam still has a very living city center structure.

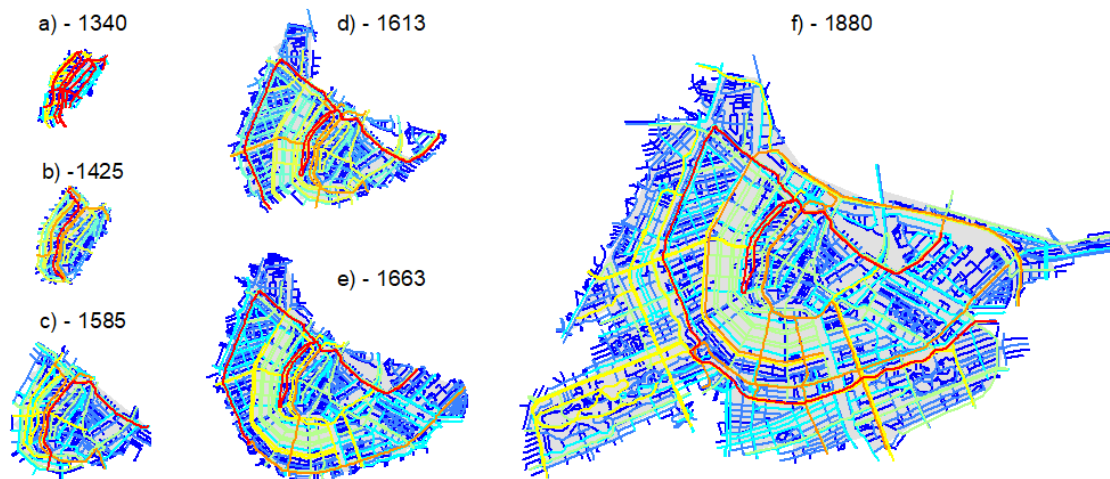


Figure 8. Historical development of Amsterdam. Well-connected streets are denoted by warmer colors (red), and the least connected streets are denoted by colder colors (blue). This shows that slow historical expansions leave living structure intact, as seen by the most well-connected street (in red) expanding and being located centrally.

5. Discussion on the Study

The change between historical and current developments leads to a destruction of living structure and even to a complete lack of living structure in cities. Our external world does not match our inner experience any more [4]. This disconnect within urban morphology can directly affect our health [35,36]. People rate and enjoy natural environments higher than geometrical unnatural places. Major threats to the preservation and creation of living structure are not only the current development speeds, but also the current dominant architectural views. Development speeds lead to shorter timespans to decide upon and design new urban areas. Once built, these areas have to last many more years; a quick decision can have a lot of effect later on. This can lead to citizens who are forced to live in environments which are sub-optimal, consciously or unconsciously. Not only the building distribution but also the buildings themselves need to be considered regarding what effect they can have on the environment in terms of overall structure—i.e., wholeness or livingness. More often than not, current architecture is detrimental to living structure [16]. For this, the current pre-existing networks and scaling patterns of the environment need to be considered when developing. When a transplantation is done in a human, both existing and new tissue are connected. A city development should not be considered only as an individual expansion, but also in terms of how it fits in the overall city.

Other possible ways of analyzing living structures include, instead of using street wholeness analysis, city buildings or city blocks being taken as a structure as a whole [33]. This type of data is also available worldwide, and the general methodology would be very similar. By assigning values to city blocks or buildings, an extra dimension within the data may be researched. Museum buildings and office buildings provoke different feelings within people, and thus their place within the urban morphology is optimally different. A combination of façade analysis [36] and analysis of the building structure as a whole can provide a detailed assessment of a city's structure and livingness. In addition to

this, the relations between objects can be determined on a polygon to polygon basis. This research uses intersections, which are point to point relations, to determine natural city structures. By considering the polygon as a whole, the analysis might become more accurate. The resulting changes will likely not be very big, but for specific locations or planned developments they may work as a tool for planning purposes. By incorporating livingness into the planning process empirically, future decisions may lead to a better and more sustainable environment.

The natural bottom-up approaches used to determine city borders, city centers, and also which roads can be considered as one are both based on a topological approach. Many common methods of GIS depend on the geometry of features, such as, for example, grid-based approaches such as kernel density estimation (KDE) or top-down definitions such as census data. The approaches taken in this paper are based completely on the data themselves, and due to these data following a power law distribution these methods can be conducted recursively, as there are similar structures on different scales. The determined city borders and city center borders are based on road density itself; population density or building density may provide different borders, however road networks itself are found to be a good proxy for the actual city edges [37].

Additional data sources can also be used to determine city borders and city density—for example, using social media outlets, geotagged data. Hollenstein and Purves used geotagged Flickr data to determine city centers; it was found that these data followed a long-tailed distribution and that they were only reliable in certain areas [38]. They then used KDE to visualize the long-tailed data. This is a good example of where the approach of this paper differs and why. Due to the data being long-tailed, it is very hard to describe them with a Gaussian-based method (KDE). This methodology is used more often [39], and the reliability of these types of data remains questionable [40]. This paper uses head/tail breaks to describe long-tailed data, which far better fits these types of data. Additionally, the shortcomings of social media-based data are that they are not always available due to privacy concerns. By using OSM data, which are much more mature and also freely available [32], we circumvent these issues.

6. Conclusions

Living structure can be measured using natural streets and natural cities. Expectations that historical cities exhibit more livingness compared to artificial cities are confirmed through the analysis of the distributions and spatial locations of natural streets and recursive natural city analysis. More data are necessary to investigate mixed cities, however, and how they can be compared and measured. Empirical measurements can be conducted to compare the degree of life of different cities with each other, however measuring livingness directly is not yet fully developed. Through the use of head/tail breaks and scaling analysis, direct comparative data are generated and compared. Only using the ht-index, however, is not sufficient for the whole analysis, and powerlaw analysis provides valuable extra information. On the other hand, natural streets and natural cities can be independently generated with a bottom-up approach, creating data which are unaffected by governmental or other influences.

The results show that the analyzed artificial cities have much more structural issues when living structure is considered compared to historical cities, but since the 1950s–1960s historical cities show similar developments to artificial cities, and their structures have also started to show more issues and similar characteristics to those of the artificial cities. This indicates that historical city centers on their own retain their relatively high degree of life due to their already established morphology, while newer developments mostly lag behind because of their development speeds and disconnectedness. In general, developments in the period before the Second World War seem to have increased livingness and wholeness, while the developments in the period thereafter have been more detrimental, which can most likely be attributed to building speeds, the focus on costs-effectiveness, and the fact that development areas are treated as their own whole. Because of the increased use of concrete, glass, and steel, building development has become much cheaper and faster, which is a good thing, however building design and architecture has followed this trend, leading to structureless buildings and urban morphology which lacks living structure.

By looking at the development path of historical cities, it is shown that development is possible where the overall degree of life is strengthened by supporting the pre-existing inner structure of the city. This can serve as an example of how to retain or improve living structure in our current cities. Other historical development paths can also be analyzed further in a similar fashion to fully understand how living structure evolves and how it can be improved or when it is decreased. Another very important step is that cities are considered as a whole. Developments should be considered as an addition to the entire existing structure, as they will not only affect the direct neighborhood, but also the greater structure of the city due to the disruption of organized complexity within the city and its subsequent adaptation to the new situation. The natural street and recursive natural city analysis provides an accessible way to do this.

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Data Availability Statement: The OpenStreetMap project data which the findings of this study are based on are available at <https://download.geofabrik.de/>. The used Clauset Matlab powerlaw code is available at <http://tuvalu.santafe.edu/~aaronc/powerlaws/>. The axwoman software for the generation of natural streets can be found at <http://giscience.hig.se/binjiang/axwoman/>. Head/tail breaks tools for the calculation of head/tail breaks are included in the axwoman software and alternatively can be found at <https://github.com/ChrisdeRijke/HeadTailBreaksCalculator>. The data the figures are based on with tutorials of how to generate them are available at: <https://doi.org/10.6084/m9.figshare.13102868.v3>.

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