THE PLEASURE OF WALKING IN A NEIGHBOURHOOD: THE PEDESTRIAN ROUTE NETWORK AND ITS FRACTAL DIMENSION AS A TOOL FOR THE ASSESSMENT OF THE RIGHT BALANCE BETWEEN CHAOS AND ORDER

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ABSTRACT

Many cities suffer from a lack of walkability. Besides physical preconditions like safe sidewalks and pedestrianized areas the density of the pedestrian network and the planar distribution of routes opening up the area of a quarter or the city. The fractal dimension (FD) is a measure that describes how far a pattern or grid spans and covers a two dimensional area. For areas in the field of view (like paintings) literature reports that values between 1.3 and 1.9 are perceived as most agreeable and stress reducing. This paper investigates if the FD can also be applied to assess the walkability of pedestrian networks. That is not trivial because, for a walking person, the network is not in direct field of view but only perceived with all senses. The research question is, if pedestrian networks behave fractal in the range where they are delivering best preconditions for walkability. For real networks, the loop-wise calculation of FD is best appropriate; here a box-counting method is used. The box edge length corresponds to the distance that a pedestrian must walk ahead until the next possibility where a decision to turn or not appears. So more such junctions exist, so more walkable is the quarter. Typical preferred distances are few meters to about 50 m. The results show well, that for as walkable perceived quarters, the network behaves in fact fractal with FD in the preferred range 1.3–1.9 and at box edge length' of 5–50 m – and vice versa. Objects of investigation were pedestrian networks out of the city of Hamburg, Germany, one car-oriented, one that is perceived as walkable and one of the newly constructed quarter HafenCity. The car-oriented quarter is widely out of the described range, the walkable one widely in. Finally, historical cities (Salamanca, Spain and the Islamic town Harar Jugol, Ethiopia) were analysed to find out if their networks (out of times without cars) are walkable and behave fractal. As to be expected, both could be confirmed. It can be concluded, that FD can well be used as an indicator for the walkability of pedestrian route networks.
Keywords: chaos and order, fractal dimension, indicators for walkability, modern space planning, pedestrian route networks, walkability of quarters, walkability.

1 THE PLEASURE OF WALKING IN A NEIGHBOURHOOD

In daily life, walking in a city is related with one of our usual routes thus starting at a location A and moving to a target B. But supplementary the process of walking itself can be a high human pleasure, sometimes we walk through a city without a special target, just for walking and exploring. All our five senses are activated and expecting positive impressions, we appreciate the physical activity itself, to watch facades and urban other elements, to be with our hands and body in direct touch with nice and natural materials and shapes, to smell the fragrance of flowers, to hear the sound of sparkling water and last but not least the urban life. All that we can enjoy only on the pedestrian level, at a scale, that corresponds to the physical scale of our bodies and thus the smallest scale in the built environment of a city.

A pleasurable walking will be complemented by periods of a shorter or longer stay to enjoy the decoration of facades, elements to sit or lean on, trees, bushes, kiosks, shop windows, places that invite to stay, to watch the human theatre, etc.

Under the five senses the visual one is dominant. Following Jan Gehl [1], our brain is asking for new (optical) information each 5–10 s. A pedestrian is walking with about 5 km/h

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Hamburg-Bergedorf, [2] | HafenCity Hamburg (picture: author)

Figure 1: Streets that are tailored for different speeds. Left for pedestrians with separations in short distances (10–15 m), delivering new impressions every 5–10 s; a pleasure to walk along. Right with separations only every 30–50 m (finer separations do exist but are nearly invisible by the contemporary architectural design), delivering new impressions every 5–10 s only for car drivers; to walk along is perceived as boring.

(1.4 m/s). That leads to the conclusion that facades should offer new impressions like different shop windows, vertical separations, etc., every 10–15 m. Because our view is horizontally that holds especially for the ground floors.

In today's life, people move forwards with different velocities, bicycles with 10–15 km/h, and cars with about 30–50 km/h. That world of different speeds is asking for new impressions at different distances (bicycle 20–25 m, car 50–75 m). Car drivers passing through a street with separations at pedestrians scale are overloaded with information and confused; pedestrians a in car-oriented world suffer under a lack of information and feel bored (see Fig. 1).

2 THE PEDESTRIAN ROUTE NETWORK AND THE ITS RIGHT BALANCE BETWEEN CHAOS AND ORDER

The term route network holds for the entirety of all walkable areas like pedestrian paths, sidewalks, plazas, etc., if the word street is used for simpler expression, its sidewalks are meant. This paper is dealing with the internal organisation of a route network, other aspects that may determine walkability even basically like protection against car traffic, width of sidewalks, distance to next public travel station etc. are not regarded here.

Walking along a street can be a high pleasure – but what happens at the end of that street or if we reach the next cross road? We have to decide where to continue, straight on, left or right. With this we open a second dimension from the linear street to the surrounding ones that form finally a route network.

Which (physical) quantities must such a route network have that we enjoy walking in it? It may not cause negative impressions like the feeling of getting lost or even the feeling of nothing new and boring. Even if one half of the brain is curious and running behind new impressions without asking where we are, the other half is behaving more rational and wants roughly to know where we are or that we need to walk only a few minutes to find a point of re-orientation. Both aspects should be fulfilled–what kind of internal organisation of the routes in the network would satisfy us best?

The answer is of course (and fortunately) that there is not only the one optimal network but infinite possibilities how it may look. In a completely chaotic network humans would not have any orientation and get lost. A completely ordered network is easy to understand and

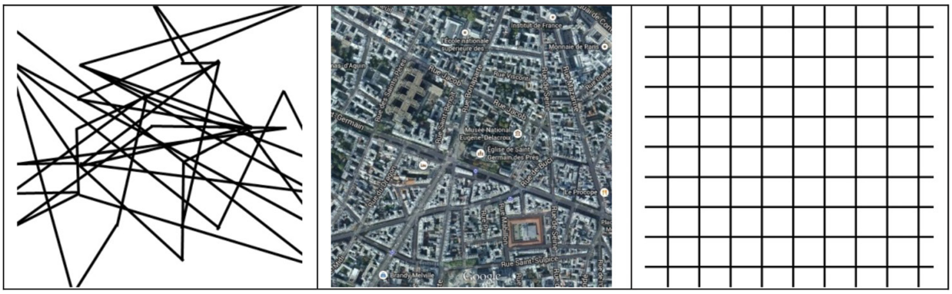


Figure 2: Three different types of pedestrian networks. In a chaotic one (left, made with a random number generator) one would feel lost. Also in a completely ordered one (right) there is now knowledge of being where (lack of reference points). The picture in the middle [3] shows a section of highly walkable Paris Saint-Germain with a lot of small streets and a few bigger streets for orientation.

orientation is possible if there is a signage with numbers or characters. But in spite of that there is a lack of orientation points and the corresponding feeling of not knowing where one is, highly ordered networks are felt as boring. The preferred system would be to find a huge number of small routes and streets with more than one option where to go on a crossroad. It is felt positively to meet from time to time a bigger street or place that helps to understand and perceive the organisation of the network. Streets should have different shape, size, facades etc. but form all together a unity that describes the identity of the neighbourhood (see Fig. 2).

This description is quite precise in regards to the human needs and perception but still diffuse in regard to the distribution of the routes in a neighbourhood. To describe walkability in general a set of indicators was developed and discussed. Most of them describe aspects like connectivity, intelligibility, visibility, diversity and others [4-6]. Related by some weight factors they can be summed up in a point system to a walkability index [7-12].

Figure 2 shows that the well-working pedestrian network is somewhere between chaos and order [13]. Several indicators were developed for the analysis of the physical organisation of the network. The simplest ones count one quantity and relate it to the area (1 km² mostly) in which it is counted: the total length of all routes, number of nodes (cross roads) as well as number of links (routes). A bit more complex is the cyclomatic number [14] that connects the number of nodes (N) and links (L) to single information; it can be used as indicator for connectivity (eqn. 1 and Fig. 3).

$$\mu = L - N + 1, \tag{1}$$

Much more advanced is the investigation if the streets follow in their width and length a Pareto distribution [14], which means that the total length of streets with a certain width increases exponentially with its decreasing width (see Fig. 4).

All these indicators are quantitative; they count only different quantities but do not regards their distribution and relation in the two-dimensional network, do not describe the quality of the network. A high cyclomatic number as well as a Pareto distribution can be reached with a completely ordered (see Fig. 3) as well as a completely chaotic network. An investigation of the fractal character of a network might help further.

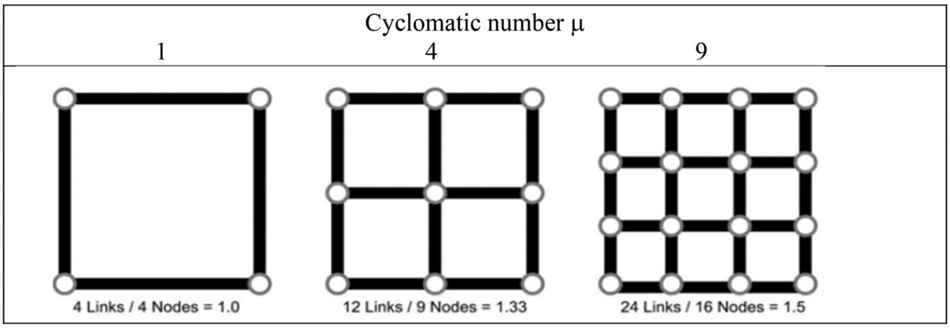


Figure 3: The cyclomatic number for selected regular networks. So smaller the grids size so higher the cyclomatic number, it acts as an indicator for connectivity.

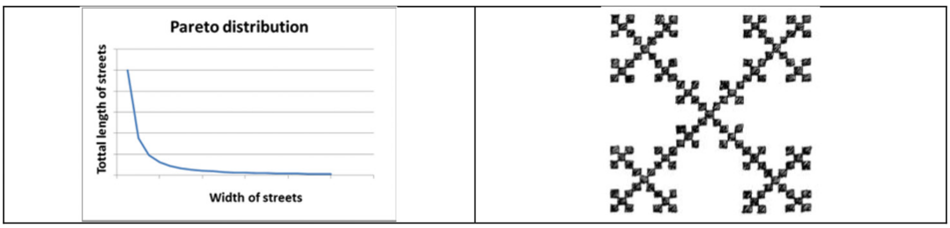


Figure 4: Left: Exemplarily Pareto distribution in a network, the relation between the total length of streets with a certain width and their street width. Right: Example of a fractal structure [12]. It shows the same distribution, the number of elements increases exponentially with their decreasing size.

3 FRACTALS IN MATHEMATICS AND THE REAL WORLD, FRACTAL DIMENSION

A fractal is a structure that shows a repeating pattern displayed at a wide range of scales. Ideal mathematical fractals have the same pattern at each scale, from the largest to the middle, smaller and also infinitive ones.

Fractals in the real world can be found in many fields. They occur in nature (see Fig. 4) as well as in architecture (facades, shape of roofs) or urban scale (street grids). Their scaling cannot be infinite like with mathematical fractals, the magnification as well as the diminution must have an end at a certain scale.

The fractal dimension describes the character how the pattern is subdivided. The example on top of Fig. 4 is subdivided in each step by a scaling factor ε of one third (in both directions, ending with 3 × 3 = 9 sub-fields). Out of these nine subfields, five are selected to form the next smaller pattern (number of new elements N). The fractal dimension D is then defined by:

$$D = -\log (N)/\log (\varepsilon). \quad (2)$$

For example, D can be determined with 1.46. If all nine elements would be chosen as new ones, D would be 2 – the fractal fills all the time the whole 2D-plane. If only three elements

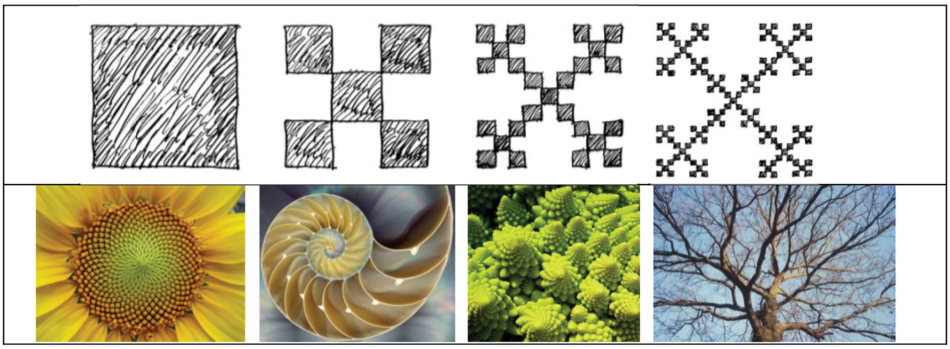


Figure 5: Examples for mathematical fractals (top, [15]) and fractal structures in real world (bottom; sunflower, snail shell, cauliflower, tree).

in a horizontal row would be chosen, D would be 1 – the fractal would reduce to a horizontal, one-dimensional line. Thus, for 2D patterns D is always a value between 1 and 2. So higher the D, so more the whole 2D area is filled with the pattern.

For fractals in the real world and especially pedestrian networks D cannot be neither 1 (that would mean only one single street with all the buildings left and right and thus no city) nor 2 (that would mean just a huge empty space for pedestrians only, without any building and thus no city at all), pedestrian routes can be only between the buildings, thus D must lie between 1 and 2.

Mathematical fractals can be subdivided and composed in both directions and infinitum. Objects on the real world cannot have the same character; there are limits on both ends by their own size and the smallest possible elements. They can behave fractal over a sequence of subdivisions. If that holds on over in minimum three subdivisions, the human eye perceives it as fractal (see Fig. 5 bottom). For that reason real objects do not have exactly one fractal dimension, it changes from subdivision to subdivision, only in the range where it behaves fractal it is nearly a constant value. Thus, the best way to determine the fractal dimension is to do it for each subdivision separately, in a loop-wise manner.

4 DETERMINATION OF THE FRACTAL DIMENSION OF REAL OBJECTS

A method that is well adapted for a loop-wise determination of the fractal dimension is to use box-counting. A neighbourhood where we like to walk along is good described by a representative section of 500 × 500 m. Inside of that quadrat all sidewalks, pedestrian paths and zones are marked in black (thus, on a standard street two sidewalks, left and right!). That 500 × 500 m is also the biggest box (one element $N1 = 1$). We count one if any part of the pedestrian network is in the box, if the box is empty, we count it with zero. The first box contains of course pedestrian routes, thus it is one filled box.

Now the box is subdivided, here a scaling factor of one half ($\varepsilon = ½$) is used. It results in four ($N2 = 4$) boxes 250 × 250 m. Very likely they are also all filled with pedestrian routes (4 filled boxes). The next subdivision gives 16 boxes ($N3$=16) with 125 × 125 m, etc. The fractal dimension of each loop can be determined with an adaptation of eqn. (2) [16, 17] (N_{before} and N_{after} is the number of *filled* boxes in the subdivision, b_{before} and b_{after} are the edge lengths of the boxes before and after resp.).

$$D = -\log (N_{after}/N_{before})/\log (b_{after}/b_{before}). \quad (3)$$

For the first two loops 500 > 250 > 125 m the result will be very likely D is equal to 2. With one of the next subdivisions the first empty boxes (= no pedestrian route in it) will occur – the part with the possibly fractal behaviour begins! If a box with only one straight line for any pedestrian route is subdivided, only one or two of the four sub-boxes will be filled; here the fractal dimension would be 1. If the box contains a crossroad where the pedestrian routes do split, more than two boxes will be filled after the next subdivision; the fractal dimension would be bigger than 1. Finally all the boxes contain only a straight route or are empty. The fractal dimension of that and all further subdivisions will be 1.

The best way to determine the fractal dimension of the network would be to present the results on accordance with the structure of eqn. (3) as a log-log plot. If the points for several subdivisions form a straight line that would be a sign for fractal behaviour and the slope would correspond to the fractal dimension D.

But for pedestrian networks another question is much more interesting: In which *range* the network behaves fractal? A human walking around in a city expects a quite dense network with a lot of small routes and streets but also a bigger street/place/landmark each few hundred meters to have good orientation. Transferred into distances that means a crossroad at about each 50–100 m and something that allows orientation all few hundred meters. Do walkable neighbourhoods show fractal character in exactly these dimensions?

5 FRACTAL BEHAVIOUR OF SELECTED NEIGHBOURHOODS IN A CONTEMPORARY CITY, THE CASE OF HAMBURG

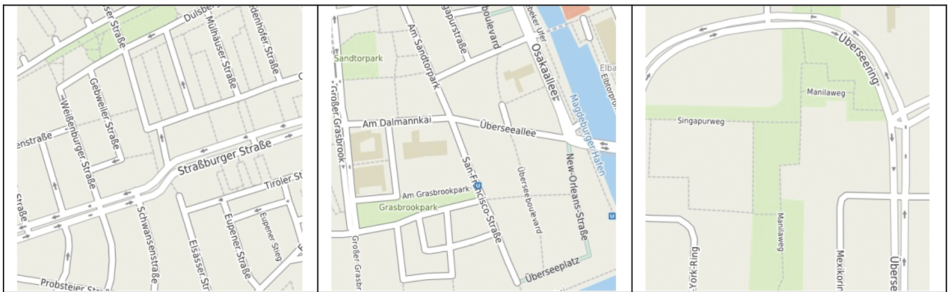
In the city of Hamburg three different quarters were selected to investigate their walkability, Fig. 6 shows the correspondent sections 500 × 500 m.

- Dulsberg: A residential quarter, erected following urban planning from 1918.
- The quarter is in general public opinion hold for walkable.
- HafenCity: A quarter with offices in majority but also apartments. Still in
- construction (2022), follows urban planning of about 2000. The public opinion fluctuates still between walkable and not walkable.
- City Nord: A clear, car-oriented urban planning from 1970.

Results show that Dulsberg and HafenCity are quite near together in fractal dimension as well as in cyclomatic number whereas City-Nord shows clearly worse values.

Visitors of HafenCity do less complain about the density of the network but more about the width of the streets (mainly 4 lines) as well as the underdeveloped separation of facades. That is in accordance with the results showing that the street grid has a good potential of being perceived as walkable (even if a bit worse than Dulsberg) but the problem is more in the buildings and the rare possibilities to cross one of the streets.

There is a lot of literature investigating the range of fractal dimensions that is preferred by humans; [19] mentions D between 1.3 and 1.5 as stress reducing while [15] cites for the as most appreciated accepted paintings like the birth of Venus by Botticelli D between 1.6 and 1.9. All that holds for visible objects. The pedestrian route network eludes from the direct view on it, because a pedestrian is walking inside of it. But nevertheless, it seems that the as most walkable perceived networks have fractal dimensions in the same range like paintings or other objects of art (like facades). $D = 1.6$ may be a precondition and a minimum for a walkable network.



Dulsberg	HafenCity	City Nord
Fractal dimension 1.68	1.62	1.45
Cyclomatic number 213	157	47

Figure 6: Three selected quarters (500 ´ 500 m) of the city of Hamburg, [18]. Left: very walkable Dulsberg, right: car-oriented City Nord (1970s), middle: new development HafenCity. The determined fractal dimension and cyclomatic number were presented, too.

A presentation of the order of the fractal dimension over the different subdivisions allows a deeper analysis. In Fig. 7 the fractal behaviour is shown over the edge size of the boxes that are used for the corresponding subdivision. Supplementary a grey rectangle shows the range of as most agreeable perceived fractal dimensions as well as the distances that a pedestrian

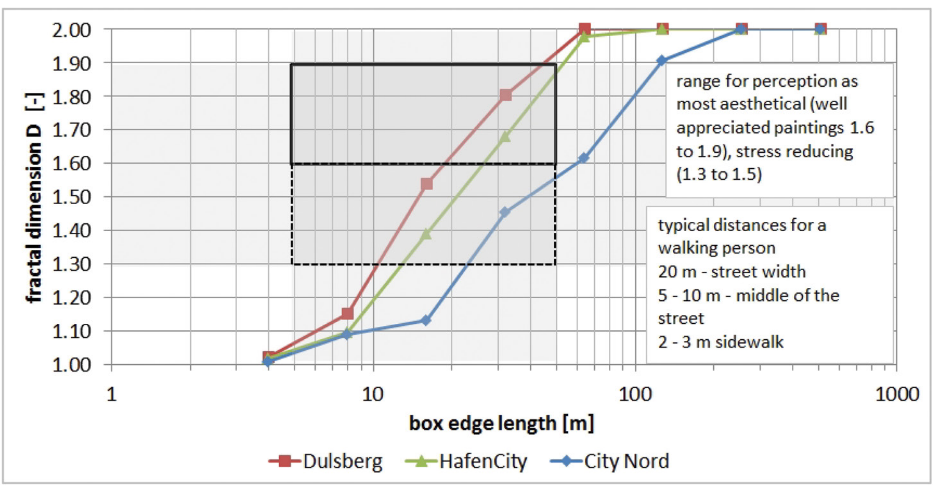


Figure 7: Fractal dimension over the edge length of the boxes from loop-wise box-counting. The curves show the behaviour of the three selected quarters of the city of Hamburg. The grey rectangles mark vertically the range of as appreciated perceived fractal dimensions and horizontally the distances that a pedestrian experiences most while walking through a neighbourhood.

walking in a neighbourhood experiences most. It can be seen that for the in public opinion as walkable perceived quarter Dulsberg the curve falls widely into that rectangle as well as for HafenCity quarter what confirms again that the street grid has a potential to be perceived as walkable. The car-oriented City-Nord quarter lies nearly out of the rectangle what confirms its non-walkable character.

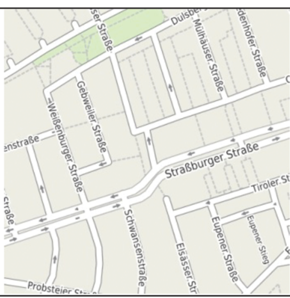
6 FRACTAL BEHAVIOUR OF SELECTED NEIGHBOURHOODS IN CITIES WITH HISTORICAL OLD-TOWNS AND DIFFERENT CLIMATES / CULTURAL BACKGROUND

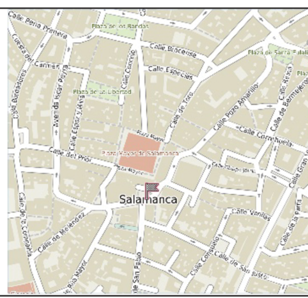
The idea was to investigate not only quarters of the near past but also historical places that were constructed before age of fast transportation. Such quarters had to be walkable by definition, thus it would be interesting if the investigation would lead to similar or better results than for the walkable quarter of Dulsberg. Cities with different climates and/or different cultural background have developed route networks that look in a first view different. But does their internal organisation, expressed by fractal dimension and cyclomatic number, show similar quantities?

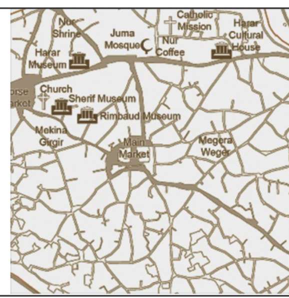
Unfortunately, the availability of appropriate map material, that has not only a high resolution but shows also the pedestrian's paths, had to be accepted as a real obstacle. Without such material a deeper investigation is not possible here, may be other researchers will be able to do that step.

Finally chosen were the historical city of Salamanca in Spain, a Roman-European city with a well-preserved historical centre and (with the aid of an Ethiopian student, [20]) the historical city of Harar Jugol in Ethiopia, one of the most important historical Islamic cities. Figure 9 shows the correspondent sections 500 × 500 m. In Fig. 8, the fractal behaviour of the route networks is shown (the presentation is equivalent to Fig. 6, see there for explanation).

It is not a big surprise that the two historical quarters behave in minimum as good as the walkable quarter Dulsberg in Hamburg. But there a few remarkable aspects to discuss.







Dulsberg (Hamburg)	Salamanca (Spain)	Harar Jugol (Ethiopia)
Fractal dimension		
1.68	1.76	1.67
Cyclomatic number		
213	215	557

Figure 8: Two selected quarters (500 ´ 500 m) of historical cities. Right: Harar Jugol (Ethiopia), middle: Salamanca (Spain), left: for comparison again Dulsberg in Hamburg, [18, 20]. The determined fractal dimension and cyclomatic number were presented, too.

The networks of Harar Jugol and Dulsberg make the two-dimensional terrain accessible in a similar quality, the fractal dimensions of the networks are 1.68 and 1.67.

Harar Jugol has an extraordinary high cyclomatic number of 557, what is a result of the typical network of an Islamic city. Many routes have dead ends, increasing the number of links (when a link between two nodes is interrupted, two links result). Consequently, the difference between links and nodes increases also leading to a high cyclomatic number.

The example of Harar Jugol demonstrates that the cyclomatic number alone can be used as an indicator to compare the quantities of different quarters only, if their character (e.g. more regular with continuing routes) or irregular with dead end routes is comparable. The cyclomatic number is used as an indicator for connectivity but it is only applicable for networks with continuing routes. A pedestrian who wants to cross Harar Jugol has to concentrate on the few main axes, all the dead-end routes do not help to cross the city, thus Harar Jugol is *less* connected than cities with networks with continuing routes like in Salamanca or Dulsberg. It will not necessarily perceived as an disadvantage, the dead-ends in Harar Jugol are all quite short, a pedestrian will find his orientation back quickly and enjoy the walk through the city.

Salamanca has a lot of pedestrian zones, Plaza Major and the surrounding streets. That does not increase the number of nodes nor links (nor the cyclomatic number) but well the fractal dimension. Pedestrians can stay and stroll everywhere around on Plaza Major and thus make the two-dimensional area more accessible. That finds its expression in a higher fractal dimension, in the general value of 1.76 and in particular in the loop wise consideration for

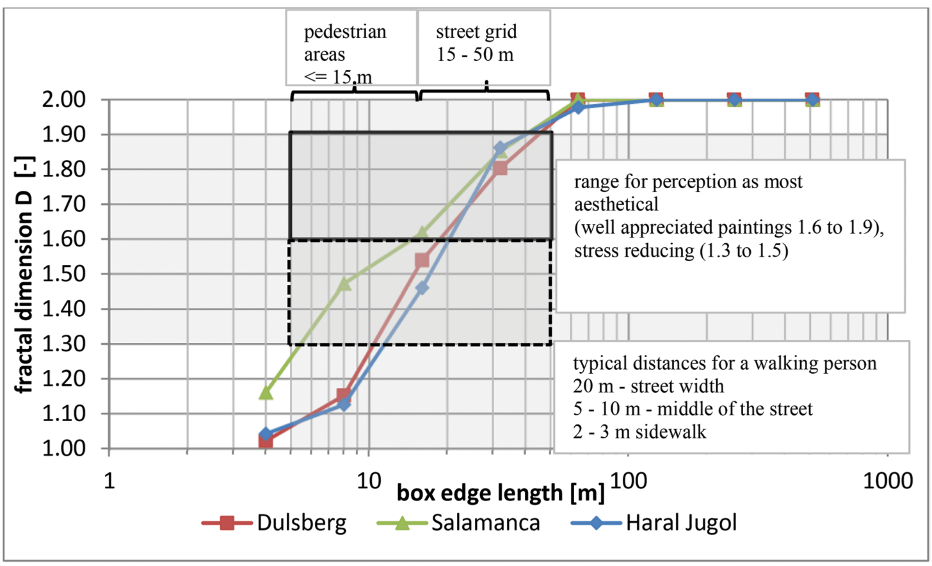


Figure 9: Fractal dimension over the edge length of the boxes from loop-wise box-counting. The curves show the behaviour of two historical cities, Harar Jugol (Ethiopia) and Salamanca (Spain), for comparison the quarter of Dulsberg in Hamburg is supplemented. The grey rectangles mark vertically the range of as appreciated perceived fractal dimensions and horizontally the distances that a pedestrian experiences most while walking through a neighbourhood.

the box edge length' that correspond to the width of pedestrianized places and streets (<=15 m). Here, the curve for Salamanca rests at high values while the one for Dulsberg, that has no pedestrianized areas, is at low values.

It can be concluded that the presence of few nearby pedestrianized places or streets would deliver the last icing on the cake for a walkable city – inhabitants could enjoy walking on an area (and not only strait forward) and freely decide where to turn next in short distances of a few meter. The loop wise presentation of the fractal dimension of the corresponding network shows well that it could represent a good indicator for the assessment.

7 REFLECTION TO THE USED METHODS

In mathematical networks a link connecting two nodes is a one-dimensional line (see Fig. 3). In street networks a connection between nodes is a two-dimensional object that has a length but also a (street) width. Out of this fact results an uncertainty about the application of the mathematical methods to determine cyclomatic number and fractal dimension, different methods are possible now, leading to different results.

That paper investigates route networks for pedestrians, thus the calculation method should be adapted to the pedestrian's behaviour (Fig. 10).

7.1 Counting nodes and links – cyclomatic number

On a street, a pedestrian can walk along the two opposite sidewalks, they are perceived as two different possibilities to walk along and should thus be counted as two different links. At a crossroad, waiting for green light, crossing the car lines and arriving on the other side to continue will be perceived as two moments where it is to decide where to continue (straight, left, right or back) thus each corner of a crossroad is interpreted by a pedestrian as a separated node. As a consequence, a standard crossroad with four streets has a node where two or more pedestrian routes meet (the sidewalks on a street) and thus in total 4 nodes, one in each corner. Also, if the route has a 90-degree turn, a pedestrian stops and decides again where to continue, it shall be counted as a node.

That means that in a completely regular street grid with sidewalks on both sides the number of links and nodes is identical (a crossroad has 4 nodes and 8 outgoing links, but these links connect to the nodes of the next crossroads and have to be counted for both) and the cyclomatic number would result in 1. Thus, a higher cyclomatic number would occur *only* if there are further pedestrian routes besides the standard ones in the regular street grid. That might neglect and hide the connectivity even of a regular street grid. But on the other hand it is known that completely ordered, regular street grids are not walkable – in that sense it is reasonable to choose a counting method that does not honour it. The cyclomatic number used here is 'pedestrian related'.

Further it must be mentioned that the cyclomatic number for a city or neighbourhood is not a constant value, it increases with the size of the area where links and nodes are counted. Thus, values that are cited in literature are not necessarily comparable. This paper bases the cyclomatic number on an area of 1 km².

7.2 Box counting method – fractal dimension

The network in investigation is covered by a regular grid, now it is to decide if the single boxes are 'filled' or not. For mathematical networks with one-dimensional links that is clearly

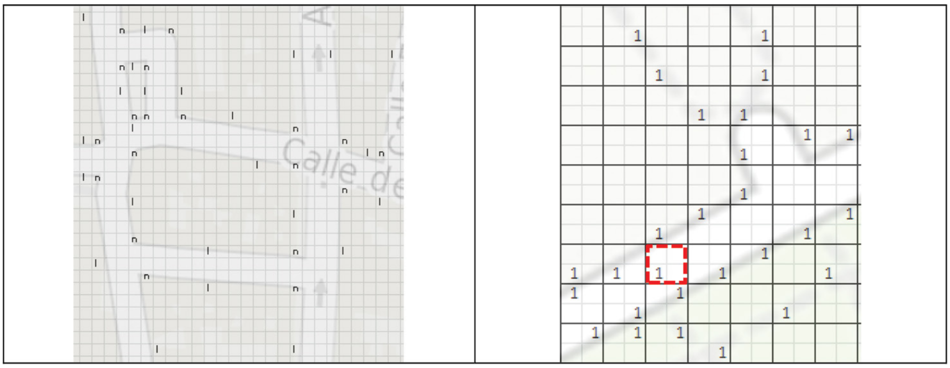


Figure 10: Methods to simulate pedestrian's behaviour for the determination of indicators for the walkability of a quarter. Counting links and nodes in a street network for cyclomatic number (left), box-counting for fractal dimension (right, the red box with the dotted line represents a pedestrianized part of the street), see text.

to decide, for a street with a two-dimensional extension and a width not, further definition is necessary.

To investigate pedestrian's behaviour, a box should be counted as filled, if in the box is an area where pedestrians can stay longer time (Fig. 10). For a street with car lanes and sidewalks, a box is filled in accordance with the definition for the cyclomatic number (ch. 7.1), if one of the sidewalks is in the box. It is not filled if there are only car lanes in it. A pure, small footpath corresponds to a one-dimensional link and is counted if in the box. For a completely pedestrianized street or a place, a box is filled if a part of it is in the box.

It must be noted, that it is very difficult to assess Harar Jugol in a fair and comparable manner. Following the available images there is no separation between different sorts of traffic (like car lanes and sidewalks), all sorts of traffic are everywhere in the main streets, pedestrians of course inclusive. Thus, the main axes and plazas could be counted as pedestrian or as street. For this paper it is counted as a street – may be to its disadvantage.

8 CONCLUSIONS

Fractal structures have a high potential to be recognized by the human eye. They have an own aesthetics and it is a pleasure to observe the structure. However, the structure of a street grid or route network is visible only from the bird's eye perspective. As pedestrians moving inside of the structure and we can only 'feel' if it is fractal and easy to understand or not. But it seems that such a perception does well exist and it is thus worth to investigate the fractal character of route networks as a hidden quality.

The results show that the fractal dimension should remain at high values of 1.6–1.9 for the network's subdivisions down to 10–15 m. As a recommendation the investigation method should be used to analyse existing quarters but – much better – in advance for newly planned quarters. That would help to avoid non-walkable networks and to create a surrounding at human scale.

The results show further that the method could be used worldwide, for all climates and cultures. Obviously all humans behave in the same way and they have the same basic needs and perceptions. We are all children of the same cradle of civilisation!

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