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FRACTAL URBAN MODELS AND THEIR POTENTIAL FOR SUSTAINABLE MOBILITY

A SPATIO-SYNTACTIC ANALYSIS

CLAUDIA YAMU, AKKELIES VAN NES

ABSTRACT

Until now, fractal urban configurations have not been reviewed in depth from a sustainability perspective. In general, fractal shapes are assumed to be efficient and have therefore been part of the sustainability debate. Focusing on fractal shapes for urban planning and design, in this paper we will critically reflect on whether and to what extent cities and neighbourhoods incorporating fractal geometries are sustainable in terms of accessibility and mobility. We will take a novel approach and apply the theory and method of space syntax to theoretical fractal geometries and comparable real-life urban configurations. This will shed new light from a network point of view on the debate about sustainable urban configurations for sustainable mobility. Research has shown that the spatial structure of the street and road networks influences the flow of movement and the location of economic activities, as well as the degree of building density, land use diversity, and street life. We will make a link between fractal urbanization patterns and movement.

In this paper, we will analyse three theoretical fractal models relevant to urban neighbourhoods and compare them with real cases or examples of the built environment. As the results of our experiments on various fractal models show, a background network that is well connected to the foreground network enhances sustainable mobility (public transport routes and walkability), whereas a background network that is poorly connected to the foreground network increases the dependency on private cars.

KEYWORDS

Fractal shapes, geometric accessibility, sustainable mobility

1. INTRODUCTION

Morphological analyses of post-industrial revolution cities have shown that urban patterns, which are often viewed as amorphous, tend to follow a fractal structural principle (Batty and Longley, 1994; Frankhauser, 1994; Shen, 2002; Tannier and Pumain, 2005; Salingeros, 2005). In general, urban growth is governed by complex bottom-up processes that generate morphologically well-defined macrostructures. These dynamic urban processes underlie a hierarchical ordering principle (Batty, 2006). With regards to a fractal logic, elements in a hierarchy appear in a similar fashion from one

scale to the next (Batty and Longley, 1994). If the elements have a high degree of geometric similarity, this is termed self-similarity following theoretical fractals; if they have a lower degree of similarity, this is termed self-affinity. For example, the street network hierarchy involves a neighbourhood to city-wide scale, following self-affinity with interdependencies (paths, streets, roads, highways). For the architectural pattern, the cascade is from building to block, neighbourhood, quarter and city.

The hierarchical ordering principle can also be found in fractals. A fractal is composed of a hierarchical system with quasi-independent subsystems linked to several higher-level systems and one holistic meta-level system. A popular example is the Mandelbrot set (Mandelbrot, 1977). The fractal dimension D was introduced in mathematics to measure the complexity of fractal geometries (Mandelbrot, 1967; 1977). It is a statistical index comparing how detail in a fractal pattern changes with the scale at which it is measured. In other words, the fractal dimension is considered a global measure of spatial organization and surface coverage of urban patterns (Arlinghaus, 1985; Batty and Longley, 1994; White and Engelen, 1993). Applying this dimension to urban structures can be used to measure the extent to which built-up areas are distributed in a uniform or spasmodic way (Thomas et al., 2008). Furthermore, a study by Thomas et al. (2008) has shown that there is a correlation between the fractal dimension D and residential satisfaction as people tend to appreciate morphological (fractal) diversity. Analysing urban patterns using the fractal dimension is a way of understanding the impacts of urban planning.

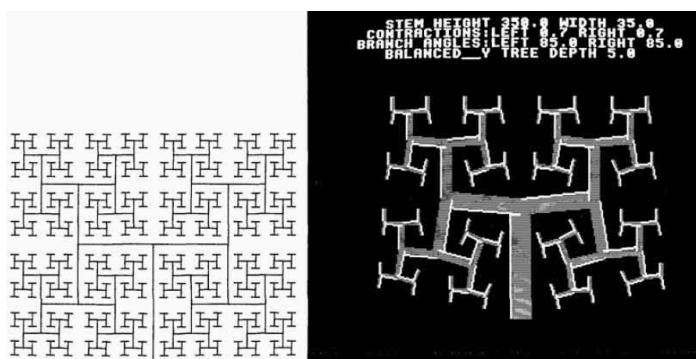
In urbanism, the debate on complexity – and, more specifically, applying a fractal logic to urban planning and design – has a long-standing tradition going back to the twentieth century. Alexander, a pioneer in this debate, published research contributing to the idea of complexity science in his article ‘The city is not a tree’ (1965). This was followed in 1977 by another work in which he and others defined a new ‘design language’ in the light of complexity science, applying a fractal logic to the planning and design of large-scale structures in the built environment (regions and cities with their hinterlands) and intermediate (communities) and small-scale (houses) structures. In 1986, Batty and Longley discussed the development of patterns of land use and activity using a geometric model of irregularity involving hierarchical cascading, whereby the rationale lay in the emerging field of fractal geometry. An example of the application of fractal logic in nineteenth-century urban planning is Hausmann’s intervention for Paris, where Frankhauser (1994) proved that the Parisian street network follows fractal scaling. Another example is Hilbersheimer’s 1957 plan for Seattle.

Hilbersheimer worked with a fractal logic as an ordering principle in his plans for urban street networks. As a form of process-oriented planning, his plans follow a clear fractal geometry in their amorphous forms and shapes (figure 1). Reminiscent of Hilbersheimer’s traffic layouts, Batty and Longley use the analogy of a classical space-filling curve for traffic systems in residential areas and towns. A simulated theoretical fractal H-tree can produce more or less realistic structures depending on the angle of its branches. Batty and Longley explain that ‘it is possible to visit every branch of the tree without crossing any other branch’ (Batty and Longley, 1994, p. 80). They also stress that this kind of model was widely implemented in the design of residential areas in the British New Towns (Batty and Longley, 1994) (figure 1) and the ‘cauliflower’ neighbourhoods (*bloemkoolwijken*) in the

Netherlands. Whereas Hilbersheimer used a descriptive morphological logic, Batty and Longley applied a morphogenetic logic following the idea of dynamically generated patterns linked to emergence and patterns that have evolved.



(a)



(b)

Figure 1: (a) Hilbersheimer's process-oriented plan for Seattle (1957) and (b) two simulated self-avoiding H-trees using different angles from Batty and Longley (1994, p. 79)

Initial attempts to apply a fractal logic to the physical form of cities using spatial modelling were also made by Batty and Longley (1994), among others. To provide evidence for a theory of the 'fractal city', they generated the Sierpinski carpet, representing the first approximation towards simulating an urban structure (Batty and Longley 1994, p. 234). Recent contributions that have built on and further developed the early works of Batty and Longley and Frankhauser include works by Yamu (2012) and Yamu and Frankhauser (2015), with a simulation model using a multifractal logic to generate strategic regional and urban development plans. Based on Yamu's work (2012), Yamu and Van Nes (2017) published a study with an integrated modelling approach that combined multifractal spatial modelling with a space syntax perspective.

In this paper, we will add to the debate by analysing urban fractal models using space syntax. This is a novel way to understand fractal shapes when considering sustainable transportation. In our study, we reveal how the foreground and background networks are connected to each other in various types of theoretical fractal models and real-life cases that are comparable to the fractal models discussed. We also link our findings to the debate about sustainable mobility.

The rationale for analysing fractal geometries with space syntax is provided by the theory of the natural movement economic process. This theory states that the spatial configuration of the street and road network affects the flow of movement and the location of economic activities (Hillier et al.,

1993). The higher the spatial integration of the mobility network, the higher the flow of people on the street (Hillier et al., 1998) and the higher the concentration of economic urban functions along these streets (Van Nes, 2002). This theory does not explicitly explain how a spatial structure affects the type of mobility, but it is inherently interwoven with the question of whether an urban configuration has the potential to provide for sustainable mobility, such as walking or transit-oriented development (TOD).

In this paper, we therefore explore how the spatial potential of three different types of fractal models can generate sustainable or unsustainable mobility. We also compare the theoretical models with real-life cases. The paper is organized as follows. In Section 1.1. we discuss the idea of hierarchy and the inner organization of cities. As a key attribute in fractals and types of urban organization that enable efficiency, hierarchy is also linked to the sustainability debate. In Section 2 we explain the datasets and methods used, and in Section 3 we apply and interpret the results of our study. Finally, in Section 4, we present our conclusions.

1.1 HIERARCHY: THE INNER ORGANIZATION OF CITIES

Batty and Longley (1994) explain that hierarchies are basic organizing devices for describing and measuring the importance of urban functions across many spatial scales. They present us with a framework linking local to global as a general system for cities and systems of cities. Pumain (2006) posits three hypotheses as to why hierarchies are so frequent in natural and social systems: a) hierarchies are simply the way that we perceive and understand our environment; b) they are spontaneous attractors in unconstrained dynamic random processes; and c) they represent the best solution for many optimization problems. This is also linked to the debate about complex systems.

With regard to a hierarchical inner organization, Alexander states in his article, 'A city is not a tree' (1965), that natural cities have the form of a semi-lattice, whereas artificial cities incorporate a tree structure. Natural cities are evolved systems, whereas artificial cities are cities or parts of cities 'which have been deliberately created by designers and planners' (Alexander, 1965, p. 47). According to Alexander, a city with a tree structure is divided into different zones. Each zone has a set of functions that do not relate to other zones. None of these zones overlap. Seemingly, a tree-like city is organized so that 'no piece of any units is ever connected to other units, except through the medium of that unit as a whole' (Alexander, 1965, p. 51). For Alexander, the underlying reason for the tree-like organization of planned cities results from the limits of the human mind. Alexander is of the opinion that our mind cannot encompass the complexity of semi-lattice structures shaping natural cities (we disagree with this reasoning; see footnote).¹ He views organizing cities in the form of trees as a means of simplifying the spatial organization of the complex environment. Semi-lattice cities have a complex transportation network, with effectively intertwined functions. The different zones overlap and are well integrated with one another. According to Alexander, this structure improves a city's economic development, safety and liveliness.

¹ We disagree with Alexander that the human mind is not capable of designing and planning semi-lattices. Their preference for tree structures over semi-lattices might result from the kind of task that they face rather than the limitation of the human mind.

As a response to Alexander, we would like to borrow the words of Batty and Longley from their book 'Fractal Cities' to show why an analysis of theoretical and real-life fractal shapes is meaningful. 'Our (...) ideas are dominated by hierarchies and networks. (...) Yet the strict non-overlapping hierarchy (...) is still useful as an initial foray into the way we might organize the relation of scales, one to another, and the fact that we can simplify scales according to a strict hierarchical order does not exclude a richer order from existing within the hierarchy' (Batty and Longley, 1994, p. 46f). The spatial analyses of theoretical fractal models contribute to our understanding of the degree of sustainability for real-life cases. Analysing theoretical fractal models validates and consolidates knowledge for planning concepts such as New Towns.

2. DATASETS AND METHODS

In this paper, we analyse and compare three theoretical fractal shapes – an H-tree, a Koch forest and a Sierpinski tree. These geometric shapes resemble the configuration of street networks in the kind of neighbourhoods that are found, for example, in urban developments and New Towns.

In this study, we conducted normalized angular integration (NAIN) and normalized angular segment analysis (NACH) to compare three theoretical fractal geometries with real-life cases. For local measures, we added a metrical radius using the 10% rule of a system's coordinates as input values for processing.

Since 2012, Hillier and colleagues have been experimenting with combining various normalized measurements, such as the mean NACH, mean NAIN with maximum NAIN or maximum NACH measures in a four-pointed star model (Hillier et al., 2012). This makes it possible to compare cities in order to describe the degree of integration of their foreground and background networks. In essence, the foreground network (identified by the NACH analyses) is needed to link together the various centres (identified by the NAIN analyses) in a city. We used this method to reveal the spatial potential of various fractal models and comparable real-life cases. We discuss the degree of sustainability in terms of mobility of these various types of theoretical fractal models, and we use some existing built-up examples that resemble these. Examples of cases used here are the cities of Zoetermeer, Lelystad and Eindhoven in the Netherlands.

We also present mean values of syntactic measures in a table for numerical comparison. We acknowledge that only artificial cities are organized as a tree structure (Alexander, 1965) and that most European cities are organized as semi-lattices. The closest examples of tree structures that we found for the Netherlands are the New Town of Zoetermeer (Koch forest network), the New Town of Lelystad (an H-tree network), and the city of Eindhoven in 1934 (Sierpinski tree network). These cases were chosen for their hierarchical street networks that follow the logic of theoretical fractal shapes.

2.1. A BRIEF HISTORY OF THE REAL-LIFE CASES

Lelystad is only 50 years old and was developed in line with modernist ideas from the 1950s. The town was planned and built on reclaimed land. Zoetermeer, with a very small historic centre, grew so rapidly from the 1960s to 1980s that this historic core of two to three streets is barely visible in the

entirely new street network. Eindhoven's urbanization pattern from 1943 is a typical Dutch example. The city was developed on sand hills. Before 1920, it was a group of six villages, with five villages surrounding a sixth one located in the middle. Eindhoven, the village at the centre, gave its name to the whole agglomeration. We use the 1934 map of Eindhoven as the best example of the Sierpinski tree network because the urban expansions after the Second World War have brought major changes to the city. DAF, a Dutch car brand, was manufactured in Eindhoven. The growth of private car ownership in the 1960s influenced city planning after that time.

3. RESULTS

In summary, the Sierpinski tree (figure 2c) is most suitable for enhancing sustainable mobility but at the same time it causes the highest potential congestion for private car transport. The Sierpinski tree is suitable for carrying out Transit Oriented Development (TOD) (see further Yamu and Frankhauser, 2015). As an urban model, the Sierpinski tree works well at the city-wide or regional scale. It does not work at the neighbourhood scale for much the same reason that linear development does not work at the local scale. However, the built form of a linear development maximizes public transport viability along the main arteries. Mixed use is found in areas with a higher density and with facilities located on or offset from the central or main road corridors. As an urban continuum, the form displays a series of fuzzy neighbourhoods and its boundaries are dynamic through time (Barton, 2005). It has high levels of permeability between the neighbourhoods and a clear route hierarchy. Pedestrian movement can be the main mode of transport at the local scale.

The opposite can be found of the H-tree and Koch forest models; both these fractal shapes work at the neighbourhood scale. The H-tree (figure 2b) shows a system of dead-end streets and is similar to a New Town logic. After the Second World War, New Towns were purposefully planned and implemented as a remedy for overcrowding and scattered settlements, providing a fresh environment for citizens. New Towns are self-sufficient for their communities. They are planned for a certain population size, or density, and do not function well if the population increases or decreases.

The Koch forest (figure 2a) also follows a neighbourhood logic in which some areas are not readily accessible. The flow of people does not occur efficiently with regard to accessibility.

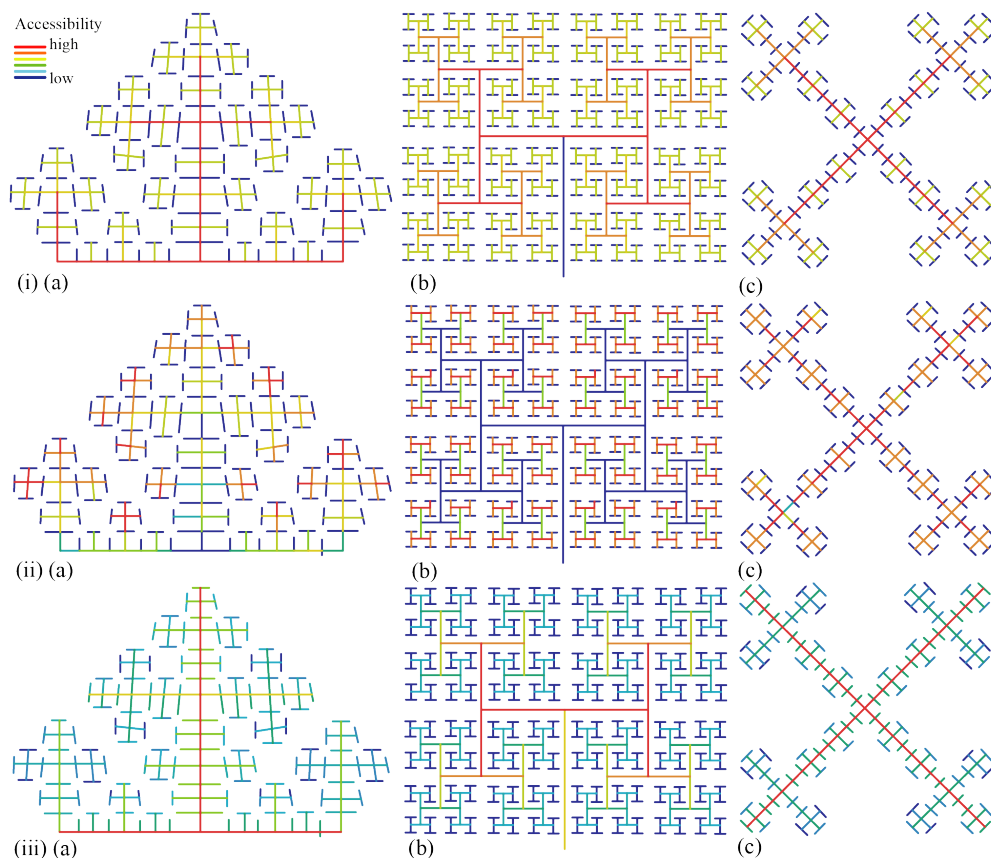


Figure 2: (i) NACH RN, (ii) NACH low metrics (10%) and (iii) NAIN for (a) a Koch forest, (b) an H-tree and (c) a Sierpinski tree.

Figure 2(i) shows the normalized angular choice (NACH) analyses with radius N of the three models. As can be seen in the figure, the main distributors are highlighted as the main routes that connect each local neighbourhood with each other. When revealing the NACH analyses with a low metrical radius of all three models (figure 2(c)), the Sierpinski tree model's main routes also have high values. For the other two models, the local streets for each neighbourhood have the highest values.

The Sierpinski tree is the only model with overlapping high values for NACH high and low metrics. Here, each local neighbourhood is well connected to the main route. Cities with this kind of street structure seem to easily implement sustainable mobility in terms of a high degree of walkability at a local scale and an efficient public transport system on a larger scale.

When revealing the overlap between the NACH with a high and low metrical radius for the H-tree, we see no overlap. There are mainly dead-end streets, which indicates that no local centres are forming due to the lack of overlap between these two variables. From a traffic safety perspective, T-junctions as found mainly in the H-tree model are safer than X-junctions. The H-tree structure is suitable for facilitating private car transport. Compared with the Sierpinski tree, there is less potential congestion in an H-tree structure grid. Conversely, it is difficult to implement a public transport system in an H-tree. Several New Towns tend to have a street pattern in line with an H-tree grid. Examples of this can be found in the Netherlands, in recently built New Towns in China (Ye and Van Nes, 2014), and in Britain (Batty and Longley, 1994). We see more or less the same pattern in the Koch forest model, regarding the relationship between the NACH with the metric low and high radii. Where the values

are high for the NACH analysis with a metrical high radius, they are low using a low metrical radius. Conversely, where the NACH analysis with a metrical high radius has low values, they are high for streets using a low metrical radius. This model has major arteries as distributor roads. The local centres are highlighted with NACH low metrics for pedestrian movement. Some of them are adjacent to the main routes.

Figure 2(c) shows the normalized segment integration (NAIN) analyses with radius N of the three theoretical fractal models. The NAIN analyses with a low metrical radius do not differ much from the radius N analyses. The distributor roads or feeders have a self-organizing economic potential. They could serve as the main shopping streets. However, in European cities, which have evolved naturally over a long time, the centres tend to be more compact, with a dense, fine-grained local street network. The foreground network generates micro-scale economic activities, an aspect that is independent of cultural background. However, the background network is culturally bound. New Towns tend to follow an international style, free from cultural background.

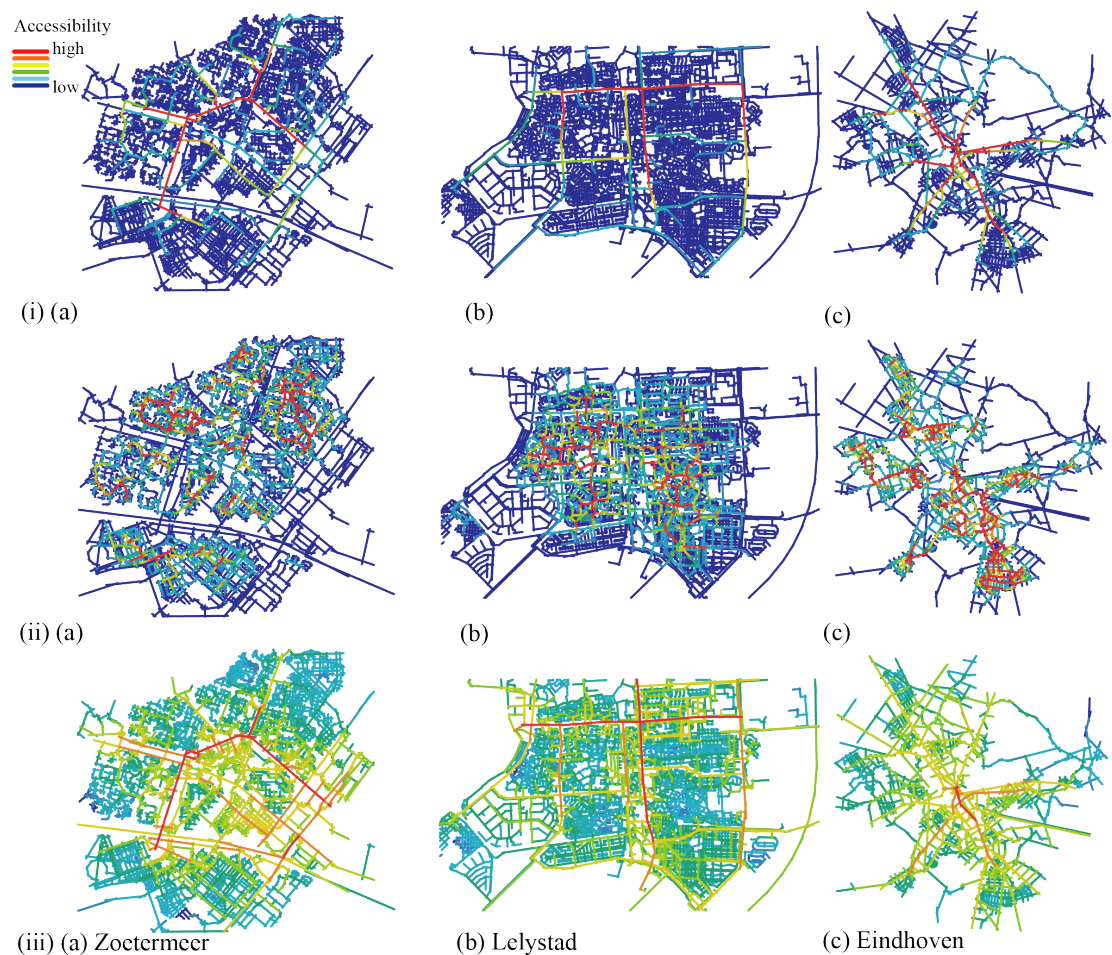


Figure 3: (i) NACH RN, (ii) NACH low metrics (10%) and (iii) NAIN for (a) Zoetermeer, (b) Lelystad and (c) Eindhoven in 1934

Figure 3 shows the spatial analyses of the Dutch towns of Zoetermeer, Lelystad and Eindhoven with NACH with a high and a low radius. The NACH with a high metrical radius shows the main route

network for all three towns where the integration values are highest. The NACH with the low metrical radius highlights the potential for local centres. The vitality of these local centres depends on being well connected to the integrated main routes. In the case of Eindhoven, the locally integrated neighbourhood centres are well connected to the integrated main routes. Today, as in 1934, these centres have vital local centres, each with a weekly street market. An efficient bus system operates on these main routes to Eindhoven's centre, where the intercity railway station is located.

In the case of Zoetermeer and Lelystad, the main routes are located around the various neighbourhoods. There are almost no shops in the local neighbourhoods. The car-based shopping centres are mainly located at the junctions of several main routes. The public transport system is also messy in these towns. In Zoetermeer, the metro network is totally disconnected from the spatial structure of the street and road network. The stops are located inside each neighbourhood, but there are no stops on the highly integrated distributor roads. In Lelystad, the intercity train station is located on the junction where all the main routes meet (where the large car-based shopping mall is also located). Buses that serve all the local neighbourhoods run from the train station. The routes that the buses take are complex and bear no logical relationship to the street network. To go from the town centre to the local destination often involves changing buses twice.

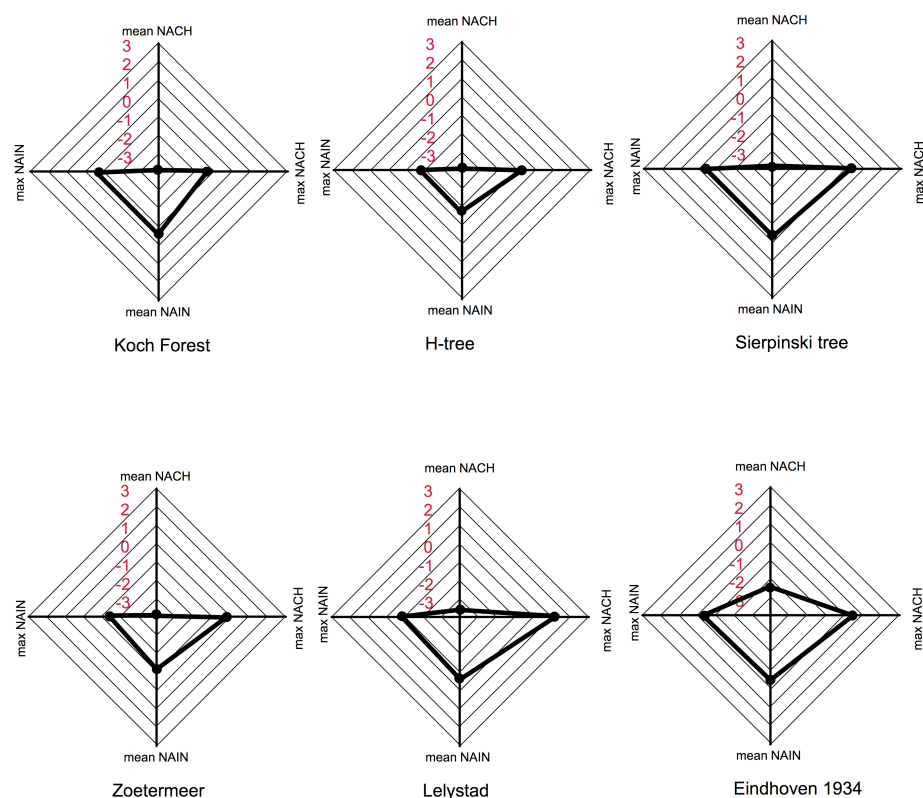


Figure 4: The four-pointed star model for a Koch forest (left), a Sierpinski tree (right) and an H-tree (middle), with examples from Zoetermeer, Lelystad and Eindhoven in 1934.

Figure 4 compares the foreground and background network of the three theoretical fractal models (top) and three Dutch cities (below) in a four-pointed star model. We have added the values from the normalized segment integration (NAIN) with the normalized angular choice analyses (NACH). The values of this four-pointed star model are Z-scores which is a standard score with basis in the fifty cities analysed by Hillier, Yang and Turner (2012). For generating the four-pointed star model, the following equation for Z for both max. NAIN and max. NACH values applies as follows:

$$Z = \frac{X_{max} - X_{mean}}{S} \quad (1)$$

Whereas S is the standard deviation, X_{max} is the maximum value for NACH or NAIN, and X_{mean} is the average value from the fifty cities analysed by Hillier et al.. In their article from 2012, Hillier et al. compared the maximum NAIN and NACH as well as the mean NAIN and NACH of fifty cities around the world. These fifty cities are representatives from America, the Middle East, the Far East, European cities and Australia. Therefore, the following X_{mean} values can be used based on these fifty cities (Hillier et al., 2012, p. 164-168): mean NACH: 0.912, max NACH: 1.5679, standard deviation mean NACH 0.098, standard deviation max NACH 0.0669, mean NAIN: 1.2206, max NAIN: 1.8705, standard deviation mean NAIN 0.522 and standard deviation max NAIN 0.767. Table 1 shows the results from the calculations as basis for the four-pointed star model.

	Eindhoven 1934	Lelystad	Zoetermeer	Koch Forest	Sierpinsky tree	H-tree
Max NAIN	1.70151	1.56903	1.11614	1.39984	1.75343	0.648906
Mean NAIN	1.04743	0.901995	0.675598	0.864538	1.12054	0.385467
Max NACH	1.6347	1.65309	1.56583	1.64707	1.65783	1.51341
Mean NACH	0.683299	0.552625	0.514821	0.410903	0.439422	0.344164
Z-score Max NAIN	-0.2203	-0.8697	-1.3226	-0.6136	-0.1526	-1.5927
Z-score mean NAIN	-0.3317	-0.6104	-1.0441	-0.6821	-0.1917	-1.5999
Z-score max NACH	0.642268	1.2734	-0.0309	-1.1834	1.3442	-0.8145
Z-score mean NACH	-2.337	-3.6671	-4.0528	-5.113	-4.8222	-5.7442

Table 1: The values of the various NAIN, NACH and Z-score values for the models and the three cities.

All theoretical fractals as well as the three Dutch cities have a very weak background network. The to-movement potentials are below average compared to the fifty cities from Hillier, Yang and Turner

(2012) for all models and cities. The maximum NACH values for the Sierpinsky tree model are higher than for the other two models. For the three Dutch cities, Eindhoven has higher values for the foreground network for to-movement potentials, whereas Lelystad has the highest value for the foreground network with regard to through-movement potentials. The background network of the Dutch cities have higher values than the theoretical fractals as they are not ‘pure’ real-life examples of the theoretical fractals. The three fractal models have a perfect ‘tree-structured’ or non-distributed street structure, whereas the real-life cases used here consist of some distributed streets. This has an impact on the syntactic calculation and evaluation. However, in general the background network is very low in Dutch cities.

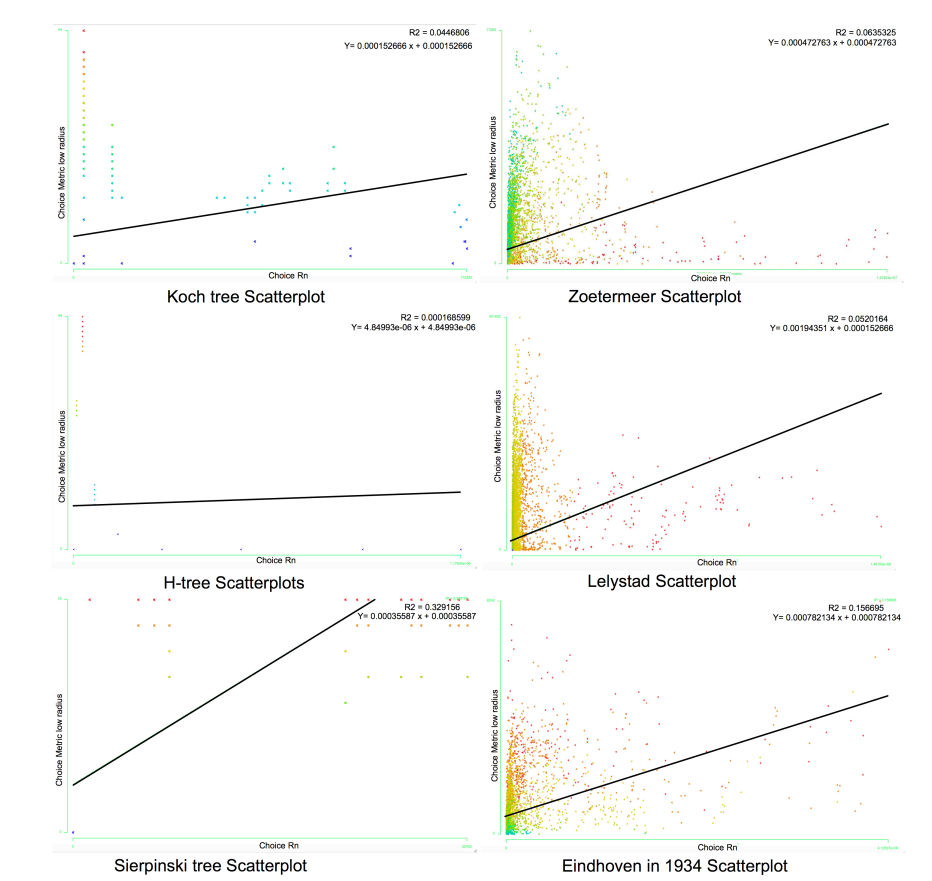


Figure 5: Scatter plots of a Koch forest, a Sierpinski tree and an H-tree, with examples from Zoetermeer, Lelystad and Eindhoven in 1934.

To reveal the relationship between the background and foreground network, we created some scatter plots of the three models and the three cities (figure 5). Here, we correlated the values from the angular choice analyses with a low and a high metrical radius. We wanted to find out how these two scales of the street network are connected to each other for each model. The Koch forest, the H-tree, Zoetermeer and Lelystad have an ‘L’ shape on the plots. This means that the streets obtaining choice values with a high metrical radius have low values where the radius with low metrical radius have high values, and vice versa. The correlation coefficient for all four cases is very low. Conversely, it is high for the Sierpinski tree structure and for Eindhoven in 1934. As indicated, there is a high degree of connectivity between the local neighbourhood and the metropolitan main route network. The

correlation coefficient also appears to indicate the degree of sustainability of various types of fractal models of urbanization patterns.

4. CONCLUSIONS

In this paper, we set out to identify the extent to which urban models are sustainable or unsustainable with regards to mobility. We found that some fractal geometries are more advantageous than others when it comes to supporting sustainable mobility. In our study, we interpreted the fractal shapes as a hierarchical street and road network, which enabled us to apply the space syntax method. These fractal shapes were linked to similar real-life cases. Complementary to our approach, fractal geometries can also be interpreted as built-up space on which a street network can be imposed (figure 6). The built-up space can then be interpreted as urban centres of various sizes at different scales related to the iteration step of constructing the fractal.

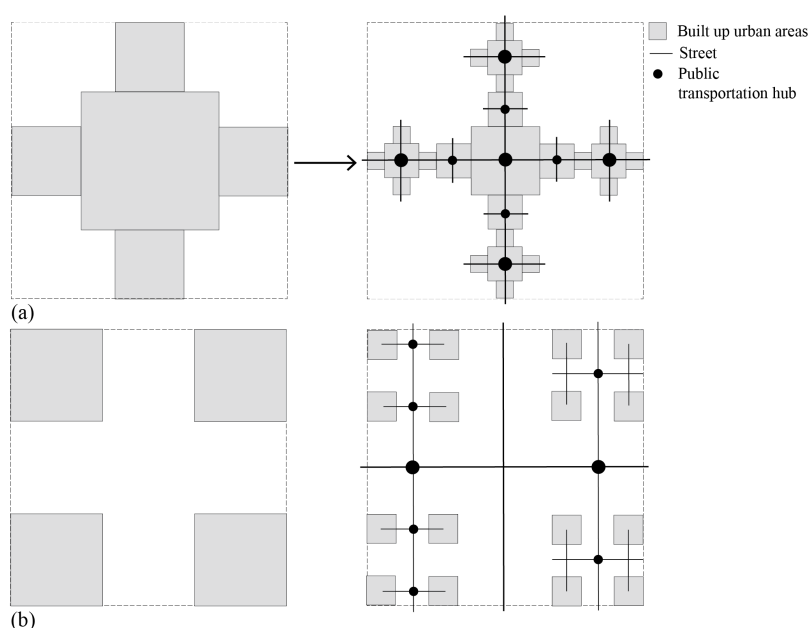


Figure 6: Sustainable versus unsustainable fractal model for urban planning. Model (a) shows a regional scale where each cell can be interpreted as an urban system, whereas model (b) shows an urban to neighbourhood scale.

To extend our discussion of sustainable versus unsustainable fractal models for mobility, figure 5 shows two different fractals for two iteration steps. Iteration steps represent scale levels. Figure 6(a) depicts a sustainable fractal model for mobility. The transportation network with its transportation hubs is well integrated into the urbanization pattern. Here, the mobility network can encourage sustainable mobility, such as providing an efficient public transport system to serve the densely built-up areas. The bottom fractal model (figure 6b) represents an unsustainable fractal model, in which the transportation network is separated from the densely built-up areas. The aim at the local scale is often to protect the residential areas from traffic noise or high traffic volumes. However, an urbanization pattern of this kind generates a dependency on private cars, and an efficient public transport system becomes costly to implement. A more holistic approach also links the sustainable versus unsustainable fractal model approach to the urban-planning debate on primary energy use. This is important as we

are confronted with rising energy consumption due to increasing mobility, which contributes to the greenhouse effect and global warming.

How can these findings, interlinked with the complexity of urban systems, provide an understanding of urban sustainability when cities, their cultures and their economies are continuously changing? Since the industrial revolution, we have seen how comprehensive technological advances have affected the spatial structure of the built environment, and conversely, how spatial products have affected social and economic behaviour. We humans are continuously changing our environment and striving to maximize profit. In our pursuit of sustainable urban areas and regions, we cannot ignore aspects of human economic behaviour and how these are influenced by the built environment. From a fractal spatial perspective, understanding what a sustainable system consists of and how we can arrive at sustainable interconnected systems requires us to take into consideration morphological and functional aspects and conditions that most closely resemble the logic of nature.

Every living system strives towards efficiency and undergoes continuous optimization. The use of fractal logic for urban planning builds upon the idea of optimization management. Compared with other approaches to urban sustainability, a fractal approach can explain spatial and functional aspects in a way that helps us to understand different spatial settings and their effects on economic and social behaviour, all in terms of sustainability. From a spatial perspective, the degree of sustainability of a fractal urbanization model depends on how the foreground network is connected to the background network, or how the street structure of local neighbourhoods is connected to the metropolitan street and road network. If the spatial parameter of connectivity between the local, city-wide and regional network is high, the potential for sustainable mobility is high.

We would like to conclude that future research should interpret fractal urban models both as networks and as built-up spaces for spatial analysis and evidence-based design. This will add to the debate not only about sustainable mobility, but also about efficient urban pattern distribution and the implications for land use and socioeconomic effects.

REFERENCES

- Alexander, C (1965) A city is not a tree, *Architectural Forum*, 122(1), pp. 58–61 and (2) pp. 58–62.
- Alexander, C; Ishiwaka, S; Silverstein, M; Jacobsen, M; Fiksdahl–King, I; Angel, S (1977) *A pattern language: Towns, Buildings, Construction*, New York: Oxford University Press.
- Arlinghaus, S (1985) Fractals take a Central Place, *Geografiska Annaler*, Series B, Human Geography, 67(2), pp. 83–88.
- Batty, M (2006) Hierarchy in Cities and City Systems, in: Pumain D (ed.) *Hierarchy in Natural and Social Sciences*, Dordrecht: Springer, pp.143–168.
- Batty, M; Longley, P (1986) The fractal simulation of urban structure, in: *Environment and Planning A*, 18, pp.1143–1179.
- Batty, M; Longley, P (1994) *Fractal Cities. A Geometry of Form and Function*, London: Academic Press.
- Frankhauser, P (1994) *La Fractalité des Structures Urbaines*, Paris: Anthropos.
- Hillier, B; Penn, A; Hanson, J; Grajewski, T; Xu, J (1993) Natural Movement: Or Configuration and Attraction in Urban Pedestrian Movement, *Environment and Planning B*, 20, pp. 29–66.

- Hillier, B; Penn, A; Banister, D; Xu, j (1998) Configurational modelling of urban movement networks, *Environment and Planning B*, 25, pp. 59–84.
- Hillier, B; Yang, T; Turner, A (2012) Normalising least angle choice in Depthmap and how it opens up new perspectives on the global and local analysis of city space, *Journal of Space Syntax*, 3(2), online December 2, pp. 155–193.
- Mandelbrot, B (1967) How Long Is the Coast of Britain? Statistical Self-Similarity and Fractal Dimension, *Science*, 156(3775), pp. 636–638.
- Mandelbrot, B (1977) *The Fractal Geometry of Nature*, New York: W.H. Freeman and Company.
- Pumain, D (2006) Alternative Explanations of Hierarchical Differentiation in Urban Systems, in: Pumain, D (ed.) *Hierarchy in Natural and Social Sciences*, Dordrecht: Springer, pp. 169–222.
- Shen, G (2002) Fractal dimension and fractal growth of urbanized areas, *International Journal of Geographical Information Science*, 16(5), pp. 437–519.
- Salingaros, N (2005) *Principles of Urban Structure*, Delft: Techne Press.
- Tannier, C; Pumain, D (2005) Fractals in urban geography, *Cybergeo* 307, online.
- Thomas I, Frankhauser P, Biernacki C (2008) The morphology of built-up landscapes in Wallonia (Belgium): A classification using fractal indices, *Landscape and Urban Planning*, 84, pp.99–115.
- Thomas I, Frankhauser P. and Biernacki C. 2008. The morphology of built-up landscapes in Wallonia (Belgium): A classification using fractal indices. *Landscape and Urban Planning*, 84, 99-115.
- Van Nes, A (2002) Road Building and Urban Change. The effect of ring roads on the dispersal of shops and retail in Western European towns and cities, PhD thesis, Agricultural University of Norway.
- White, R; Engelen, G (1993) Fractal urban land use patterns: a cellular automata approach, *Environment and Planning A*, 25, pp. 1175–1199.
- Yamu, C (2012) Strategic Planning for the Development of Sustainable Metropolitan Areas using a Multi-Scale Decision Support System: The Vienna Case, PhD Thesis, Université de Besançon/Université de Franche-Comté.
- Yamu C; Frankhauser, P (2015) Spatial accessibility to amenities, natural areas and urban green spaces: using a multiscale, multifractal simulation model for managing urban sprawl, *Environment and Planning B*, 42, pp. 1054–1078.
- Yamu, C; van Nes, A (2017) An Integrated Modeling Approach Combining Multifractal Urban Planning with a Space Syntax Perspective, *Urban Science*, 1(37), online, doi:10.3390/urbansci1040037
- Ye, Y; van Nes, A (2014) A Quantitative tool in urban morphology: Combining Space Syntax, spacematrix and mixed-use index in a GIS framework, *Urban Morphology*, 18, pp. 97–118.