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Proceedings

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A PLANNING CONCEPT FOR A SUSTAINABLE DEVELOPMENT OF METROPOLITAN AREAS BASED ON A MULTIFRACTAL APPROACH

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ABSTRACT

In this paper we discuss the theoretical background and methodology of a multifractal planning decision support system. It enables to avoid fragmentation of continuous open space and continuous built-up space while at the same time ensuring good traffic flow between green spaces and urbanized areas. Thus it supports to create a sustainable and sustaining built environment.

KEYWORDS

Urban geography, spatial modelling, development of metropolitan areas, sustainable development

1. INTRODUCTION

Urban sprawl is splinter development of the countryside involving damage to nature and a generation of increasing traffic volume. These are the main criticisms in the context of sustainable and sustaining planning. Following a study by Newman and Kenworthy (Newman and Kenworthy 1989) on the relationship between settlement density and energy consumption, the compact city model used to serve as the solution for urban sprawl.

However, households not only consume urban amenities integrated into densely populated areas, but also aspire to having access to green and leisure areas. More concretely, different studies have shown that households which choose living on the outskirts often prefer a calm, quiet residential environment as well as individual housing. Therefore spatial densification is rejected. Thus, it is not surprising that policies favouring the compact city turned out to be less efficient than expected. Breheny (1997) emphasizes that these types of outskirts induce an increase in housing costs, traffic congestion and reduced accessibility to leisure areas. Schwanen et al. (2004) showed that households usually optimize their residential choice with respect to accessibility to diverse types of amenities. Hence, the overly compact city may generate traffic flows for accessing green and leisure areas, or changes of residence due to a favouring of sites that lie farther away from the centre than the dwellers' current places of residence. Moreover, compactness and densification can create ecological problems such as a lack of fresh air corridors.

Thus, we aim to find a solution for managing urban sprawl in such a way that we can marry the opposing twin pair of green/built-up space in a highly efficient manner. This solution also needs to incorporate dynamic aspects of a city as well as minimising traffic costs and emissions and avoiding the scouring of agricultural land. Based on the observation that urban space is founded on the principle of fractal geometry, it seems interesting to explore to what extent fractal geometry may be drawn upon for solving the spatial antagonism of compactness and urban sprawl (Frankhauser 2008).

Let us recall that fractal objects are multi-scale and self-similar. The term multi-scale defines the existence of a hierarchical ordering principle – the presence of same elements on different scales. This ordering principle follows fractal logic. It is based on cascades with similar elements on different scales with inherently different attention to details. In an urban context this is, e.g.: house, block, quarter, city or: path, residential street, side street, main street, through road, freeway, and highway.

2. WHY FRACTAL PLANNING CONCEPTS ARE OF INTEREST

Morphological analyses of cities have shown that urban patterns after the industrial revolution, which are often sensed as amorphous, mostly follow a fractal structural principle (Frankhauser 1994 and 2008, Batty and Longley 1994, Batty 1996, 1999, Benguigui 2000, Shen 2002, Salingeros 2003, Tannier and Pumain 2005, Franck 2005, Thomas et al. 2010). Urban growth appears to be governed by complex dynamic processes generating morphologically well-defined macrostructures. This is reminiscent of other evolutionary systems such as clouds, trees, leaves or the human vascular system. However, this hierarchical ordering principle is changing with increasing car traffic, and the form that this change takes is that agglomerations are becoming more and more uniformly distributed due to the increased growth of remote suburbs (Frankhauser 2008).

Using fractal geometry for urban planning assumes implicitly that fractality corresponds to underlying optimization criteria, as this is supposed for natural structures. Indeed, fractal surfaces seem to be optimal for spatial systems requiring a high articulation between subsystems. Then, hierarchical structures seem very efficient. This holds for many natural networks such as lungs or vascular systems. In urban planning, an example could be the urban street network. For Paris it had been showed that the street system, including Haussmann's street openings of the 19th century, indeed follows a fractal scaling (Frankhauser 1994). Since every building must be accessible, transportation networks generally play a crucial role for urban growth. Therefore, during the trolley period, public transportation networks generated axial growth, as can still be seen in the case of Berlin, where the suburban railway network structured urban space. Railway networks are usually hierarchically organized and cover space less uniformly than street networks do nowadays. This explains why emerging urban patterns showed particularly fractal properties as long as using public transportation preponderated. In Berlin this type of growth later became the base of planning strategies by privileging development around the suburban railway axes. This holds even more explicitly for Copenhagen's Finger Plan. Privileging transportation axes as development axes is an important aspect of the fractal planning concept.

Another well-known property of urban systems is the emergence of a central place hierarchy known as rank size distribution, which corresponds to a fractal hierarchy. The concept presented for the planning model refers to such a hierarchical organization of metropolitan areas. The hierarchical structure of an agglomeration, developed on the basis of social and economic interaction and interdependency between the locations (e.g. villages), has been investigated in urban geography for a long time. These observations served Christaller as the foundation for his central place theory (Christaller 1933), which is based on a reflection about the catchment areas of different levels of services depending on how often the services are used. That is why the services for everyday life (e.g. supermarkets) are close to housing, whereas weekly or monthly services require bigger catchment areas. Christaller's theory is constrained to only concerning a functional hierarchy, not reflecting the spatial structure (topography). This explains why in Christaller's theory, locations are evenly distributed across the spatial surface plane. The accessibility of such a distribution is disadvantageous for several reasons. On one hand, it demands a pseudo-homogeneous traffic infrastructure; on the other hand, all of the remaining free spaces are approximately the same size. In our research, Christaller's theory, which was already installed as a regional model in post-war Germany, undergoes a reconception that is clearly differentiated from Hillerbrecht's ideal city structure of the Regionalstadt (regional town). Christaller's conception leads further to the sustainable concept of a city of short distances supporting a functional, administratively sustainable urban planning concept.

The concept used modifies the Christaller scheme by introducing an uneven spatial distribution of settlements where urbanized areas are concentrated close to public transportation axes (Frankhauser 2008). Nodes of a hierarchically structured transportation network are the privileged locations for services and shopping areas. This calls to mind the concept of decentralized centralization or, as Calthorpe formulates it, the regional town (Calthorpe et al. 2001), which also enables an intraregional supply for in-between spaces of global axes. However, here we explicitly present a multiscale planning concept where fractal measures become norms for planning. Planning is done on the metropolitan scale and goes down to local scales. The metropolitan area is thus an organic entity in which different parts of the agglomerations are linked to each other.

3. HOW THE PLANNING CONCEPT CAN BE APPLIED

When Christaller published his theory of central places in Southern Germany, it was clear that important functions providing for the population *extra muros* oriented themselves towards the very centre of the city. Commerce and services were mostly located near the market place as the core of European cities. It was quite apposite that Christaller called these functions “central function”, providing that infrastructures with the highest importance tended towards the most central locations. Furthermore, Christaller noted a strong hierarchy among “central places” (Borsdorf 2004). Borsdorf stresses the fact that within this system, surrounding villages near a central city could never gain a higher centrality, as Christaller’s theory took gravitation and transportation costs (= distance) as a basic principle (Borsdorf 2004). Borsdorf’s view on Christaller is correct if we try to implement Christaller as a rigid, non-flexible system that is not embedded in the surrounding built environment.

However, if we vary Christaller in the sense that we see his scheme as a modular system and imaginarily further rescale it, adding new hierarchies and interfaces for agglomerations (working, living, leisure) – we will find surprising new insights and possibilities for use in a differentiated spatial context. Hillebrecht’s Regionalstadt (regional town) addresses central locations for commerce, service and workplace. In the present-day search for a sustainable future, planners need to give up the idea of an a priori linking of regional spatial hierarchies with functional hierarchies. It is well-known that vital European city centres are often the crystallization points of economic, political and cultural power. It is important to make this distinction when addressing new planning strategies with the underlying idea of the central place theory.

An aspect not taken into account by Christaller, but crucial to the concept presented herein, is the spatial system of green and leisure areas. The importance of green areas and open spaces for a good quality of residential environment has been stressed by many authors (Guemard 2006, Bonaiuto et al. 2003), as has the presence of vegetation in urban space (Botkin and Beveridge 1997). Other authors point out, too, the importance of accessibility to leisure areas (Guo and Bhat 2002, Barbossa et al.).

A first step for conceiving a fractal concept of planning and developing a tool for elaborating fractal development scenarios was realized in the framework of the PREDIT research program¹ – a planning concept as well as the associated interactive decision support system MUP-city were developed at the Institute ThéMA², Université de Franche-Comté and CNRS³, France. Results were presented in Frankhauser et al. (2007, 2010) and Tannier et al. (2010).

The method used in the previous project uses a grid which covers the study area. The grid size is progressively modified, allowing the consideration of soil occupation at different scales. Hence, this grid serves as a spatial reference system. For practical use, at each step we identify whether a mesh contains buildings or not – what we, in previous papers, called “fractal decomposition”. Several morphological rules based on fractal geometry and topological properties control whether or not meshes may be opened for urbanization. This makes it possible to avoid fragmentation of built-up space as well as of open landscape, but ensures good accessibility to leisure areas (Frankhauser et al. 2007 2010). This procedure is well-suited to tackling urbanization scenarios on the scale of suburban villages or possible neighbourhoods.

However, it becomes less operational for metropolitan areas. Indeed, here it seems important to include, from the very beginning, the various sizes of settlements according to the Christallerian logic described above. This is not really possible when using a unifractal reference model as used in the previous projects, which was a usual Sierpinski carpet and which corresponds directly to the described grid-like logic. Figure 1 illustrates how this fractal is generated by iteration. The support is a grid, the mesh of which is reduced stepwise. In this example, the grid size is reduced by a factor $r = 1/3$ in each step. As shown in this figure, the pattern at each iteration step consists, of black meshes corresponding to built-up sites and white ones representing undeveloped land (including transportation networks). In each step, the size of all grid

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²Théoriser et Modéliser pour Aménager

³National Centre of Scientific Research

elements is the same. It would be possible to introduce clusters of black meshes, but the logic of iteration would separate them in the course of iteration and generate isolated white islands of different sizes within the urbanized area, which is contradictory to our goals (Figure 2). Let us emphasize that fractal iteration by no means requires the existence of a grid. This logic was just used in order to simplify the multiscale planning tool and make it possible to identify whether a grid element contains buildings or not.

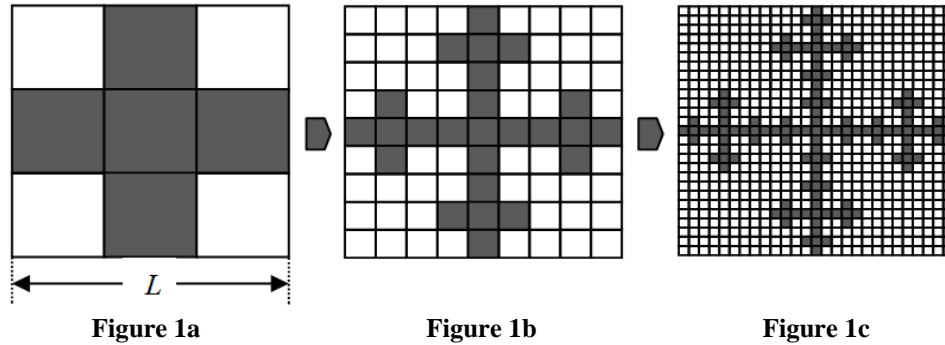


Figure 1: The three first iteration steps for generating a unifractal Sierpinski carpet on a grid, which the width of the meshes is reduced by 1/3 at each step. This model is the reference model used in anterior research.

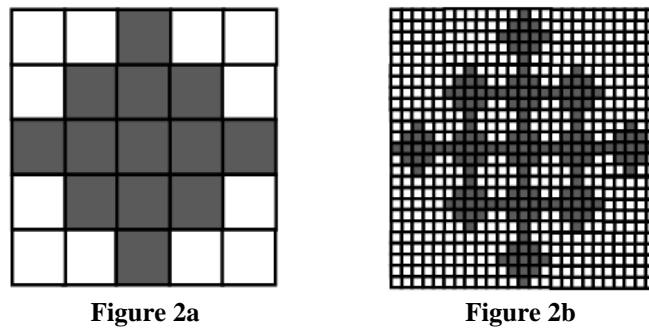


Figure 2: The first two steps of another unifractal Sierpinski carpet in which the iteration generates inner isolated lacunas.

Thus we propose here a *multifractal reference model* which combines different reduction factors (Feder 1988). As in previous work the reference model serves just for illustrating the basic principles of the planning concept and for defining the procedure for an application to real-world cities. Herein we use as reference model a multifractal version of the Sierpinski carpet of figure 1.

We still have square-like elements but obtain now at each iteration step squares of different size (figure 3). Hence such logic is no longer compatible with a grid-like support. The figure 3a represents the so-called generator which defines the iteration procedure. A square of base length L is reduced by the reduction factors $r_1 = 0.5$ and $r_2 = 0.25$. One square of size $0.5 \times L$ is placed in the centre and four small ones of size $0.25 \times L$ are placed around it. In the next step this procedure is applied to each of the generated squares. Hence in course of iteration the two factors are combined what yields in the n -th iteration step the set of values: $r_1^n, r_1^{n-1} r_2, r_1^{n-2} r_2^2, \dots, r_1 r_2^n$. Figure 3 shows the first three iteration steps.

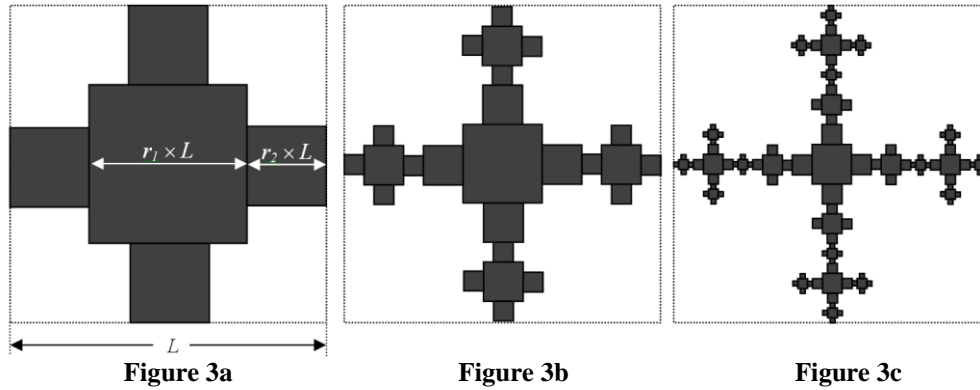


Figure 3: The first iteration steps of a multifractal Sierpinski carpet which generates a hierarchy of squares of different sizes. This fractal serves as one possible reference model for fractal urban planning on a metropolitan scale.

We interpret the square of size L as a metropolitan area consisting of two main axes which we assume intersect in the centre of the main agglomeration, which corresponds to the big black square and which is surrounded by four smaller sub-centres. In contrast to previous work, we consider these black squares as catchment areas of the central places of different supply levels, for which we assume suitability for further developments. Settlements lying outside these areas are considered as “rural hinterland” – lying too remote from any centres and not suitable for future developments. This illustrates our basic principle that we aim to concentrate urban development close to existing centres in order to avoid large-scale traffic flows. With an ongoing iteration, we refine our spatial model by generating additional sub-centres localized on the intersections of the main transportation axes and secondary shorter branches. The next steps generate an increasing number of additional smaller network branches and smaller centres with local catchment areas localized on the network intersection points. Since each step generates free space, we obtain a complex border of the areas which are opened for urbanization.

Due to iteration, the spatial system follows a strong hierarchical organization principle, which allows the definition of a sequence of centres referring to different levels of supply according to their catchment areas. The underlying radio-concentric logic guarantees good accessibility of the service and shopping centres. Similarly to the unifractal Sierpinski carpet, the model avoids detached patches of built-up space, i.e. sprawl, but also avoids fragmentation of non-urbanized areas, i.e. natural landscape. Fractality allows, however, a multiscale articulation of built-up areas and open space by lengthening the urban border. This provides good accessibility of leisure areas and green areas in direct neighbourhood of urbanized areas.

For real world application, a new decision support system, software “*fractalopolis*”, is actually under development. Therefore, we will discuss the procedure and illustrate it by means of a manual simulation of the Vienna-Bratislava metropolitan region.

The first step is now to delimit the metropolitan area we want to tackle corresponding to the base length L of the initial square. The square-like area should be centred (gravity centre) on the main agglomeration. In the next step we define the generator, which usually will be less symmetric than that of the reference model. We fix the extent $r_1 \times L$ of the catchment area of the main agglomeration and define size $r_2 \times L$ and position of the catchment areas of first order sub-centres (Figure 4a). This may be done by using the existing employment areas but also by estimating them according to planning purposes when sub-centres should be more developed. This step also serves to define the number of elements by the reduction factor r_2 . It should be emphasized that catchment areas are not necessarily adjacent but may be separated by “empty zones”. This is, however, less realistic when going on with iteration and thus working on detailed intra-urban scales. As far as possible, the squares representing the catchment areas of the sub-centres should be centred on these cities according to the underlying radio-concentric logic.

In the next step, the software user repeats this procedure for each of the defined potential development areas, i.e. the squares localized in the previous step. Zones lying outside this square cannot be developed

and will be blocked by the decision support system. Within each square, again, one big and four small squares may be localized. Hence, at each step the user can delineate the future development zone by choosing the position of the squares. As in previous research, additional constraints are introduced. Additional morphological rules avoid fragmentation of continuous open space as well as built-up space, ensuring good traffic flow (interlinkage) between green space and urbanized area (teragon boundary). The fractal constraint and the additional morphological rules may not be infringed (strict rules).

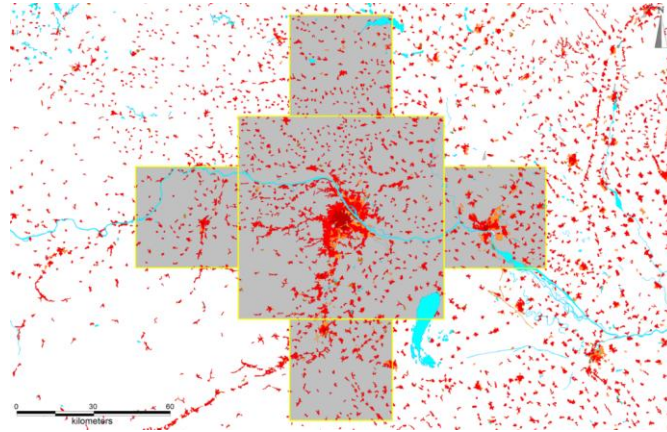


Figure 4a: Iteration step 1

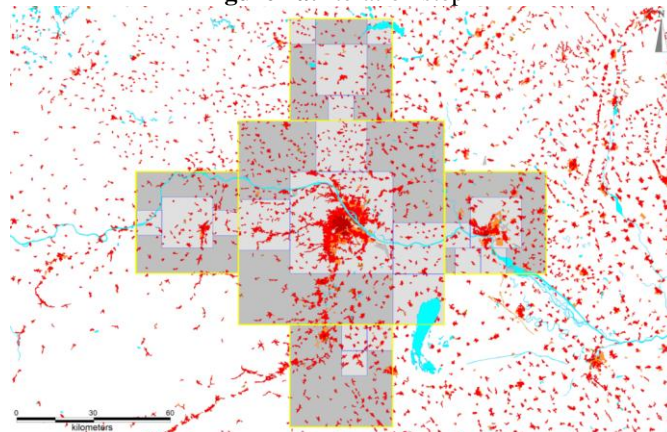


Figure 4b: Iteration step 2

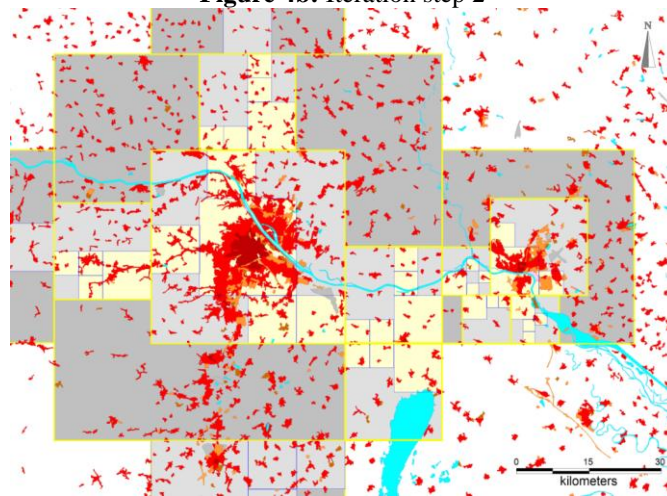


Figure 4c: Iteration step 3 (zoom)

Figure 4: Manual application of “fractalopolis” on the basis of the CENTROPE metropolitan region of Vienna. The second and third step is only applied to the axis Vienna-Bratislava.

By taking into account the localization of existing or possible new shopping and service centres, it is possible to compute the accessibilities for each site. This makes it possible to evaluate to what extent the different sites are suitable for development. To this purpose, clusters of services and shopping amenities are constituted by using the aggregation method used in MUP-city (cf. Tannier et al. 2010). Since the position of the elements is no longer constrained by a grid, this information is given by means of a “suitability map” which provides information on a rather fine scale. Similar information is introduced concerning the accessibility of leisure areas. However, the intention is to take into account the size of the accessible leisure areas, since a small wooded area has not the same function as a big forest.

As in MUP-city, the user will be informed by values about the accessibility of service, shopping and leisure amenities. For this aim, the logic of MUP-city will be used by introducing a synthetic measure combining the accessibilities to different kinds of amenities by means of fuzzy aggregation (cf. Tannier et al. 2010).

Additionally to the distinction between areas for which further development is admitted, we intend to introduce the intensity of the soil occupation index for each of these areas. To this purpose we introduce an additional multifractal model. This can be done by assigning a weight to each element of the generator. According to the same logic used for generating the multifractal Sierpinski carpet, the following iteration steps combine these factors. In our case, we distribute a given total amount of ground space P to the whole metropolitan area among the different elements of the generator. Using the model of Figure 3 we assign a weight p_1 to the central agglomeration and the same weight p_2 to each of the four secondary centres, which yields

$$p_1 + 4 p_2 = P, \text{ usually with } p_1 > p_2$$

In the following step, ground space is distributor among the five elements lying within each of these five areas. Hence we have factors $p_1^2, p_1p_2, p_2p_1, p_2^2$. This lets us introduce higher concentrations within central zones, taking into account the usual decay of soil occupation intensity with respect to increasing distances from the city. The principle is illustrated in Figure 5. By specifying the factors, simulations can be realized. If sufficient data about the buildings is available, the impact of the different factors can be made according to the real world situation in order to minimize the deviation between development simulation and reality.

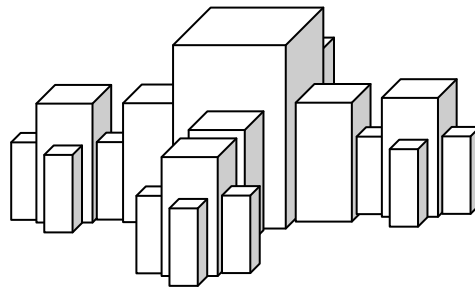


Figure 5: Illustration of the principle of multifractal weighting the elements of Figure 3b

4. ACKNOWLEDGEMENTS

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