

# Fractal Geometry for Landscape Architecture: Review of Methodologies and Interpretations

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**Abstract:** This paper presents the summary of a literature review of the methods and interpretations of fractal geometry currently used in landscape architecture. Over 40 studies were examined for their use of fractal concepts within the analysis of landscape-related elements. Although much work has been done on the quantification of landscape parameters for the purpose of visual assessments and preference predictions, the links between applied landscape design and fractal principles remain tenuous. Several methodological hurdles, such as issues of signal transformation and segmentation, as well as the inevitable questions surrounding the ecological validity of landscape surrogates still stand in the way of making fractal geometry a useful tool for landscape architects.

**Keywords:** Review, methodology, fractal geometry, fractal dimension

## 1 Introduction

Fractal geometry, the corpus of mathematical principles behind organic forms and patterns as collated by Benoit Mandelbrot in 1975 (MANDELBROT 1975), is a topic of fascination within both design disciplines and the environmental sciences, and landscape architecture is no exception. In fact, as the roots of the discipline are firmly planted in both arts and science, it could be argued that no academic field is better suited to the study and application of fractal principles.

This is particularly true when considering the many attempts at quantification of landscape characteristics which have animated the discipline, most often in order to predict preference through visual assessment (see for example some of the works derived from the Kaplans' information processing theory (Purcell & Lamb 1998) or the work of Stamps (2002) on the theory of fractal fit). For these endeavours, fractal geometry offers the seductive promise of ordering chaos and distilling the complex nature of landscapes and of their elements into simple numerical measures, still generally considered more manageable and persuasive than qualitative data. However, publications on fractals from the landscape architecture perspective are few and far between, and practical applications of the geometrical principles themselves in the context of landscape design are yet to be explored.

Therefore, this paper attempts to produce a comprehensive review of the current state of knowledge on the use of fractal analysis methods in landscape architecture and its close neighbouring disciplines. This review includes both research and design contexts as long as the unit of study is at the landscape scale and/or from a landscape-oriented perspective. In doing so, this paper intends to answer two main questions: What are the methods of fractal analysis currently used in landscape architecture? And how do they interpret or consider the definition of its core concept, the fractal dimension?

## 1.1 Definition of Terms and Concepts

Fractal geometry is less of a unified theory and more of “a collection of examples, linked by a common point of view” (LORIMER et al. 1994, p.1) of mathematical methods to model natural forms such as coastlines and rivers.

Within this framework, Mandelbrot defined the necessary calculations to estimate the fractal dimension (noted  $D$  or  $FD$ ) a constant characteristic of the object of study. Although the mathematical definition of that indicator is fairly clear, as it describes the power law relationship between content and scale, the interpretation of the resulting numerical value (which is without unit) is often up for debate. The main aim of fractal analysis is typically to estimate that value.

There are many methods used to perform fractal analysis or produce fractal forms of specific dimensions and their detailed description is beyond the scope of this paper. Interested readers might want to refer instead to LOPES & BETROUNI (2009) and their excellent review of methodologies.

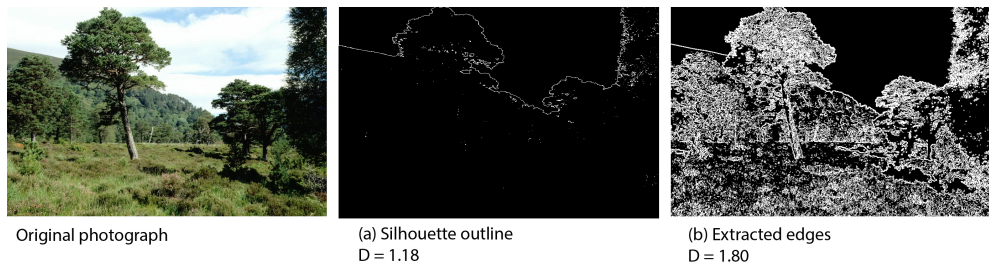
Probably the most well-known approach is the box-counting method, based on the application of grids of increasing or decreasing mesh size onto the selected pattern. By counting the number of squares, or “boxes”, containing bits of the pattern for each grid, one effectively analyses the content of the pattern at different scales. The resulting values can be entered into a log-log plot against the dimension of the boxes at each stage and the curve thus traced has a slope which approximates  $D$ .

However, this method has been heavily criticised for its limited application to binary patterns and its sensitive analytical parameters which require careful consideration of the type of data being processed (LOPES & BETROUNI 2009, OSTWALD 2013). Specifically, in order to know what box to include in the analysis, a distinction must be made between the “object”, or pattern which is the subject of the analysis, and the “background” which is the rest of the image. This image segmentation can be particularly difficult to systematize in the case of landscape photographs, where elements are not necessarily distinct from each other and the object of study is the general view rather than discrete patterns. Different techniques of image transformations have been tested, each with their own specific results (See Fig. 1, PATUANO 2018).

## 1.2 Review Methodology

Landscape Architecture is a multifaceted discipline which, much like the concept of *landscape*, its object of study, tends to resist a strict definition. For the purpose of this paper, studies were considered relevant if they dealt with natural environments with built elements, physical or perceived, and the shaping of these environments or the responses they induce.

Studies on fractal geometry were then originally collated in relation to visual perception of natural environments then classified according to their field of study. They were then categorised by their dimensionality, that is whether the stimulus used as a basis for analysis was one-, two- or three-dimensional, as this aspect greatly affects the applicable methodology. Although this paper primarily focuses on the fractal analysis of real data (as opposed to the production of digital fractal patterns of specific properties), studies investigating the perception of fractal dimensions through the use of digital surrogates were also considered.



**Fig. 1:** Different image segmentations yield different FD, from PATUANO 2018. Studies from neighbouring disciplines were also considered with regards to the applicability of their approaches to Landscape Architecture studies.

## 2 Results

Over 40 studies were compared ranging from 1981 to 2019, less than 10 of which could be considered strictly Landscape Architecture, either because of their specific focus or the explicit affiliation of the journal in which they were published. Others come from fields as diverse as Landscape Ecology, Soil Sciences, Vegetation Taxonomy, Environmental Psychology, Urban Planning and Architecture.

### 2.1 Purpose of Using a Fractal Approach

Historically, although it was first harnessed by biological and physical sciences who used it for its ability to accurately model complex and chaotic phenomena, the power of fractal geometry was soon applied to aesthetic concerns as a way to tease out the links between arts and nature (SHORT 1991).

One aspect which seems consistent across disciplines is the hypothesis that FD is an estimation of complexity, regardless of how that complexity is defined, be it a question of visual variety (COOPER & OSKROCHI 2008), roughness of surfaces (PENTLAND 1984) or an amount of information (FORSYTHE et al. 2011). However, some authors also noticed its correlation with the presence or amount of vegetation (KELLER et al. 1987, CHALUP et al. 2009, COOPER et al. 2013) and, on this basis, some have also associated it with naturalness (PERRY et al. 2008, PATUANO 2018).

Regardless of how it is defined, FD is also generally considered a composite measurement of several variables (COOPER 2003) and a statistical approximation of content across scales rather than a precise measure.

#### 2.1.1 In Other Disciplines

Fractal geometry is still commonly used in medical sciences, where it can be combined with medical imagery as a diagnostic tool. For example, the fractal analysis of images of blood vessels or cells can be used to reveal quantifiable changes and evolutions in the development of pathologies (BANKMAN 2009). Disciplines such as these are some of the main drivers of research behind the development of robust methods of fractal analysis which can then be adapted to other objects of study.

A very fertile ground for the development of methodologies of fractal analysis which could be applied to Landscape Architecture studies seems to be Architectural studies, with many attempts to estimate the FD of architecture and surrounding context and the first applicable guidelines for the fractal analysis of real architectural or urban data being produced by OSTWALD (2013). Using this technique in “The Fractal Dimension of Architecture”, VAUGHAN & OSTWALD (2016) calculated the visual properties of eighty-five building designs and investigated how they relate to each other. However, they found it impossible to distinguish architectural styles using FD alone. By contrast, in urban design, COOPER (2005) was able to assess the fractal dimension of street edges by tracing building frontages using 1:2000 plan outlines and derive a typology of street characteristics based on these values.

Nevertheless, Architecture has the advantage of working from fixed lines, with perhaps a more straightforward relationship between façade elevation on paper and the physical or perceived reality.

### **2.1.2 In Landscape Architecture**

Within Landscape Architecture, methods of fractal analysis are usually integrated into explorations of visual perceptions of landscapes, either through landscape visual assessments or for the purpose of preference studies (STAMPS 2002, HAGERHALL et al. 2004, PATUANO 2018, TARA et al. 2019). Similarly, many studies in and outside of the discipline used the fractal dimension of scenes as a way to perpetuate the long-standing tradition of systematic comparison between urban and natural scenes typologies (PERRY et al. 2008, WANG & OGAWA 2015).

However, no study has yet managed to bridge the gap between research and practice by applying fractal geometry to Landscape Design. The closest use of fractal principles in landscape practice is through what is often referred to as “Biophilic design” (JOYE 2007, TAYLOR & SPROTT 2008), an approach to make the built environment look more natural by using shapes, textures and colours inspired by nature. However, even within this framework, fractal geometry is only used as an inspiration rather than an applied method. Furthermore, there is no equivalent approach appropriate to Landscape Design, which primarily uses vegetation rather than built forms, and is therefore already considered somewhat natural.

Most notably, PERRY et al. (2008) have tried to tackle this question, acknowledging that, “although Baird (2002), and Spirn (1988), have suggested that fractal geometry could form the basis of a new aesthetic, no indication is given about how this might occur” (p. 6). They therefore undertook a pilot study to explore the development of an ecological aesthetic based on fractal geometry but realised that the way to perceived fractal patterns was not straightforward. Indeed, as Mandelbrot warned, FD is not enough on its own to characterise an image, and two very different views can be assessed as having the same FD while looking nothing alike (see Fig. 2).

## **2.2 Methods Used for the Fractal Analysis of Real Data**

Although technology arguably gets better every day and could allow the production of increasingly realistic digital surrogates, a great deal of effort has been put into refining our ability to model real-life data and produce results directly applicable to real-life situations (CHALUP et al. 2009, HAGERHALL et al. 2004). When applying fractal geometry to the analysis of real data, most studies rely on the box-counting method or variants of it, regardless of the discipline (OSTWALD 2013, CHALUP et al. 2009, HAGERHALL et al. 2004).



Silhouette outline:  $D = 1.23$

Silhouette outline:  $D = 1.27$

**Fig. 2:** Two images of similar fractal dimensions but opposite typologies

The second most-used method is the fractional Brownian motion (KELLER et al. 1987, WANG & OGAWA 2015). Methods of image segmentation and transformation vary widely between papers.

Regardless of the method, the data used as landscape surrogate are often photographs (PERRY et al. 2008), which typically need to be segmented prior to analysis, either as greyscale (PERRY et al. 2008), silhouette outline (HAGERHALL et al. 2004) or extracted edges (PATUANO 2018). These transformations each drastically alter the original data, by summarizing the information contained within the digital photographs into a simple binary pattern which can then be analysed with box-counting.

### 2.3 Fractal Analysis Methods Relying on the Use of Digital Data

The digital data has offered opportunities for fractal research to study the landscape beyond the limitation of real-world information and perception. This allowed studying various compositional and structural attributes of the landscape. Two-dimensional digital representations through modelling and rendering techniques applied by STAMPS (2002) to compare the fractal dimension of the skyline with the surrounding landscape to study the contextual fit. GAO et al. (2019) used Digital Elevation Models (DEM) as the digital source for estimating the fractal dimension of the gradient model of landscape patterns. The fractal dimension of the visible space was investigated by using city models extracted from point clouds (TARA et al. 2019). In this research, the fractal dimension of 3D volumes was estimated using voxels or cube counting method. This method is a good example of a technique adopted from medical research and developed for Landscape Architecture.

## 3 Discussion

One of the main issues with fractal analysis techniques as applied to Landscape Architecture is the ecological validity of the data. Indeed, all methodologies but particularly the box-counting method rely on the use of fixed simulations or visualisations of the landscape. Furthermore, the estimation of  $D$  will typically be highly dependent on the resolution, brightness, contrast and, eventually, the chosen method of segmentation of the original image into a

binary pattern. Even when looking at elevations or traces, the precision and thickness of the lines, who drew them, when and why, will also be critical for the calculation. Overall, it is still unclear what the perceptual links between landscape visualisations and on-site experience are, so any extrapolation of results obtained from surrogate supports to principles applicable to real-life environments should be carefully considered and well-justified. This is illustrated, for example, by the issue of viewpoints described by PATUANO (2018), where two pairs of photographs taken from different points of view but in the same landscape yielded wildly different values of FD.

Similarly, although the expressed purpose of fractal analysis is to provide a quantifiable measure of landscape characteristics which can subsequently be used in predictions and comparisons, different methods of analysis will yield vastly different values of FD. Indeed, the descriptions and definitions of FD that the various methodologies of fractal analysis rely on each have a specific way to estimate the value of fractal dimension. Since they all measure something different, comparing values of FD obtained through different methods is meaningless at best not to mention theoretically flawed.

However, a prolific strand of research has been focused on defining values or ranges of FD values which would be considered the “most preferred” or “most natural” (TAYLOR 2006, TAYLOR & SPROTT 2008, HAGERHALL et al. 2004). Such a number would vary greatly depending on the method used for estimation but is also meaningless on its own as it only captures a specific aspect of the pattern. This highlights another lack of understanding of not only the method itself – as mentioned in the case of the study by PERRY, REEVES, AND SIM (2008), Mandelbrot did warn that  $D$  was not enough to accurately describe a specific pattern and that two patterns could share a value of  $D$  despite looking nothing alike – but also of its application. The aim should not be to quantify for quantifiability’s sake but perhaps to look at  $D$  as an added environment variable, such as elevation or hygrometry, which requires contextualisation in order to be interpreted.

Some of the methodological issues encountered with the fractal analysis of real-data could also be due to landscapes being more akin to multifractals, where different elements of varying properties are nested within each other. This is supported by studies looking at individual species of plant and finding that different types of vegetation exhibit different fractal dimensions (BRUNO et al. 2008).

### **3.1 Further Research**

Despite these issues, two specific trends of research still appear promising.

#### **3.1.1 Methodological Developments**

Ubiquitous and innovative digital technologies in sensing landscape offer opportunities for fractal analysis and methodologies to develop further. Capturing the landscape through point cloud data and extract models have potentials for expanding the fractal research in Landscape Architecture. New methods of image segmentation such as quadtree decomposition can be considered as new ways of image segmentation of 2D digital photos to calculate fractal dimension. A similar concept can be applied on three-dimension volumes through oct-tree voxelisation. Although there are always some levels of invalidity of landscape surrogates compared to real world experience, new technological advances in sensing landscapes through terrestrial laser scanners and immersive technologies provide opportunities for methodology-

ical developments which can then facilitates new and fruitful lines of research in preferences studies.

### 3.1.2 In Neighbouring Disciplines

An area of research which seems particularly fertile resides in the overlap between landscape design and environmental psychology and considers the concept of perceptual fluency or the bottom-up processing of visual data as a possible explanation for humans' affinity for fractal patterns (JOYE 2007, JULIANI et al. 2016). This strand of research can be traced back to TAYLOR (2006) who first compared different types of images based on their fractal dimension and ability to induce stress-reducing benefits usually attributed to the visiting of natural environments. Although this approach has often focussed on determining a single preferred value of FD instead of considering fractal patterns as a whole and although it tends to overly rely on the urban/nature dichotomy, the original hypothesis on which it is founded is well supported by some preliminary evidence (HAGERHALL et al. 2015). However, until the methods of fractal analysis of real data or the validity of digital landscapes as surrogates for the on-site experience are improved, such research should proceed with caution.

### 3.1.3 Application to Design

To pursue fractal research in Landscape Design, it is necessary to shift from realisation to abstraction of space, in order to extract the main formal elements of design, analyse them and eventually compare them. This is done by OSTWALD (2013) in Architecture and could potentially be developed in Landscape Architecture. Systematic methods of simplification of the space and extraction of the design are therefore also necessary. By developing these, it would be possible for example to assess to what extent different designs can result in different FD. It would eventually be interesting to see the impact of specific FD in the three dimensions of Landscape Design: First on plan views, space composition and subdivision of key parks and gardens could be studied to estimate the FD and how it is reflected in the visitors' experience; In perspective, height and depth could be studied through the interplay of built and natural elements, perhaps comparing different proportions, placements or the impact of different vegetation choices; And finally by considering time variability and seasonality and comparing the FD of a landscape across seasons. Ultimately, although the link between FD and experience is still unclear, design research shouldn't necessarily be limited by perceptual validity but instead embrace this uncertainty as the new frontier of knowledge.

## 4 Conclusion

Fractal geometry seems to be as useful a concept as Biophilia, with which it is often associated: both serve as umbrella terms for a perceived resonance to natural elements while offering little explanatory value as to how this resonance might actually operate. Similarly, both "theories" suffer from not being theories at all, in the sense that they offer no useful and articulated conceptualisation of phenomena, but from being instead a collection of examples. Finally, this review highlights the current gaps in our understanding of the full potential of fractal geometry to understand and design landscapes. More research, and principally practice-based research such as research by design, could be the key to bridge the gaps between the mathematical theory and landscape architectural practice.

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