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Benchmarking Tree-Inspired-Fractal Branching Dendriform Structures From BC to L-System Based Contemporary Structures

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Abstract: Nature has its own complex geometry, which couldn't be explained using traditional methods until the advent of Fractal Geometry. Nowadays, we can observe and represent almost every geometry using quantitative tools. In this study, the compatibility of geometric compositions, referencing Euclidean geometry from hand-drawing environments to digital drawing and computational Computer-aided design (CAD) tools in the architectural products of complex parametric designs, was observed. Historical structures such as Maison Carrée, The Sakyamuni Pagoda of Fogong Temple, Saint Chapelle, Gloucester Cathedral, King's College Chapel, La Sagrada Familia, and the Stuttgart Airport Terminal, as well as contemporary structures generated by Parametric Design Tools, were examined. Both past and current parametric design examples were benchmarked. The plans and column head views of buildings were analyzed using the Fractal Analysis Method with the FracLac software, which functions as a plug-in within ImageJ. The sophisticated column geometry was created as a dynamic geometry utilizing L-System rules and iteration principles, and then a solid substance was built using a Dynamo-PythonScript node, which acts as an interface command in Autodesk Revit. As a result, contrary to popular belief, dendriform structure geometry behaved unexpectedly and was not complicated than modern times.

Key words: Computational architecture, Computer-aided design (CAD), Fractal geometry, Iterative generation method, Parametric design.

Ağaçtan İlham Alan Fraktal Dallanan Dendriform Yapıların Antik Dönemden L-Sistem Tabanlı Çağdaş Tasarımlara Kadar Karşılaştırılması

Öz: Doğa, Fraktal Geometri ortaya çıkana kadar geleneksel yöntemlerle açıklanamayan kendine özgü karmaşık bir geometriye sahiptir. Günümüzde, hemen hemen her geometriyi niceliksel araçlar kullanarak gözlemleyebilir ve temsil edebiliriz. Bu çalışmada, karmaşık parametrik tasarımların mimari ürünlerindeki el çizimi ortamlarından dijital çizim ve hesaplamalı Bilgisayar destekli tasarım (CAD) araçlarına kadar Öklid geometrisini referans alan geometrik kompozisyonların uyumluluğu gözlemlenmiştir. Maison Carrée, Fogong Tapınağı Sakyamuni Pagodası, Saint Chapelle, Gloucester Katedrali, King's College Şapeli, La Sagrada Familia ve Stuttgart Havaalanı Terminali gibi tarihi yapıların yanı sıra Parametrik Tasarım Araçları ile üretilen çağdaş yapılar incelendi. Hem geçmiş hem de güncel parametrik tasarım örnekleri kıyaslanmıştır. Yapıların planları ve kolon başı görünümleri, ImageJ içinde bir eklenti olarak işlev gören FracLac yazılımı ile Fraktal Analiz Yöntemi kullanılarak analiz edildi. Sofistike kolon geometrisi, L-Sistem kuralları ve iterasyon ilkeleri kullanılarak dinamik bir geometri olarak oluşturuldu ve ardından Autodesk Revit'te bir arayüz komutu olarak işlev gören bir Dynamo-PythonScript düğümü kullanılarak katı bir madde oluşturuldu. Sonuç olarak, sanılanın aksine, dendriform yapı geometrisi beklenmedik şekilde davrandı ve modern zamanlardan daha karmaşık değildi.

Anahtar kelimeler: Hesaplamalı mimari, Bilgisayar destekli tasarım (CAD), Fraktal geometri, Yinelemeli üretim yöntemi, Parametrik tasarım.

1. Introduction

The intricate and inspiring geometric patterns present in nature are more complex than traditional methods of explanation. However, the definition of the concept of fractals, which is contained in Mandelbrot's seminal article "Fractal Geometry" [1], has illuminated this complexity. Fractals are geometric patterns that are generated from repeated forms, and can be observed in natural context such as leaves, waves, and mountains. . From antiquity, the human mind and artisanal skill have not only adeptly imitated these forms but have meticulously integrated their proportions into all elements of construction, decorative elements, and architectural typologies.

Fractal geometry has been an important tool in understanding and modeling complex relationships between natural and artificial structures. Defining fractals and applying them to architecture establishes a bridge between

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aesthetics and functionality [2], [3]. Fractal systems represent an effective method for modelling the complex structure of city centres, encompassing both spatial and temporal dimensions. This is achieved not only at the building scale but also at the urban scale, thereby reflecting the self-similar, hierarchical and dynamic nature of cities. The scale-independent similarity of urban elements, including roads, buildings and green spaces, can be analysed using fractal geometry. The fractal dimension is a measure of the growth, concentration and complexity of urban centres, and also enables the analysis of changes over time. Systems with fractal properties, such as transport networks, can be employed to comprehend and simulate alterations in traffic flows. Moreover, fractal systems facilitate urban planning by elucidating intricate interrelationships between infrastructure, population density and economic activities. When integrated with remote sensing, GIS and agent-based models, this approach can be implemented in domains such as urban growth, land use and infrastructure optimisation to support the design of sustainable and resilient city centres. For several decades, designers have employed fractal geometry to develop innovative architectural forms through the utilisation of parametric modelling tools and the finite element method.

Historical buildings preservation as well as analysis is reliant on computer-aided methods. Image compression, characterization, and recognition techniques are employed in assessing the preservation status of structures [4]. In light of the available case studies, this study compares human cognitive intelligence and ingenuity with both the material and immaterial aspects of the structures obtained through an artificial universe, specifically a computer environment, in the context of fractal geometry, which is often referred to as the geometry of nature.

1.1. Dendriform Structures and Architecture

Natural form adaptation in architecture largely depends on dendriform structures. Innovative structural solutions can be found via L-systems that model such a type of structure [5]. Nouri et al.'s research work [6] discusses how these systems can be used for deriving complex geometries via dendriform structures with consideration to enhancing both form and function. Also Md Rian and Sassone [7] were investigated tree dendriform structures in architectural branching structures. They compared that structures from BC to modern times.

1.2. The application of L-systems and algorithmic generators in Computer-aided design (CAD)

By integrating fractal geometry into the design of architectural structures, a new method has been developed to convert the intriguing and practical principles observed in nature into buildings and structures. A significant advancement in this area is Prusinkiewicz's investigation of the structures of plants using L-Systems [8]. These systems are intended as instruments that generate complex forms that are inspired by the natural world, these forms are created through the use of parametric design tools.

The use of L-Systems in architectural design, and the possibility of parametric design were explored. The investigation by Toussi [9] explains how L-Systems can be used as algorithmic digital generators in architectural design processes. On the other hand, Nouri et al.'s [6] article shows how complex structures can be derived from simple geometric forms through the application of L-Systems. In contrast, Roudavski [10] considered some issues that limit and enable parametric design with emphasis on developing algorithms for handling custom scaling and dynamic properties. This literature review calls for architects to employ L-systems and parametric designs to create innovative and esthetically enriched buildings.

The fractal sorting depends on two main factors. One of them is that knowledge of the nature of fractals must be supported by a straightforward and unalterable method for determining their dimensions. Secondly, unlike mathematical fractals, buildings are not an example of mathematical ones but they bear the characteristics of natural fractals that vary with the scale. This necessitates customized methods for sorting architecture to take into account specificities of different built environments [11].

The use of algorithmic techniques, such as recursion and iteration, has become prevalent in the creation of computer graphics models for fractal objects in a virtual setting. This is due to the self-similarity aspect of fractal geometry. These techniques, which offer efficient model construction, have progressively emerged as the primary means of visually depicting fractal objects in the realm of computer graphics [12].

The use of parametric design enables designers to effortlessly explore and improve shapes by manipulating various parameters. This approach facilitates the seamless connection of the complex and different ways of nature into architectural designs. Combining parametric design with inspiration from nature offers numerous advantages. These designs have the big potency to be visually fascinating, enhance productivity, and support sustainability. A prime example of this can be seen in the Mercedes-Benz Museum located in Stuttgart, Germany, expertly crafted by Schlaich Bergermann and Partner. The museum's roof draws inspiration from fractal geometry, allowing for the use of natural light and energy conservation [13].

2. Theory/calculation

This study demonstrates the potential use of computer algorithms and parametric design tools for generating and replicating natural geometric shapes. However, it also indicates that architectural products produced prior to the advent of computer-aided design were more successful in capturing natural proportions. This discovery suggests that nature possesses a depth of complexity and aesthetics that cannot be replicated solely through the use of mathematical parameters. The acquisition of artifacts that are proximate to Euclidean geometry, which is regarded as the fractal ratio of natural forms, and the attainment of proximate results from the data derived from the analysis of these artifacts and the data derived from the analysis of computational and low-error-margin geometries generated in the computer environment, reveals the distinction between the structure and vehicle comparison based on the study and the existing fractal analysis studies.

The geometry of natural shapes contains a hidden proportion that can be replicated and easily produced using modern technological methods such as CAD environments, computer algorithms, software application programming interfaces (APIs), and scripts. However, prior to these developments, artisans and other artists were solely reliant on their own abilities to convey ideas. Their designs were meticulously detailed and crafted by hand. The objective of this study is to contrast the profound realm of human cognition with the computational capabilities of computers, thereby emphasizing the significant distinctions between them. In contrast to computers, which are designed solely for computation, humans possess an exceptional capacity to perceive and experience the emotions of nature. Fortunately, humans also possess the ability to achieve results that are computationally similar to those achieved by computers since ancient times (Figure 1).

3. Imitating Natural Geometries

Computer algorithms and parametric design tools are important for mimicking natural forms. However, this research shows that there is a complexity in the natural geometry which cannot be achieved through mathematical parameters alone. There are many geometric shapes that happen to be mathematically precise within nature itself; for instance, the organization of leaves around a stem follows the Fibonacci sequence. The beauty of these geometrical patterns found in Renaissance artworks indicates how artists have been able to utilize natural geometries into human creations. In contrast, current technological advances in architecture and engineering have been driven by the imitation of natural geometric designs, so-called biomimetic design, as evidenced by the creation of structures such as those derived from termite mounds. These developments demonstrate the remarkable capabilities of mathematical laws, which underpin the functioning of both living and non-living entities, across a range of disciplines, including science, technology, and the arts.

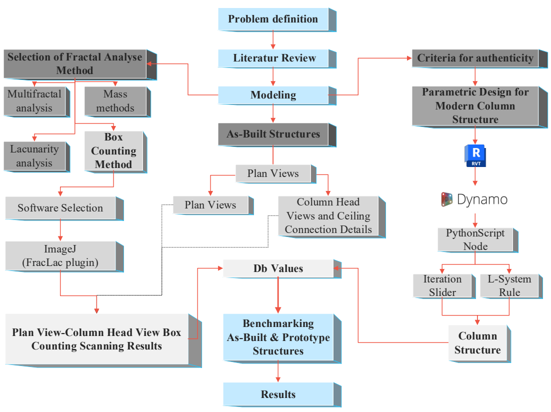


Figure 1. The framework of the study methodology.

3.1. The Role of Human Mind and Skill

In the past, architectural designs were created by humans, rather than computers, which were better able to imitate the natural proportions of architecture. This suggests that the mind can understand the intricacy and beauty of nature through intuitive processes.

In human perception, knowledge about shape, color, texture, and composition, as they relate to one another visually, helps us make sense of our environment. All of these elements combine to form rich patterns that are foundational for how we think. Among these features, it is notable that shape is recognized first and remembered best by the brain, thus serving as a basis for further interpretation. Composition, on the other hand, emerges as key in cognitive processing since it greatly influences our perception. While shape can determine what kind of thing an object belongs to, its uniqueness often gets copied, especially where there are differences in arrangements. Here, different compositions act like catalysts, triggering novel stimuli, leading to personalized visual experiences among individuals [14].

3.2. The Limits of Nature-Inspired Design

The architectural style that employs nature-themed designs is currently a popular trend. However, this study also identifies the limitations of this approach. It asserts that the intricate and beautiful forms of nature cannot be fully replicated through a purely mathematical methodology. This finding has significant implications for environmentally influenced designs in buildings in the future. Architects must not only consider relevant mathematical principles but also the intuitive capacity and skill of humans to imitate the complexity and attractiveness found in natural things.

Biomimicry refers to the design of systems or processes that emulate the functioning of living organisms or their components. These solutions are inspired by the inherent properties of nature, particularly those observed in other species, which are then adapted or proposed as solutions to human aspirations and concerns. An illustrative example is the regulation of bioclimatic conditions in termite nests, the structural stability of spider webs, and the trapping of heat in fur coats among animals. Technological examination of these characteristics of nonhuman nature may have direct practical applications, as well as encouraging appreciation for the cleverness and creativity of other creatures and the natural world [15].

3.3. Tree Branching Form From Historical Times to Present

The architectural design process may benefit from emulating the strength and beauty of natural tree structures. In particular, the manner in which trees branch out can be utilized as a model for increasing stability and longevity in constructions. This organic shape not only leads to a harmonious arrangement in design but also communicates an inherent unity within the system.

With regard to the field of architectural design, an examination of the shapes of trees in relation to their structural roles can result in significant gains through the utilisation of materials' inherent structural capacities and arrangements. While it is widely acknowledged that branches support leaves, which gather sunlight for photosynthesis, it is often overlooked that they are also adept at carrying loads and resisting external forces. From an architectural standpoint, therefore, where durability is a primary concern while ensuring that structures remain stable, tree-like branching strategies could be employed within the design of any given edifice, or even just specific sections thereof. For instance, during load optimization for stability purposes, branches may be employed to distribute weight evenly throughout different sections, thereby ensuring safety while not compromising the structural integrity of the edifice. This is particularly relevant when dealing with heavy items such as those found on roofs. It is possible to make trunks thick enough to bear more vertical loads, thereby enhancing collective strength. This can be done during the planning stages, when necessary, based on specific requirements concerning various elements forming part of the structure. The overall design and intended use must also be considered.

Trees have different mechanisms to cope with external and internal loads. Particularly, when exposed to external factors like wind, they adjust their shapes to withstand strong wind forces and bending moments. Similarly, internal loads such as axial compression due to their own weight are carried by tree stems and trunks. Under wind exposure, stress changes from tensile on the convex side to compressive on the concave side of a component. This highlights how trees utilize their natural engineering abilities and physical properties to interact with external loads [7].

In this study, tree dendriforms which are extended from AD to present examples have been investigated by observing their complex structural generations. The chosen buildings in historical times have almost more complex natural forms then from now. But fractal geometry results from that buildings are lower than modern, simple and non-organic kubic form structures. In other words, “more technology” doesn’t mean “more simplicity”. Literally human brain has been a gift by its creative, productive, handcrafter ways throughout history. Chosen buildings (Table 1) have indicated their potential which had been proved by fractal geometry values.

After fractal geometry is developed, the conscious use of fractal algorithms in constructing building elements emerges. The fractal approach serves as a research method and is widely employed in designing and modeling architectural forms for modern buildings. Utilizing the regularities found in natural structures during the shaping process enables architects to create buildings with fractal characteristics.

In the early 20th century, fractal analysis methods were utilized in urban planning practices. Many architects have applied architectural shaping methods based on fractal geometry and nonlinear Dynamics [16].

Dendriform structures in architecture have ancient roots, possibly stemming from humanity’s fascination with trees and plants, as evidenced by prehistoric cave art. Early architectural examples, such as Egyptian palaces and pyramids, showcased vegetal motifs, including dendriform columns. Luxor Temple’s papyrus-cluster columns (1400 BC) exemplify this, with capitals resembling papyrus plant umbels.

4. Materials and Methods

4.1. Fractal Geometry

The concept of fractals originates from chaos theory and denotes specific behavioral patterns within complex systems. These patterns, rooted in irregularity and uncertainty, enable a deeper comprehension of the intricate structures and arrangements found therein. Mandelbrot’s seminal work, “The Fractal Geometry of Nature” underscores the remarkable semblance between fractals and traditional art forms, as well as architectural compositions. Fractal geometry thus represents a rigorous mathematical endeavor aimed at quantifying and comprehending the inherent complexity and irregularity present in natural phenomena.

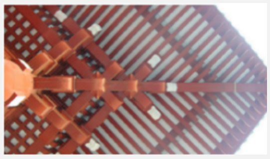
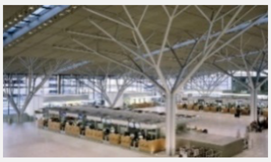
In the realm of architecture, fractal geometry offers a systematic approach to examining the similarities and complexities exhibited by architectural forms across varying scales. Notably, architectural designs influenced by fractal principles often display recurring patterns and motifs inspired by natural phenomena, exemplified by the works of Frank Lloyd Wright. Through fractal geometry, architects can conduct detailed analyses of architectural compositions at both micro and macro levels, revealing underlying structural patterns and scale-invariant characteristics. Chaos, contrary to perceptions of randomness or anarchy, is actually concerned with examining the order within disorder. While fractals deal with the geometry of this disorder, chaos theory focuses on the dynamics within it [17], [18].

Mandelbrot’s quote, highlighting the inadequacy of Euclidean geometry in describing natural phenomena such as clouds, mountains, coastlines, and bark due to their rough, irregular structures, underscores the significance of fractals. Fractals demonstrate this irregularity across various scales, commonly observed in natural environments and architecture. As traditional geometric methods prove insufficient in modeling natural shapes, fractal geometry emerges as a more effective tool for modeling natural objects like trees, clouds, mountains, and seaweed (Figure 2).

Furthermore, fractal geometry exerts a profound influence on architectural design processes by guiding the incorporation of geometric principles into various aspects of architectural expression. From the articulation of tectonic movements to the intricacies of spatial planning and detailing, fractal geometry fosters a holistic understanding of architectural form and organization. The recognition of architectural structures as exhibiting fractal formations enables a deeper exploration of their inherent complexity and naturalistic qualities, ultimately enriching the aesthetic and functional aspects of architectural design.

Euclidean geometry has been widely employed for expressing architectural style over an extended period, while another avenue for articulating complexity within a style is directed towards non-Euclidean geometry. Several studies have demonstrated the use of fractal geometry in ancient architecture as a symbol of natural biomimicry [26].

Table 1. Building's chronological identity informations**.**

REFERENCE	NAME	GENERAL VIEW	LOCATION	TIME PERIOD
[7]	THE SAKYAMUNI PAGODA OF FOGONG TEMPLE		China	771 BC - 476 BC
[19]	MAISON CARRÉE		Nîmes, France	16 BC
[20]	SAINT CHAPELLE		Paris, France	1242 AD – 1248 AD
[21]	GLOUCESTER CATHEDRAL		Gloucester, England	1351 AD
[22]	KING'S COLLEGE CHAPEL		Cambridge, England	12th century AD
[23]	LA SAGRADA FAMILIA		Barcelona, Spain	1982 -
[24]	STUTTGART AIRPORT TERMINAL		Stuttgart, Germany	1991
	PARAMETRIC GRIDAL COLUMN PROTOTYPE		Computer Environment	**2024**

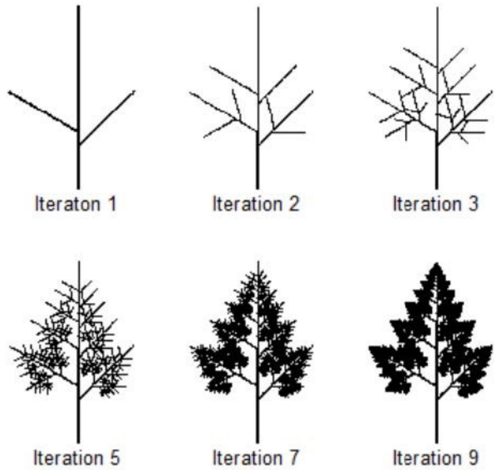


Figure 2. Six iterations of a simulated fern leaf [25].

4.2. Fractal Dimension

Fractal dimension is a mathematical term used to measure the complexity and self-similarity of fractals. Unlike Euclidean dimension, fractal dimension is expressed as a fractional number. A fundamental method for calculating fractal dimension involves examining the number of similar parts of a fractal and how these parts grow proportionally. For example, a fractal like the Koch curve (Figure 3b) divides into three similar parts with each iteration, and the length of each part is divided by three. In this case, the fractal dimension is determined by how the parts are proportioned to each other. While a point is considered dimensionless in Euclidean space, a line has one dimension, a plane has two dimensions, and a cube has three dimensions. However, fractals can have fractional dimensions (e.g., 1.4 or 2.1).

Fractal dimensions can be better understood through mathematical equations. For instance, when you double the length of a line, you get two copies, but when you double the length and width of a square, you get four copies of the original shape, and similarly, for a cube, you get eight copies. This characteristic is used to determine the dimension of a fractal (Figure 3a).

If we we double the sides and get a similar figure, we can write the number of copies as a power of 2 and the exponent will be the dimension. In an another words, if dimension is d then the number of copies or the magnification factor $n = 2^d$. The number of self-similar pieces is 2 (Equation 1) [27].

Therefore it is clear that,

$$\textit{Magnification factor} = (\textit{Number of Self similar Pieces})^{Dimension} \quad (1)$$

The first iteration for the Koch curve consists of taking four copies of the original line segment, each scaled by **r** = 1/3.Therefore Equation 2 states that,

$$\textit{Fractal Dimension} = \frac{log(\,number\ of\ self{-}similar\ pieces)}{log\ (\,magnification\ factor)} \quad (2)$$

$$\textit{Fractal Dimension} = \frac{\log(4)}{\log(3)} = 1.262 \ \textit{(which is a non-integer)} \quad (3)$$

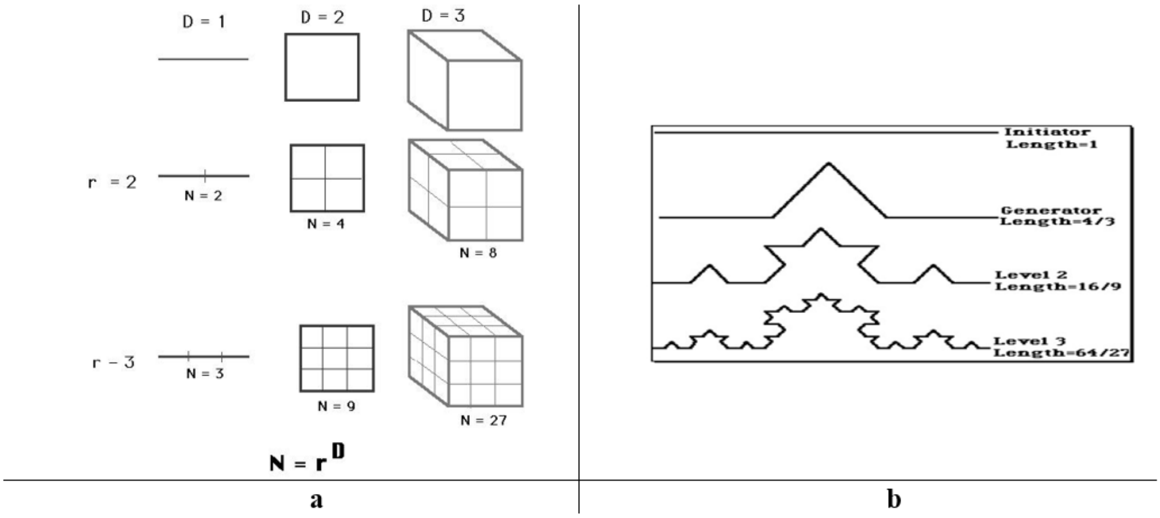


Figure 3. Fractal magnification factor exponential representation. a) Dimensions, b) Koch Curve [27].

To comprehend the notion of a non-integer or fractal dimension, consider the Koch curve as an illustrative example. Initially conceived as a continuous one-dimensional line, the curve undergoes a recursive process wherein each segment is divided into three equal parts, with the middle segment subsequently replaced by the two sides of an equilateral triangle identical in length to the segment removed. This iterative procedure results in the one-dimensional line increasingly occupying a two-dimensional space. Consequently, the fractal dimension (Equation 3) of such a line lies within the interval between 1 and 2, reflecting its complex, self-similar, and non-Euclidean geometric properties [27].

Therefore, fractal dimension is an important tool for mathematically measuring the complexity and self-similarity of fractals. Calculating fractal dimension is a fundamental step in understanding fractal geometry and complex systems. In the end, the fractal dimension of a structure provides a measure of the level of detail within it. A higher fractal dimension indicates a greater degree of intricacy and detail present in the form.

4.3. Box Counting Method

While there are several methods available for measuring fractal dimensions, the box counting method stands out as the most graphical approach for approximate calculations. Although it may not capture intricate details of the base curve as accurately as other methods, its low computational demands make it a recommended choice for obtaining an initial approximation of the fractal dimension.

The method for calculating the fractal dimension of buildings is popular due to its simplicity and effectiveness. It involves the following steps:

a) Place a grid of a specific size (S1) over the elevation of the building.
b) Count the number of occupied grids (C1) containing lines.
c) Double the grid size (S2) and count the occupied grids (C2). Repeat this process and record the results. It's important to note that slight variations in the grid can lead to different values for C (Table 2).

Table 2. Grid Size and Box Count for each iteration [27].

Grid Size	Box Count
S1 -	C1
S2 -	C2
S3 -	C3

d) Utilize a log-log plot of resolution scale versus the number of occupied boxes to ascertain the fractal dimension (D) across scales 2 to 1. The fractal dimension (D) across scales 2 to 1 can be calculated using the formula [27]:

$$\boldsymbol{D}(2to1) = \frac{[\log(C2) - \log(C1)]}{[\log(S2) - \log(S1)]} \tag{4}$$

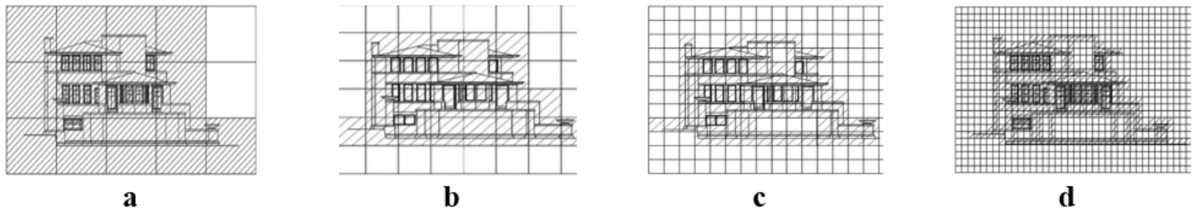


Figure 4. Grid-based calculation of the fractal dimensions of facades a) Grid 1: 5 x 3 grid; the number of boxes is 13 or 1/s1 = 5 and N (s1) = 13, b) Grid 2: 10 x 6 grid; the number of boxes is 29 or 1/s2 = 10 and N (s2) = 29, c) Grid 3: 20 x 12 grid; the number of boxes is 93 or 1/s3 = 20 and N (s3) = 93, d) Grid 4: 40 x 24 grid; the number of boxes is 307 or 1/s4 = 40 and N (s4) = 307 [18].

The obtained *Db* value for Grid 1-2 is 1.156, indicating a relatively low fractal complexity and a uniform distribution (Equation 4). In contrast, for Grid 2–3, the *Db* value increases to 1.681, reflecting a greater degree of fractal density and structural variation. Finally, the *Db* value for Grid 3–4 rises to 1.724, signifying the highest level of fractal complexity among the intervals analyzed. The aggregation of the outcomes from the three box counts yielded an estimation of the fractal dimension, which was calculated as follows: D = 1.520 [18].

The box-counting method is the most common mathematical approach for determining the approximate fractal dimension of an object. In its architectural variant, this method begins with a drawing of the exterior façade of a house. Subsequently, a large grid is placed over the drawing, and the presence of lines in each square is checked. Squares containing detail are recorded. Then, a smaller-scale grid depicting the same façade is placed, and again, the presence of detail within each square is determined. By repeating this process on multiple grids of different scales, an estimate of the fractal dimension of the façade is generated (Figure 4). While this process can be performed manually, the Benoit and Archimage programs automate this operation. Several variations of the method address known deficiencies. Four common variations are associated with balancing the proportion of "white space" and the "starting image" line width, scaling coefficient, and moderating statistically divergent results [28]. In recent years, the software called ImageJ with FracLac (Figure 5) plugin has been used for analyzing the Euclidean geometry value, which varies between 1 and 2, in the box-counting method.

4.4. L-System

The developmental processes are traced using the formalism of L-systems. These systems, introduced by Lindenmayer in 1968, served as a theoretical framework for studying the development of simple multicellular organisms in plants and were subsequently applied to the investigation of more complex plants and plant organs. Following the incorporation of geometric features, plant models expressed through L-systems became sufficiently detailed to allow for realistic visualization of plant structures and developmental processes via computer graphics [29].

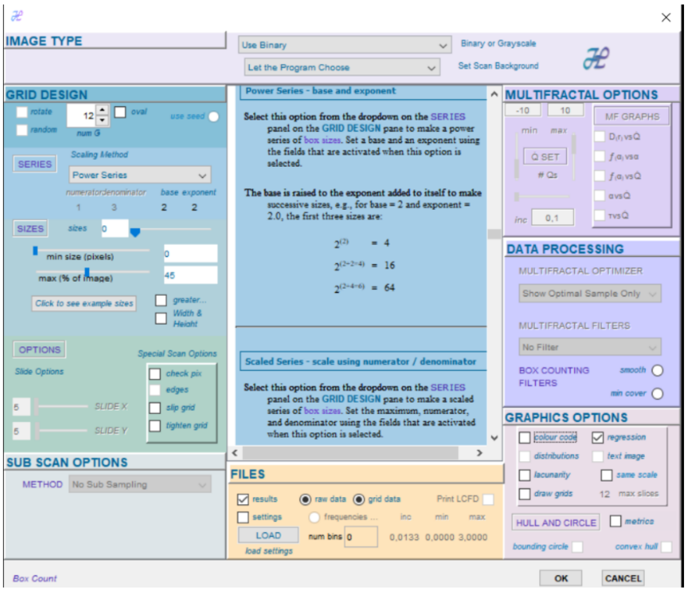


Figure 5. FracLac interface with chosen options and values for each building images.

The computer has played a pivotal role in replicating branching structures akin to those found in natural trees. One such algorithm, known as L-System, has been instrumental in this endeavor by simulating the growth dynamics of plants and generating natural fractals. This system presents architects with a fertile ground for integrating natural forms into architectural designs, thus offering a realm of creative possibilities. A notable illustration of this application is evidenced in the construction of the Tote Restaurant in Mumbai in 2009, where the L-System algorithm was effectively harnessed for architectural form development [7].

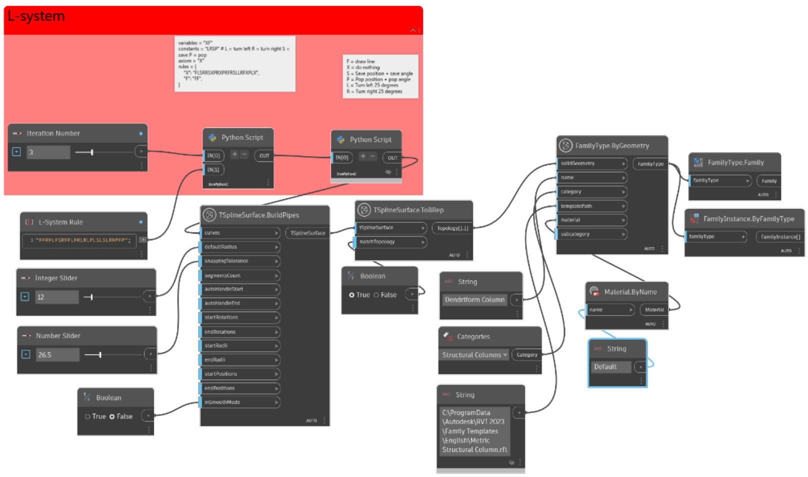


Figure 6. Dynamo interface with node connections.

4.4.1. Parametric Column Structure

As previously mentioned, tree dendriforms can be generated using various techniques in the digital environment, which offers abundant options such as software specifically designed to generate L-System algorithms. In this study, the tree column head, or in other words, the branching structure resembling a tree dendriform, was initially created using a Python code that operates within the Dynamo node (Figure 6). Dynamo is an visual programming tool located within the Manage tab in Autodesk Revit. The objective was to obtain a parametric column geometry that changes according to manually adjustable rules. Additionally, the geometry should have changed based on the iteration number. As a result, with this prototype, an artificial forest was created (Figure 7). The purpose of this approach is to achieve different variations and produce a grid-like structure with each iteration being unique (Table 3).

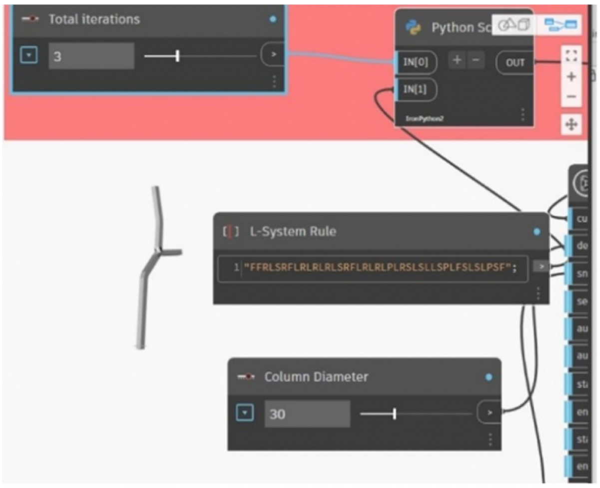
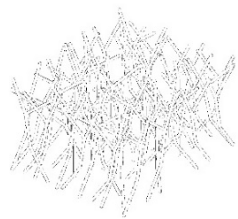
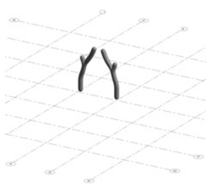
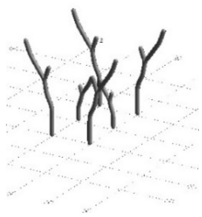
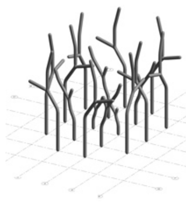
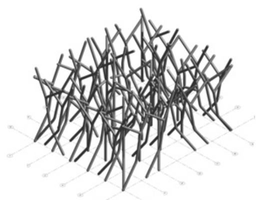


Figure 7. L-System rule for iteration 3 levels.

Table 3. Column geometries for each ıteration prototype and their locations on grid system.

Iteration 1	Iteration 2	Iteration 3	Iteration 4
			
			

5. Results and Discussion

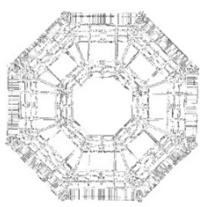
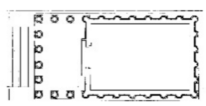
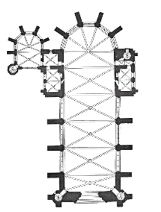
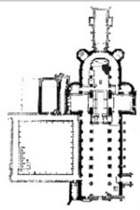
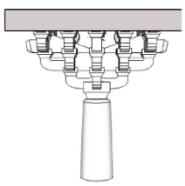
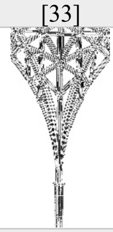
In the initial stage, plans and column head drawings of historical buildings were analyzed using FracLac. Following the assessment of as-built structures, a new structure generated by an L-System-based rule code was employed to benchmark all structures based on their fractal values.

After analyzing buildings and prototype structure, the results were unexpected. This unexpected outcome can be attributed to the lack of computer-aided design (CAD) systems or any digital tools during that time. For more realistic outcomes, the artificial structure was designed with simple plan and column geometries and orientations.

This decision stemmed from the experience with the previous building, Stuttgart Airport Terminal, which featured a complex plan ratio generated by computational environments (Table 5). Consequently, the plan ratio of the subsequent structure was simplified to allow for a comparative analysis between the two technological products. Other as-built structures exhibited more diverse results due to their organic forms, but this did not account for the high fractal values. Today, we have nearly infinite tools for creating or generating designs from various natural substances and living creatures. However, in the past, people, designers, architects, and craftsmen did not have access to digital devices for drawing or production. The human brain was the sole tool for conceptualizing with all possibilities, while hands were the only means for achieving tangible results.

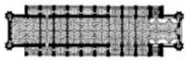
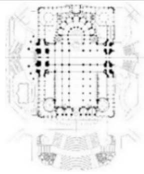
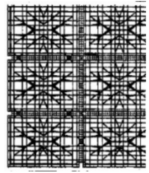
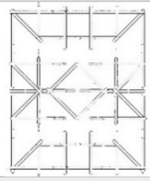
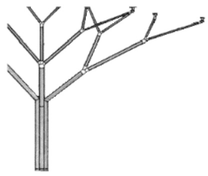
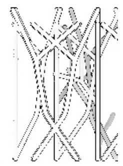
The perplexing outcomes gained from the initial examination prompt intriguing questions about the planning tactics employed in historical buildings. While models based on L-Systems offer a valuable tool for analyzing complex fractals, they may not fully represent structures designed without computers due to their reliance on recurring motifs. This limitation is further highlighted by the significant difference between the Stuttgart Airport Terminal (complex plan) and its simplified prototype. By further simplifying the model, it would be possible to make a fair comparison. However, this might conceal the architectural achievements of past eras. Certain historical buildings contain natural shapes that suggest different methods employed by architects in achieving high fractal values during ancient times. These techniques, which could be imitative of nature or traditional building, should be investigated further. In ancient times, the geometries of column heads and plans exhibited close resemblances to each other. These structures often mimicked dendriform patterns, resembling various forms found in nature, particularly tree-like shapes.

Table 4. The analysis drawings and Db values of structures dating from 771 BC to 1351 AD.

TIME PERIOD		771 BC - 476 BC	16 BC	1242 AD – 1248 AD	1351 AD
Building Name		THE SAKYAMUNI PAGODA OF FOGONG TEMPLE	MAISON CARRÉE	SAINT CHAPELLE	GLOUCESTER CATHEDRAL
Plan					
Reference Number		[30]	[31]	[32]	[33]
Column Head					
Reference Number		[7]	[34]	[35]	[33]
Db	**Plan**	**1.6366**	**1.4660**	**1.5602**	**1.6107**
	Column Head	**1.3913**	**1.7500**	**1.7405**	**1.7362**

The geometrical ratios observed in plan views ranged from 1.4660 to 1.6366 Db values (Table 4), indicating a proximity to Euclidean geometry due to the values of the structures. However, the results for column heads were more intricate and higher compared to plan views, owing to their detailed levels and connection points. Interestingly, the column heads generated in computer environments appeared simpler and lower in complexity compared to those from ancient times.

Table 5. The analysis drawings and Db values of structures dating from 12th century AD to 2024.

TIME PERIOD		12th century AD	1982 -	1991	2024
Building Name		KING'S COLLEGE CHAPEL	LA SAGRADA FAMILIA	STUTTGART AIRPORT TERMINAL	PARAMETRIC PROTOTYPE
Plan					
Reference Number		[36]	[37]	[38]	
Column Head					
Reference Number		[36]	[39]	[40]	
Db	Plan	1.8511	1.3428	1.8145	1.4529
	Column Head	1.7828	1.6785	1.3710	1.4865

6. Conclusions

The study revealed that design tools are intricately related to the fractal complexity of buildings. While models based on L-systems provide a robust analysis framework, they may lack the capacity to fully capture the nuances of historical computer-less structures. Consequently, it is essential to identify the diverse methodologies employed in the past for designing and their interrelationship with contemporary architecture.

Future research must delve deeply into the L-System rules by integrating biomimicry principles with conventional design philosophies. This approach will enable a more detailed historical evaluation while serving as a foundation for the creation of new architectural styles that integrate both old and new systems. By understanding how people designed without complex tools, we can expand our current limits of architectural design in the digital world. This highlights the significant difference between natural intelligence and artificial intelligence. Feelings, inspirations, and emotions stem from nature for the natural intelligence, whereas the artificial intelligence relies solely on human creation. The geometric proportions of natural forms, while easily replicated by computer software today, have been expertly imitated by human intelligence and craftsmanship since ancient times. This study is distinctive in its focus on architectural design tools and methods from a historical perspective. It compares the nuances of designs created without the aid of computers in the past with those produced using digital tools in the present. Moreover, by integrating the principles of biomimicry with traditional design philosophies, the study proposes an original approach to both enhance the historical evaluation and create new architectural styles that integrate old and new systems.

The distinction between natural intelligence and computer-based design in the architectural domain, the geometric proportions of natural forms in relation to both human expertise and contemporary technology, imbues the study with both philosophical and practical depth. This represents an innovative perspective that not only reconciles past and future, but also demonstrates how the natural and digital realms can coexist in harmony. This approach consistently respects and honors nature, resulting in outcomes that rival modern technology in their precision and harmony with the natural world.

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