BACK TO REALITY

Dendritic structures using current construction techniques

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Abstract. Architects throughout time have designed tree-inspired structures, not only to decorate their creations, but also to explore biomimicry to solve mechanical and structural problems. With the predominance of digital simulation tools, these dendritic-shaped structures are now more easily explored. However, these explorations tend to lack the rationalization required to make them applicable to current production means. In this paper, we take a step back and ensure the connection between the creation and the production of the designs generated with these new digital approaches. The present investigation combines design and analysis tools in search for tree-inspired structures that take advantage of the current techniques of building construction.

Keywords. Biomimicry; Dendritic structures; Algorithmic design; Performative architecture; Structural analysis.

1. Introduction

The term Biomimicry first appeared in scientific literature in 1962, growing in popularity amongst scientists in the 1980s. It is defined as the new science that studies nature's models and imitates these designs to solve human problems (Benyus 1997). By mimicking and emulating nature in its analogies, phenomena, and patterns, it allows distinct fields and areas of research to learn from the largest dataset of information available to humanity - nature.

Since the Greco-Roman period, where columns were made to structurally resemble tree trunks, and acanthus plants were used to decorate the capitals, architects have drawn inspiration from trees and plants. Nowadays, computer-supported algorithmic (Terzidis 2006) and parametric techniques (Woodbury 2010) provide the tools for the design and construction of these dendritic structures. The popularity of these tools has created a shift in the way architects design, as they almost effortlessly, support the generation of more elaborate and innovative shapes.

Furthermore, an increasing emphasis on building performance - kindled by the possibility of future innovations and technological progress in construction (Hensen and Lamberts 2012) - is influencing the processes and practices

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of building design, by blurring the distinctions between geometry and analysis, appearance and performance (Kolarevic and Malkawi 2005). This led to the development of several simulation-based analysis tools and optimization methodologies. One of the challenges in performance-driven design methodologies is the effective integration of simulation and optimization techniques with parametric design and generative procedures (Oxman 2008).

Recently, different approaches to tree-inspired performance-driven design have emerged. Rian and Asayama (2016) use Barnsley´s (2014) Iterated Function System (IFS) to generate a parametrized branching structure. Bialkowski (2015) finds branching structures when applying Topology Optimization to material layout optimization under loads and boundary conditions. Nevertheless, these methods end up creating designs with a very complex geometry, which is hard to manufacture with the current production process (Bialkoswki 2016).

Differently from the previous research, our methodology aims to (1) unify algorithmic design and analysis tools applied to tree-inspired dendriforms structures; (2) implement these algorithmic-based approaches considering current techniques of building construction.

2. Biomimicry overview

Biomimicry was defined by Janine Benyus in her 1997 book *Biomimicry: Innovation Inspired by Nature*. As a new science that applies nature's models to human problems, Biomimicry aims to promote nature as a *model, measure, and mentor* (Benyus 1997).

A biomimicry-oriented design typically falls into two distinct categories: (1) the Top-Down approach (*Design Looking to Biology*), where a human problem is formulated, and then a solution that can be correlated is sought in nature; and (2) the Bottom-Up approach (*Biology Influencing Design*), where the study of different features in nature can then be translated into a solution for a human problem (Knippers and Speck 2012; Helms 2009).

Besides these approaches, there are three different levels of Biomimicry that can be applied to design problems: form, process, and ecosystem (Zari 2007). These levels represent three different scales of mimicry: (1) the organism level mimes the characteristics of an organism, the way it looks or what it produces; (2) the behavior level mimics a certain behavior of an organism, or between organisms; (3) the ecosystem level, which is defined by the mimicry of a characteristic of a whole ecosystem. Each scale can be stratified into five distinct dimensions: form, material, construction, process, and function. The three levels of biomimicry and the correspondent five dimensions are described in Table 1.

Table 1. A framework for the application of Biomimicry (Adapted from Zari 2007).

Levels of biomimicry	Example: Building that mimics termites	
Organism level	Form	The building looks like a termite
	Material	The building is made from the same material as a termite, a material that mimics termite exoskeleton/skin for example
	Construction	The building is made in the same way as a termite; it goes through various growth cycles for example
	Process	The building works in the same way as an individual termite; it produces hydrogen efficiently through meta-genomics for example
	Function	The building functions like a termite in a larger context; it recycles cellulose waste and creates soil for example
Behavior level	Form	The building looks like it was made by a termite; a replica of a termite mound for example
	Material	The building is made from the same materials that a termite builds with; using digested-https://www.overleaf.com/project/5c03448fe519a806b7c7def3 fine soil as the primary material for example
	Construction	The building is made in the same way that a termite would build in; piling earth in certain places at certain times for example
	Process	The building works in the same way as a termite mound would; by careful orientation, shape, materials selection and natural ventilation for example, or the building mimics how termites work together
	Function	The building functions in the same way that it would if made by termites; internal conditions are regulated to be optimal and thermally stable for example. It may also function in the same way that a termite mound does in a larger context
Ecosystem level	Form	The building looks like an ecosystem (a termite would live in)
	Material	The building is made from the same kind of materials that (a termite) acosystem is made of; it uses naturally occurring common compounds, and water as the primary chemical medium for example
	Construction	The building is assembled in the same way as a (termite) ecosystem; principles of succession and increasing complexity over time are used for example
	Process	The building works in the same way as a (termite) ecosystem; it captures and converts energy from the sun, and stores water for example
	Function	The building is able to function in the same way that a (termite) ecosystem would and form part of a complex system by utilizing the relationships between processes; it is able to participate in the hydrological, carbon, nitrogen, cycles, etc. in a similar way to an ecosystem for example

2.1. BIO-INSPIRED STRUCTURES

Humanity's fascination with nature is as old as its ability to recognize patterns. Several ancient parietal arts, from the pre-historic ages, have been found depicting figures of trees and plants. These vegetal shapes can be considered one of the most significant decorative elements in the earliest examples of architecture.

Early examples can be seen in the Ancient Egypt, where papyrus-cluster columns were built in sandstone with a sculpted capital imitating the umbels of papyrus plant in bud (Shaw 2000). Additionally, in the Classical and Greco-Roman ages, capitals of the Corinthian and Composite order, some friezes, and most aesthetical embellishments, use the acanthus plant as a source of inspiration, replicating its intricate shapes and enriching the architectural ornaments.

Nevertheless, only later would start the biomimetic pursuit that led to the emergence of tree-inspired designs. Dating back more than two thousand years, the Chinese Dougong Brackets, the first dendritic structures, were built in the Chinese temples and palaces. Inspired by the organization of tree branches as a cantilever, the Dougong is an assemblage of structural cantilevers placed in between the column and the beam, that carries the load of the beam and the overhanging roof into the column. (Rian and Sassone 2014)

Later in the medieval period, the Catholic church reached its apogee, reason why the cathedrals became one of most current typologies to be built at the time. In their interior, this formal tendency also manifested itself through tree-inspired fan vaults. The first appeared in the Sainte-Chapelle church (Figure 1) in Paris in 1248 (Walter and Leedy 1978) and were characterized by ribs which formed a conoid shape. The interior spaces in between the sequence of conoids were filled with flat central spandrels as keystones, providing both compressive forces along the entire upper edge of the conoid, and stress equilibrium, as well as granting structural strength (Walter and Leedy 1978).

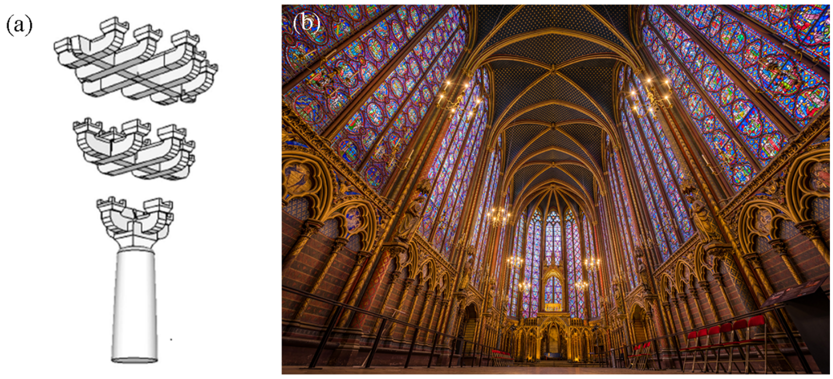

Figure 1. Dugong brackets from China - The Sakyamuni Padoga of Fogong Temple, 1056 A.D. (Adapted from Rian and Sassone 2014) (a); Fan vault in the Sainte-Chapelle church in Paris, 1248, from https://homesecurity.press (b).

From the late 19th century up until the 20th century, during the period that represented the crowning of the decorative arts in architecture, the Art Nouveau, some tree-inspired structures can be seen in the designs of Antoni Gaudi, like the Sagrada Familia, in Barcelona. He resorted to physical models (Figure 2), inspired in mechanical and structural characteristics of nature, to find the most suitable form.

Throughout the 20th century, there was a predominance in the use of steel to construct new buildings. Though, the structural significance of dendritic shapes was not addressed until the study of lightweight structures by Frei Otto. (Nerdinger 2005). Otto methodically researched the structural aptitude of branching structures for the Stuttgart Airport (Figure 2), dated from 1939.

Figure 2. Gaudi catenary arches model (Reprinted from Antoniou et al. 2016) (a); Frei Otto, Stuttgart Airport, 1939, from https://homesecurity.press (b).

3. Performative Architecture

Performative architecture can be defined as an architectural design focused on the project's performance. However, this concept is not entirely new. For instance, the formerly mentioned examples of Gaudi and Otto were already exploring form-finding techniques that maximized performance.

Pioneer in experimenting a form-finding approach, Gaudi studied the loads in a structure by suspending it inversely with cables, letting gravity portrait the structural potential of those shapes (Kilian 2004). He produced a group of arches that were only subjected to compressive axial forces, hence free from bending (Bletzinger et al., 2011).

Otto's lifelong research was into lightweight structures, i.e., objects with very little mass, carved to withstand great loads. That led him to be inspired by a natural philosophy that focused on a relationship between architecture and nature, and their performance. Otto conducted experiments with lightweight tents and soap films, suspended constructions, dome and grid shells, and branching structures (Ahmeti 2007).

Nowadays, as digital technologies are assuming a prominent role in performance-based design, these form-finding methodologies have evolved into simulation and analysis tools available to any architect or engineer. In fact, they have allowed for the redefinition of a term that has now become one of the techniques most frequently associated with performance - optimization (Oxman and Oxman 2014).

Optimization defines the process of making something, such as a building's design, as functional or as effective as possible (Nguyen, Reiter and Rigo 2014). To this end, the optimization process requires parametric design, so that multiple variations of a design can be evaluated. Regarding structural evaluation, the work of Veenendaal and Block (2014) shown which parameters are relevant to achieve a structurally fit design. Due to its intrinsic parametric nature, algorithmic design can be combined with simulation tools to better perform a cycle of generation/evaluation/moderation, capable of optimizing the building's performance (Oxman and Oxman 2014), while pursuing the preferred design.

4. Algorithmic Design

Since 1963, with the invention of the world's first interactive graphic system by Ivan Sutherland, computers grew to become an essential tool in the design of a building. First, as a mechanism of automation and digitalization, helping architects and engineers to have a platform to produce and show the technical drawings of the design; and, later, as a procedure to calculate and determine a design rationale by mathematical or logical methods (Terzidis, K., 2006). These digital tools have evolved to computer-assisted design software and 3D modeling applications that changed the way architects approach building design. Moreover, with the development of parametric designs driven by algorithmic processes, analysis tools can also be integrated into the design process.

Algorithms are sets of rules given by a human to be performed by a computer (Burry 2011). Algorithmic Design (AD) defines the creation of architectural designs through these algorithmic descriptions (Gerber and Ibanêz 2014). This type of approach to digital modeling allows the user to explore a variety of different ideas without having to rework on the model for every due change (Woodbury, R., 2010).

Additionally, new tools start to incorporate these algorithmic rationalizations into a programming environment capable of converting them into a modeling tool, enabling the architect to visualize and iterate his design at the earliest stages (Castelo Branco and Leitão 2017).

5. Algorithmic design approach to dendritic structures

Performance-based structural design can take inspiration from dendritic shapes. For instance, form-finding techniques, such as Iterated Function System, Topology Optimization, and Cell-based Venation Systems, have proved to be successful in generating complex geometry whilst granting a good structural performance.

Nevertheless, these methods lack the feasibility to be built with the current practical methods. They are composed by intricate organic shapes that require additive manufacturing, such as large-scale 3D printing, to be produced. (Bialkowski 2016) Unfortunately, that technology is still very expensive and is not readily available. Moreover, if we look at the prior dendritic-inspired designs, like Frei Otto's Stuttgart Airport or Calatrava's Orient Station, they all had a rationalization behind the formulation of the design. Thus, within the boundaries of the currently economic construction techniques, by controlling the organicity of the design, they optimized not only the design's performance, but also its construction.

Nowadays, it is possible to be aided by the digital tools available: (1) algorithmic design allows a rationalization of the concept of a model and contributes to the optimization of the construction process; (2) simulation models are responsible for the evaluation of performance of the building, helping the architect discover the most feasible choice, within the scope of objectives desired.

In the following chapter we will demonstrate how dendritic structures can be combined with algorithmic approaches to pursue a performance-driven design. We explored a Top-Down approach, focused on mimicking their shape, in a organism level, and their function in a behavior level. The methodology used starts by (1) establishing geometrical rules and formalizing the rationalization behind the dendritic shape to (2) generate a model. The same model will be (3) used in connection with a structural simulation tool, Robot, to further (4) evaluate the structural strength of the design. (Figure 3)

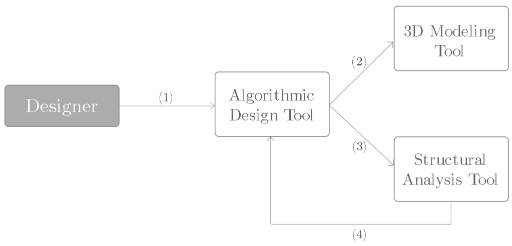

Figure 3. Proposed workflow.

5.1. CASE STUDY

To understand the limitations of the current means of manufacture, an already existent building was chosen, which will function as an evaluator of the viability of the framework. Consequently, we studied the geometry of the structure of the Oriente Station (Lisbon, 1998), by Santiago Calatrava, to reproduce its mathematical relations through algorithmic design. We created a program that is then used to generate both the geometrical model in AutoCAD, and the structural model in Robot, without relying on import/export operations (Aguiar, Cardoso and Leitão, 2017). As a result, it produces a visual model, that can be re-iterated and refactorized to accomplish other creative needs, and a structural model used for the optimization study on the structural feasibility of the design.

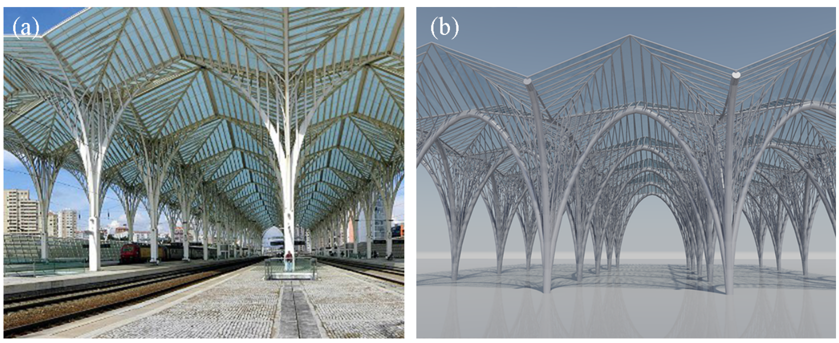

Figure 4. Santiago Calatrava, Oriente Station, Lisbon, 1998, from https://boasnoticias.pt (a); Oriente Station model re-creation with algorithmic design, rendered in AutoCAD (b).

To guarantee a good structural behavior (1) the load per square meter of vertical loads on the roof is calculated, and then (2) the nodal force of each roof node is found. Using Robot, we obtained the maximum displacement on each node, and a displacement model of the structure. The results were then compared with the allowed maximum displacement of such structure.

Regarding the structural optimization, two different scales were used: (1) on a macro scale, the width and height of the model were considered. The first being correlated to the maximum node displacement capacity, and the second being essential to evaluate the structure own weight and the relation with the overhangs; (2) on a micro scale, the radius and thickness of the truss bars were examined.

Three case studies (Figure 4) were then created, inspired in dendritic structures, to show the potential of this practice. A range of different structural strength designs was used to promote a more generalized study into these structures. After the creation of the geometric algorithms, the same structural optimization was applied. We used steel S460 and laminated glass 6+6mm, as the material for the structure and the roof, respectively. The results can be seen and compared in Tables 2 and 3.

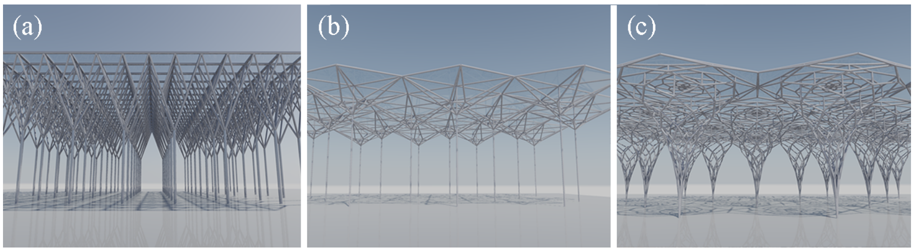

Figure 5. Case study 01 (a); Case study 02 (b); Case study 03 (c).

Table 2. Macro-scale study of each iteration compared to the max displacement (Dmax).

Width (m)	Height (m)	Oriente Station (cm)	Case Studies (cm)		
			01	02	03
20 $D_{max} = 10cm$	20	-1.8	-4.0	-6.8	-2.8
	15	-7.6	-3.5	-6.8	-4.0
	10	-10.2	-3.9	-6.8	-6.9
15 $D_{max} = 7.5cm$	20	-3.6	-1.1	-1.6	-0.8
	15	-2.8	-1.0	-1.6	-1.0
	10	-1.9	-0.8	-1.6	-1.7
10 $D_{max} = 5cm$	20	-0.9	-0.2	-0.2	-0.2
	15	-0.6	-0.2	-0.2	-0.2
	10	-0.4	-0.2	-0.2	-0.2

Table 3. Micro-scale study of each iteration compared to the max displacement (Dmax).

Radius (cm)	Width (m)	Height (m)	Oriente Station (cm)	Case Studies (cm)		
				01	02	03
0.15	15	15	-2.8	-1.0	-1.6	-1.0
0.4	$D_{max} = 7.5cm$		-0.8	-0.8	-0.5	-1.0

6. Conclusion

This research demonstrates how architects, designers, and engineers can explore dendritic shapes to pursue a more performance-focused design, while taking advantage of current construction techniques. We presented a framework capable of combining tree-inspired structures with algorithmic design and simulation tools. This way, the architect can leap into the creative space and strive for more innovative shapes, as he lets the algorithmic program generate the intended design variations in his preferred modeling tool. Additionally, this ensures the connection between the different visualization and simulation tools, which gives the architect a broader knowledge of the different areas that compose a building design, in an earlier stage of the design process.

The main findings show that the different tree-inspired design all present similar structural feasibility. This validates the framework as a tool to help design fit structures that can be produced with current construction techniques. The success of this approach can be further analyzed by studying the defining traits of present manufacture, and how they can be re-factorized into design defining parameters.

A topic yet to be resolved is the lack of dendritic organicity created by the framework, a consequence of the priority given to the relation between the simplicity of the geometry generated and the currently available processes of construction. Cell venation-based simulations (Klemmt and Bllinger, 2015) could be used to control organicity constraints if designed to perform with the limitations of the current construction techniques. This way, a rationalization can be made to promote a more natural dendriform while retaining normalized materials to allow for the construction of the building.

Lastly, this research shows that it is possible to combine biomimetic approaches to architecture with the economic viability demanded by current construction techniques. It strives for a better correlation to the actual practices in the architectural and engineering world, in order to provide a smoother transition between current and future techniques.

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References

Aguiar, R., Cardoso, C. and Leitão, A.: 2017, Algorithmic Design and Analysis Fusing Disciplines, *ACADIA 2017*, 28-37.

Ahmeti, F.: 2007, *Efficiency of lightweight structural forms: the case of tree-like structures; a comparative structural analysis*, na.

Antoniou, D., Liapi, K., Bakas, N., Liassides, I., Georgiou, I. and Varlagkas, N.: 2016, FORM FINDING ON PARAMETRIC SURFACES. OPTIMIZATION AND CORRELATIONS OF ARCHITECTURAL FLUIDITY AND STRUCTURAL, *no title given*.

Benyus, J.M.: 1997, *Biomimicry: Innovation inspired by nature*, Morrow New York.

Bialkowski, S.: 2016, Structural Optimisation Methods as a New Toolset for Architects, *34th eCAADe Conference*, **2**, 255-264.
Bialkowski, S. and Kepczynska-Walczak, A.: 2015, Engineering Tools Applied in Architecture, *Proceedings of the 33rd eCAADe Conference*, **1**, 261-268.
Bletzinger, K.U. and Ramm, E.: 2001, Structural optimization and form finding of light weight structures, *Computers \& Structures*, **79**(22-25), 2053-2062.
Branco, R.A.C. and Leitão, A.: 2017, Integrated Algorithmic Design, *35th eCAADe Conference*, **1**, 729-738.
Burry, M.: 2011, *Scripting cultures: Architectural design and programming*, John Wiley \& Sons.
Gerber, D.J. and Iba\˜nez, M.: 2015, *Paradigms in computing: making, machines, and models for design agency in architecture*, eVolo Press.
Helms, M., Vattam, S.S. and Goel, A.K.: 2009, Biologically inspired design: process and products, *Design studies*, **30**(5), 606-622.
Hensen, J.L. and Lamberts, R.: 2012, *Building performance simulation for design and operation*, Routledge.
Leedy Jr, W.C.: 1978, The Origins of Fan Vaulting, *The Art Bulletin*, **60**(2), 207-213.
Kilian, A.: 2004, Linking digital hanging chain models to fabrication, *Proceedings of AIA/ACADIA*, 110-125.
Knippers, J. and Speck, T.: 2012, Design and construction principles in nature and architecture, *Bioinspiration \& biomimetics*, **7**(1), 015002.
Kolarevic, B. and Malkawi, A.: 2005, *Peformative Architecture: Beyond Instrumentality*, Routledge.
Nguyen, A.T., Reiter, S. and Rigo, P.: 2014, A review on simulation-based optimization methods applied to building performance analysis, *Applied Energy*, **113**, 1043-1058.
Otto, F., Meissner, I., Barthel, R. and Brensing, C.: 2005, *Frei Otto: complete works: lightweight construction, natural design*, Birkh"auser.
Oxman, R.: 2008, Performance-based design: current practices and research issues, *International journal of architectural computing*, **6**(1), 1-17.
Oxman, R. and Oxman, R.: 2014, *Theories of the Digital in Architecture*, Routledge.
Rian, I.M. and Asayama, S.: 2016, Computational Design of a nature-inspired architectural structure using the concepts of self-similar and random fractals, *Automation in Construction*, **66**, 43-58.
Rian, I.M. and Sassone, M.: 2014, Tree-inspired dendriforms and fractal-like branching structures in architecture: A brief historical overview, *Frontiers of Architectural Research*, **3**(3), 298-323.
Shaw, I.: 2003, *The Oxford history of ancient Egypt*, Oxford University Press.
Terzidis, K.: 2006, *Algorithmic architecture*, Routledge.
Woodbury, R.: 2010, *Elements of parametric design*, Taylor \& Francis Group.
Zari, M.P.: 2007, Biomimetic approaches to architectural design for increased sustainability, *The SB07 NZ Sustainable Building Conference*.