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Architectural form finding in arboreal supporting structure optimisation

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ABSTRACT

Sustainable Development Goals have become a key factor in the design in the twenty-first century. The relationship between the architectural and structural systems is becoming a matter of relevance for sustainable design. The search for minimum material consumption can be seen by drawing inspiration from the solutions found in Nature. The high efficiency of natural forms, has become a contribution to research on tree-like structures. The purpose of the research was to identify the main aspects of arboreal supporting structures shaping and optimization at the early state of design. The methodology is to optimize the geometry of dendriforms, based on optimizing the shape of the bending moment diagram and adjusting it to the shape of the final bar structure. The primary conclusion of the studies indicates that the structural and architectural optimization, implemented in an early stage of designing might significantly improve material consumption without substantial changes in architectural appearance.

1. Introduction

The contemporary design of buildings is linked to the interdependence of aesthetic quality with structural optimization. The construction sector is one of the main economic sectors in which the consumption of natural resources is the highest. Therefore it is undergoing transformations involving savings in the management and production of building materials and increased innovation in ecological methods of their production. Improvements in the AEC (Architecture, Engineering, and Construction) sector can significantly improve energy efficiency through sustainable design and decrease climate changes, as well as preventing rapid erosion of buildings [1]. The pursuit of non-ecological materials minimization in construction is regulated by the European Union and many scientific studies [2,3,4]. The EU growth strategy, called:*'Europe 2020'* and earlier conventions such as Aarhus Convention [5], Helsinki Convention [6], and the Convention on Biological Diversity [7], demonstrate the need to adapt to Sustainable Development Goals by the construction sector. Higher productivity and cost optimization in the field of construction has a significant impact on the development of national economies [8](the value of the construction sector is 8–10% of GDP on average).

1.1. Sustainable development

The search for rational design solutions, which are the basis for sustainable development, leads to the search for inspiration in Nature, which 'has been sustainable and Energy-efficient for billions of years' [9]. Freeman Dyson pointed out that the 20th century belonged to the development of physics, while the 21st century is the time of development of biology and all its related fields [10]. Biology measures the economic consequences of made decisions [11]. Beauty in architecture becomes a result of finding effective solutions, the source of which is not difficult to find in Nature. They are subject to the same laws of physics and seek the minimum energy consumption necessary to survive [12]. Frei Otto said that in the search for the proper shape of the object, "the architect is more acting as a midwife than God the creator" [13], in his project, he was mainly looking for topological optimization and minimal use of material. The biomimetic inspiration of freeform designs is visible in the last century not only in AEC but also in other sectors such as fashion, where the interrelation of building skin and clothes is significant [14].

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1.2. Design engineering and optimization algorithm

Basic requirements for the profitability of both contemporary and future investments are new optimization tools understandable to designers. "Design engineering," understood as the cooperation of architects and structural designers at the early design stage, allows increasing the effectiveness and rationalization of solutions [15]. Cooperation in an interdisciplinary environment, at the conceptual stage, with specialists from different industries, such as bioengineering, biology, IT, improves the quality of solutions and stimulates development in the AEC sector [16]. Thanks to such actions, structural optimization is not conducted posterior, but parallel to the stages of architectural design. The use of optimization algorithms has changed the way of designing. In the work of designers of the last century, such as A. Gaudi, F. Otto, B. Fuller, F. Candela, P.L. Nervi, or S.de Chateau, the inspirations were taken from structures found in Nature, and the research was conducted on physical models [12,17]. The observations of phenomena and attempts to their usage in architecture were made by many designers, including Leonardo da Vinci, who noticed that the cross-sectional area of tree branches equals its parent trunk [18,19]. The last decades have brought a greater understanding of how living organisms evolve and develop their strategies for adapting to the external environment. Computational technologies have gained new tools to exploit issues such as evolution, adaptation, mutation, genetic coding, or morphogenetic [20]. The use of the phenomena observed in Nature and their translation into genetic algorithms understandable by the designer environment allowed to use them in architecture [21]. The development of computer-aided design, visible at the turn of the 20th and 21st century, introduced many tools that improved calculation methods, allowing to develop algorithms that generate shapes according to the "form follows forces" principle at the initial design stage [22]. Topological optimization has become a technology, where not only the calculation methods of the structure are improved but also, among others, the automation of the fabrication. Attempts to characterize topological optimization are known [23]. Nowadays, there is a noticeable emphasis on two types of creative searches: Form-finding and Structural Optimisation, both of them, however, are the basis of a more advanced method, which is Structural Morphology [22]. It has become possible to be inspired by bionics in search of the properties of materials at the nanoscale, use minimal energy, and optimize structures with advanced geometry. The knowledge of mathematical algorithms and relations between the acting forces are described by the patterns found in Nature is a fundamental tool of contemporary design.

1.3. Topological transformations

It should be noticed that the search for optimal solutions, taken from Nature observation, should be as intuitive as possible for designers - especially for architects in the early conceptual phase and allow for making decisions logical with the principle of eliminating unnecessary geometry. At present, the leading research on the search for geometry and form optimization is being carried out by researchers performing advanced structural calculations [24,25,26,27]. In the search for modern inspirations in architectural shaping, it has become essential that the processes of topological transformations should be a search for aesthetics but also structural logic [28]. Among the features describing both structures encountered in Nature and human-made structures, it can be seen that both variants are shaped based on principles described by mathematical formulas, describing the analysis of the flow of physical forces or reduction of unnecessary geometry. The visible inspiration from arboreal systems shows that the cross-sectional characteristics of natural structures coincide with the graphical interpretation of bending moments (see Fig. 1). In trunks and branches, the most significant cross-section occurs in place of the largest bending moment and the smallest at the ends on the side of growth cones (as those carrying the smallest load).

1.4. Topology optimization

The article presents examples of topological optimization based on geometry and analytic solutions of arboreal structures, as an example of bionic inspiration. The research carried out on cantilever structures is based on an analogy to the tree geometry in its winter form (without leaves). The tree is thickest near its base, and as it grows, its branches become thinner (Fig. 1a). The analogy to this arrangement is visible in the diagrams of the maximum moment of the cantilever structures (Fig. 2b-c). The value of the maximum moment is the biggest next to the fixed support and decreases towards the free end. The selected geometry of the structure according to the shape of the bending moment diagram (as load, which is directly proportional to the strain of the elements) allows the material optimization. In Fig. 1, a simplified static dia-

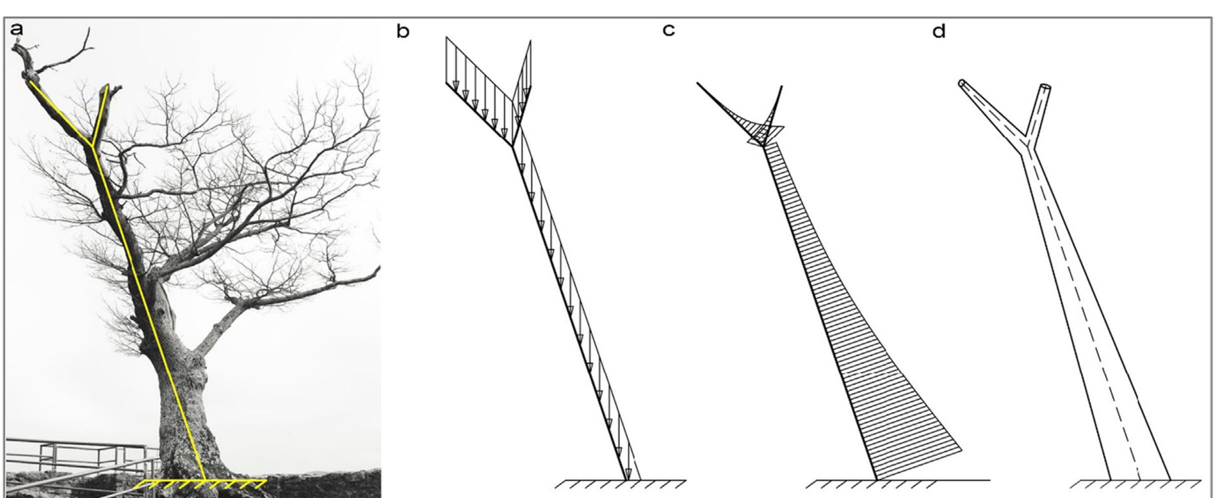


Fig. 1. Comparison of the tree geometry with the statically determinable cantilever: (a) tree and marking of a simplified scheme of boughs and branches, (c) bending moment diagram, (d) structure with variable cross-section, analogous to the shape of the moment diagram (author's compilation).

gram of the tree is presented, as well as the bending moment diagram shape and the structure geometry. The geometry of the structure selected based on the moment diagram is identical to the simplified geometry found in Nature in trees (i.e., the thickest cross-section at the base, and decreasing with growth). The research presented in the article is an initial phase of work on an algorithm for optimizing bar structures. The case studies in the paper have been simplified to bending moments analysis only, as they are leading force determining the cross-section of bent elements (such as the geometries shown in Fig. 1). The other forces (Normal, Shear) have, compared to the moment, a small influence on the size of the bars optimization in the context of the final architectural form. The aim of the algorithm is the initial optimization of the geometry shape. The subsequent dimensioning of the structure serves to check the correctness of the geometric shape (see Fig. 3).

The paper presents the case studies indicate that there is a need to link architectural and structural optimization processes at the early stage of designing to achieve multicriterial sustainable results. The research presents an introduction algorithm that, bases on interdisciplinary cooperation between those two sectors, and in the future, might be used to enhance the construction processes.

In recent years many research and construction of buildings based on fractal and arboreal pattern optimization were conducted. Some of the most relevant examples of such studies were shown in the literature review. The research methodology describes boundary conditions and the case studies analysis flowchart. The description of the case studies, with visual representations of the results, indicate the need to implement parametric algorithmization based on arboreal patterns to the early stage of support structure optimization. The paper is concluded with an explanation of the need for combining aesthetic expression with structural logic basing on computational design methods based on biostructural parametric algorithms.

1.5. Background

Bionics inspiration in contemporary architecture and construction is an inspiring and complex phenomenon, and the effects of these activities are not always carried out following the optimization of the structure, but rather an architectural vision. Nowadays, thanks to the use of digital tools, it is possible to design the geometry of load-bearing structures which, thanks to "skillful application of the achievements of human thought in the field of technology and aesthetics" [29] achieve forms that are surprisingly similar to those observed in Nature.

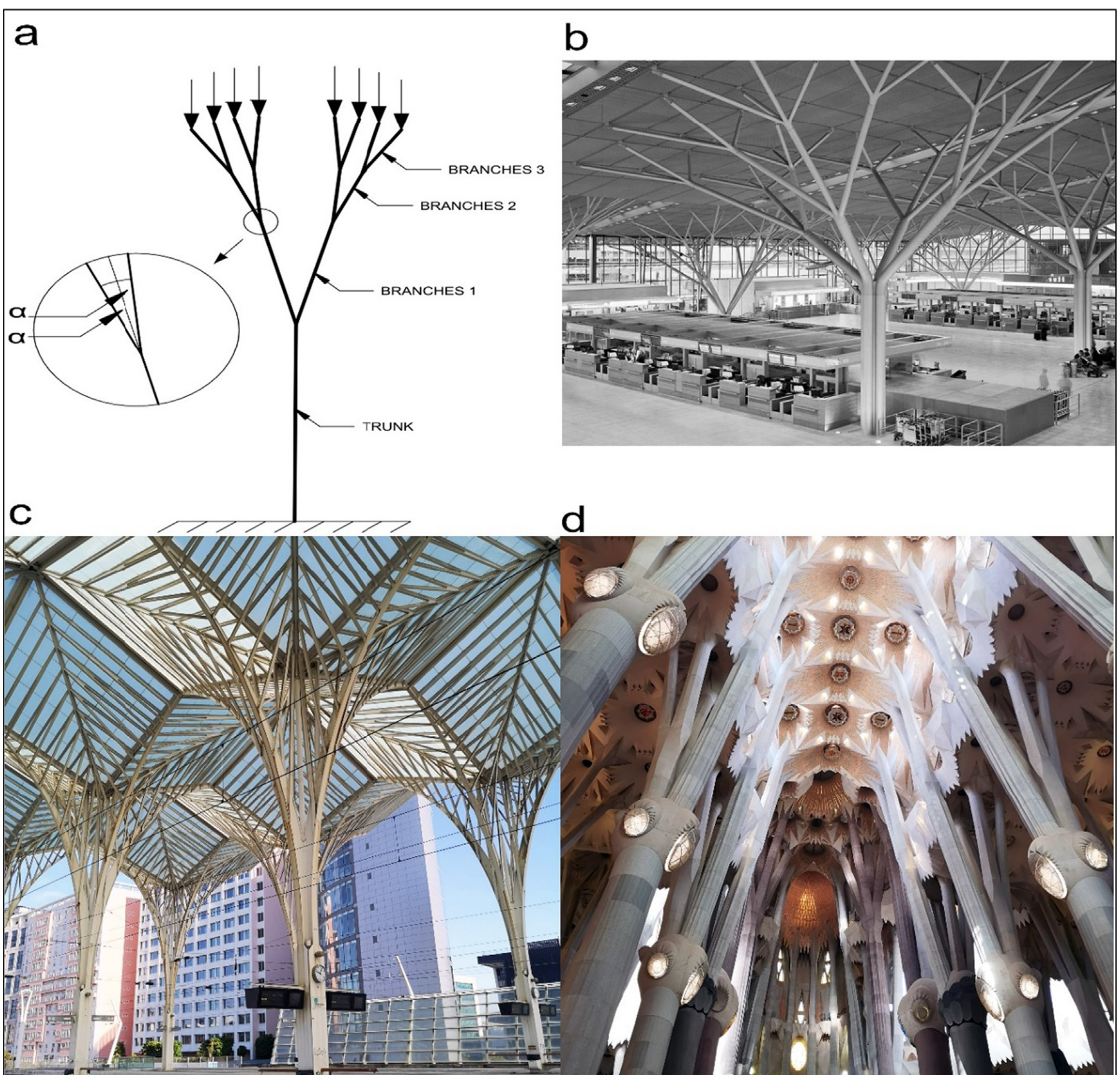


Fig. 2. Examples of basic structural elements inspired by natural processes: (a) research and design based geometry, (b) arboreal structure, Airport, Stuttgart, Germany, 2004, (c) Canopy at Railway Station, Lisbon, 1998, (d) Sagrada Familia, Barcelona.

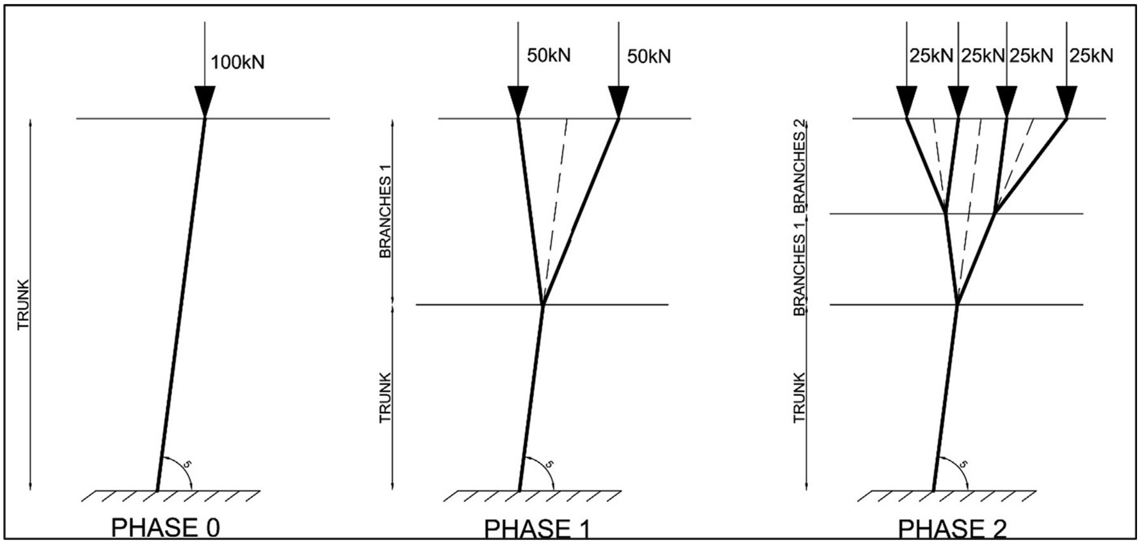


Fig. 3. Phases of growth divisions of trunk and branches: (a) phase 0- single trunk, (b) phase 1- in the middle of the trunk length division into two branches, (c) phase 2- in the middle of the family 1 branches lengths division into two new families 2 branches (author's compilation).

Comparative analyses of various inspirations taken from the natural world were the starting point for research on the optimization of the geometry of arboreal support structures used in 21st-century architecture. Tree-like branching structures [30], are also known as *'dendritic structure*' [31] and '*arboreal*,' which means *'relating to or resembling a tree*' [17]. Often, due to the geometric similarity, fractally divided arboreal support systems are noticeable in two main types of structures. In the first one, where the independence between the canopy and supporting structure is visible in material and geometry, and the other where supporting structure 'seamlessly' passes into roofs. Inspiration from such phenomena is not only the domain of the 21st century and the use of digital tools.

It is essential to emphasize the diversity of mechanical work in the tree, which varies depending on the season. The analogies of tree mechanics and arboreal structures discussed in the article are based on the winter work system. The work of the tree structure is similar to the work of load-bearing columns (limited impact of wind force through the lack of leaves, compared to the dead load). In the simplified arboreal structures analyzed in the paper, the wind load was omitted, the structure is designed as interior structural elements. Arboreal systems have appeared in human activity since prehistoric times. Tents, as described by Frei Otto, are "something biological, something non-technical, or rather: pratechnical" [29]. In his most famous work - Sagrada Familia Antoni Gaudi also uses arboreal systems in load-bearing columns. The research on tree structures and fractal divisions were carried out based on simplified mathematical models, characterized, among others, by the angle of inclination of branches to their length or the assumption that branches have a constant cross-section along their entire length [32,33]. However, they were aimed at seeking growth simulation rather than material optimization. Hui-jun et al., in the research [34], conduct topological optimization with the use of advanced construction software (e.g., ANSYS) on arboreal structures. In the research, the structural divisions were programmed according to the algorithm creating fractal geometry divisions.

2. Literature review

2.1. Research-based

The use of bionic patterns is a well-known system. Examples of tree structures geometries, as one of many bionic geometries, have become a part of the form-forming optimization of structures [21]. A rapid increase in the use of those patterns in the 20th and 21st century is related to the Biomimetics initiative by a researcher Janine Benyus, described in her book *Biomimicry Innovation Inspired by Nature* [35]. The researcher describes nature inspirations as "*the new science that studies nature's models and imitating these designs to solve human problems*." By describing these models as "Models, Measure, and Mentor," she initiated biomimetic research. In the last 20 years, there has been a convergence of these directions with the search for structural optimization. The bionic modeling can be distinguished between the main aspects: the search for patterns, form-finding, and the operation of entire ecosystems [3,36]. Living organisms depend on abiotic factors such as terrain geometry, climate (temperature, air humidity, sunshine winds, atmospheric pressure). The pursuit of the implementation of Nature's technology solutions in architecture takes place on several levels. The most common and intuitive action is to imitate the shape patterns of organic forms, which can seek innovative tectonic solutions, not necessarily related to structural logic [37]. Searches for functions describing patterns found in Nature are visible, among others, in research on fractal geometry and its implementation in architecture [38,39]. In the context of structural optimization, shaping processes- the way of formation of organisms in variable conditions is possible thanks to the growth algorithms. It conditions the design process to a set of boundary factors corresponding to the load's cases rather than the stylistic code [40]. The development of advanced computational programs has resulted in significant interest in creating geometry with forms notices from Nature (Rian, Sassone 2014) [17].

2.2. Design-based

Modern design combines theoretical knowledge with the craft. Advanced calculations for material optimization often go beyond the technological possibilities of their execution [41]. It has already been pointed out by Newton, who emphasized that what is entirely accurate is geometric, less accurate is in mechanics, because errors are in the execution [42].

An essential aspect of modern architecture is interdisciplinarity and the phenomenon of "borrowing" the effective systems or patterns from Nature and implementing them into architectural design. It is particularly visible in generative systems. The use of tree-like structures is visible in such architects' designs as Antoni

Gaudi (see Fig. 2.d. Sagrada Familia) or Santiago Calatrava (see Fig. 2.c. La gare de Oriente, 1994). Due to the mechanics of the work, the following terminology of arboreal structures has been proposed in the article: a trunk-element fixed in support (no possibility of movement or rotation)- an independent load-bearing element carrying an external load or supporting branches (located in the free end of the trunk). The highest family of branches, formed by divisions of the trunk, or lower family branches at their mid-length, transfers the load from its free end to the lower elements of the structure (see Fig. 2.a). In Sagrada Familia, the columns were designed in a way that the angle of the branches allows the load transfer by the shortest possible route; this issue was later continued in tree-inspired dendriform and fractal-like branching structures in architecture [17]. One of the largest building (in terms of area), with arboreal supports, was the airport terminal completed in 2004 in Stuttgart (see Fig. 2.b). The trunks, located every 25.0 m or 18.0 m, were divided symmetrically into four branches and then into the next family of three branches. In the optimization phase of the structure, the main parameter was to minimize the bending moments and to transport mainly Normal forces. An example of an object where arboreal patterns were used is The Tote in Mumbai, where the supporting structure is formed by trusses imitating a rain forest.

3. Research methodology

The use of arboreal structures in architecture is a standard method, which aims to achieve not only architectural aesthetic needs but also real economic effects, with the principle of sustainable development [20,19,30]. However, the use of these systems does not accurately reflect the structural work of a real tree [43], where gusts of wind cause significant vibrations, the most challenging load-type to sustain [44]. The uneven distribution of branches prevents harmonic overlapping of the vibrations caused by wind load in the structure of the tree body [45]. However, it has long been known (e.g., Kang et al., 2011) [46] that the reduction of the branch cross-section as it grows is analogous to the shape of the bending moment diagram (also minimizing the wind impact area where possible). Tree structures, e.g., Sequoias, growing up to 100 m in height, due to their static work they are the congest cantilevers in Nature, with high efficiency transferring the resulting stresses and own weight [47].

As logic structures found in Nature, arboreal supporting structures were an objective of the case studies. As indicated in the literature review, the tree structures used in architecture, as in the research carried out by A. Gaudi, are supposed to transfer loads from large areas of a roof to supports in the shortest possible way, rather than the actual system of tree mechanics (resistance to wind load). The fast way of transferring loads is connected with the transfer of Normal forces only (compression and tension), at the same time eliminating the bending Moments in the structure. The way the structure works changes from counteracting dynamic to static load, transferred from the elements above the arboreal structure. The use of divisions in branches as they grow reduces the distance between the branches' free ends and the trunk's support base, which results in the optimization of the amount of material necessary for designing. The tests are conducted in the most unfavorable configuration so that bending moments occur in all members of the structure as mainly influencing force on the section thickness. In the study only bending moments are considered as the most destructive forces in longitudinal column structures, influencing the most on the cross-section thickness. The tests are conducted in the most unfavorable configuration so that bending moments occur in all bar members. To achieve this also the trunk was leaned from Z-axis.

In mentioned architectural examples of arboreal structural supports, the aim was to search for more aesthetic expression than material optimization. In the analyzed literature, there are multivariant optimization attempts based on essential factors such as maximum deformations, stresses, buckling. Analyses presented in the article, originate from geometry shaping on the family of fractal divisions. Furthermore, the process of shaping arboreal structures according to the material used is investigated.

Topological optimization was carried out with the use of solid steel bars with variable cross-section to minimize the material usage, as the profiles can be adapted to the geometry of the Bending Moment diagram. At the same time, as an eco-friendly material, compared to other easily shapeable materials, e.g., reinforced concrete, it does not have such a negative impact on the environment in all phases of maintenance. The use of materials with low carbon footprint, material minimization, recycling, and reuse of materials, as well as the use of local resources with minimized transport [48] allows the reduction of Greenhouse Gas (GHG) emission.

The study's initial geometry was based on the fractal divisions of trees and the probability of branch proliferation [32,33]. The analysis studies geometry patterns with the changes in the forces distribution and shape adjusting, caused by bending Moments optimization. The structure form and methods of topological optimization were based on biomimetic patterns. Shape testing was carried out using the early stage optimization tools (Grasshopper/Karamba), while geometry dimensioning was carried out using Robot Structural Analysis software.

A base geometry as a 6.0 m high trunk (a cantilever fixed in the ground) was assumed. In order to attain the bending moments in the structure, the element was leaned by the angle of 5st). In the next phase, the trunk was divided into two branches, in the middle of its length (supporting as fixed support the start points of the branches, which carried equal load) (see Fig. 4).

To identify cases and illustrate the geometry shaping factors in the design of arboreal systems, the study based on the following assumptions:

- A simplified structural system, statically determined, was used to show trends in structure operation and to determine the direction of future research;
- The arboreal structure is cantilever, settled in fixed support, the structure was statically determinable, and all segments were straight;
- The main trunk is leaned from Z-axis (5° deviation from the Z-axis); thus the operation of the structure under unfavorable bending Moment loading conditions is calculated;
- The branch edges location is limited to a square area with H/2 side, the center of which is the free end of the main trunk (Fig. 5);
- The length of the trunk is 6.0 m, analogously to the height of the column in industrial halls of steel construction;
- Solid-profile steel was used as the construction material, as a homogeneous material;
- The point load was applied at the ends of the branches. A simplified load case model was used (the sum of loads in each case of the geometry was 100kN, the load assumed by the analogy of the published results (Zhao et al., 2017) [49]), the deadweight was skipped.

The following division scheme was used in the subsequent phases of geometry shaping (Fig. 3):

Phase F_0: Cantilever-fix supported trunk, full height (no branches)

Phase F_1: cantilevering trunk, divided at mid-height into two branches (trunk + 2 daughter branches)

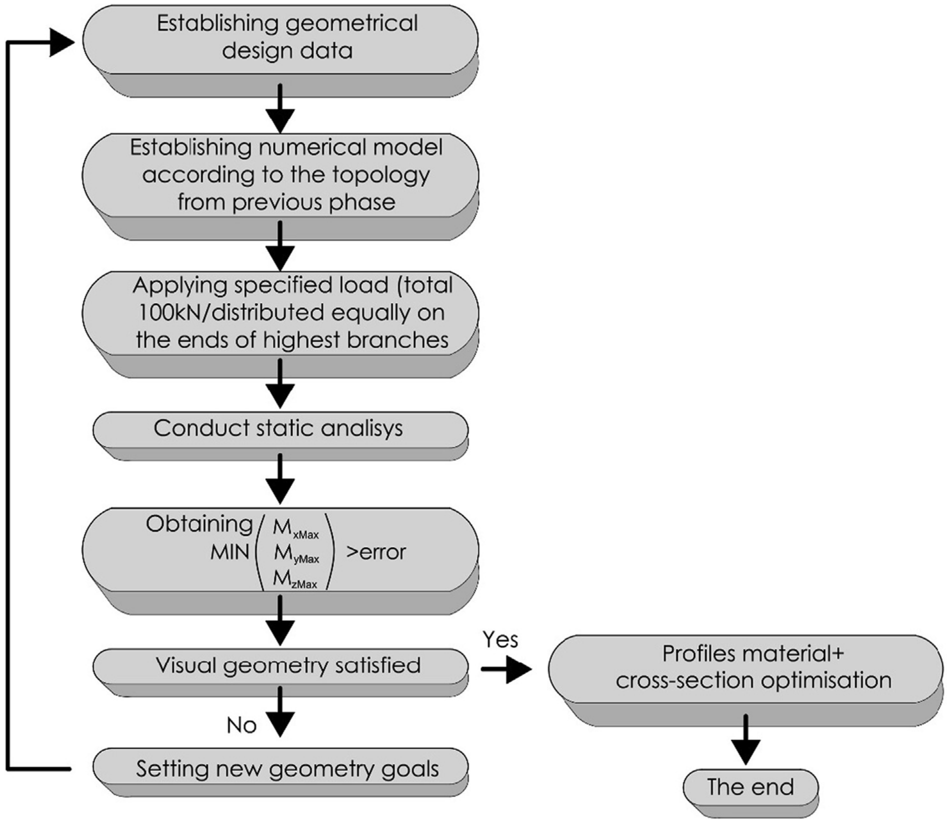


Fig. 4. Form-finding analysis flowchart (author's compilation).

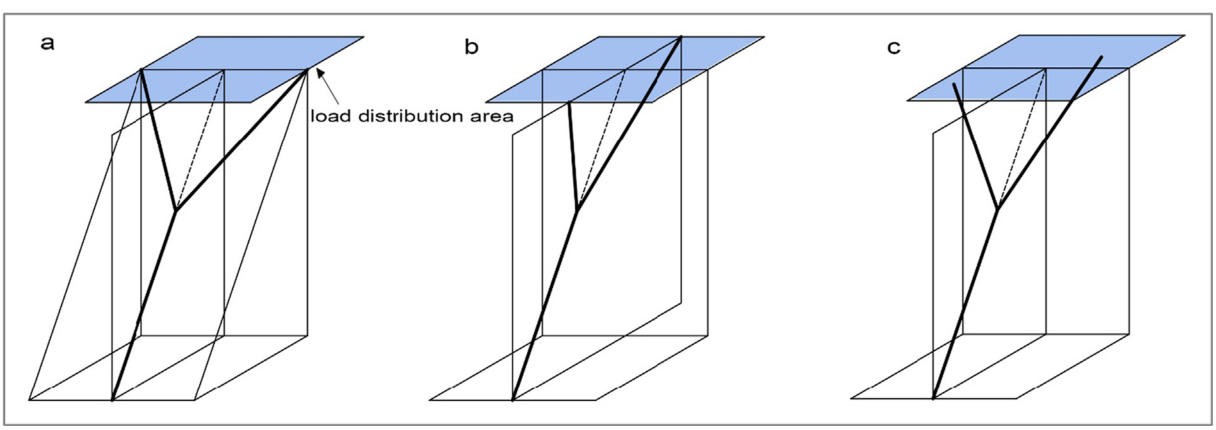


Fig. 5. Sample geometries, Variant A- all points are on the same plane, formed along the bough's inclination (the angle between the bough and both branches is equal), Variant B- all points are on the same vertical plane (the angle between the bough and both branches is equal), Variant C- points do not belong to the same plane, the length of the branches and the angle of inclination to the bough is different (author's compilation).

F_{1A}- the angle between the branches and the trunk is equal, a line forming between the tops of the branches perpendicular to the main trunk (all nodes on one plane)

F_{1B}- the angle between the branches and the branch is the same, a line forming between the tops of the branches parallel to the main trunk (all nodes on one plane)

F_{1C}- the angle between branches and trunk unrestricted, geometry shaped using the form-finding method, using Grasshopper/ Rhinoceros and extensions to optimize the Karamba design.

4. Results and discussion

The main objective of this study was to simulate tree supporting structures based on the maximum bending moment optimization. The determining parameter in geometry optimization was the minimization of the maximum bending moment. In the calculation model, a population of 500 models in each of the geometric variants was examined. The reference geometry was generated in phase 0 column-trunk, without divisions into branches. As a result of the optimization of variants F_{1A} and F_{1B}. It was noticed that the span of the branch ends was tending to zero, thus maintaining constant Mmax values of −50 kNm and −25 kNm, respectively. Variant F_{1C}, where the branches were formed independently, the lowest possible Mmax was achieved. Fig. 6. shows the stages of automatic optimization of the distribution of branches in the geometric variant F_{1C}.

The study was carried out on the designated arboreal geometries. As a measure of quality, the values of maximum moments and the weight factor k were analyzed. A factor k defines the proportion of the weight of particular geometries to a single trunk, according to the formula:

$$k_i = \frac{k_n}{k_{ref}}$$

where:

k_i-weight factor of the tested variant (unitless)

k_n- weight of the Phase 1 structures of the variant F_1 in kg

k_{ref}-weight of the Phase 0 geometryF_0 [kg]

The comparison of arboreal structures F_1 to the reference geometry F_0 shows that it is possible to optimize the weight of the structure by using tree-like structures. As a result of the analyses, it was proved that the results obtained are following the initial assumptions. With a simplified calculation model, the scope of research was limited to statically determinable cantilever systems. The first phase of optimization, consisting of topological transformations, consisted in analyzing the geometry for obtaining a minimum M_{max}. Fig. 6 shows the individual stages of the calculation algorithm. Verification of the assumption that the optimal shaping of profile sections according to the geometry of bending moment diagrams was performed in Robot Structural Analysis. Full structural calculations were performed based on variable solid-profile steel sections, depending on the geometry of the bending moment diagram shape. As the reference weight k = 1,0, the result of material optimization of the reference geometry F_0 was assumed. As a result of algorithmic optimization F_{1C}A significant weight reduction is visible.

The results of research on the designed computational algorithm, presented on a selected reference geometry group, confirm that optimization of cantilever structures using arboreal divisions and variable profile cross-section geometry can be a new direction in interdisciplinary design (see Table 1). The presentation of research on homogeneous material helped to illustrate the relationship between the Moment diagram geometry and its numerical value to applied geometry of cross-section (available materials are steel, concrete, glued laminated timber). The same design parameters apply to all possible materials. However, this factor in composite materials, which most often consist of materials with different properties (such as reinforced concrete), is more challenging to interpret without the use of advanced structural dimensioning programs graphically. The authors intended to present a simple algorithm for shaping topology and geometry regardless of the material used. Because minimizing M_{max} regardless of the material used will reduce the weight of the structure. Solid-profile steel cross-sections allowed to adjust the shape of the structure according to the value and the geometry of the bending moment diagram. The largest profile cross-section and the M_{max} were located next to the fixed support. The smallest profile cross-section and M_{min} were located at the branches' free ends, thus minimizing the weight of the structure. The material that could be used correspondently for analysis could be glued laminated timber. However, steel gives unlimited possibilities of shaping, not only the elements traditionally used in construction but also a modern fabrication, e.g., in 3D printing. Based on the current state of material engineering research on new building materials, it can be assumed that steel will be a material with similar structural features to those of the new not yet invented. In contrast to the current trends in design (e.g., the BESO method), which may result in impossible to fabricate structures, the design logic presented in the article seems to be much more practical and possible to imply in the current fabrication knowledge. The scientific literature shows a trend of searching for compromises between geometry design and fabrication process [50]. As well as stresses the need for integrating 3D printing technologies into Architectural Education [51].

The study aimed to present the trend in shaping contemporary curvilinear structures on the example of simplified schemes of arboreal structures. The results suggest that this direction of research should be continued, based on the elimination of complex structural analyses and replaced by a simplified generative algorithm for the early stage of geometric shapes search. Analyzed variants, based on statically determined diagrams, allows the application of geometric optimization for both architects and constructors.

While comparing the results with the other similar research based on simplified arboreal support structures, it is visible, that geometries based on fractal divisions achieve more optimal results when determined by form-finding analysis. Most contemporary research of arboreal structures in architecture is based on graphic fractal divisions [32,33,52]. A few are based on structural logic and material optimization [30,49,53], with visible limitation to geometry shaping. The significant aim in all the above examples was to follow strict rules of fractal divisions, while in the paper, thanks to the generative algorithm, the arboreal structure adjusts its geometry to the load cases in order to achieve the minimum bending moment.

The analysis presented on a homogeneous material has shown the relationship between the values of moments and the sizes of variable geometry cross-sections easily. Understanding the assembly technique and material properties are essential factors for structural optimization, especially in the FEM method [54]. The material used in work, in the form of cast steel, is not commonly used today. Still, due to the rapid development of modern fabrica-

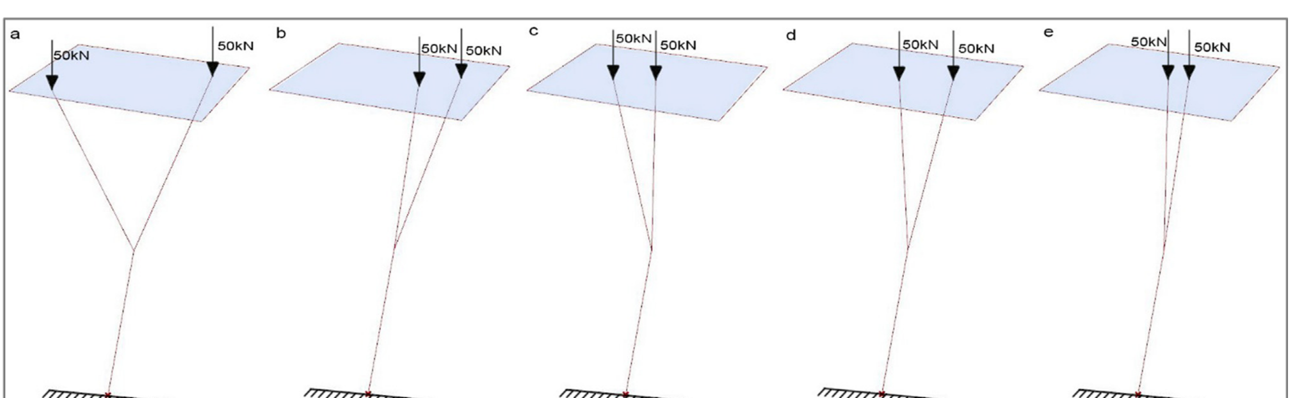
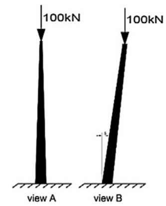
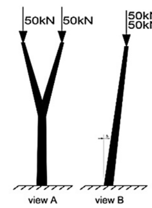
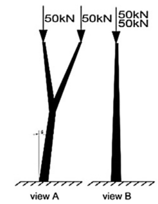
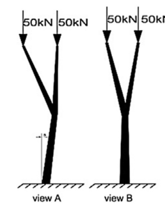


Fig. 6. Phase 1, variant C, automatic structure optimization, visual representation of chosen geometries, (a) M_{max} = 55 kNm, (b)M_{max} = 44 kNm, (c)M_{max} = 33 kNm, (d)M_{max} = 25 kNm, (e)M_{max} = 14 kNm (author's compilation).

Table 1
Statistics values of the best results in each tested family group.

	F_0	F_{1A}	F_{1B}	F_{1C}
Max bending momend value [kNm]	−50	−50	−25	−14
weight factor of the tested variant (unitless) k_i	1,0	1,15	0,79	0,77
Structure shape scheme after full shape optimization in the robot structural analysis program				

tion in 3D printing technology, materials with homogeneous characteristics should be seen as playing a significant role in the future.

5. Conclusion

The studies present that optimization conducted at the early stage of architectural designing, based on bionic algorithms might have an essential impact on structural form-finding. A biomimetic form-finding approach in designing highlights the need for in-depth studies of technical objectives [55]. Bionic inspirations in designing based on Sustainable Development were launched into architecture in the previous century. However, nowadays, computational tools development allows more rational practice implementation principles.

The availability of algorithmization tools for optimization allows combining aesthetic expression with structural logic. The high efficiency of nature forms, including trees, has become a contribution to structural and architectural research on arboreal structures.

5.1. Limitations and the future scope of the study

Limitations of such an approach are still not sufficient knowledge in associating architectural form-finding and structural optimization. The optimization of cantilever structures using arboreal divisions and variable geometry of profile cross-sections can be a new and significant direction in interdisciplinary design.

The search for minimum material consumption is evident in drawing inspiration from solutions found in Nature. The availability of algorithmic tools for optimization combines aesthetic expression with structural logic [56,57]. Arboreal divisions can be an infinite set of topologies of structures with an attractive geometric form to obtain. This multitude of attractive forms is particularly useful for architects at the architectural design concept stage. As shown in the paper, the possibility of weight optimization is already at the stage of topology selection, but also later geometrical changes. This optimization, combined with the joint work of the constructor and the architect, will generate attractive arboreal forms that are, at the same time, optimal in terms of the material required for their manufacture. This type of pro-ecological design, in the light of current EU directives and regulations, will be increasingly required from designers.

The results demonstrate that not only the choice of form-finding method and structural optimization but also the usage of contemporary tools are essential to obtain an appropriate final structural element.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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