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Original
Design Optimization of Tree-Shaped Structural Systems and Sustainable Architecture Using Bamboo and Earthen Materials / Frangedaki, Evangelia; Sardone, Laura; Lagaros, Nikos. - In: JOURNAL OF ARCHITECTURAL ENGINEERING. - ISSN 1076-0431. - ELETTRONICO. - 27:4(2021). [10.1061/(ASCE)AE.1943-5568.0000492]

Publisher:
American Society of Civil Engineers - ASCE

Published
DOI:10.1061/(ASCE)AE.1943-5568.0000492

OPTIMIZED TREE-SHAPED BAMBOO STRUCTURAL SYSTEM FOR SUSTAINABLE ARCHITECTURE

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ABSTRACT

The objective of this study is to propose a structural parametric design optimization procedure for designing a tree-shaped structural system, equivalent to the column-beams system. The ultimate scope of the work is to support sustainable design where renewable materials (such as plant-based materials, soil, etc) are used for the construction. The use of renewable materials and earthen construction techniques in structural design represents an important construction method due to its negative carbon footprint. In this direction, the proposed structural support system will be constructed using renewable materials like bamboo, that is probably the most well known renewable material, and it has long been valued as an alternative to wood. Thus, the main goal of the study is to design the tree-shaped structural system with the characteristics of the material "Guadua Angustifolia" in order to test the effectiveness of the material itself in different design intentions. An ellipsoidal and a quadrangular structural system is parametrized and optimized to effectively support self weight of the material itself and the design loads imposed by the roof.

INTRODUCTION

Sustainable architecture has come to the fore in recent decades in the field of design and attempts to equilibrate the dialogue between the natural and the artificial as a try to comply with architecture design with sustainability. This is happening through variations in design procedures related to the term low-tech, bioclimatic, eco tech, bio architecture, in general a design which can contribute to the environmental load removal.

The Architecture, Engineering and Construction (AEC) Industry until now generated around 40% of greenhouse gas emissions and account for 20% of all solid waste produced in developed countries [1]. The main construction materials as steel, concrete and aluminum are responsible around 50% of all global industrial Co_2 emissions and the demand will be doubled by 2050 [2, 2b]. Through these data, it is not difficult to imagine that sustainable architecture will soon have to be considered as the only way to continue designing new buildings and minimize damage to the environment. At the same time it is expected an increase of population from 3.5 to 5 billion by 2030, with 95% of the urban expansion taking place in the developing world. European citizens spend over 90% of their time indoors, meaning that human health and well-being is strongly linked to the way the built environment is constructed, maintained and renovated. (3) Sustainable architecture seeks to build a combination of energy-efficient technology, and innovative design with renewable materials, such as bamboo and earth which can achieve the objective of creating bioclimatic and sustainable spaces for housing, community, schools or leisure use. This approach reduces waste and also minimizes the environmental impact of new constructions. The use of bamboo in construction can contribute to sustainable management of the Earth's resources. Certain bamboo species hold a record of the fastest growing plant. Bamboo is an excellent eco-friendly construction material because of its high renewable rate, low embodied energy, reduction of pollution, high strength-to-weight ratio, and low cost. Different species are native to diverse climates around the world and many environmental organizations are promoting bamboo due to its variety of excellent properties. In this research the models will be simulated to the characteristics of Guadua Angustifolia. With the advent of generative design, the possibility arose to explore an infinite number of parameters within an architectural / structural project that allow the designer to control the morphology of each project without neglecting the structural aspect by integrating architectural language and stability. Parametric design allows the control of free forms that allow greater freedom of expression, leaving aside the production of elements in series, typical of the era of industrialization. With the advent of generative design, the possibility arose to explore an infinite number of parameters within an architectural and structural project that allows the designer to control the morphology of each project without neglecting the structural aspect by integrating architectural language and stability. The use of design software and the standardization of innovative materials can also contribute significantly to the development and application of the ecological principles, which can drive to an inclusive transition towards a climate-neutral Europe. (3) The design with natural materials and the connection of modern engineering science with traditional techniques is an approach which can lead to the waste and pollution reduction. The combination of earth and bamboo can also give a solution to the housing crisis. The design with natural materials and the connection of modern engineering science with traditional techniques is an approach which can lead to the waste and pollution reduction but also produce low cost dwellings. In low-cost housing, the roof structures can account for up to one third of total building costs, which can be significantly decreased with bamboo . An eco material like soil (in raw earth construction techniques) has been used in architecture along the years, due to its reduced cost, its availability globally and its recyclability; combining eco-friendly construction with low footprint. (4) The roof of traditional earth constructions is usually made of wood but because of luck of timber in many places also with plants and leaves. Common materials such as earth, stone, bamboo and wood, mostly taken directly from the site of the construction, reduce adverse effects from the transport of building materials from their source to the construction site. The earth is low-strength material, so it is used to make thick walls or timber supported walls for the longer life cycle of the construction. (5) In earthen constructions it helps to have a light roof while keeping window and door openings small, for better stability of the structure. Many historical earth constructions, already part of Unesco heritage, such as the houses of Hakas in China or the fortified rammed earth constructions in Portugal, have withstood several strong earthquakes in recent centuries. The construction composition of bamboo for building vaults and slabs is very promising according to traditional structures in many countries and those structural types can be a sustainable solution through a new design approach for raw earth construction techniques.

STATE OF ART

The world record for the fastest-growing plants in the world belongs to some species of bamboo . There are around 1500 species of bamboo and they are classified as herbaceous or woody; the Guadua has a high strength to weight ratio and for this reason it is frequently used in construction. Also it is a low costs and with many environmental benefits construction material because of its high renewable rate, embodied energy, reduction of pollution, high strength-to-weight ratio. Its use is limited because of its variations in properties, and composition and also the difficulty of making connections. (6) These plants can grow anywhere and do not need the use of fertilizers for their growth. Guadua bamboo represents the most important species in Latin America, especially in Colombia where the plant is native. It is an excellent plant for construction due to its physical and mechanical properties. Furthermore the International Organization for Standardization applies to the use of bamboo structures (ISO) ISO 22156: Bamboo – structural design (ISO, 2004a) which provides basic design guidance construction and also it is supported by ISO 22157-1 Bamboo – determination of physical and mechanical properties. (7) The Guadua poles can reach heights equal to 20 m, which are cut into different parts according to their cross-sections. Each part is used for different purposes. The highest and thinner part is called "sobrebasa", used mainly for walls and furniture. The intermediate part is called "basas", with enormous strength in relation to its weight; they are the most used parts in construction especially as beaBamboo as construction material. Thanks to the morphology of the Guadua, the diameter of the canes is very constant, with a maximum reduction or taper value of about 5 mm/m and its wall thickness is generally quite thick, and it varies between the different sections chosen. These pieces are perfect for working on beams and straps. (8) Another eco friendly material which can support sustainability is earth. There are many earthen construction techniques for walls and only a little for roofs because of a wide use of timber. Dome structures enable whole spaces to be enclosed with little material other than earth, but such roof structures would be difficult to design for earthquake loading except over a very small space. An alternative is to cover a specially designed roof structure with a layer of planted or grassed earth. This can integrate a house both visually and ecologically into its natural landscape, but is also heavy, and it needs quite a lot of earth walls to hold up an earth roof which means extensive work and an increased need of material for walls. For the bamboo roof support system the calculation will be according to inclined roofs filled with lightweight loam, which is commonly used tile-covered after roofs and then be filled with lightweight loam (in order to increase their thermal and sound insulation). If the space created by a typical 16-cm-high after is filled with lightweight loam with a density of $600kg/m^3$ and the ceiling made of timber boards, the roof achieves an U-value of $0.8W/m2K$. The combination of earth in construction with bamboo-reinforced in housing has been used since many decades before, in countries like Guatemala (1978) mainly with the transmission of loads to walls or to a big number of columns which divided space to sections.

Nowadays structural analysis of bamboo structures has mainly focused on the development of engineered (laminated) bamboo or on synclastic doubly curved bamboo gridshells (for example the shell constructed at UNAM, Mexico which was presented at the 2015 IASS conference (9). The complexity of these forms has attracted attention in architectural design with the reproduction of structural shapes inspired by nature. The "biomimetics" had a key role to design these new types of structures and gave rise to a series of production of structures inspired by natural forms. Among these types are the “dendriform” structures, inspired by the shape of trees. (10)

“Trees are organisms that stand by themselves, and therefore their shape has an inherent structural rationality”. (11) Trees are exposed to external loads, and the most important of all is those of the wind. The tree has a configuration that can cope with the wind force and the consequent bending moments. Its own weight represents the axial compression that is absorbed by the stems and trunk of the tree. When the tree is exposed to the wind (bending conditions) the stresses change: from traction on the convex side to compression on the concave side (Fig2).

The trees have a configuration that can distribute the loads homogeneously, so this structure can be considered optimized considering the distribution of the loads. (10) According to the principle of the minimum lever arm, having a larger branch means increasing the chances of breaking under the pull of gravity. To avoid this, trees adapt a compromise point by exposing a larger number of leaves, however limiting the length of the branch (Fig.3) (12)

The branched structures, known as "dendriforms", first had a decorative role in architecture and then a structural use (Fig.4).

Over time the shape of the dendriform structures also changed as new materials were used in architectural design . Through the new materials, the sections of the supporting columns have thinned bringing the three-column structures to resemble more and more to the typical structure of the trees. Over the centuries, the forms of nature have continued to interest architecture and engineering. In movements like Art Nouveau the morphology of trees and the plant world in general had a primary role. From 1890 to 1920 AD the artistic movement was inspired entirely by plants and the iron castings played an important role, not only to define decorative but also structural elements (Fig.5). (13)

The combination of concrete and steel has been widely used in tree design structures since the early 1990s; with many experimentation searching for solutions which aimed at saving iron. One of the first examples were Baroni's studies which ventured on double-inverse curvature thin reinforced concrete roofs resistant in shape. Among his experiments was a design in 1938 known as the "Baroni tree" which had double advantage: saving of metallic material and better distribution of forces, very close to later fields of structural optimization (Fig.6). (14)

Around 1950s, dendriform structures take on another meaning: as an interest in Biomimetics arises (from the Greek $\beta\iota\sigma$, life, and $\mu\iota\mu\eta\sigma\iota\sigma$, imitating) according to the scientist Otto Schmid. (15) The term "biomimetics" first appeared in the scientific literature in 1962, becoming increasingly popular in the 1980s. In fact between 1950 and 1960, Felix Candela designed a series of thin shell structures supported by umbrella columns. This design combined engineering with biomimetics. The column inspired by the shape trees not only acts as a support for the roof but also acts as a roof itself. As F. Candela said, “these structures require extremely elementary calculations since the stability of the "umbrellas" depended solely and exclusively on the proportions of the structure itself and also the optimum rise, which depends on the area covered by the umbrellas (Fig.7). (16) On this simple proportion depends the success in the design of these structures, since the necessary calculations are elementary. (17)

Just as the tree, the principle of the minimum lever arm applies to these structures: the longer a branch, the more likely it is that it will break under gravitational action. Many designers have experimented with nature-inspired dendriform structures, with well-known works such as the Frei Otto in the 1970s and even large structures of modern architecture (Fig.8).

In recent decades a need has arisen to design new architectures capable of being structurally performing but with the ability to limit the environmental impact through the improvement of energy efficiency and with the use of renewable materials which increase environmental damage.

METHODOLOGY

This study is done through design approaches for covering with bamboo proper earth building constructions, mainly made from adobe bricks, cob, rammed earth, straw bales and other earth techniques. The primary interest of this study is to investigate the application of structural bamboo on structures created through Algorithm Aided Design (AAD). In particular, in order to treat the object of study, a dendriform structure is designed with the characteristics of the material "Guadua Angustifolia".

The main aim of this research is to test the efficiency of the material itself compared to a shape optimized structure (geometry optimization) capable of effectively supporting the loads given by the material itself and the typical overloads of a roof. Furthermore, the goal is to use parametric design in order to give another postmodern approach to structural designs of bamboo. Following a dendriform structure in design, it will be demonstrated how to use the Algorithm - Aided Design (AAD) to tackle the coding of the cross-sections by using bamboo as a material. An optimization process is proposed to support a fabricable tree-structure design through encoding the material's properties and morphology optimization of the structure. The approach approximates the given shape using a finite set of bamboo elements with standard shape and dimension. The model will provide insight into producing required structure elements for the final assembly and the optimized morphology of the entire structure capable of making it high performing. The software used to define the geometry is Grasshopper3D® software or rather visual programming language and environment that runs within the Rhinoceros 3D Computer-Aided Design (CAD) application. The outputs to these components are connected to the inputs of subsequent components. Within the Grasshopper 3D workspace, there are existing different plug-ins for setting up the FEA simulation that is using the visual programming language. In this case, Karamba3D is used. The geometry was tested with the aid of Karamba3D for FEA simulation and the ’Octopus’ algorithm (MOEA) at University of Applied Arts Vienna and Bollinger+Grohmann Engineers, in order to solve the optimization problem. Furthermore, this study can be considered as the first step for future elaboration of the joints, useful to make the structure completely realizable. One of the main considerations for the design of this case study is that the object must provide a roof overhang so preventing rain from coming into contact with the loam walls. For earthen constructions it is not the material which is responsible for structural failures, but instead the structural system of a given layout and also the weights of the roof. Also a roughly symmetrical structure will be tested because of a more predictable behavior in earthquakes. Two different approaches were taken to implement the design of a structure to support centrally the roof,according to traditional use of poles to obtain the surface needed for roof.((i) Curved bamboo as a Tree-column structure with quadrangular morphology and (ii) An elliptical morphology for column and truss elements.

THE CASE STUDY FOR TREE-COLUMN STRUCTURE

As mentioned in the introduction, in this section it will examined the two parametrically defined case studies. The workflow in order to analyze the two dendriform structures the next steps will be followed:

- The definition of geometries
- Implementation of material properties
- Cross-section properties
- Implementation of loads and supports
- Finite Element Analysis results

The definition of the geometry for Quadrangular morphology

The first step in order to obtain a parametric model to be subsequently analyzed and optimized is to clearly define the geometry. The free geometry was produced through precise parameters and, with their interconnection, it was possible to obtain the starting surface (Fig.10(a)).Delimited the three initial polygons with a variable radius and height, through the "loft" component the starting surface has been defined which will represent the base mesh on which the beam elements will be applied (Fig.10(b)). The variables defined as h_1, h_2, h_3 - which represent the height of the structure - and the radius of the polygons - defined as R_1, R_2, R_3 - have been predefined in the conceptual phase; their domains (in meters) are structured as follows (Fig.9):

(Eq. 2):

$$h_0 \in [0,0]\ (m)\ \ h_1 \in [0,6]\ (m)\ \ h_2 \in [0,6]\ (m) \tag{1}$$

And

$$R_0 \in [0,2]\ (m)\ \ R_1 \in [0,4]\ (m)\ \ R_2 \in [0,6]\ (m) \tag{2}$$

With the construction of the curves described above the positions of the structural elements were extrapolated; these curves will subsequently be discretized in order to set the main beams and columns connected to the poly-surface (Fig.10).

Bamboo Material and Cross Section properties

The third phase of the development of the Guadua Angustifolia plant is the ideal growth moment for its use in construction (Guadua Matura); the physical-mechanical properties of bamboo depend on innumerable factors: growth region, age, moisture content and this justifies rather heterogeneous results of the studies conducted so far. It was considered useful to use the general characteristics for this study as summarized in the Table 1 (Luna at al.)(18).

Above mentioned characteristics were implemented within the software considering that the type of material has anisotropic behavior; this step is essential before analyzing the final structure to correctly determine the main directions of elasticity for each body. In this case it will be used the ‘O-Section’ which defines a circular hollow section based on dimensions imposed (Table2). According to the standard dimension of the structural bamboo the dimensions used for the cross sections are summarized in the Table 2.

The diameter of the poles of the Guadua variety is very constant with a taper reduction of about 5mm/m.

Three different cross-sections will be coded for the three types of elements — a larger one for the vertical elements (column), a smaller one for the horizontal elements (Beam), and a third one to define the thickness of the connection element (mesh panel)(Fig.11).

Load and Support Implementation

For a valid structural simulation model it should be specified one or more loads that are applied to the model trough ’Loads’ component of the Karamba toolbar. This component allows to specify different types of loads for the model. The first type of load that which is needed to apply in this model is ‘Gravity Load’ which calculates the force due to gravity applied to each element in the model (self-weight effects) and the second one is ‘MeshLoadConst’, i.e. a uniformly distributed loads local to mesh. This component needs to have as input the points belongings to the mesh and to specify a vector of magnitude; in this case it will be applied a load equal to 30 Kgf/m2 in the negative z-direction in order to simulate the variable loads(Fig.12).

To conclude the structural model, it is necessary to define the supports. The ’Support’ component receives as input points within the geometry to convert them to fixed points in the model. In this case, the input points for the support are located on the bottom nodes of the entire structural model and on the nodes of the beams/columns. The six radio buttons within the ’Support’ node allow the designer to specify how to fix support points based on the six degrees of translational and rotational freedom. The constraints should be sufficient so that the model does not move freely in space; In this case, it will implement nodes with zero-degrees of freedom.

FEA Results Test Case 1

Once the model has been calculated, the simulation results can be extrapolated using the ‘Model View’ components that allows to label various components of the model and visualize the shape of the model under deformation (Fig. 13).

To have the results of the FEA simulation –in order to compare them with the results of the next step concerning the optimization problem – it is needed to extract the numerical values. To conclude this paragraph section, the metrics will be extracted from the Karamba3D model for use in generative design (Fig.14).

The results are summarized in Table 3.

This design is made to explore the applicable morphology connected to bamboo element types considering the varying distances from one node to the other according to the standard dimensions of the bamboo poles on the market. One of the objectives is to evaluate the optimal shape of the entire structure in order to have a design that is resistant in shape and meets the possibilities offered by structural bamboo for future constructions. With the specified encoding scheme for applicable bamboo element types, the genetic algorithm will be employed to identify an optimal morphology of the structure -taking into account the geometric constraints imposed. After the definition of the dendriform - bamboo structure it will be introduced to the second stage of the work: the optimization phase.

The definition of the geometry for elliptical morphology

In nature, as in engineering and architecture, the morphology of certain objects - combined with specific materials - assume different behaviors. This means that in most cases the success of a structure is entrusted to structural morphology. The structure previously analyzed - as seen from the results of FEA simulation - is characterized by regular shapes and good structural response. However, in this study, the aim is to study the relationship between the structure and function of morphological features (functional morphology) and to demonstrate how the shape can affect structural performance.

Geometry

Through the same workflow as the previous tree-column structure that uses quadrangular shapes as transversal sections, a second geometry with elliptical sections has been implemented (Fig.15)

The three elliptical sections called R_0, R_1, R_2 (lower, middle, upper section) (Fig. 15(a)) were conceived parametrically by setting the geometric constraints in the space $\mathbb{R}^3$ (x, y, z) (Fig. 16) as in the previous example.

Since the equation of the orbital ellipse is:

(Eq. 3):

$$\overline{PF_1} + \overline{PF_2} = 2a \ . \tag{3}$$

The domains F_1 and F_2 for each transversal section (R_0, R_1, R_2) are structured as follows:

(Eq. 6):

$$F_1, F_2 \in R_0 = \left[\hat{\imath} = (0,2)\,, \hat{\jmath} = (0,2)\,, \hat{k} = (0)\right] ; \tag{4}$$

$$F_1, F_2 \in R_1 = \left[\hat{\imath} = (0,5)\,, \hat{\jmath} = (0,5)\,, \hat{k} = (0,3)\right] ; \tag{5}$$

$$F_1, F_2 \in R_2 = \left[\hat{\imath} = (0,7)\,, \hat{\jmath} = (0,7)\,, \hat{k} = (2,5)\right] \tag{6}$$

This means that, when it will be set the optimization problem, the designer will be allowed to select the optimal shapes between the elliptical and circular shapes:

(Eq. 7):

$$dom\hat{\imath} = dom\hat{\jmath} \forall \ F_1 \ , \ F_2 \in R_0, R_1, R_2 \ . \tag{7}$$

If (Eq. 31):

$$\hat{\imath} = \hat{\jmath} \rightarrow \ (x - x_c)^2 + (y - y_c)^2 = r^2 \ . \tag{8}$$

If (Eq. 32):

$$\hat{\imath} \neq \hat{\jmath} \rightarrow \ \sqrt{(x - x_1)^2 + (y - y_1)^2} + \sqrt{(x - x_2)^2 + (y - y_2)^2} = 2a \ . \tag{9}$$

In order to determine the positions of the support elements from the entire geometry, the isolines were extrapolated from the surface (Fig.17); they will represent two other design variables i.e. the number of the segment in v direction (number of columns) and the number of the segment in u direction (number of beams); in this case, the domain was structured as follows:

(Eq. 10):

$$(v) = [4, 20] \ ; \ (u) = [3, 20] \ . \tag{10}$$

Bamboo Material and Cross Section properties

In this section, the aim is to compare the behavior of the geometries chosen as a case study. The same type of material (Guadua Angustifolia Kunth) is selected for both cases with anisotropic behavior and the same cross-sections for the definition of the poles that will be used to define the supports of the structure (Table 1 - Physical and Mechanical characteristics Bamboo Guadua Angustifolia Kunth (Luna et al.), Table 2 - Standard dimensions of structural bamboo poles).

Load and Support

To define Load and Supports, the same parameters as the previous structure will be used, i.e. a gravity load (self-load) and uniformly distributed loads local to mesh (equal to $30Kgf/m^2$ to the negative z-direction). In order to complete the definition of the model, it is necessary to set the supports. In this case, the input points for the support are located on the bottom nodes of the structural model (Fig.18).

FEA Results Test Case 2 and Morphology Comparison

The Table 4 shows the values of both structure before optimization (FEA Results and Comparison).

The results obtained by the second structure can vary considering the variable number of beams and columns. In this case, the above results consist of 13 columns and 9 beams.

THE OPTIMIZATION PROBLEM

A common multi-objective optimization problem can be formulated as the following:

(Eq. 11):

$$(f1\,(x)\,,\ f2(x), ...,\ fk(x)) \tag{11}$$

Subject to

(Eq. 12):

$$x^l \leq x \leq x^u \tag{12}$$

in which (Eq. 12) $x = \{x_1, \dots, x_j, \dots, x_n\}$ is the design variable vector (the collection of n system parameters to be identified), $x^l = \left\{x_1^l, \ldots, x_j^l, \ldots, x_n^l\right\}$ and $x^u = \left\{x_1^u, \ldots, x_j^u, \ldots, x_n^u\right\}$ are vectors of its lower and upper bounds (Eq. 12), respectively.

Solving an optimization problem means finding the best vector of design variables (i.e. the best solution) that minimizes or maximizes the objective function.

Sometimes, the optimization problem is also subjected to some equality and/or inequality constraint functions, depending on design variables, as follows:

(Eq. 13):

$$h_i\,(x) = 0, \;\; i = 1, \ldots \tag{13}$$

(Eq. 14)

$$g_j\,(x) \leq 0, \;\; j = 1, \ldots \tag{14}$$

Tree-column structure: Test case 1

Considering the previous equations, the optimization problem can be formulated as follows:

(Eq. 15)

$$(f_1(x), f_2(x)) \tag{15}$$

in which

- $f_1(x)$ represents mass
- $f_2(x)$ presents the total displacement of the structure.

The design variables are defined as follows(fig.19):

(Eq. 19)

$$h_0 \in [0, 0]\;(m) \;\; h_1 \in [0, 6]\;(m) \;\; h_2 \in [0, 6]\;(m) \tag{16}$$

in which h_0, h_1, h_2 represents the different heights of the sections of the structure,

(Eq. 19)

$$R_0 \in [0, 2]\;(m) \;\; R_1 \in [0, 4]\;(m) \;\; R_2 \in [0, 6]\;(m) \tag{17}$$

where R_0, R_1, R_2 represents the radius of the sections of the structure, (Eq. 19)

$$\emptyset_0 \in [13, 15]\ (cm)\ \ \emptyset_1 \in [11, 13]\ (cm) \tag{18}$$

in which Ø represents the diameter of the cross-sections belonging to the beams and columns, (Eq. 19)

$$T_0 \in [0.8, 4]\ (cm)\ \ T_1 \in [0.8, 4]\ (cm)\ \ T_2 \in [0, 10]\ (cm) \tag{19}$$

where T identifies the thickness of the cross-sections.

Subject to

(Eq. 20)

$$h_1 < h_2\ R_1 < R_2\ disp \leq \frac{1}{200}L \tag{20}$$

in which 'disp' represents the maximum displacement allowed.

The above-mentioned optimization problem will be coded and solved using Octopus which is a plug-in for Grasshopper that introduces the multiple fitness values (multi-objective) to the optimization process. It is based on the SPEA-2 multi-objective evolutionary algorithm (strength-pareto evolutionary algorithm for multi-objective optimization – core algorithm). (19)

Results

The optimization problem is applied to the entire structure. The results – after 2000 generations – shows the results, summarized in Table 5. Furthermore, the above mentioned constraints are satisfied. The geometry obtained after optimization (Fig. 20)shows the characteristics / dimensions in Table 6.

Furthermore, the radius - after optimization - for the transversal sections of the tree -column are: $R_0 = 100cm$, $R_1 : 70cm$, height on z axis: $300cm$, $R_2 : 400cm$, height on z axis:$450cm$

However, the result of the optimization cannot be considered as unique: multi-objective optimization has produced a set of solutions that fit the initial requirements. Some of them have a higher value when defining better the design intention of the engineer. This group is generally called Trade-off or Pareto - front.

Tree-column structure: Test Case 2

The optimization problem concerning the elliptical structure is formulated as follow:

(Eq. 21)

$$(f_1(x), f_2(x)) \tag{21}$$

in which (Eq. 21)

- $f_1(x)$ represents mass
- $f_2(x)$ presents the total displacement of the structure.

The design variables are defined as follows:

(Eq. 30)

$$F_1, F_2 \in R_0 = \left[\hat{\imath} = (0, 2)\, , \hat{\jmath} = (0, 2)\, , \hat{k} = (0)\right]; \tag{22}$$

(Eq. 30)

$$F_1, F_2 \in R_1 = \left[\hat{\imath} = (0, 5)\, , \hat{\jmath} = (0, 5)\, , \hat{k} = (0, 3)\right]; \tag{23}$$

(Eq. 30)

$$F_1, F_2 \in R_2 = \left[\hat{\imath} = (0, 7)\, , \hat{\jmath} = (0, 7)\, , \hat{k} = (2, 5)\right] \tag{24}$$

where F_1 and F_2 represents the foci of the ellipse on plane x, y, z.

(Eq. 30)

$$\emptyset_0 \in [13, 15]\ (cm)\ \ \emptyset_1 \in [11, 13]\ (cm) \tag{25}$$

in which (Eq. 30) Ø represents the diameter of the cross-sections belonging to the beams and columns.

(Eq. 30)

$$T_0 \in [0.8, 4]\ (cm)\ \ T_1 \in [0.8, 4]\ (cm)\ \ T_2 \in [0, 10]\ (cm) \tag{26}$$

where T identifies the thickness of the cross-sections.

Subject to

(Eq. 27)

$$h_1 < h_2 \; R_1 < R_2 \; disp \leq \frac{1}{200}L \tag{27}$$

in which 'disp' represents the maximum displacement allowed.

Results Test Case 2

The results – after 2000 generations – shows the results summarized in Table 7, 8.

The geometry obtained after optimization shows the following characteristics (Fig. 21) :

(Eq. 30)

$$F_1, F_2 \in R_0 = \left[\hat{\imath} = 0.21, \hat{\jmath} = 0.41, \hat{k} = 0\right]; \tag{28}$$

(Eq. 30)

$$F_1, F_2 \in R_1 = \left[\hat{\imath} = 1.55, \hat{\jmath} = 1.27, \hat{k} = 3\right] \tag{29}$$

(Eq. 30)

$$F_1, F_2 \in R_2 = \left[\hat{\imath} = \hat{\jmath} = 2, \hat{k} = 4\right] \tag{30}$$

From the geometry description above, the transversal sections used at a height of less than 3 meters corresponds to an ellipse, over 3 meters corresponds to a circular section since:

If

(Eq. 31):

$$\hat{\imath} = \hat{\jmath} \rightarrow \; (x - x_c)^2 + (y - y_c)^2 = r^2 \; . \tag{31}$$

If

(Eq. 32):

$$\hat{\imath} \neq \hat{\jmath} \rightarrow \; \sqrt{(x - x_1)^2 + (y - y_1)^2} + \sqrt{(x - x_2)^2 + (y - y_2)^2} = 2a \; . \tag{32}$$

The entire structure after optimization consists of 4 vertical supports (columns) and 5 transverse elements (beams), including the bottom element of the structure. The interesting result concerns the structural morphology: the transversal elements act as an internal connection rather than being positioned in the centerline of the mesh panel. This configuration makes the structure more rigid allowing the external geometry to have free shapes. As the vertical supports increase, the beams will also increase by assuming the configuration of the external mesh panel in a directly proportional way, penalizing the total weight. Also in this case, the solution is not unique, so there will be different morphological solutions capable of satisfying the constraints imposed in the optimization process, whose mass and displacement will be less than the initial configuration (Pareto-front, Fig.22).

FUNCTIONAL MORPHOLOGY: COMPARISON

The Table 9 shows the optimization results for both structures.

The interesting fact is represented by the clear difference in weight between the two structures: the reason is due to the distribution of material concerning the tubular cross-sections of the bamboo poles, the thickness of the connection mesh between the structural elements, the total length of the structure and, most important fact, the morphology. In fact, evaluating the length of both structures following the quadrangular conformation (Test Case 1):

(Eq. 34):

$$1200 : 1639 = 690 : x \tag{33}$$

it will be obtained that the second test-case with a total length of 690 cm would weigh 942 kg compared to the current 126 kg (after optimization).

If the length of the two structures is evaluated according to the ellipsoidal morphology (Test Case 2):

(Eq. 34):

$$1200 : x = 690 : 126 \tag{34}$$

then it will be obtained that the first structure with a total length of 1200 cm would weigh 219 Kg compared to the current 1200 Kg (after optimization).

From the previous observations, it is noticed how the ellipsoidal conformation is more performing than the quadrangular one. However, the structural conformation of the two morphologies after optimization must be observed(Fig. 23):

the solver, despite having at his disposal a wide domain relating to geometric variables, has equaled the morphology of the two structures going back to the family of quadrangular polygons; this means that, in general, structures with polygonal shapes have better structural performance than circular structures despite the result of optimization by evaluating the free-form mesh.

CONCLUSION

Requirements like symmetry and simplicity in the choice of the aesthetic shape are of fundamental importance for the design of a framed structure. In this scientific contribution, emphasize was given to the notion that design constitutes a common responsibility between the choices of an aesthetic nature and those of a purely structural nature. Unfortunately, this awareness is rather rare in design practice and there is often a dichotomy between purely aesthetic and strictly structural choices. After the study of these two dendriform structures the conclusion is that the morphology itself is the foundations for good structural behavior. If at the moment of conceptual design certain basic requirements are not guaranteed, the entire structural design - considered detached from the aesthetic design - cannot in any way optimize performance but only try to limit the damages deriving from wrong morphological conception. The close link between problems of morphology and those of engineering requires synergic work from the moment in which the idea of the design project is born without distinguishing between element conceived by the architect's idea and the one created for purely structural needs. This type of methodology turns out to be a practical application to have control over structural safety and at the same time over the morphology of architecture. The geometry which was implemented by Grasshopper® software, with the aid of Karamba3D for FEA simulation and the 'Octopus' algorithm (MOEA) solve the optimization problem and delivers models according to design parameters. This study consisted in searching for the optimal morphological structure by minimizing the displacement and the mass, imposing specific constraints. It is of no doubt that bamboo is a material which can give a big range of designs based on parametric design and can be used in contemporary architecture to cover structural and aesthetic needs. It is a very promising material for excellent design approaches and gives a new direction to sustainable architecture.

List of Tables

TABLE 1. Physical and Mechanical characteristics Bamboo Guadua Angustifolia Kunth (Luna et al.)

Bamboo Guadua Angustifolia (1)	Values (2)
Density (dry)	500 - 800 Kg/m3
Culm height	6-25 m
Internodal space	250-500mm
Diameter	50-200mm
Modulus of elasticity E_0.5	7000-17 000N/mm2
Wall thickness E_0.5	10% of outside diameter
Bending	15 Mpa
Tension	18 Mpa
Shear	1.2 Mpa
Compressione parallel to fibres	14 Mpa
Compression perpendicular to axis	1.4 Mpa
Poisson's ratio	0.5

TABLE 2. Standard dimensions of structural bamboo poles

	Columns (1)	Beams (2)	Mesh Panel (3)
Ø (diameter – cm)	13-15	11-13	
Wall Thickness (cm)	0.8-4	0.8-4	0.0-0.10
Maximum pole length (cm)	590	590	

TABLE 3. FEA Results Test Case 1

	Mass (Kg) (1)	Displacement(cm) (2)	Compression(kN) (3)	Tension (kN) (4)	Moment(kNm) (5)	Shear(kN) (6)
Total	2404	0.87	0.42	0.27	0.06	0.06

TABLE 4. FEA Results and Shape Comparison

	Mass (Kg) (1)	Displacement(cm) (2)	Compression(kN) (3)	Tension (kN) (4)	Moment(kNm) (5)	Shear(kN) (6)
Test_1	2404	0.87	0.42	0.27	0.06	0.06
Test_2	2380	0.93	0.52	0.29	0.12	0.06

TABLE 5. Optimization Results Test Case 1

	Mass (Kg) (1)	Displacement(cm) (2)	Compression(kN) (3)	Tension (kN) (4)	Moment(kNm) (5)	Shear(kN (6)
Before Optimization	2404	0.9	0.42	0.27	0.06	0.06
After Optimization	1639	0.6	0.54	0.22	0.044	0.48

TABLE 6. Optimization Results Test Case 1, Design Variables

	Columns (1)	Beams (2)	Mesh Panel (3)
Ø (diameter – cm)	13.00	13.00	
Wall Thickness (cm)	3.90	0.80	6.00
Maximum pole length (cm)	590	590	

TABLE 7. Optimization Results Test Case 2

	Mass (Kg) (1)	Displacement(cm) (2)	Compression(kN) (3)	Tension (kN) (4)	Moment(kNm) (5)	Shear(kN) (6)
Before Optimization	2380	0.93	0.52	0.29	0.12	0.06
After Optimization	126	0.07	0.6	0.03	0.02	0.04

TABLE 8. Optimization Results Test Case 2, Design Variables

	Columns (1)	Beams (2)	Mesh Panel (3)
Ø (diameter – cm)	15.00	11.00	
Wall Thickness (cm)	1.90	0.8	0.51
Maximum pole length (cm)	590	590	

TABLE 9. Optimization Results - Comparison

	c. Lenght (cm) (1)	Mass (Kg) (2)	Displacement(cm) (3)	Compression(kN) (4)	Tension (kN) (5)	Moment(kNm) (6)	Shear(k
Test1	1200	1639	0.60	0.54	0.22	0.044	0.48
Test2	690	126	0.07	0.60	0.03	0.02	0.04

List of Figures

Fig. 1. Bamboo/Earthquake-resistant prototype building, Alhué,Chile, 2001 (5) A reference here (**?**).

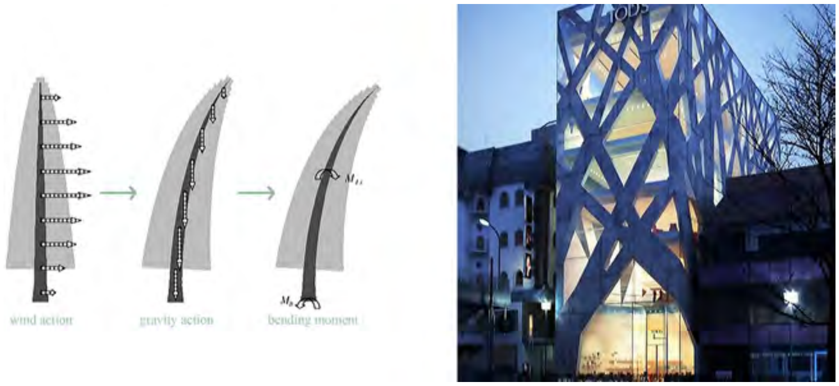


Fig. 2. (a) Schematic forces acting on the tree shape (Ancelin et al., 2004); (b) TOD'S Omotesando Building. A reference here (**?**; **?**; **?**).

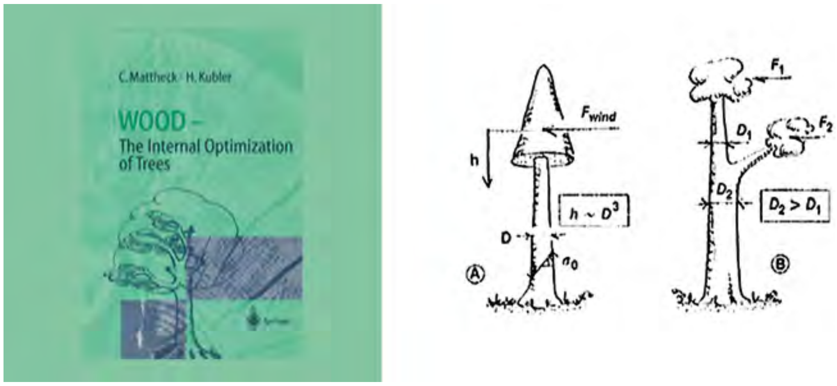


Fig. 3. (a) Book cover (references) of "Wood - The internal Optimization of Trees"; (b)) tapering of tree to achieve constant stress distribution. A reference here (**?**; **?**).

Fig. 4. (a) Greece - Corinth: [Possibly] Temple of Octavia; (b) Exterior view of Gardens by the Bay, Singapore. A reference here (**?**).

Fig. 5. (a) Victor Horta Maison et Atelier Horta, Bruxelles, Belgio, 1898-1900; (b) Abbesses metrò entrance, Paris A reference here (**?**).

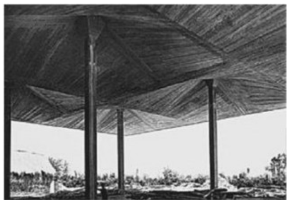


Fig. 6. Mushroom inverted umbrella structures, known as Baroni'sTrees, designed by GiorgioBaroni in 1938. A reference here (**?**).

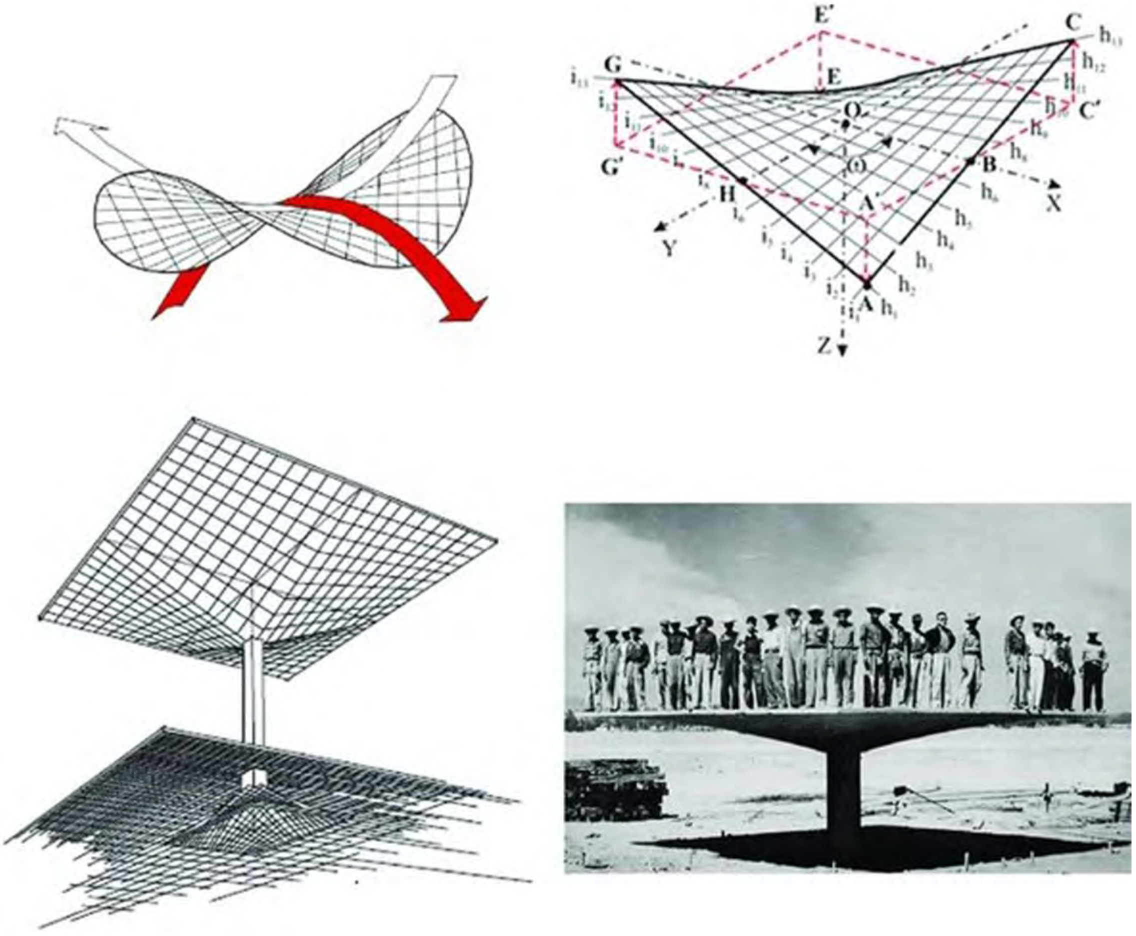


Fig. 7. Felix Candelashypars and umbrella column shell; (a) hyperbolic paraboloid with curved edges, (b) hyperbolic paraboloid with straight edges, (c) prototypical ‘umbrella’ structure showing foundation, which is also an umbrella form, and (d) second experimtal umbrella in Valejjo, Mexico, 1953. A reference here (**?**; **?**).

Fig. 8. (a) Frei Ottos hanging models of branching system, (b) Fractal Branching in Agri Chapel, Yu Momoeda, 2018 A reference here (**?**; **?**).

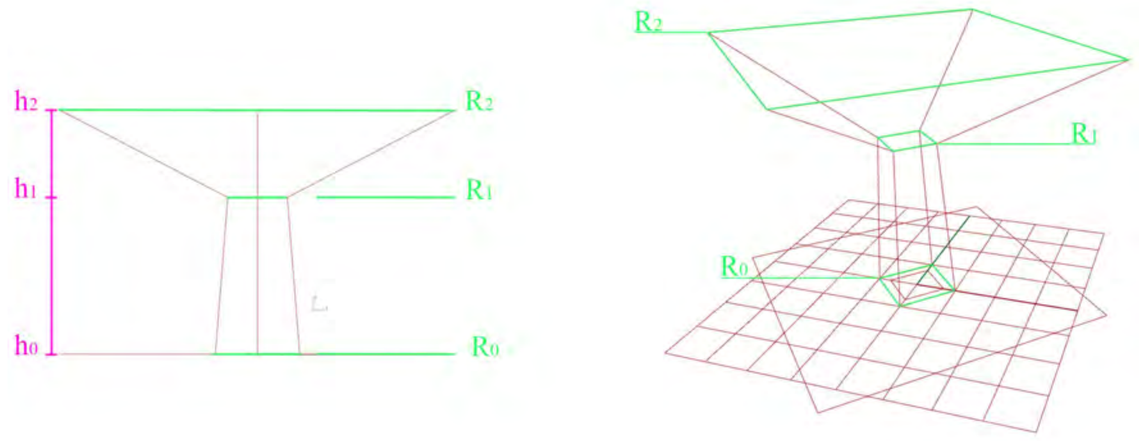


Fig. 9. (a) Design domain of variables (height and radius) ;(b) Definition of the geometry of the tree-column structure.

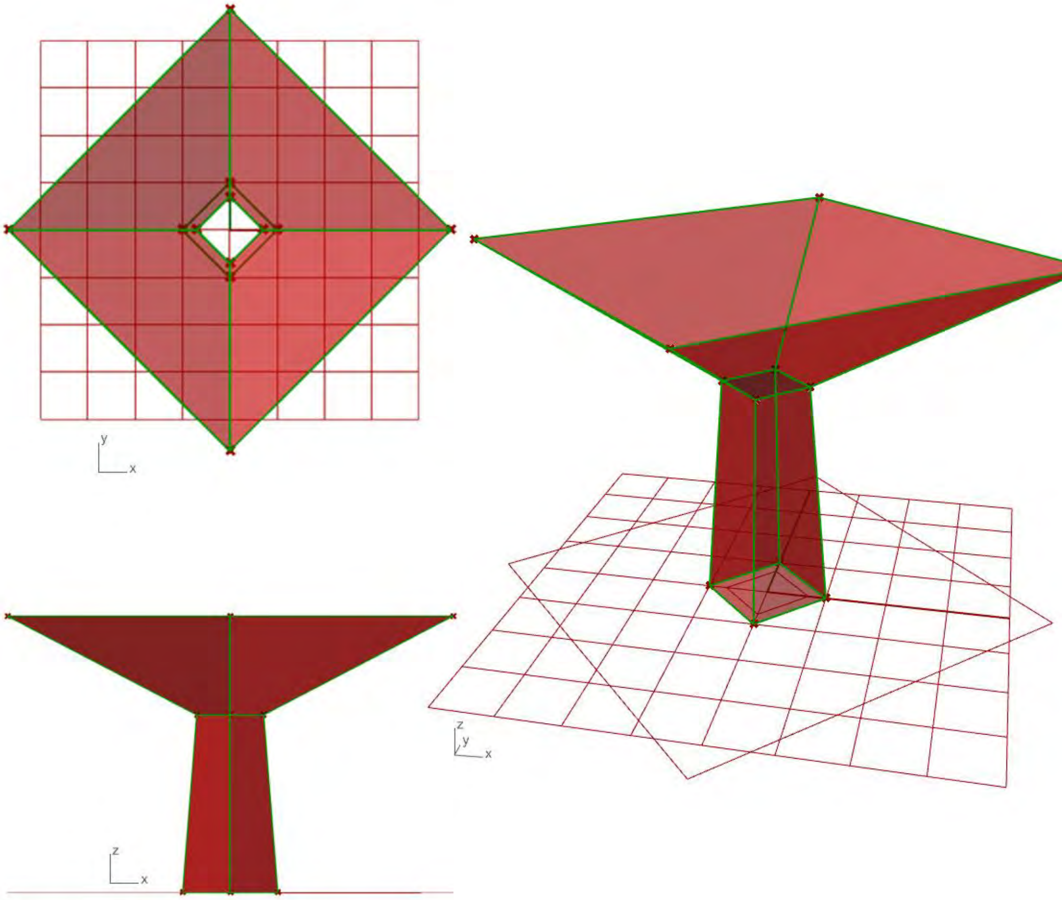


Fig. 10. Creation of polysurface.

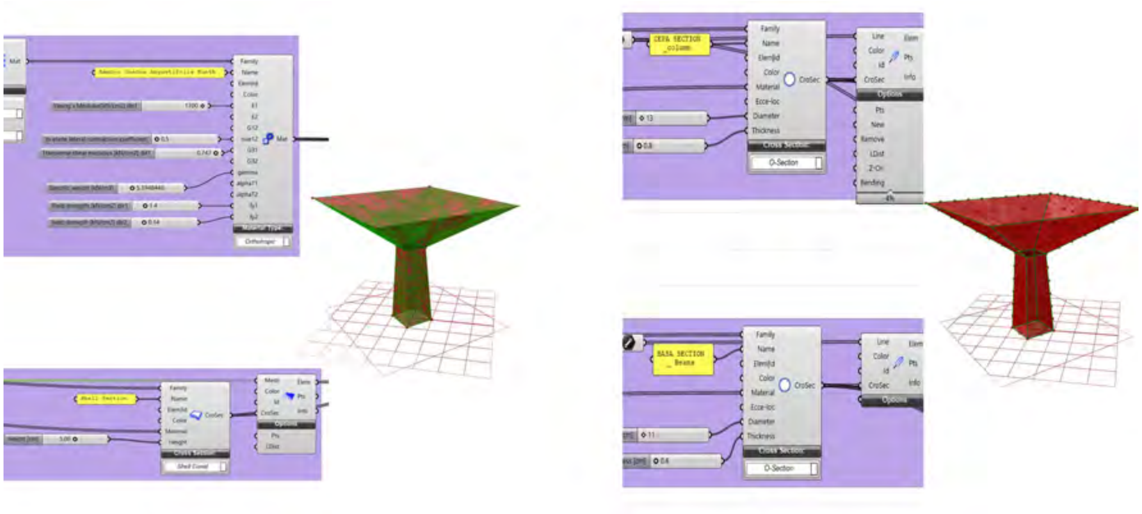
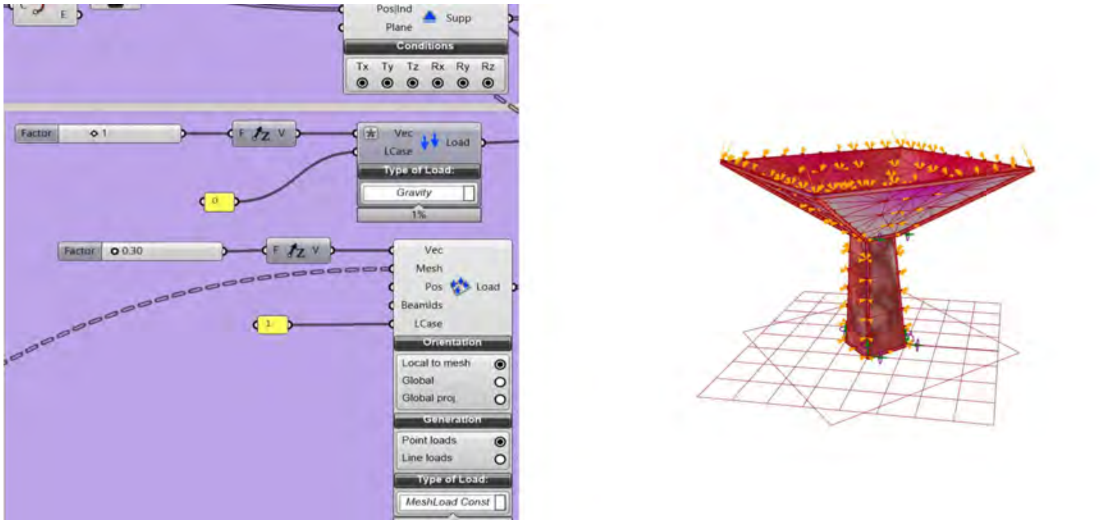


Fig. 11. (a) Coding of Bamboo material and Shell Constant Cross-section (columns); (b) Cross-section Horizontal elements (beams) and Cross Section Vertical elements.



Factor 1

Type of Load: Gravity

1%

Factor 0.30

Orientation: Local to mesh ● Global ○ Global proj ○

Generation: Point loads ● Line loads ○

Type of Load: MeshLoad Const

Fig. 12. Support and Load Case.

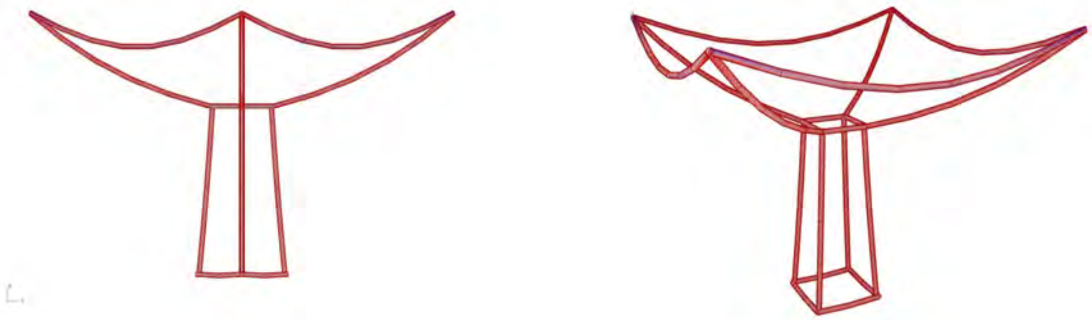
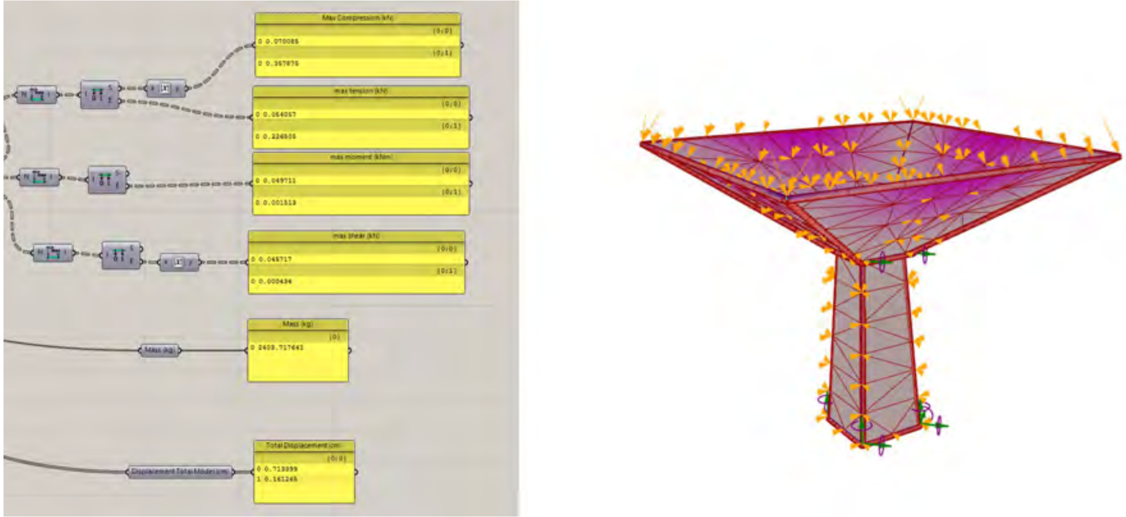


Fig. 13. Model under deformation.



```
Max Compression (kN)
{0;0}
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{0;1}
0 0.357875

max tension (kN)
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{0;1}
0 0.224505

max moment (kNm)
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{0;1}
0 0.001513

max shear (kN)
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{0;1}
0 0.000434

Mass (kg)
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Total Displacement (cm)
{0;0}
0 0.713399
1 0.161265
```

Fig. 14. FEA analysis results.

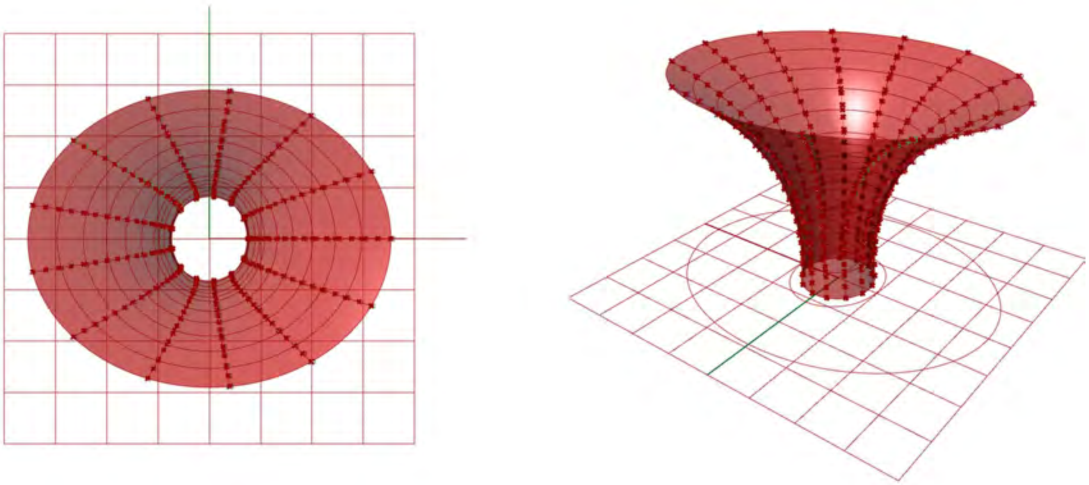


Fig. 15. Implementation of Elliptical Geometry.

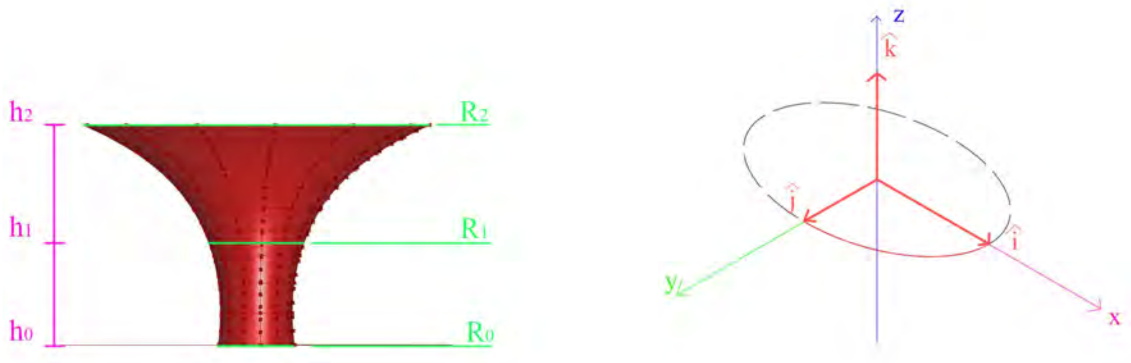


Fig. 16. (a) Design domain of variables (height and radius) ;(b) Geometric Constrains in the space $\mathbb{R}^3$ (x, y, z).

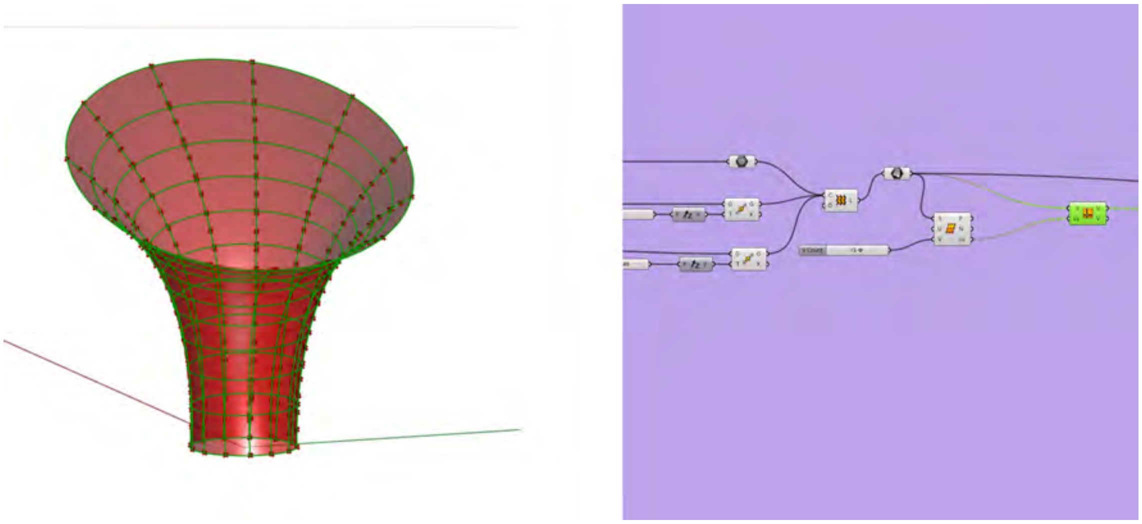
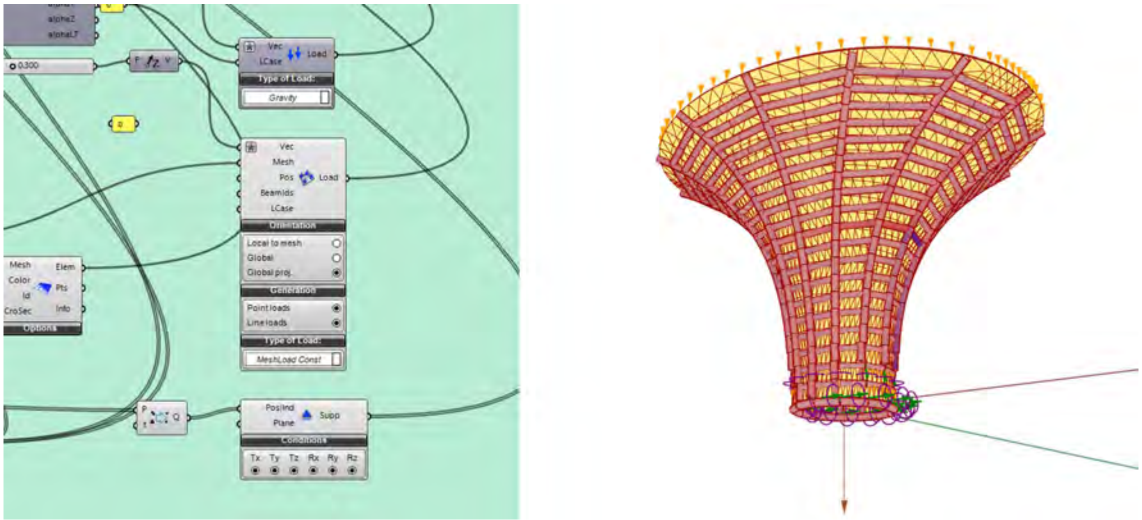


Fig. 17. Isolines in v and u direction.



Type of Load:
Gravity

Orientation
Local to mesh ○
Global ○
Global proj. ●

Generation
Point loads ●
Line loads ●

Type of Load:
MeshLoad Const

Conditions
Tx ● Ty ● Tz ● Rx ● Ry ● Rz ●

Fig. 18. Load and Support implementation – gh code.

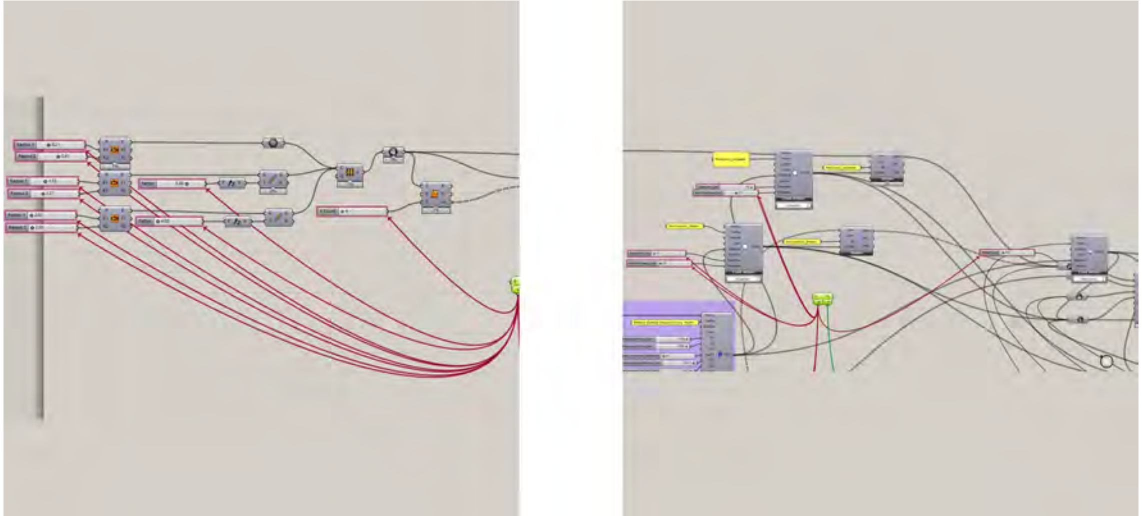


Fig. 19. Design Variables $_{V}isualScriptinGhdefinition$.

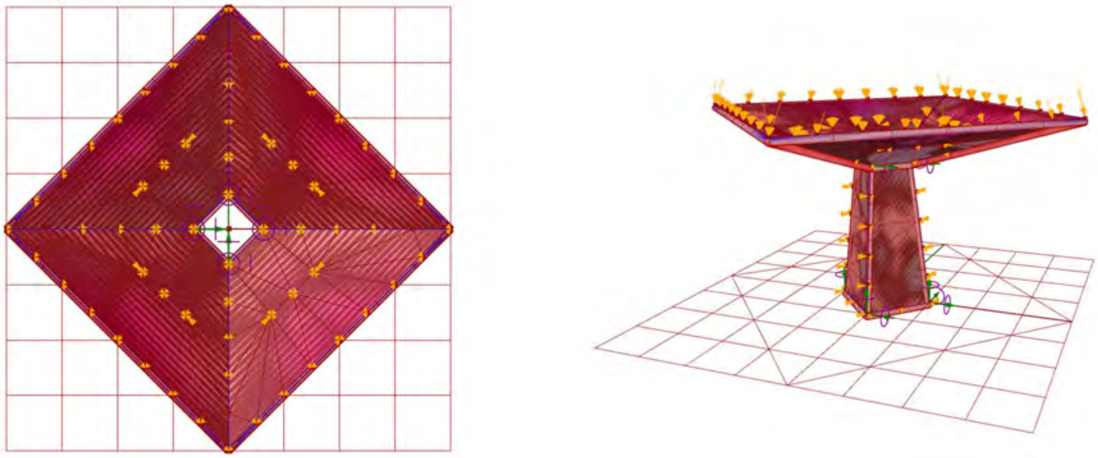


Fig. 20. Optimized morphology, Test Case 1.

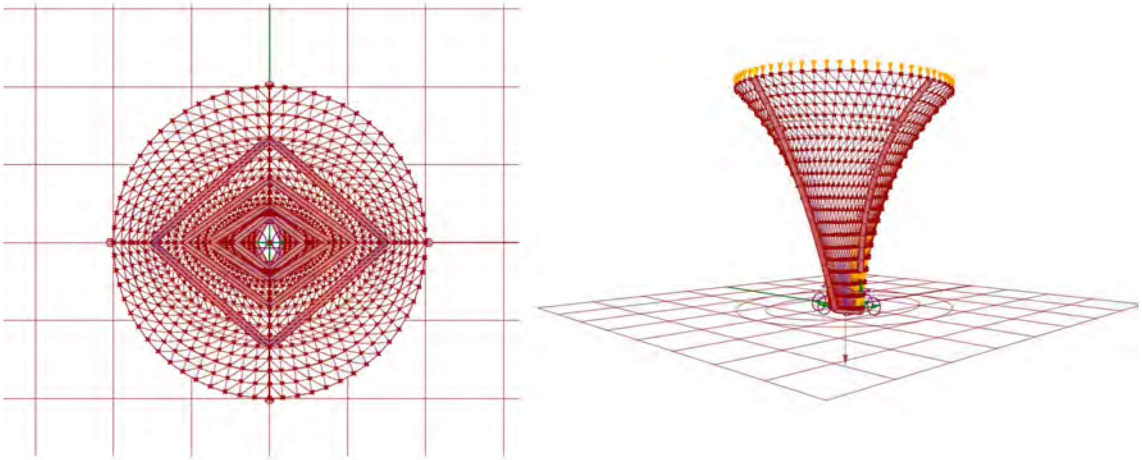
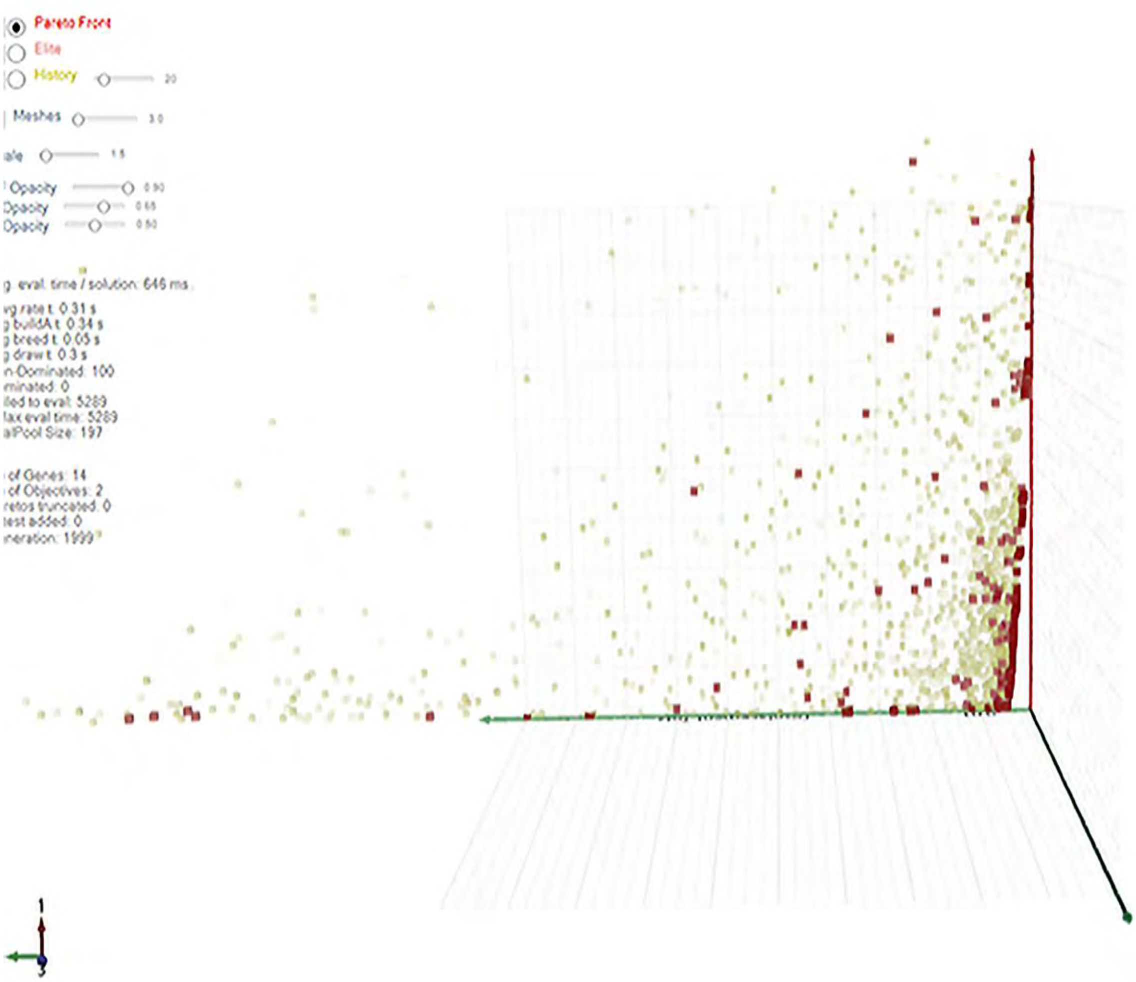


Fig. 21. Optimized morphology, Test Case 2.



```
g. eval. time / solution: 646 ms

vg rate t: 0.31 s
g buildA t: 0.34 s
g breed t: 0.05 s
g draw t: 0.3 s
n-Dominated: 100
minated: 0
lled to eval: 5289
lax eval time: 5289
alPool Size: 197

of Genes: 14
of Objectives: 2
retos truncated: 0
test added: 0
neration: 1999
```

Fig. 22. Pareto-front $_{e}ndoptimization.$

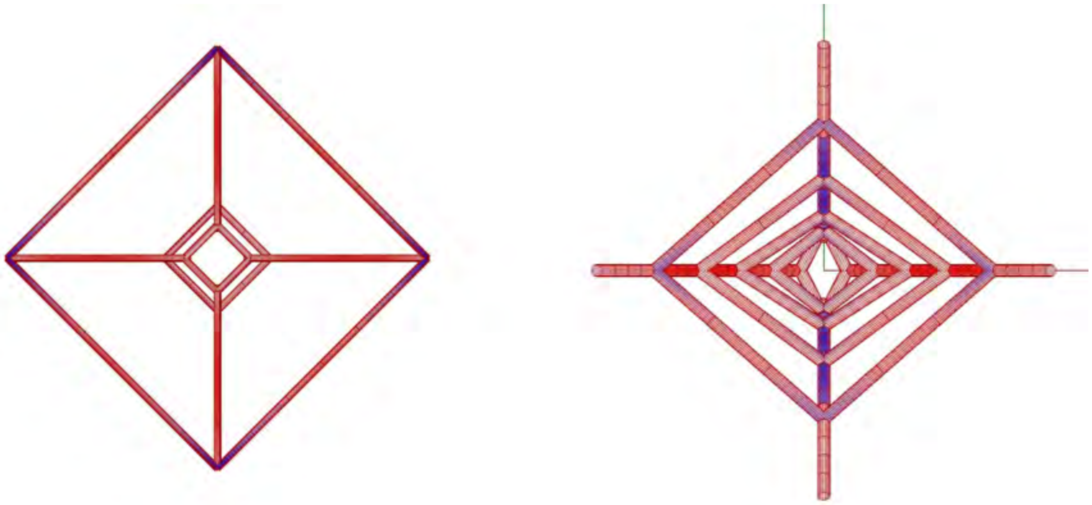


Fig. 23. Support Comparison.