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Original Research Article

Analyzing and Modeling the Computational Vascular Structure in Plants' Leaves as a Structural Building Envelope and a Comparative Comparison with Common Structures*

Morteza Khorsandnikoo[1], Saeed Haghir[2**], Mohammadreza Matini[3]

1. Ph.D. Candidate in Architecture, Faculty of Fine Arts, University of Tehran, Iran.
2. Associate Professor of Architecture, Faculty of Fine Arts, University of Tehran, Iran.
3. Assistant Professor of Architecture, Faculty of Architecture and Urban planning, Art University, Tehran, Iran.

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Abstract

Problem statement: Natural structures have been developed over the centuries to obtain acceptable solutions to external factors. During this process, only the most efficient natural forms have survived for millions of years. One of these natural structures is the vascular structure in plants' leaves, which is discussed in the present article. Undoubtedly, the plants' structure follows principles similar to that of human-made engineering, but with more complex and precise technology. The extreme complexity behind the natural elements sometimes make hard to understand the behavior of them. But nowadays, by using computer analysis and modeling abilities, we can understand the natural complex structures and attempt to simplify and extract their algorithmic structure. In this research, we have carried out a computational analysis of vascular structure in plants' leaves, in order to obtain a plugin to design structural building envelope s inspired by nature. Therefore, according to structural sustainability in the leaves, the present research seeks to answer these questions; can the structure, which a leaf conforms to, be used in a human-made structure on a large scale? Compared to common structures, would it provide more favorable conditions? On the other hand, does the structure, designed based on the vascular structure in plants' leaves, have more loading capability than the common structures?

Research objective: The purpose of this research is to design a different structure, inspired by the vascular structure in plants' leaves, which will help improve the structural function towards increasing structural loading capability, and also achievement of visual attraction in beam and column systems is another goal in this paper by avoiding orthogonal structures.

Research method: This research is descriptive-analytic, and the data are gathered and analyzed through documentology.

Conclusion: The designed plugins, using plants' vascular structure, enable users to create a vast spectrum of cover construction in different sizes by altering the devised parameters. This ability to make changes allows the architect to create more complex forms, which would be impossible without using these plugins, due to complexity in shape or the design's structure.

Keywords: *Growth algorithm, Computational design, Plants vascular structure, Plugin, Open and closed structures.*

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** Corresponding author: saeed.haghir@ut.ac.ir, +989124434927

Introduction and problem statement

Ever since humans first chose a cave as their place of residence, and now that they are gradually moving toward smart houses, they look at their surrounding nature as a source of inspiration. Humans, as their function gets closer to nature, guarantee their survival more because natural structures have evolved through centuries to achieve acceptable solutions against external factors. During this process, the most effective and strongest natural forms survived for millions of years. Plants, as a natural element, have been the source of inspiration for many architects throughout history. Undoubtedly, the plants' structure follows principles similar to that of human-made engineering, but with more complex and precise technology. The extreme complexity behind the natural elements sometimes make hard to understand the behavior of them. But nowadays, by using computer analysis and modeling abilities, we can understand the natural complex structures and attempt to simplify and extract their algorithmic structure. The necessity of extracting the algorithm of natural structures through computer software and turning them into plugins that can be accessible for everyone is a major factor to complete software systems. This can provide the possibility to expand, configure, personalize, and adapt these systems. Among these, vascular structures in leaves, which are used both as nutrients paths in the plants and as a structural factor, can be a suitable topic for research for the structural feasibility study of these structures as artificial cover constructions. Therefore, in this research, after gathering theoretical foundations and evaluating and introducing previous works, the existing vascular structure in the plants' leaves, as a cover construction, was turned into computational data to create a labile model in the C# programming software environment. By calculating and reasoning the difference between previously used models in architecture, the newly introduced method in this article is a generative plugin in the Grasshopper environment to help architects based on plant vessels algorithm, as a beam and column system with open and closed patterns in covering different surfaces. Eventually, the obtained model was compared with other common structures, using finite element analysis (FEA) and through the Karamba plugin.

Also, this research attempts to achieve visual attraction in the beam and column systems, by avoiding orthogonal structures and organizing a space for users' more effective use to get closer to nature. In fact, the purpose of this research is to design a different structure, inspired by vascular structures in plants' leaves to increase humans' interaction with nature and improve the structural function to increase the structural loading capability. Now, given the existing structural sustainability in the leaves, the question arises that whether the structure, which a leaf conforms to, can be used in a human-made structure on a large scale, and comparing to common structures, would it provide more favorable conditions? On the other hand, does the structure, designed based on the vascular structure in plants' leaves, have more loading capacity than the common structures?

Research background

Utilizing natural paradigms, rules, and systems governing them has a very long background, has improved, and corrected itself through time. With a more professional look at the topic, since the present research is formed based on computational modeling of vascular structures in plants' leaves, some of these theories are mentioned in table 1.

Some of the mentioned models lead to open patterns and some to closed patterns. The mentioned models and other combined models are used as the basis for beginning advanced modeling and various articles with different approaches have attempted to solve different problems. In an article under the title "Modeling based on growth in pressure structures", "Christopher Klemmt" examines the vascular structure of the "Victoria SPP" plant's leaves by examining the model proposed in the "Calgary University", and by simulating this vascular system and comparing it with concrete slab system, concluded that the vascular system has higher loading capability and lower shape liability than the concrete slab structure (Klemmt, 2014).

"Sabri Gokmen" has used the vascular structure in plants' leaves to design a building's façade. This shape simulation, according to the author, has the advantage that it gives architects the freedom to access various structures in terms of shape and form, and before construction, they can test an infinite number of natural forms and choose from them; therefore, achieve a dynamic structure (Gokmen, 2013).

"Martin Tamke" believes that structures inspired by plants' growth are more compatible with the incoming forces. In his research under the title "The Rise", he studies the plants' functional structure. The achieved structure, like plants, is capable of understanding and dynamic compatibility with the environment and even like this natural structure, can grow, using smart materials and precise computational simulations. His intended structure can replace traditional constant structures in the future (Tamke, Stasuik & Thomsen, 2013).

In addition to the articles mentioned above, also other topics inspired by plants' structures have been studied by researchers. For example, sustainability (Pawlyn, 2011), Creating compatible environment and materials (Hensel, Menges & Weinstock, 2006), Structural optimization, and exploitation (Waggoner & Kestner, 2010; Li, Wang & Gandomi, 2011). Studying materials for structural engineering (Barthelat, 2007) and many other fields are other examples.

The mentioned research have weaknesses because, on the one hand, they are not placed in the field of architecture and are solely concerned with the existing algorithm in the vascular structure in the plants' leaves, and on the other hand, the topics mentioned in the field of architecture are not usable by everyone and cannot be expanded by ordinary users. In order to fulfill this need and make these algorithms accessible and easily usable by architecture researchers, based on previous examinations in the field of existing vessels in the plants' leaves and using C# programming language, a plugin was designed in the Grasshopper

Table 1. Computational growth models. Source: Authors, based on Dimitrov & Zucker, 2006; Sachs, 2003; Fujita & Mochizuki, 2006; Rodkaew, Siripant, Lursinsap & Chongstitvatana, 2002; Raven, 2019; Kenrick & Crane, 1997.

Title of Model	Details
Meinhardt model	Auxin is created in some parts of a leaf and released toward veins and remove from them. Distribution and concentration of auxins guide new veins toward the spaces which veins concentration is lack.
Vasculature formation	This hypothesis is based on the theory that the transition parameter is related to flow. Feedback loop resulted from transition and flow character, make flow canals between auxin sources and veins and this canals transformed to new veins.
Dimitrov model	Veins, flow based on Auxin release toward the maximum source
Vasculature formation	This model is proposed by Gotelib. In this model, leaf growth results in the vacant area between veins and lets the auxin new sources place in these vacant spaces. New veins are formed by connecting to the nearest vein and, in some models to all veins which are in specific distance.
Rodkaew model	Starts with some particles distributed in leaf. These particles move toward a vacant area down the leaf. If the distance is less than the specified limit, they attract each other.
Peter H. Raven model	Vascular pattern forms from the transition path. These models result in open patterns and some close patterns.
Peter Crane	Leaf growth has an important role in the biomechanical model proposed by peter crane. This model considers a Hypothetical similarity between vascular pattern formation and cracks in materials when stretch. Although the researcher has used a physical model for simulation, the models created by software can be used.

environment, which enables the designers and architects to create various covers in different sizes and intends densities based on the amount of loading. Using this plugin is easy and can also be expanded by the users.

Theoretical foundations

Whatever exists in nature has continuously tried to be compatible with the environment, survive, grow, reproduce, and achieve sustainability and optimization at different times (Benyus, 1997). Since human life is a part of this nature, humans have always sought the answer to their questions in nature, and with the advancement of science, especially computer, have expanded the range of exploiting nature and its answers to their questions day after day (Park & Lee, 2016). Increasing the visual and structural quality of artificial covers has always been one of the major concerns among architects. Fortunately, nature is very rich in this field and provides numerous examples, which must be examined thoroughly and extract that, which is proper. Plant vessels are one of the indefinite examples existing in nature, which play an important structural role in the leaves' structure. By extracting the algorithmic structure in the plants' leaves' vessels, in this research, we have attempted to design a plugin, which architects can utilize, in order to strengthen their structures by altering the existing parameters in the plugin.

- **Vascular structures in the plants' leaves**

Vessels play a vital role in carrying nutrients in the plant, and also a structural and esthetic role. This research focuses on the existing vessels in the plants' leaves. In order to understand this structure, among the existing theories, the "canalization" theory, which is based on the movements of the plant hormone "Auxin" (Sachs, 2003; Sieburth, 1999) and is more credible than other theories, is used in the present research. This theory will be briefly explained in the following.

- **The process of growth in the leaf and canalization theory**

The leaf's growth and the development of its vascular system take place in two specific phases: the primary phase, cellular growth, and the second phase, cellular development. The primary vessels, which are thicker, are developed in the cellular growth phase, and the secondary vessels, which are less thick, are developed in the cellular development phase and by a hormone, known as Auxin, in the plants' leaves (Sack & Scoffoni, 2013; Blonder, et al., 2018).

The vascular pattern depends on the plant's type and shape. The leaves of monocots usually have main almost parallel vessels, which are compatible with the long and wide shape of the plant's leaves (Sack & Scoffoni, 2013). Dicots with flat leaves usually have vessels with a symmetric formation with the main vessel, which diverges from the petiole and stretches to the top of the leaf. Dicots with finger leaves usually have multiple main vessels, from which the auxiliary vessels diverge radially (Runions et al., 2005) (Fig. 1).

These vessels may have free ends, in which case they create an open pattern, and they may be connected to each other and create a closed chain-like pattern (Aloni, Schwalm, Langhans & Ullrich, 2003).

- **Canalization theory**

The most accepted theory, concerning the formation of vascular patterns, is the "canalization" theory, which was proposed by Sachs (Sachs, 2003). According to this theory, the vascular pattern begins with a signal that disperses along with the leaf, and other vessels connect to each other. A part of this signal has a plant hormone, known as "Auxin" (Sieburth, 1999). "Auxin" stems from the leaf and moves toward existing vessels, and is carried to the stem and bottom of the plant. During this process, "Auxin" is canalized to smaller paths, like what happens at the streambed of a river. During Auxin's movement, new vessels are formed by these canals. Experimental observations show that Auxin sources are disjointed. The canalization theory has some limitations due to the difficulty of measuring the accuracy of Auxin (Gokmen, 2013) (Fig. 2).

- **Creating the leaf's paradigm**

As previously mentioned, vessels have two types of open and closed patterns. Both of them will be explained here.

- Open vascular patterns

In the formation of open patterns, first, the placement of Auxin sources are important. Auxin sources are located at locations further from the "kill distance" of the set of nodes and sources. The kill distance is an area where the Auxin sources will be removed when the nodes enter that area. The location of sources is chosen randomly. In such a way that a random set of points are spread in the intended range as sources, and these new points are evaluated in terms of kill distance, relative to each other, and if the intended distance is not passed, they will be chosen as newly accepted members, otherwise, they will be removed. The existing sources will remain in the game as long as they do not get closed to the produced vessels (pass the kill distance). This process is briefly shown in figure 3 (Runions et al., 2005).

The most important parameter in the density of vascular structures is determining the kill distance. By reducing the amount of which, density in vascular structures increases and more vessels are produced; therefore, leaves' sustainability increases. Another effective parameter in the vessels' density is the number of Auxin sources, which are randomly added to plants' beds. By increasing these sources and reducing the kill distance, too, density increases.

- Closed vascular patterns

Closed vascular patterns are the same algorithm used in open patterns. The difference is that there may be more than one vessel, growing towards a mutual source. Such occurs in nature when multiple vessels are close to one source and at the same time are far enough from each other. This concept can be formulated with the "relative neighbor" effect (Runions, 2008).

If a point like "n" is closer to the source (point "s") than to another point like "v", then point "n" is considered the relative neighbor of point "s", but if a point like "u" is closer to "v", rather than "s", then point "u" is not the relative neighbor of point "s" (ibid.). This concept is shown in figure 4.

With respect to the research conducted at Calgary University on open and closed patterns and canalization theory, using C# software and grasshopper plugin in the Rhino environment, achieved a plugin that allows users to easily simulate

Fig. 1. The vascular formation in monocots, dicots, and finger dicots, respectively from left to right. Source: www.pinterest.com

the existing vascular algorithms in the plants' leaves and compare them with common structures, in terms of loading capability. In order to simplify and obtain a better result, the first design is considered constant. In fact, it is assumed that increasing Auxins and nodes are not effective on the leaves' growth and only help to complete and strengthen the plants' bed; this plugin is explained in the following.

- **Plugin description**

Every software system includes three phases; definition, development, and maintenance. The definition phase is the answer to the questions that define the expectations of this system. This phase consists of receiving information from users, the information processing and the output giving to the users. In the development phase, software design and programming will be done. In this phase, the proper algorithm must be used, and eventually, the maintenance phase, which is usually applied after marketing the system .In this phase compatibility and future development must take into consideration.

Since the research topic is concerned with the system before marketing; therefore, the definition and development phases must be discussed.

In order to achieve the intended purpose, a range of intervened fields and a set of inputs and outputs must be defined. These parameters must be so accurate and have a high approximation to the expected result, and also the parameters shouldn't slow down the system that becomes inoperative for the users. The complexity and the number of parameters must be so that, firstly, the user himself cannot guess the answer without the system, and secondly, the number of parameters must not confuse the users. The method and algorithm governing the system must be thoroughly examined, and only get into the architecture field with a proper understanding of the algorithm and the abstraction of that mechanism.

According to the examination of the plants' vessels' structure and understanding their complexity, this research attempted to simplify and visualize this structure, and given this topic, inputs and outputs are taken into consideration, which are discussed in the following (Figs. 5 & 6).

The primary shape of the ceiling has no limitations in terms of measurements and form and is determined based on the designer's needs. It is mentioned as the plugin's input (Figs. 5-a & 6-a).

The number of Auxin sources is determined by the user. The bigger the load put on the structure, the higher the number of Auxins will be chosen. A bigger number of Auxins results in a more dense vascular structure and more members, which of course, in turn, makes the process of processing in the computer heavier. It must be noted that in this plugin, the Auxin sources are added to the system in one stage (Figs. 5-b & 6-b).

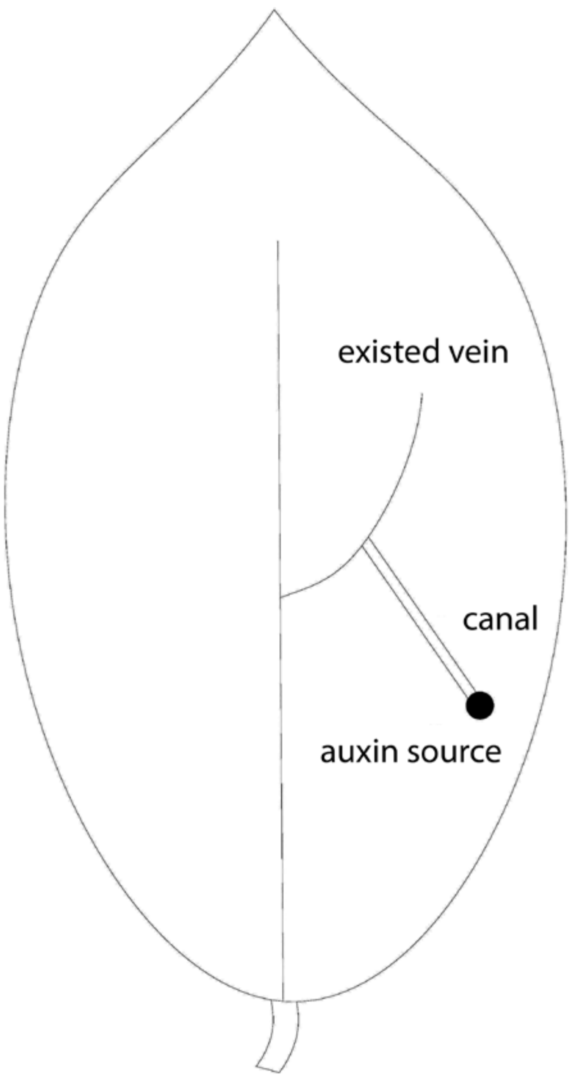
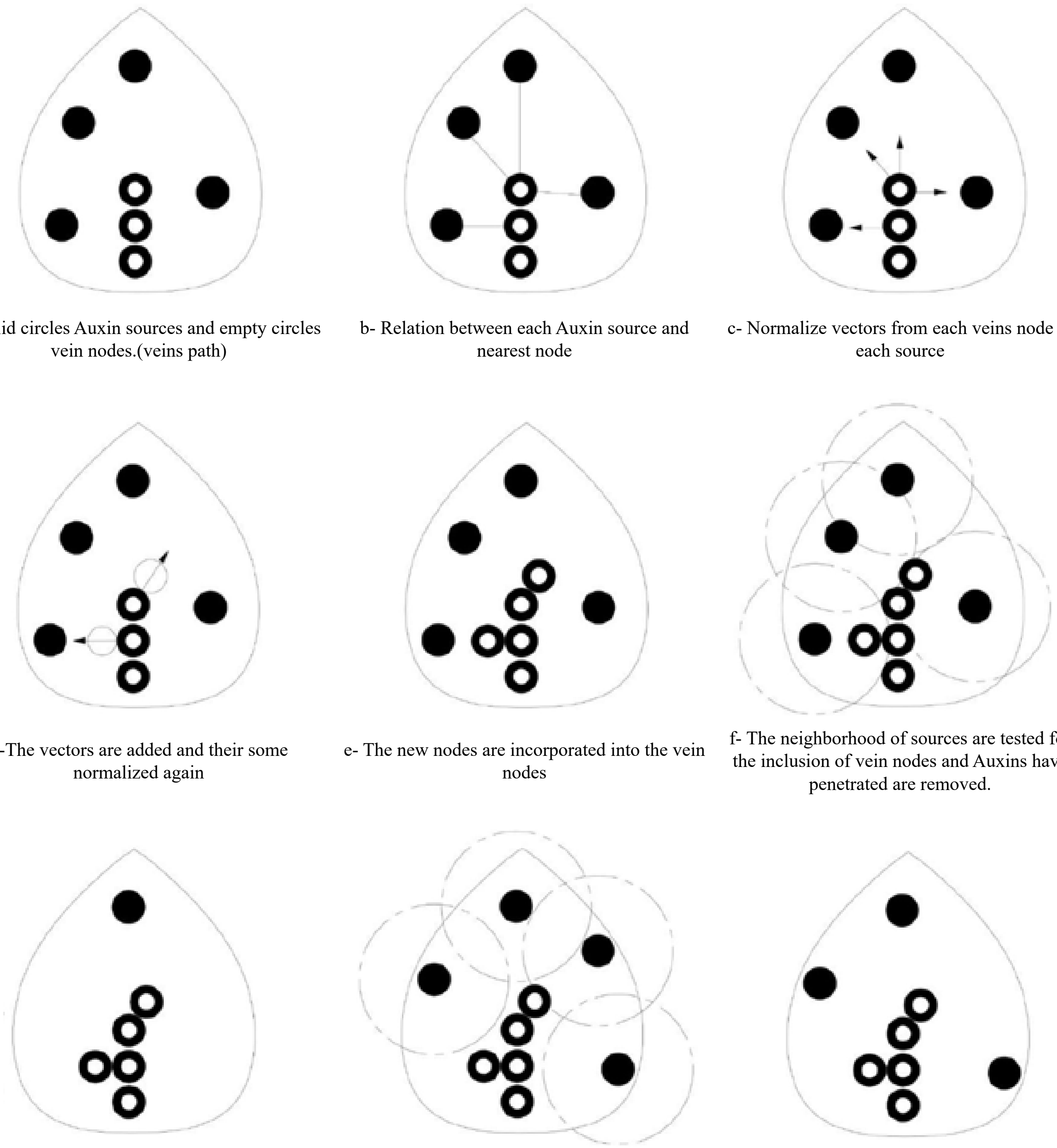


Fig. 2. A graphic image of the canalization theory. Source: Authors.

The placement of Auxin sources is chosen randomly, according to the model proposed at Calgary University. By changing the input number, the placement of Auxin sources changes. By changing the input number, the Grasshopper software automatically creates a random structure (Figs. 5-c & 6-c).

By adjusting the required inputs, Auxins' outputs are used as Auxin input in the final plugin (Figs. 5-4). The number and placement of support, which is determined by the user, can be more than one support. In fact, the support is the beginning point of vessels, and since it acts as a structure and in a 3D environment, we choose its location out of the roof and on the ground (Figs. 5-e& 6-d).



a- Solid circles Auxin sources and empty circles vein nodes.(veins path)

b- Relation between each Auxin source and nearest node

c- Normalize vectors from each veins node to each source

d-The vectors are added and their some normalized again

e- The new nodes are incorporated into the vein nodes

f- The neighborhood of sources are tested for the inclusion of vein nodes and Auxins have penetrated are removed.

g- The leftover Auxin go to the next stage

h- Auxin sources add randomly

i- Repeat the previous staged till compete the pattern

Fig. 3. The process of completing the leaf's vascular pattern by nodes and Auxin. Source: Runions et al., 2005.

The kill distance mentioned in theoretical foundations is determined by the user. The more load is put on the roof; the number chosen for kill distance will be smaller. It is obvious that a smaller number for kill distance means a more dense structure (Figs. 5-6 & 6-e).

In this part, it is determined whether the vascular system is open or closed. Choosing number zero means the system is open, and the number one means a closed vascular system (Figs. 5-7).

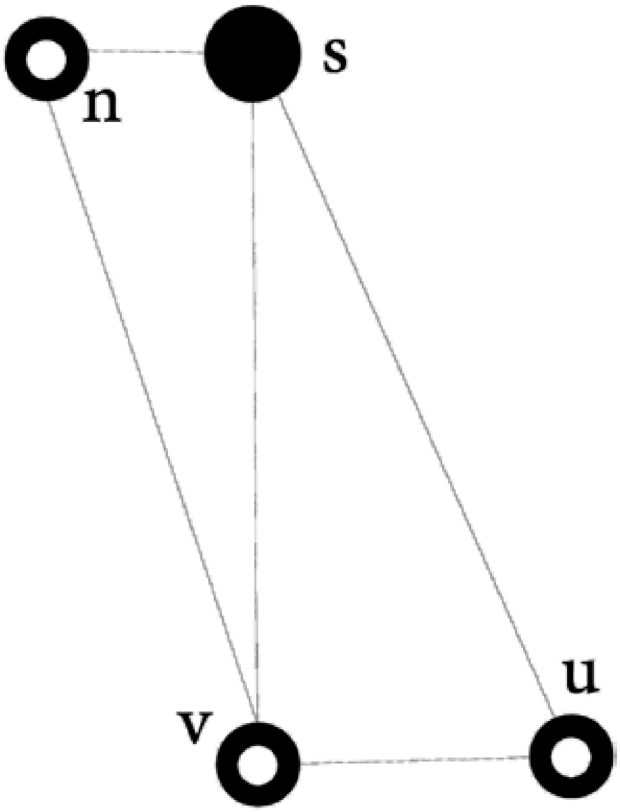


Fig. 4. Relative neighbor in a closed vascular system. Source: Authors.

By completing the inputs in the final plugin, the system starts creating the vascular system that exists in the plant's leaves, which can be observed in the Rhino software (Figs. 5-h).

Figure 7 shows the process of the formation of the structure obtained by the plugin in two dimensions with a primary node, and then in three dimensions with four primary nodes (four supports) and based on an open system.

Since the proposed vascular structure is a beam and column system, where beams are not formed directly, but based on the algorithm existing within the plants' leaves' vascular structure. First, the vascular structure with one support is compared with a radial cantilever beam and column system. Then, in order to show the infinity in the designed plugin, and more importantly, to optimize the vascular design, open and closed systems will be compared with two beam and column and concrete slab systems.

Research methodology

In this research, first, library documents were used in order to gather information. Then, this information was compared and evaluated through

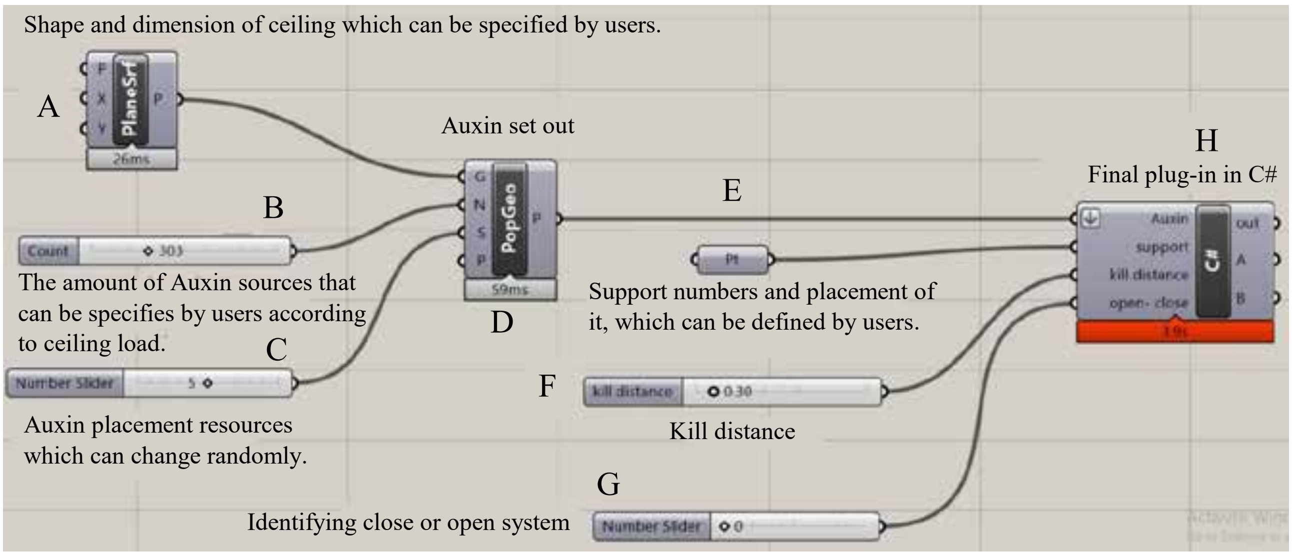


Fig. 5. The plugin designed based on open and closed vascular patterns. Source: Authors.

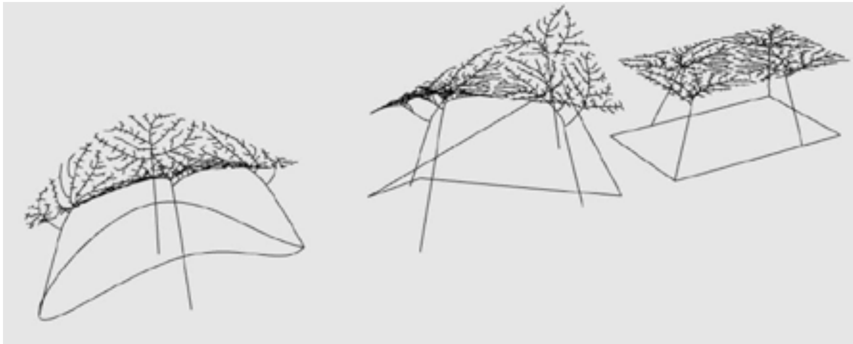
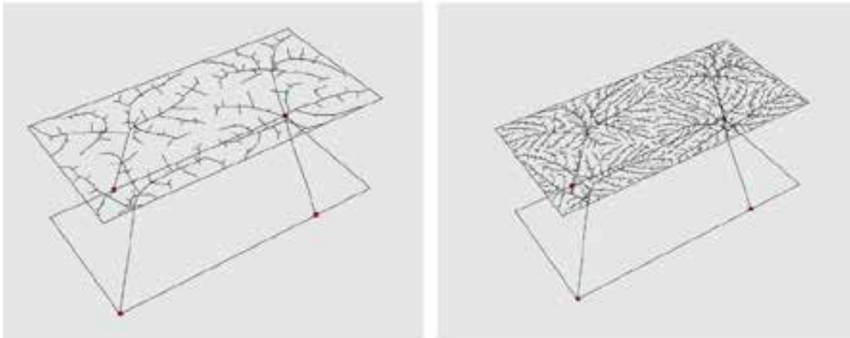
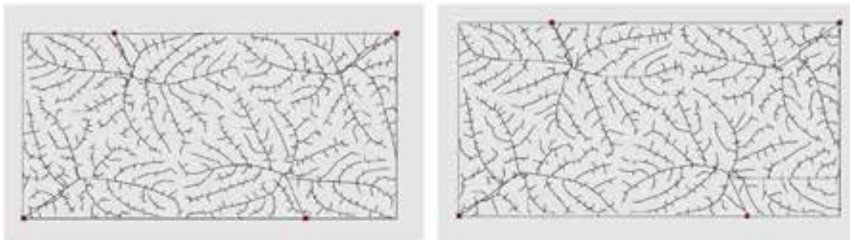
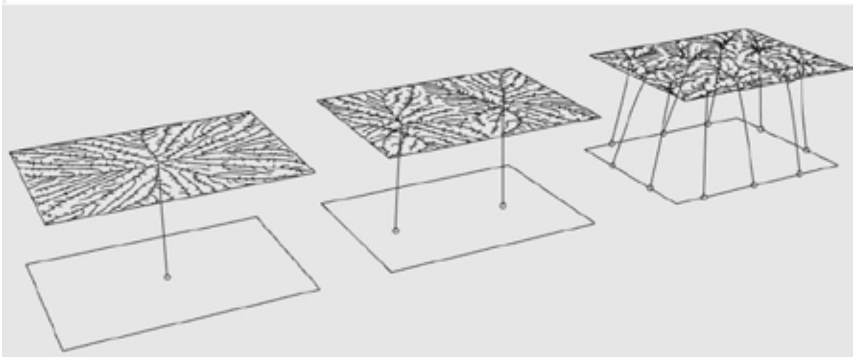
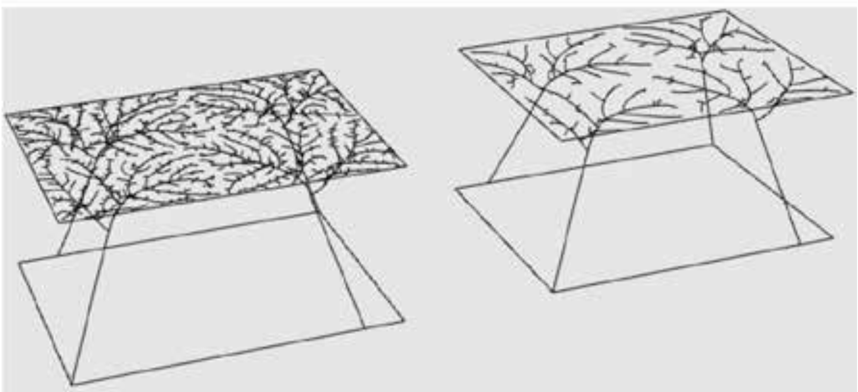
A- The initial shape of ceiling which can be specified by users.	
B- The amount of Auxin sources specify by users. The amount of Auxin is 250 and 1000 from left to right	
C- Placement of Auxin sources that will be changed by users. The random numbers are 1 and 5 from left to right.	
D- Number of support can be specified by users. 1,2 and 10 supports from left to right.	
E- Kill distance 0.2 to 0.8 from left to right.	

Fig. 6. The impact of changing parameters in the structure. Source: Authors.

the descriptive-analytic method. In the next step, using information extracted from the research part, we attempted to design a plugin within the Grasshopper environment. Research tools included the Grasshopper environment with the Rhino software, and the programming language C# was used to create a system to help designers based on plants' vascular algorithm in the formation and covering different types of surfaces. Finally, after simulating the final configuration, in order to optimize the system's structural behavior obtained from the mentioned plugin, this system was comparatively compared with common systems through the Karamba plugin.

Discussion

• Comparing vascular structures with other structures, using the mentioned plugin

Since the vascular structure is a beam and column structure, where beams follow the algorithm, existing in plants' vessels, at first, the structure achieved from the plugin with an open algorithm is compared with a radial beam and column cantilever structure in terms of maximum deformation. In this

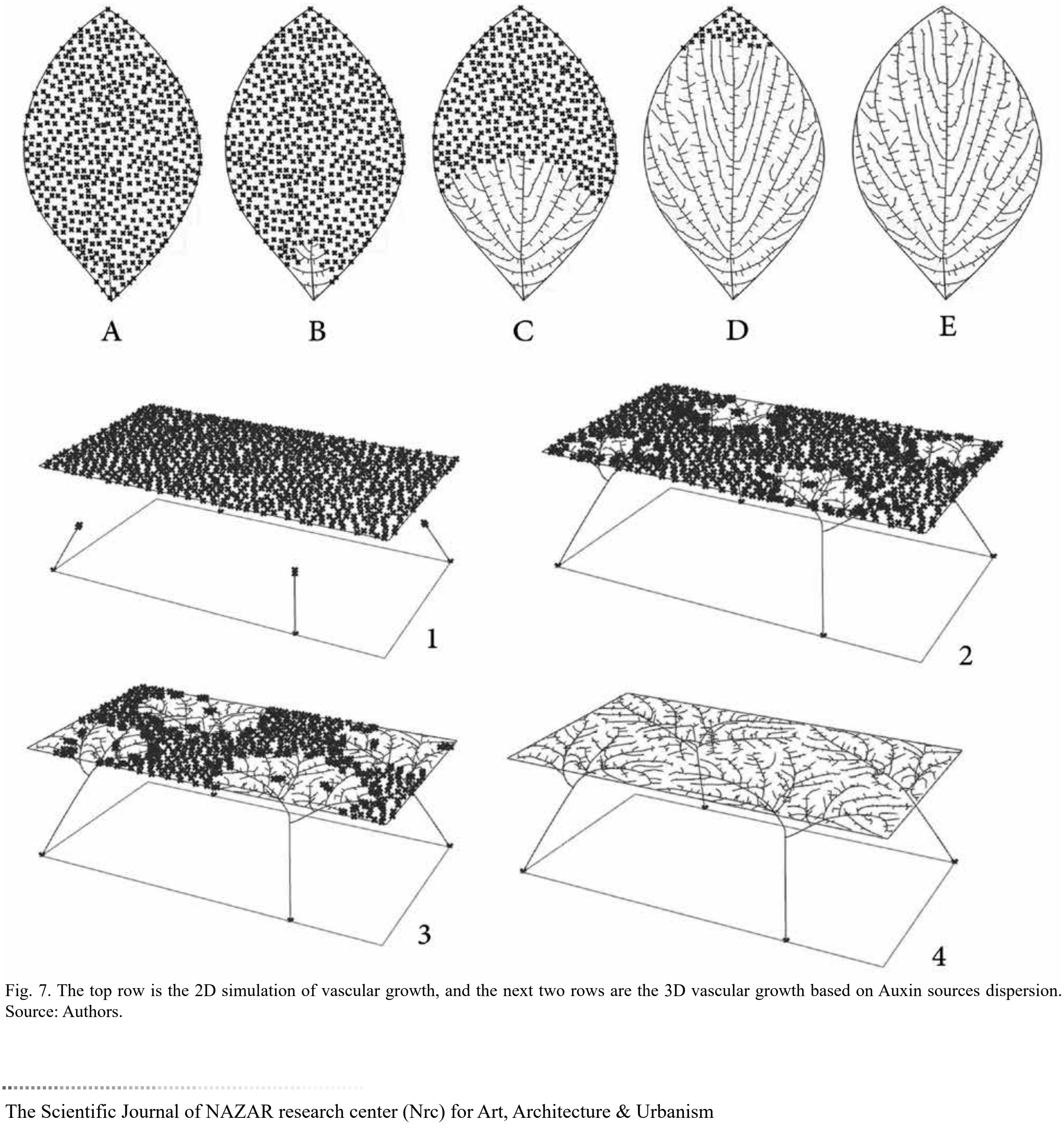


Fig. 7. The top row is the 2D simulation of vascular growth, and the next two rows are the 3D vascular growth based on Auxin sources dispersion. Source: Authors.

comparison, the parameters, including cross-section shape, structure's material, beams' measurements, and the number and type of supports, are considered constant (Fig. 8).

The results of the comparison and constant and variable parameters in this comparison are presented in table 2.

This comparison shows that radial beam and column structure with unyielding support, taking the mentioned constant parameters into consideration, will go through less deformation than the vascular structure achieved from the leaf algorithm. Therefore, in order to achieve a sturdier structure with higher loading capacity, the existing parameters in the plugin must be altered. This comparison can also be made with more supports and with more common structures and alter the parameters' values to reach improvement in vascular structural behavior.

- **Comparative comparison of open and closed vascular structures with diagonal beam and column system and concrete slab**

In this comparison, parameters, including material, shape, and cross section measurements, are considered constant in the three diagonal beams and column, open vascular, and closed vascular structures since they are cognate. In addition to comparing them with each other, they are also compared with the concrete slab structure, which

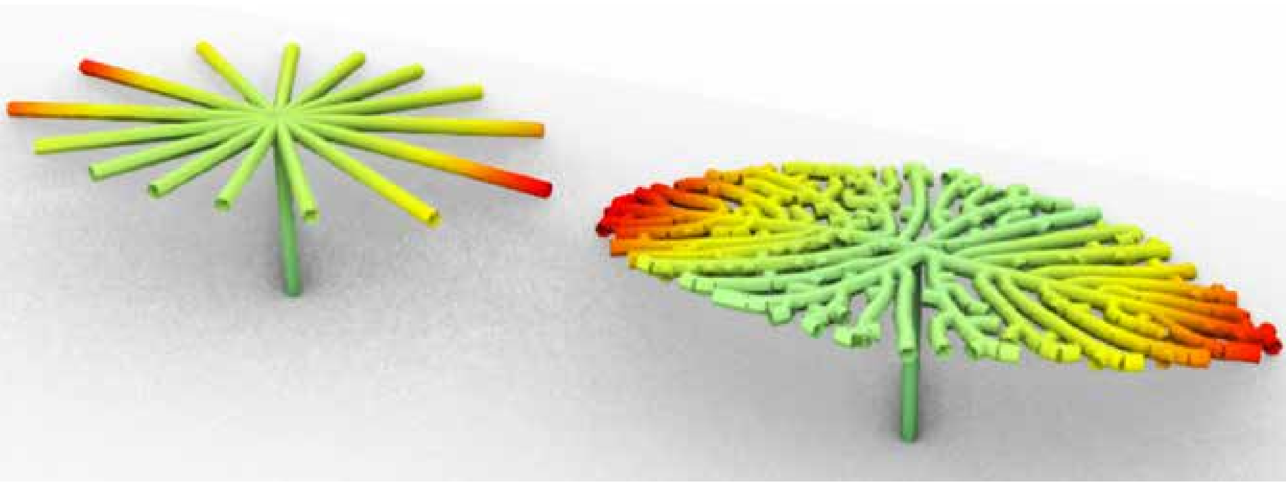


Fig. 8. Respectively from left to right, the radial cantilever structure and vascular cantilever system. Source: Authors.

Table 2. Comparing two vascular cantilever and radial cantilever structures. Source: Authors.

Parameter	Radial cantilever	Vascular cantilever beam
Cross section shape	tube	tube
Cross section dimension	20 cm	20 cm
Material	steel	steel
Load	weight + uniform distributed load	weight + uniform distributed load
Members	16	492
Number of supports	1	1
Type of supports	rigid	rigid
Maximum deformation (cm)	1.58	3.26
Amount of loads	13.57	29.84

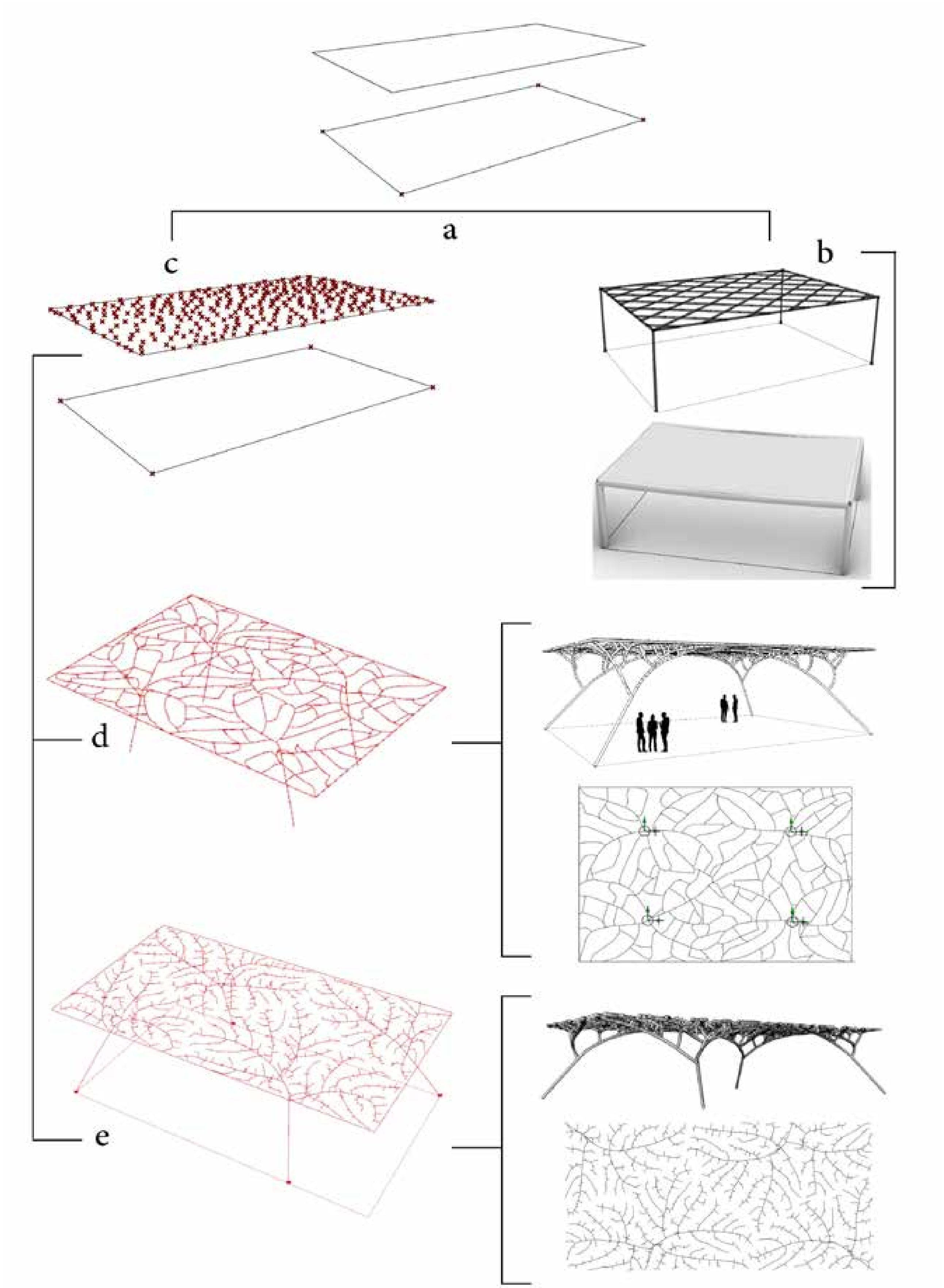


Fig. 9. The process of the structure's formation. Source: Authors.

is one of the common structures, in order to alter the vascular structure's parameters and achieve better results, using the information achieved from this comparison. Because by gathering specific information about the common structures, they can be used as proper criteria to best optimize the vascular structures. For comparison, first, according to figure 9, the intended structures are designed by the plugin:

- First, the roof area is considered a 7*10 rectangle, and its four corners are considered on the ground as the starting points for supports. The height of the roof is assumed three meters for all structures (Fig. 9-a).
- With the mentioned measurements, two diagonal and concrete slab roofs are designed (Fig. 9-b).
- The default points (location of Auxin sources) for two open and closed vascular systems are created on the roof. As previously explained, the number of these points is determined by the user. The more points are chosen, the more dense the structure will be and the loading capacity will be higher. And on the one hand, in terms of weight, it will be heavier and the process of computer processing will be longer. In this example, Auxin number 850 is chosen (Fig. 9-c).
- As previously mentioned, in this example, there are four support points assumed for the structure. The number and placement of these points are determined by the user as the start of the vascular nodes' process. It should be noted that as long as the vessel divergences reach the two-dimensional page defined as the roof, they will continue their path on the roof's two-dimensional space. Also, by changing the parameter related to determining the open or closed pattern, two closed (Fig. 9-d) and open (Fig. 9-e) will be created.

Divergence will occur until all the determined points on the roof participate in the formation of the vascular network.

- **The proposed structure's analysis**

In this comparison, items such as maximum deformation, number of members, and the amount load put on each structure will be compared and this comparison will be carried out by Karamba plugin in the Grasshopper environment, and the results are as shown in table 3.

The result of the members' deformation, evaluated in

Table 3. Comparison of the closed, open, diagonal beam, and concrete slab vascular structures. Source Authors.

Parameter	Concrete slab	Diagonal beam	Open vascular structure	Close vascular structure
Cross section shape	Flat slab	tube	tube	tube
Cross-section dimension	15 cm	15 cm	15 cm	15 cm
Material	concrete	steel	steel	steel
Load	weight + uniform distributed load	weight + uniform distributed load	weight + uniform distributed load	weight + uniform distributed load
Number of members	4	166	882	1146
Number of supports	4	4	4	4
Type of supports	rigid	rigid	rigid	rigid
Amount of Auxin resources	0	0	850	850
Kill distance	0	0	0.2	0.2
Maximum deformation	4.2	2.64	0.95	0.37
Amount of loads	270	24.39	32.04	35.44

four samples, is as follows (Fig. 10). In the attached color spectrum, the color blue represents the lowest degree of deformation and the color red, the highest degree of deformation.

- **Results of the structural comparison**

In terms of maximum deformation, given then kill distance, the closed vascular structure's determined number of Auxin and supports will go through a

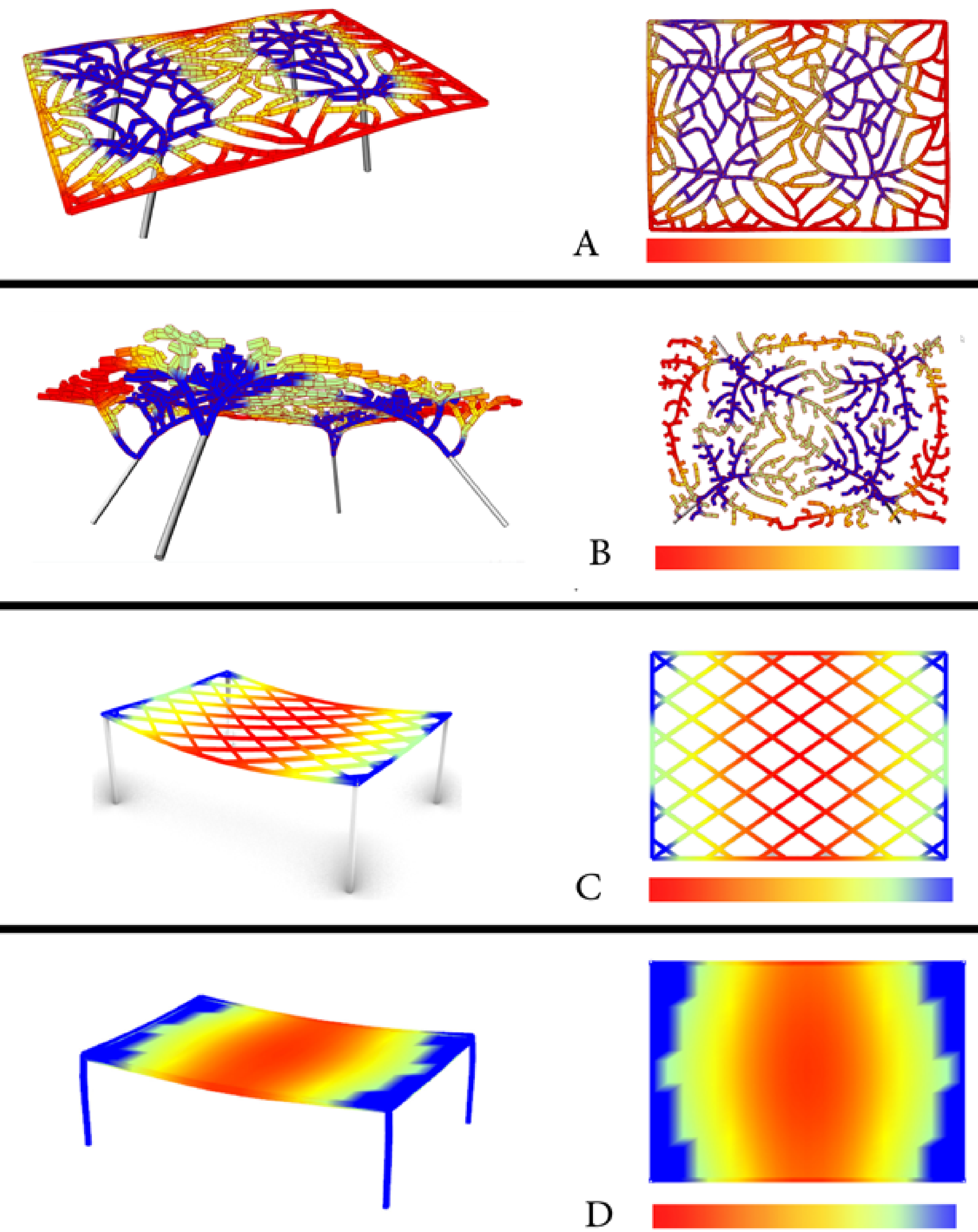


Fig. 10. Respectively from top to bottom, deformation in the members of closed, open vascular structures, diagonal beam, and concrete slab. Source: Authors.

lower degree of deformation, compared to other structures. However, the closed and also open vascular structures are executed more difficultly than the common diagonal beam and concrete slab structures. The closed system, the open vascular structure, and the diagonal beam structure will respectively go through lower degrees of deformation. The concrete slab structure, due to heaviness, will go through a higher degree of deformation under the conditions mentioned above. It must be noted that all of the obtained numbers in table 3 can be changed by altering the parameters to achieve a more suitable structure. Also, this comparison can be carried out with more structures, in order to achieve a more suitable criterion for optimizing the vascular structure.

Conclusion and future works

Using plants' vascular structure, the plugin enables users to create a vast spectrum of cover constructions in different sizes by altering the parameters defined within the plugin. This ability to make changes allows the architect to create complex forms, which would be impossible without using the plugin due to too many complexities in the design shape or structure. This plugin gives users the opportunity to use the simulated digital algorithms as design and structural patterns and also building facades because the obtained structures, given the exploitation of natural structures, in addition to inherent esthetics in nature can also create sturdier structures with higher loading capacity. Also, this plugin is designed open-source so that other researchers can develop and optimize it in future research in the following fields:

A) The possibility of developing a structure, considering the ability to grow in simulation, was not considered in this research.

B) Determining the degree of higher structural density in certain and specific parts of the roof, where more load is applied.

C) Using multipurpose evolutionary algorithms to weight different purposes.

D) Considering the structure's material and weight in the plugin.

E) The plugin's relation with Building Codes.

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