Load Responsive Angiogenesis Networks

Structural Growth Simulations of Discrete Members using Variable Topology Spring Systems

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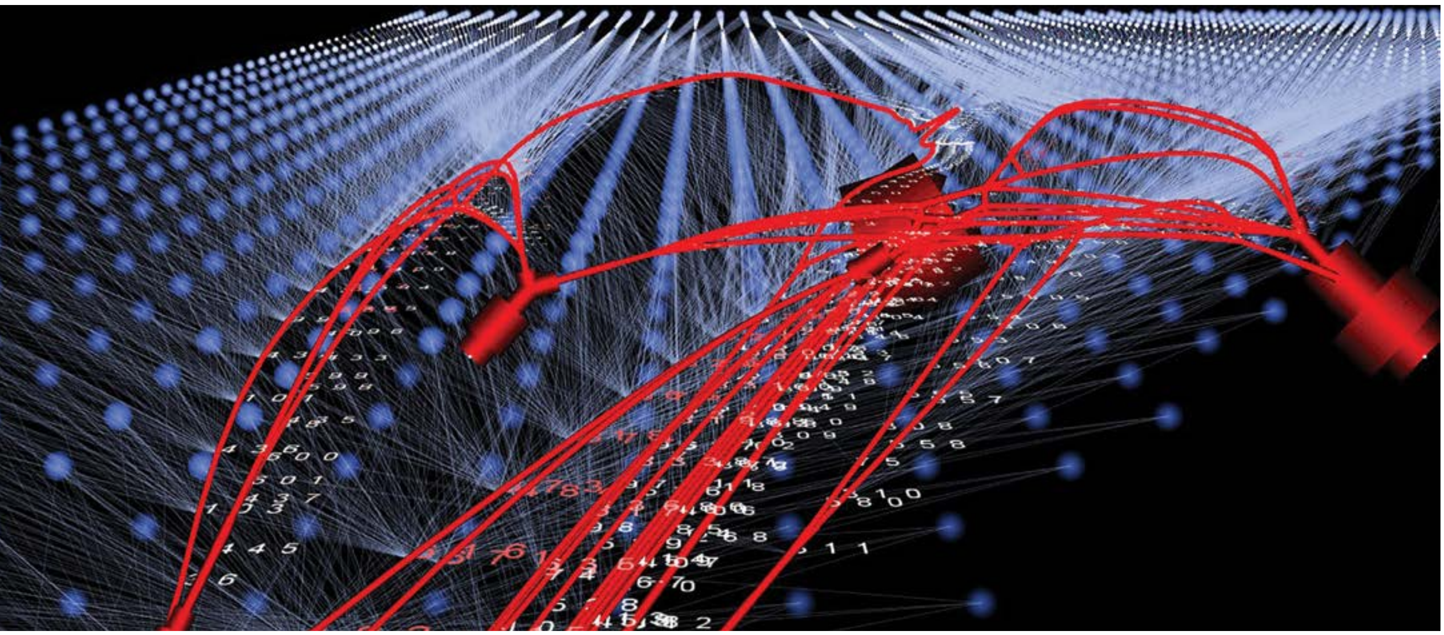


1 Angiogenesis Network.

ABSTRACT

Venation systems in leaves, which form their structural support, always connect back to one seed point, the petiole of the leaf. In order to develop similar structural networks for architectural use which connect to more seed points on the ground, an algorithm has been developed which can develop from two or three seed points, inspired by angiogenesis, the process through which the vascular system grows. This allows for the generation of structurally suitable topologies based on discrete members, which can be evaluated using Finite Element Analysis and which can be constructed from linear structural members without an additional interpretation of the results.

The networks have been developed as load bearing spring systems above the support points. Different structures have been compared and tested using Finite Element Analysis. Compared to traditional column and beam structures, the angiogenesis networks as well as the venation networks are shown to perform well under load.

INTRODUCTION

The venation systems in leaves fulfill both circulatory as well as structural functions (Roth-Nebelsick et al. 2001), and their generation has been shown to relate to physical stress (Laguna et al. 2008). The systems have been used by various designers to create formations for architecture and product design (Andraos 2015, Tamke et al. 2014, Seepersad 2014), often digitally simulated by algorithms similar to the one developed at the University of Calgary (Runions et al. 2005, Runions et al. 2007, Runions 2008). Following this algorithm, a network is grown from seed points towards a set of target points which need to be reached (Runions et al. 2005, Runions et al. 2007, Runions 2008). Digitally generated venation systems have been shown to perform well as architectural load-bearing structures (Klemmt 2014).

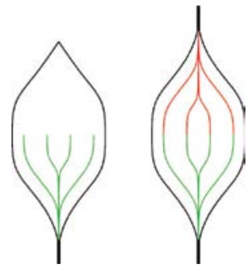
Venation systems always connect back to a single support, the petiole of the leaf, which makes their use as architectural load-bearing structures difficult. Structural beams and arches, which form connections between two different support points, cannot be generated using the venation algorithm.

Previous work attempted to solve this by growing networks from different support points towards the same target points. This led to separate structures, each supported above a single seed point, which were leaning against each other, connected by a set of the thinnest members along their common edges (Klemmt 2014).

In order to grow similar networks which can generate beam-like formations on top of two or three support points, an algorithm based on angiogenesis has been developed. Every target point in the network is connected to at least two support points and therefore lies on a connection between those supports (Figure 2).

While the growth following the venation algorithm starts from the seed point, the growth of the angiogenesis algorithm starts from an initial line which connects two seed points. This connection then splits up repeatedly in order to reach the set of target points which are to be supported (Figure 3).

The proposed methodology allows for the generation of structurally acting topologies. Unlike the ESO/BESO topology generation (Querin et al. 1998, Huang et al. 2007), the proposed system does not use a voxel grid but instead uses discrete members, which means that the outcomes can be evaluated using Finite Element Analysis (FEA), and the resulting networks can be constructed from linear structural members without an additional interpretation of the results.



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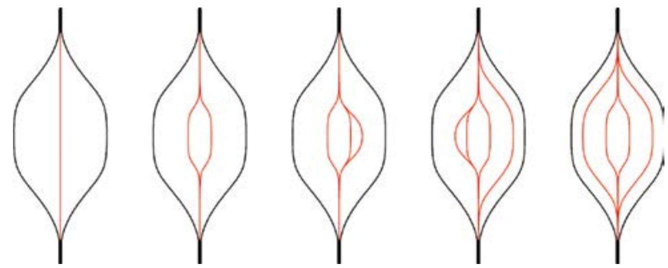

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2 Left: Venation network connecting to one seed point.
Right: Angiogenesis network connecting to two seed points.

3 The network is developed through a division and refinement of one initial connection between the two seed points.

ANGIOGENESIS

Angiogenesis is the process by which new blood vessels grow from existing ones. The veins of leaf venation systems contain both xylem and phloem cells which transport water and sap towards and away from the leaf cells. By contrast, vascular systems are directional and the blood always flows in a defined direction through its arteries and veins. Therefore, a venation system has a single starting point, while a vascular system has a starting as well as an end point, the atria and ventricles of the heart (Birbrair et al. 2014).

A growth model based on angiogenesis can therefore be used to generate networks which connect two support points together. The vascular network attempts to reach proximity to every cell in the organism. This behavior is translated to the requirement of the structural system to reach proximity of every load point which is to be supported. Both the support points as well as the load points are given, and the algorithm generates a network between the support points through a splitting of connections, with the aim of supporting the load points.

As the load points are placed at a higher level than the support points, the network is pulled upwards from the support points. It is expected that the networks form shell-like formations with possible similarities to the rib systems below Gothic domes.

Two types of angiogenesis are known: sprouting angiogenesis, the formation of a new vein between two existing veins, and intussusceptive angiogenesis, the splitting of a vein into two parallel veins. Vasculogenesis, the initial embryonic formation of the first veins, is a different process (Risau and Flamme 1995). This paper explores simulations using intussusceptive angiogenesis.

The aim of the research has not been to realistically simulate the development of vascular systems as they develop in nature, but rather to explore the biological precedent of angiogenesis in the development of iteratively refining spring systems.

RELATED WORK

Related Work in Design and Engineering

In structural engineering, algorithms are used to develop efficient structural systems, as with the use of genetic algorithms (Byrne et al. 2011, Clune et al. 2012).

Tools are available for the generation of topology, such as the voxel-based SIMP method (Bendsoe and Sigmund 2013) and the ESO and BESO algorithms (Querin et al. 1998, Huang et al. 2007). However, as those methods are voxel-based, the outcomes need to be interpreted in order to be constructed as systems with discreet structural members (Huang and Xie 2009).

In parametric architectural design, structural performance is often used as a driver to influence the parametric or algorithmic models (Makris et al. 2013, Turrin et al. 2011).

Research into a growth or additive development of structural systems has been explored using physical components (Dierichs & Menges 2012a, Dierichs and Menges 2012b, Zhao et al. 2015) or algorithmic simulations (Andraos 2015, Sugihara 2015, Richards et al. 2012, Richards and Amos 2014, Kicinger et al. 2005a, Kicinger et al. 2005b).

Related Work in Biology and Medicine

In developmental biology, the growth of organisms is studied on a cellular level (Wolpert et al. 2011). The growth of angiogenesis and the factors influencing it are of special interest in the field of cancer research, as an inhibition of angiogenesis can stop the growth of a tumor. Simulations of angiogenesis in this field are used as a research as well as visualization tool (Shirinifard et al. 2009, Szczerba & Székely 2002).

ALGORITHM FOR TWO SUPPORT POINTS

In the computational model, the vein network is represented by nodes which are connected by the vein segments. Similar to the previous experiments with venation systems (Klemmt 2014) that also aim to support loads, support points are placed at the bottom and the load points are placed at a higher level above.

In relation to the biological precedent of a vascular system and its angiogenesis, the blood flow leads from one of the two support points through the veins to the other.

Set-up

The inputs for the simulation are two support points, S_A and S_B, and a set of load points. The load points are to be supported by the vein structure on top of the support points.

In an initial step, the two support points are connected in a straight line by a set of evenly spaced nodes with spring connections (the veins) between them.

In relation to the biologic precedent, this can be seen as establishing an initial vein from S_A to S_B, and it serves to define a flow axis along which, in the vascular vein model, the liquid would flow from S_A to S_B. This flow axis can be defined at every node in the network. It can be calculated as a unitized vector which points from the neighboring node in the direction of S_A (upstream) towards the neighboring node in the direction of S_B (downstream). This flow axis is used in the simulation to control the splitting of the veins in a sideways direction.

After a vein has split, the node at the junction will have two or more neighbors in the direction of either S_A or S_B. For the purposes of calculation, the flow axis is defined as the unitized vector which points from the midpoint of all neighboring nodes in the direction of S_A towards the midpoint of all neighboring nodes in the direction of S_B.

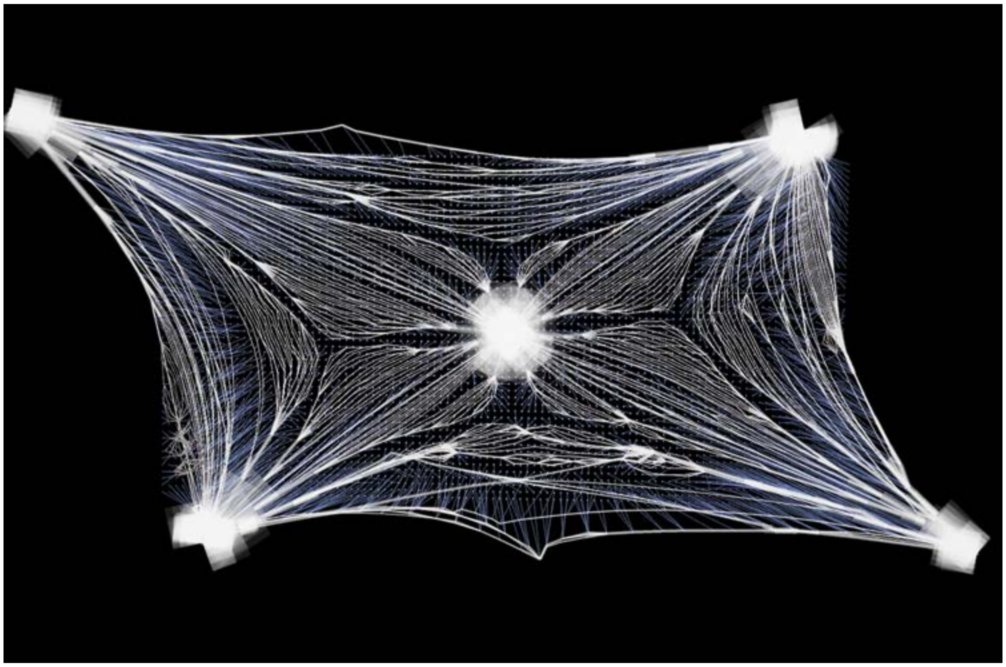
Every load point establishes a spring connection towards the node closest to it. Those load point springs have a smaller strength than the vein springs. There is a fixed amount of load point springs, one per load point, while the amount of vein springs in the network grows when the veins split.

Iterative Calculations

During each iteration, the springs of the network are relaxed. All springs are calculated as having a rest length of 0. The new positions of all nodes are updated, and the flow axis and the strength of forces acting on the nodes is recalculated.

The node with the strongest forces acting on it will split into two. The two new nodes are moved apart from each other sideways, orthogonal to the flow axis.

The new nodes are re-establishing spring connections to the neighbors of the previous node, separately for the upstream and downstream neighbors. If there is only one neighbor in a direction before splitting, both of the new nodes will connect to it. If



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4 Set of eight adjacent two-support-point systems, plan. Each two-support-point system starts as a straight line in plan. The distribution of the target springs (in blue) result in the fanning and the deformations.

there is more than one neighbor in a direction, the neighbors are distributed evenly between the two new nodes.

Also, the load points which had been connected to the splitting node become evenly distributed between the two new nodes. Therefore, if a node only has one load point connection, it is not allowed to split, and the node with the next strongest forces acting on it will split instead (Figure 4).

ALGORITHM FOR THREE SUPPORT POINTS

In order to generate a three-point support system, the algorithm has been adjusted to use three support points, S_A, S_B and S_C. Initially, those points are connected to their midpoint (resulting in a Y-formation) and those connections are evenly subdivided by nodes.

Flow Directionality

As in the algorithm with two support points, it is necessary to identify a main flow axis at every node, so that a splitting of the node can be programmed to happen sideways to this flow axis. In the version with two support points, the flow axis can be identified at every node from one support point towards the other. This is not possible in the version with three support points, but it is still possible to identify which support point is closest to any node. This can be used to trace a path from a node to each of the support points. Every neighbor of a node is marked towards which support point it is leading, and the acting forces are traced towards each of the three supports. This can be used to describe a main flow axis at the node along which the forces are acting.

Angiogenesis

The splitting of the cells happens as in the algorithm with two support points, however, the reassignment of the neighbors becomes more disparate, especially in order to avoid diagonally crossing connections. The neighbors are reassigned to the two new nodes while at the same time being marked as leading towards one or two of the support points. The neighbors are therefore distributed between the new nodes along the flow axis, while ensuring that each node still has at least one neighbor leading towards each support point.

FINITE ELEMENT ANALYSIS

Analysis Setup

The generated networks have been tested using Finite Element Analysis (FEA) and have been compared to a column and beam structure and to a venation structure as developed previously (Klemmt 2014).

The support points have been placed at the corners of a right triangle of 10 m width and 15 m length. The load points have been placed in the same triangle 5 m above the supports, in a square grid of 250 mm. A slab has been simulated by connecting the load points with structural members, which have been tested in three different sizes. Steel has been used as the material of all members. In order to compare the performances, all member sizes have been scaled so that the overall mass of each model was 10 t.

A load of 1 kN/m² has been applied at the load points, as separate load cases in the X, the Y and the Z direction.

Networks

The following networks have been tested:

- A column and beam structure, with vertical columns above the three support points and three horizontal beams connecting the columns
- A reticulate venation system as described by Klemmt 2014 (Figure 5)
- A two-support-point angiogenesis network, consisting of three systems which each form a connection between two of the three support points (Figure 6)
- A three-support-point angiogenesis network with one load point spring per load point as structural member
- A three-support-point angiogenesis network with every load point spring of the simulation as structural member (Figure 7)

In the venation network, every member has a value according to the amount of load points it supports, which is used as the member size (Klemmt 2014). In the angiogenesis models, the force of every spring connection equals its length, which defines the member size.

DEFLECTION RESULTS

Low Slab Strength

Slab member length: 629.14 m
Member diameter: 1 mm
Slab mass: 4.938 kg

Table 1. Deflection with low slab strength, in mm.

	Load Direction		
	X	Y	Z
Column Beam	238.88	167.88	2147483
Venation	91.15	83.76	76.89
Angiogenesis 2 Supports	6751.71	781.30	211.04
Angiogenesis 3 Supports 1 member per load point	1613.02	374.42	875.94
Angiogenesis 3 Supports all members	65.88	53.79	11.03

Medium Slab Strength

Slab member length: 629.14 m
Member diameter: 10 mm
Slab mass: 493.877 kg

Table 2. Deflection with medium slab strength, in mm.

	Load Direction		
	X	Y	Z
Column Beam	168.19	136.28	6008.83
Venation	72.98	66.14	43.74
Angiogenesis 2 Supports	207.11	111.31	58.17
Angiogenesis 3 Supports 1 member per load point	109.70	60.21	20.73
Angiogenesis 3 Supports all members	37.03	27.41	6.17

High Slab Strength

Slab member length: 629.14 m
Member diameter: 100 mm
Slab mass: 49387.65 kg

Table 3. Deflection with high slab strength, in mm.

	Load Direction		
	X	Y	Z
Column Beam	79.68	67.63	49.07
Venation	21.84	11.98	5.20
Angiogenesis 2 Supports	16.68	12.60	5.92
Angiogenesis 3 Supports 1 member per load point	35.30	30.65	3.38
Angiogenesis 3 Supports all members	28.90	19.46	1.01

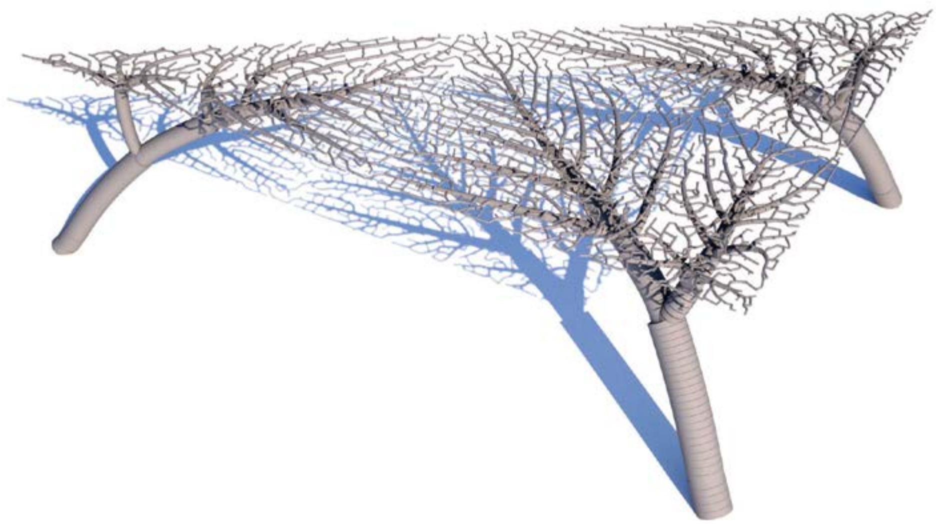
Table 4. Topological comparison of the structural networks.

	Member length (m)	**Diameter small**(mm)	**Diameter large**(mm)
Column Beam	74.84	130.46	130.46
Venation	625.21	3.98	275.69
Angiogenesis 2 Supports	1689.55	20.65	81.86
Angiogenesis 3 Supports 1 member per load point	1311.12	17.33	117.82
Angiogenesis 3 Supports all members	13817.4	8.72	59.29

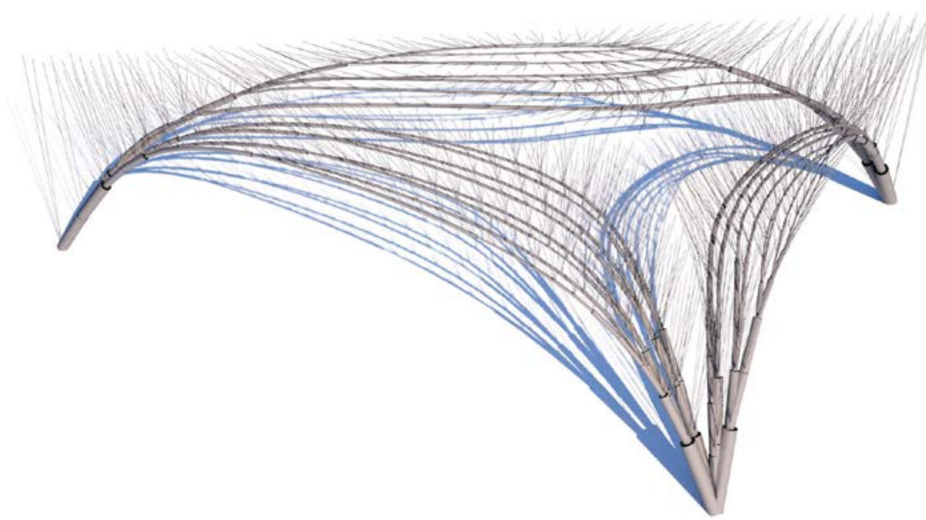
EVALUATION

Amongst the tested structures, the column and slab structure performs least well, especially the central areas of the slab which are furthest away from the beams and deform the most.

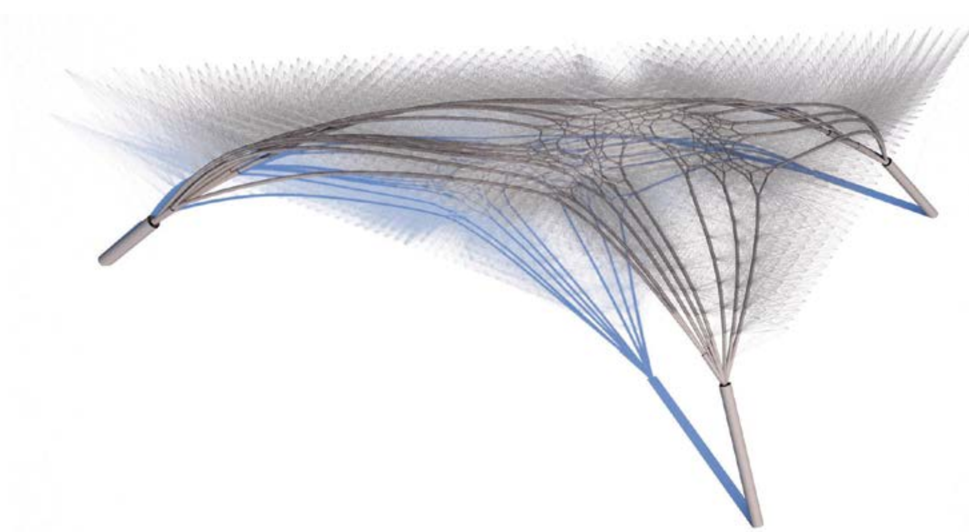
Similarly, the central slab area of the two-point angiogenesis structure deforms significantly as it is relatively far away from any supporting beam members. However, this deficiency can be made up for by a stronger slab. This model then also works well



5 Venation System.



6 Two-Support-Point Angiogenesis System.



7 Three-Support-Point Angiogenesis System.

for the lateral load cases. The arches which have been generated between the support points appear to perform well in taking the lateral loads.

The three-support-point angiogenesis structures perform very well, especially the one with all load point springs used as structural members. The dense load point springs then form a space frame geometry below the slab. However, this network consequently has a large amount of individual members which may make it less feasible for construction.

As the algorithm used to develop the angiogenesis networks has a structural logic, it was expected that those systems would act better as load-bearing networks than the venation structure. However, the venation structure performs very well in comparison. Also the venation structure has a shorter cumulative length of the members, which makes it more economically efficient to construct physically (Figure 8).

CONCLUSIONS AND FUTURE WORK

By using the process of angiogenesis as a precedent, an algorithm has been developed that can successfully generate branching networks that develop from two or three seed points.

The algorithm has been used to generate load-bearing networks which have been tested using Finite Element Analysis. The generated structures were shown to perform very well. However, structures generated with the venation algorithm (Klemmt 2014) perform similarly well, even though the algorithm to generate those does not have a structural logic.

The proposed methodology is a first step towards the algorithmic generation of structural topology based on discreet members. Currently, the simulations generate shell-like formations, which should be generalized to various other topologies.

The algorithm which has been developed uses springs to simulate forces. However, this does not reflect the bending moments which occur in structural members. Future developments will provide a more accurate simulation by taking those forces into account.

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REFERENCES

Andraos, Sebastian. 2015. “Generating Adaptable Structural Systems Using Natural Growth Algorithms.” Master’s thesis, ENSA Paris Malaquais, http://andraos.co.uk/GeneratinganAdaptableStructuralSystem_LR.pdf

Birbrair, Alexander, Tan Zhang, Zhong-Min Wang, Maria Laura Messi, John D. Olson, Akiva Mintz, and Osvaldo Delbono. 2014. “Type-2 Pericytes Participate in Normal and Tumoral Angiogenesis.” *American Journal of Physiology - Cell Physiology* 307 (1): C25–38. doi:10.1152/ajpcell.00084.2014.

Bendsøe, Martin P. and Ole Sigmund. 2013. *Topology Optimization: Theory, Methods, and Applications*. Berlin: Springer Science & Business Media.

Byrne, Jonathan, Michael Fenton, Erik Hemberg, James McDermott, Michael O’Neill, Elizabeth Shotton, and Ciaran Nally. 2011. “Combining Structural Analysis and Multi-Objective Criteria for Evolutionary Architectural Design.” In *Proceedings of the 2011 International Conference on Applications of Evolutionary Computation - Volume Part II*, edited by Cecilia Di Chio et al. Berlin, Heidelberg: Springer-Verlag. 204–213

Clune, Rory, Jerome J. Connor, John A. Ochsendorf, and Denis Kelliher. 2012. “An Object-Oriented Architecture for Extensible Structural Design Software.” *Computers & Structures* 100–101 (June): 1–17. doi:10.1016/j.compstruc.2012.02.002.

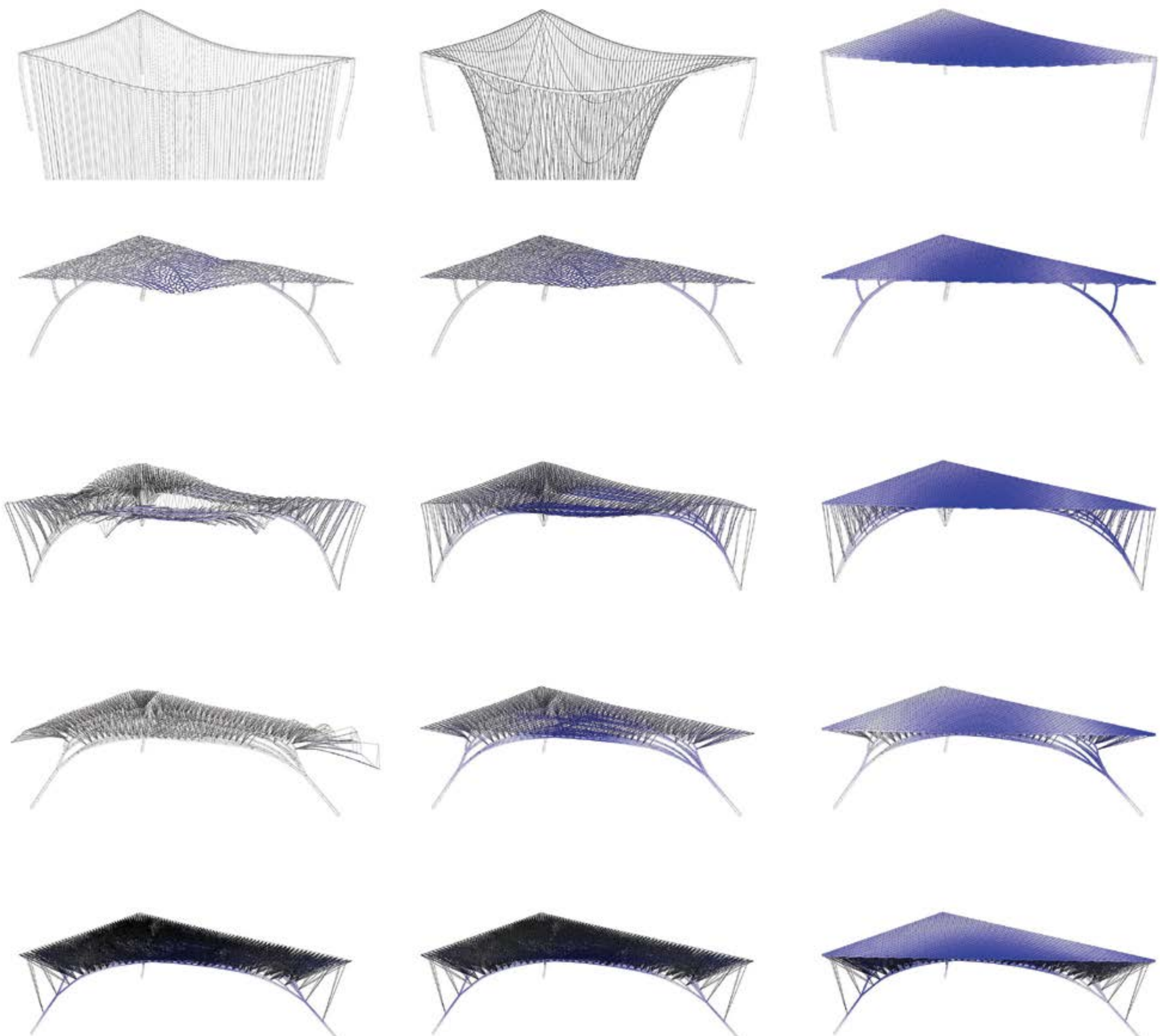
Dierichs, Karola, and Achim Menges. 2012. “Functionally Graded Aggregate Structures: Digital Additive Manufacturing with Designed Granulates.” In *Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, edited by M Cabrinha, J Johnson, and K Steinfeld. San Francisco: ACADIA. 295–304.

Dierichs, Karola, and Achim Menges. 2012. “Aggregate Architectures, Observing and Designing with Changeable Material Systems in Architecture.” In *Change, Architecture, Education, Practices – Proceedings of the International ACSA Conference*, edited by X Costa and M Thorne. Barcelona: ACSA. 463–468.

Huang, Xiaodong, and Yi Min Xie. 2009. “Bi-Directional Evolutionary Topology Optimization of Continuum Structures with One or Multiple Materials.” *Computational Mechanics* 43 (3): 393–401.

Huang, Xiaodong, Yi Min Xie, and Mark C. Burry. 2007. “Advantages of Bi-Directional Evolutionary Structural Optimization (BESO) Over Evolutionary Structural Optimization (ESO).” *Advances in Structural Engineering* 10 (6): 727–737.

Kicinger, Rafal, Tomasz Arciszewski, and Kenneth De Jong. 2005. “Evolutionary Computation and Structural Design: A Survey of the State-of-the-Art.” *Computers & Structures* 83 (23–24): 1943–1978.



8 Deflection under loading in the Z-direction. Columns from left to right show low, medium and high slab strength. Rows show from top to bottom: Column and Beam structure, Venation system, Angiogenesis system with two supports, Angiogenesis system with three supports with one connecting member per load point, Angiogenesis system with three supports with all members connecting to the load points.

Kicinger, Rafal, Tomasz Arciszewski, and Kenneth De Jong. 2005. "Parameterized Versus Generative Representations in Structural Design: An Empirical Comparison." In *Proceedings of the 7th Annual Conference on Genetic and Evolutionary Computation (GECCO '05)*, edited by HG Beyer. New York: ACM. 2007–2014.

Klemmt, Christoph. 2014. "Compression Based Growth Modelling." In *Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, edited by David Gerber, Alvin Huang, and Jose Sanchez. Los Angeles: ACADIA. 565–572.

Makris, Michael, David Gerber, Anders Carlson, and Doug Noble. 2013. "Informing Design through Parametric Integrated Structural Simulation: Iterative Structural Feedback For Design Decision Support of Complex Trusses." In *eCAADe 2013: Computation and Performance–Proceedings of the 31st International Conference on Education and research in Computer Aided Architectural Design in Europe*. Delft, The Netherlands: eCAADe.

Querin, Osvaldo M., Grant P. Steven, and Yi Min Xie. 1998. "Evolutionary Structural Optimisation (ESO) Using a Bidirectional Algorithm." *Engineering Computations* 15 (8): 1031–1048.

Richards, Daniel, Nick Dunn, and Martyn Amos. 2012. "An Evo-Devo Approach to Architectural Design." In *Proceedings of the 14th Annual Conference on Genetic and Evolutionary Computation*. Philadelphia: ACM. 569–576.

Richards, Daniel, and Martyn Amos. 2014. Evolving "Morphologies with CPPN-NEAT and a Dynamic Substrate." In *ALIFE 14: The Fourteenth Conference on the Synthesis and Simulation of Living Systems*, edited by Hiroki Sayama, John Rieffel, Sebastian Risi, René Doursat, and Hod Lipson. New York: ALIFE. 255–262.

Risau, Werner, and Ingo Flamme. 1995. "Vasculogenesis." *Annual Review of Cell and Developmental Biology* 11 (1): 73–91.

Roth-Nebelsick, Anita, Dieter Uhl, Volker Mosbugger, and Hans Kerp. 2001. "Evolution and Function of Leaf Venation Architecture: A Review." *Annals of Botany* 87 (5):553–566.

Runions, Adam, Brendan Lane, and Przemyslaw Prusinkiewicz. 2007. "Modeling Trees With a Space Colonization Algorithm." In *Proceedings of the Eurographics Workshop on Natural Phenomena*. Aire-la-Villa, Switzerland: Eurographics. 63–70.

Runions, Adam, Martin Fuhrer, Brendan Lane, Pavol Federl, Anne-Gaëlle Rolland-Lagan, and Przemyslaw Prusinkiewicz. 2005. "Modeling and Visualization of Leaf Venation Patterns." *ACM Transactions on Graphics* 24 (3): 702–711.

Runions, Adam. 2008. Modeling Biological Patterns Using the Space Colonization Algorithm. M.Sc. Thesis, University of Calgary.

Seepersad, Carolyn C. 2014. "Challenges and Opportunities in Design for Additive Manufacturing." *3D Printing and Additive Manufacturing* 1 (1): 10–13.

Shirinifard, Abbas, J. Scott Gens, Benjamin L. Zaitlen, Nikodem J. Popławski, Maceij Swat, and James A. Glazier. 2009. "3D Multi-Cell Simulation of Tumor Growth and Angiogenesis." PLoS ONE 4 (10): e7190.

Sugihara, Satoru. 2015. "Guidelines for the Agent Based Design Methodology for Structural Integration: Inanimate Material Physics Simulation and Animate Generative Rules." In *Paradigms in Computing: Making, Machines, and Models for Design Agency in Architecture*, edited by David Jason Gerber and Mariana Ibanez. eVolo Press. 92–15.

Szczerba, Dominik, and Gábor Székely. 2002. "Macroscopic Modeling of Vascular Systems". In *Proceedings of the 5th International Conference on Medical Image Computing and Computer-Assisted Intervention-Part II (MICCAI '02)*, edited by Takeyoshi Dohi and Ron Kikins. London, UK: Springer-Verlag. 284–292.

Tamke, Martin, Paul Nicholas, and Jacob Riiber. 2014. "The Agency of Event: Event based Simulation for Architectural Design." In *ACADIA 2014 Design Agency: Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by David Gerber, Alvin Huang, and Jose Sanchez. Los Angeles: ACADIA. 63–74.

Turrin, Michela, Peter von Buelow, and Rudi Stouffs. 2011. "Design Explorations of Performance Driven Geometry in Architectural Design Using Parametric Modeling and Genetic Algorithms." *Advanced Engineering Informatics* 25 (4): 656–675.

Wolpert, Lewis, Cheryll Tickle, Thomas Jessell, Peter Lawrence, Elliot Meyerowitz, Elizabeth Robertson, and Jim Smith. 2011. *Principles of Development*. Oxford, UK: Oxford University Press.

Zhao, Yuchen, Kevin Liu, Matthew Zheng, Jonathan Barés, Karola Dierichs, Achim Menges, and Robert P. Behringer. 2015. "Packings of 3D Stars: Stability and Structure." *arXiv*:1511.06026

IMAGE CREDITS

Figures 1–8: Christoph Klemmt, 2016.

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In 1983 Klaus Bollinger and Manfred Grohmann established the practice Bollinger + Grohmann, now located in Frankfurt am Main, Vienna, Paris, Oslo and Melbourne with around 100 employees. The office provides a complete range of structural design services for clients and projects worldwide. For years they have been collaborating successfully with numerous internationally recognized architects and strive to always provide the best solution through their creativity and technical excellence. Their scope of work includes building structures, facade design and building performance for commercial, retail and exhibition facilities as well as classic civil engineering structures such as bridges, roofs and towers.

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