A Morphogenetic Approach for Performative Building Envelope Systems Using Leaf Venetian Patterns

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Abstract. *Recent developments in theory and technology in performance based design show an interest towards generative systems. In this paper a morphogenetic approach will be introduced that looks at Goethean morphology and leaf venation patterns. To instrumentalize this approach an algorithm will be introduced to generate various leaf venation patterns on complex mesh surfaces. As a case study, the paper tests the applicability of such system as performative algorithms for building envelopes. The role of simulation is to generate self-organizing forms and provide a framework for design development. The overall approach is to consider performance as a direct input to guide the computation of form at an early design stage.*
Keywords. *Performative façades; growth; morphology; goethe; simulation.*

INTRODUCTION

Current developments in performance based design indicate an interest towards generative algorithms that offer a robust approach for form-finding problems in architecture. These systems are often controlled by parametric variables and the final configuration of design is validated through simulation.

Simulations are central to performance based design to provide feedback on specific design iterations and means of their improvement. However in many cases these simulations are made on forms and components of design that have been decided and placed. This states that the performance analysis of such systems becomes an evaluation of the design that can only be altered if the evaluation data is integrated as feedback. Such an approach limits the ability and variability of performative systems presenting a gap between the design of such systems and how the analysis data is able to modify the system. In this paper an alternative approach will be presented that considers a growth based system for a performative outcome. Leaf venation patterns will be studied to compute facade components through simulation. In this process form will be generated in a bottom-up process guided by the performance criteria and parameters. The final configuration of design is directly informed by the desired performance data and form is generated through simulation.

GROWTH AND FORM

Growth is an essential part of nature and it provides self-organizing principles to forms that are in constant transformation. Historically one of the first in-depth studies on form was conducted by German artist Johann Wolfgang von Goethe in the late eighteenth century who developed morphology as a unifying science to understand form (Goethe, 1988). Goethe's started working on annual plants through Linnaeus's writings which later became influential to the establishment of biological sciences. Prior to Goethe, Linnaeus had classified plants under similar properties according to their physical characteristics. Goethe was influenced by this taxonomical work but he considered the external properties of plant forms to be an expression of an internal principle. For him the external or physical characteristics of plants were not constant and changed according to environmental conditions. Thus he sought a constant innate principle that resided beneath the changeable properties.

In his botanical writings Goethe defined the leaf [*Urplanze*] as a template that guides the development of the plant and generates variation and complexity over time (Goethe, 1993). Goethe's conception of "the leaf" considers all plant forms to be related by the same principles of nature and growth. This unifying conception not only connects different types of leaf forms, but also explains the variation of same types of leaves under different environmental conditions.

For Goethe type is not a fixed form to define genera or species. On the contrary the type is generative and could change based on environmental conditions where the potentialities existing in it are expressed. Thus his understanding of form is not reductive that tries to classify the existing forms for identification, on the contrary he considered form to be generative that is able to transform and create novel products under changing conditions.

FORM IN ARCHITECTURE

In architecture, form is mostly understood as a topological entity following an overall schema or as a replication of an existing type that appears fixed (Garcia, 2010). In many cases architects work with typologies for various buildings and variations are achieved by topological operations. This idea is often complemented by parametric design to produce smooth variable systems. In this holistic framework a dynamic function or a rule contains and controls the variability of parts in a top-down process. With its ability to control the overall behavior of design, parametric systems have been extensively used for the evaluation and adaptation of a performance based approach in design solutions. However these systems are ineffective to provide a morphogenetic approach towards design.

Compared to parametric systems, morphology considers form as the result of a bottom-up process. This development is guided by the interaction and configuration among parts that lead to novel and varying forms. In this sense, form is not an instance of a class or type to be shaped, but it is directly grown and transformed to achieve a novel structural entity.

In this work Goethe's understanding of morphology will be pursued by combining morphogenesis and performance based design. In morphogenesis, form and parts are not pre-given but are developed over time. In this generative approach the parametric ability is not given to the overall system but to the parts that have the ability to interact and transform. This interaction results in the final configuration of form that is an outcome of the bottom-up system. This alternative approach supports Goethe's ideas on plant morphology where the overall form of the leaf is acquired through the interaction and distribution of veins. Using computation this process could be simulated and can establish a quantifiable relation between morphogenesis and design.

LEAF FORMS

Goethe's ideas on form were studied by many twentieth century scientists. One of them was the pioneering biologist D'Arcy Thompson who emphasized the gradual and unequal increments of the successive stages of development for biological forms (Thompson, 1992). This principle informs the final configuration of the whole material structure of a form following interaction among parts. In leaf venation, development occurs in a similar fashion. Veins follow smooth and continuous variation through precise morphologies of leaf contours creating self-organizing material structures. This developmental process creates variation of leaf types that are expressed by vein patterns and blade shapes.

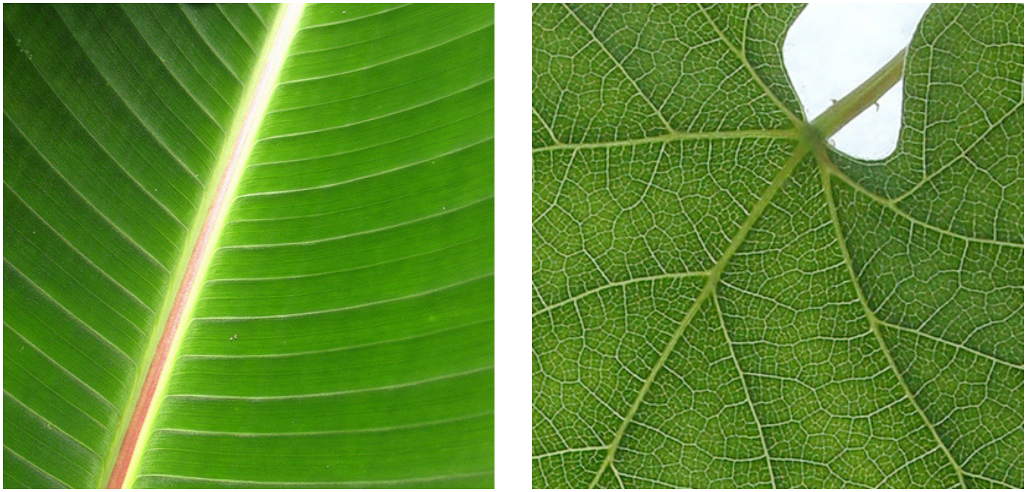


Figure 1
Various leaf venation patterns. Left: Ginger leaf with pinnate pattern. Right: Grape leaf with reticulate pattern.

Vein patterns are strongly correlated to the overall shape of the leaf blade that can be in different forms. The leaf blade can be toothed, dissected or smooth which informs the overall patterning and distribution of veins. Different types of vein patterns can also be found from pinnate to reticulate (Figure 1). The vein connectivity and hierarchy is related to the growth of the leaf which controls the distribution of fluids along the leaf for photosynthesis. This process initiates when the leaf blade is first formed, guiding the further development and articulation of the vein pattern.

While leaves adapt to the changing environmental factors, they maintain an overall structural coherence within the plant. In a single plant, variations of different leaf forms occur following a common underlying organization of the leaf type. This gives each leaf a performative behavior producing variations even under the same leaf typology. This generative and variable nature has been extensively studied in biology and computation (Prusinkiewicz et al. 1990, Runions et al. 2005). However, leaf venation systems have not been used in computational architecture. It is the aim of this paper to introduce an algorithmic approach towards using leaf venation systems for architectural design problems.

LEAF VENATION PATTERNS

Although scientists are still not certain about the guiding principles behind the leaf venation patterns, there are different theories on how the leaf morphology is achieved. One of these theories is called *canalization theory* which focuses on the activity and distribution of the growth hormone auxin in growing plant leaves (Sachs, 1991). The cellular patterning in plant leaves is dependent on the activity of auxin transport, tissue polarity and vascular differentiation. In addition the transport of auxin directly informs the structuring of vascular strands (Dengler and Kang, 2001). As cells are fled with more auxin they become better transporters. As a result, the fluid transportation is canalized through these cells whose polarization and differentiation continues throughout the development of the leaf.

In plant leaves, auxin is produced close to the leaf blade and it is drained away by cells. During its transportation the cellular structure creates a pathway for rapid flow of fluids along the leaf. The activity of auxin promotes cellular changes among leaf cells causing some of them to be transformed into vascular tissue to carry the fluids along the leaf and plant. This overall activity is highly influential in the overall patterning process and the development of leaf venation. In this process the concentration and distribution of auxin sources guide the differentiation of vascular tissue that later become veins for fluid transportation.

COMPUTATION OF LEAF VENATION PATTERNS

There have been various different attempts to simulate plant growth within computer animated environments. An example of this could be found in L-systems developed by Lindenmayer and Prusinkiewicz that simulates the growth pattern of various plants using fractal-like recursions (Prusinkiewicz et al., 1990). Another approach looks at growth hormones in plant forms which guide the development and distribution of vein nodes (Runions et al., 2005). While the former approach offers a formal grammar to replicate the growth process, the latter offers a dynamic approach that is based on simulation.

With the integration of computational tools, it has become possible to utilize growth simulations in architectural design problems. The development and geometric computation of leaf venations could be simulated to create performative and interactive structures. This investigation will be carried in two main parts. Firstly leaf venation patterns will be generated two-dimensionally to explain how the algorithm and process is implemented. Then the same approach will be applied on three-dimensional surfaces that enable form generation on generic architectural problems. In both cases the applications are written in Processing which is a Java based object-oriented programming tool.

In this section an algorithm that uses auxin sources for leaf venation patterns will be introduced (Runions et al. 2005). This algorithm works in multiple steps to achieve open patterns (tree-like). Auxin sources (as point attractors) are generated on leaf blade using Poisson disk distribution. Then the root nodes are specified from which the patterns will start growing. At each time step the closest vein node to each auxin source will be defined. Then these nodes will grow towards the average direction influenced by the auxin sources. When the vein node gets closer to an auxin source the source is removed during the simulation. There are two main parameters for the algorithm. The first one is the birth distance that specifies the distribution and distance of the auxin sources during the simulation. The second one is the kill distance that controls when the auxin sources are removed during the simulation. When the kill distance is small the resulting patterns become more articulated.

In order to achieve closed patterns (with loops) the algorithm could be changed to achieve anastomosis among veins. In this case the vein nodes that do not have any auxin sources to grow towards will connect to the closest vein node that is within their orientation (Figure 2). These nodes will be deactivated when they converge to another vein node to create closed loops. During the simulation the growth is initiated from the root node. At each time step the active veins are thickened to maintain a hierarchy among veins and achieve more realistic results.

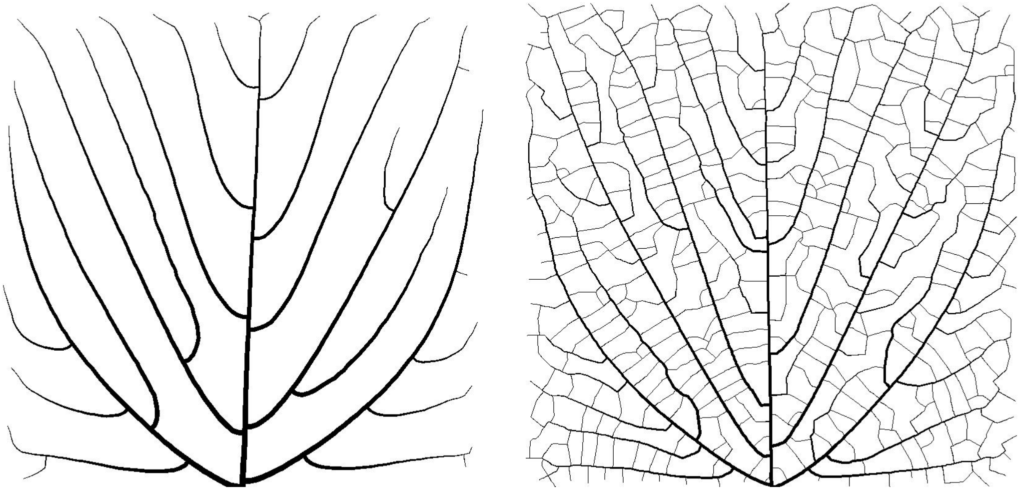
In both open and closed patterns the final outcome of the pattern could be controlled by the distribution of auxin sources and parameters for vein nodes for growth. For the placement of the auxin sources the birth distance parameter could be further manipulated using a density map (Figure 3).

The alpha channel of the gradient map controls the birth distance parameter during the auxin source placement. The darker areas inform the birth distance to be small, while on the lighter areas the birth distance is large. This way the auxin source distribution could be concentrated and controlled using the density map as influence. This creates a direct effect on the venation patterns while maintaining the continuity and consistency of the pattern. In addition, this gives the ability to control the final pattern distribution by providing an input to the simulation.

Simulation of Leaf Venation Patterns on Mesh Surfaces

The leaf venation algorithm could also be implemented on three-dimensional mesh surfaces. In this case the overall outline of the algorithm is similar but various methods are added to construct three-

Figure 2
The leaf venation algorithm in 2D. Left: Open leaf venation pattern with large kill distance. Right: Closed leaf venation pattern (anastomosis) with small kill distance.

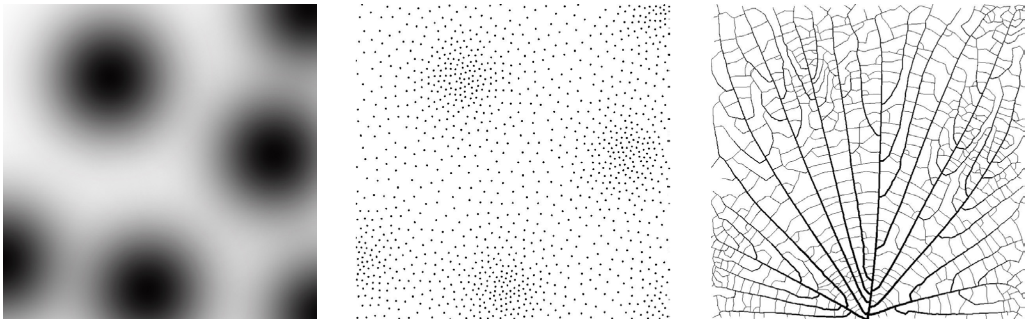


dimensional geometries efficiently. The auxin sources are placed on the mesh surface to guide and constrain the placement of vein nodes. For a uniform result, the auxin sources are placed at the center of each triangle mesh. The vein nodes are placed by the user to decide on the centers of growth over the surface. During the simulation the construction of vein geometries is controlled using collision detections with the mesh to guide the form generation over the surface. Similar to the two-dimensional implementation, the auxin sources are removed when the vein nodes are too close. The input mesh informs the overall topology of the final leaf venation configuration (Figure 4).

For the construction of the vein geometries the normal vectors from the mesh surface are used to model continuous forms while maintaining hierarchy among parts. Starting from the root node the veins grow over the mesh surface finding the closest auxin sources. For the simplicity and efficiency of the algorithm the distances between the vein nodes and the auxin sources are calculated by euclidean distance. This gives a satisfactory result to define the average direction for the growth of vein nodes and reduces the computation time.

The vein geometries are constructed using the normals of the mesh surface. In addition, the veins are thickened in the perpendicular direction to increase

Figure 3
The leaf venation algorithm with different densities. Top left: The input density map using gradient. Top right: The auxin source distribution guided by the density map. Bottom: The generated leaf venation pattern with anastomosis. Notice the concentrated parts on the pattern where the auxin sources are dense.



the inner structure and connectivity of veins. The overall performance and execution of the algorithm presents unpredictable patterns, yet the patterns are always connected and continuous achieving structural geometries that have leaf venation patterns.

PERFORMANCE OF GENERATIVE BUILDING ENVELOPE SYSTEMS

In many performance simulation systems there is still a lack of direct connection between simulation results and how these values are integrated in architectural design models. There have been previous studies that addressed this problem to redefine performance as not only an analysis tool, but as a direct feedback to a generative design mechanism (Oxman et al., 2007; Grobman et al., 2007). Generative systems offer parameters to control the behavior of the system that guides the final outcome for a desired effect. Although most of these systems are able to produce variability of architectural and formal solutions for design, they still rely on architects to control the overall behavior of the system and choose from the various alternatives that are generated. This issue presents a gap between the designed product and the analysis data that is extracted from the simulation.

While the performance analysis of a design follows a schematic approach, the integration of the data back to the design is not established due to the non-generative approach towards design (Becker, 2008). For instance, in a parametric façade system architects work with topological variations of fixed elements of design. The analysis of the performance and the integration of the data back to the system are achieved after these systems are already created and designed. This limits the performative quality of these building elements as their freedom is pre-given and restricted by the design.

An alternative to this approach could be considered when the parametric ability is given to the parts before the design evaluation process. Rather than starting with an overall configuration of a façade with fixed components, these flexible individual parts will be able to interact and change achieving form as a collective outcome. An advantage of this approach is the ability to integrate various pre-given performance criteria for the final design of a building form. This way the performance criteria could be integrated within the design process opening up new negotiations within the design process.

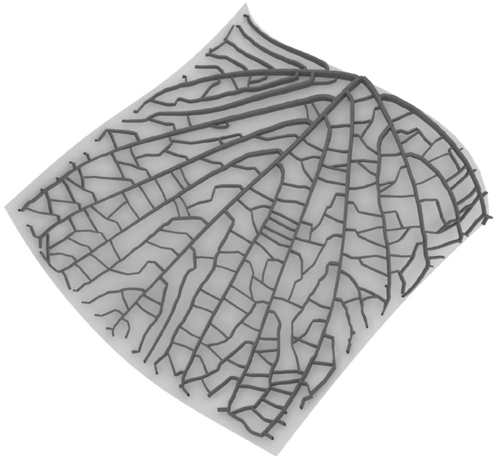


Figure 4
The leaf venation algorithm on a 3d mesh surface. The auxin source distribution is uniform to produce an evenly distributed closed venation pattern over the surface.

The leaf venation patterns that are presented in this paper are an example of how this bottom-up process could be implemented for the design of building envelopes. These systems could be generated on mesh surfaces with changing densities to create continuous systems. It is also possible to use solar radiation analysis as an input to generate pre-determined performance values based on the topology of the surface (Figure 5). This input surface to the program is used for the placement of auxin sources that will inform the distribution and computation of the venation pattern. As a result, the building envelope that is generated has changing densities, and patterns that relate to a specific local performance behavior (Figure 6). As an alternative automated process, this approach considers performance and evaluation as pre-conditioning factors for the generative behavior of the leaf venation algorithm. While the input of the system could be controlled by the architect the outcome of the system is computed. This provides an automated outcome for the design

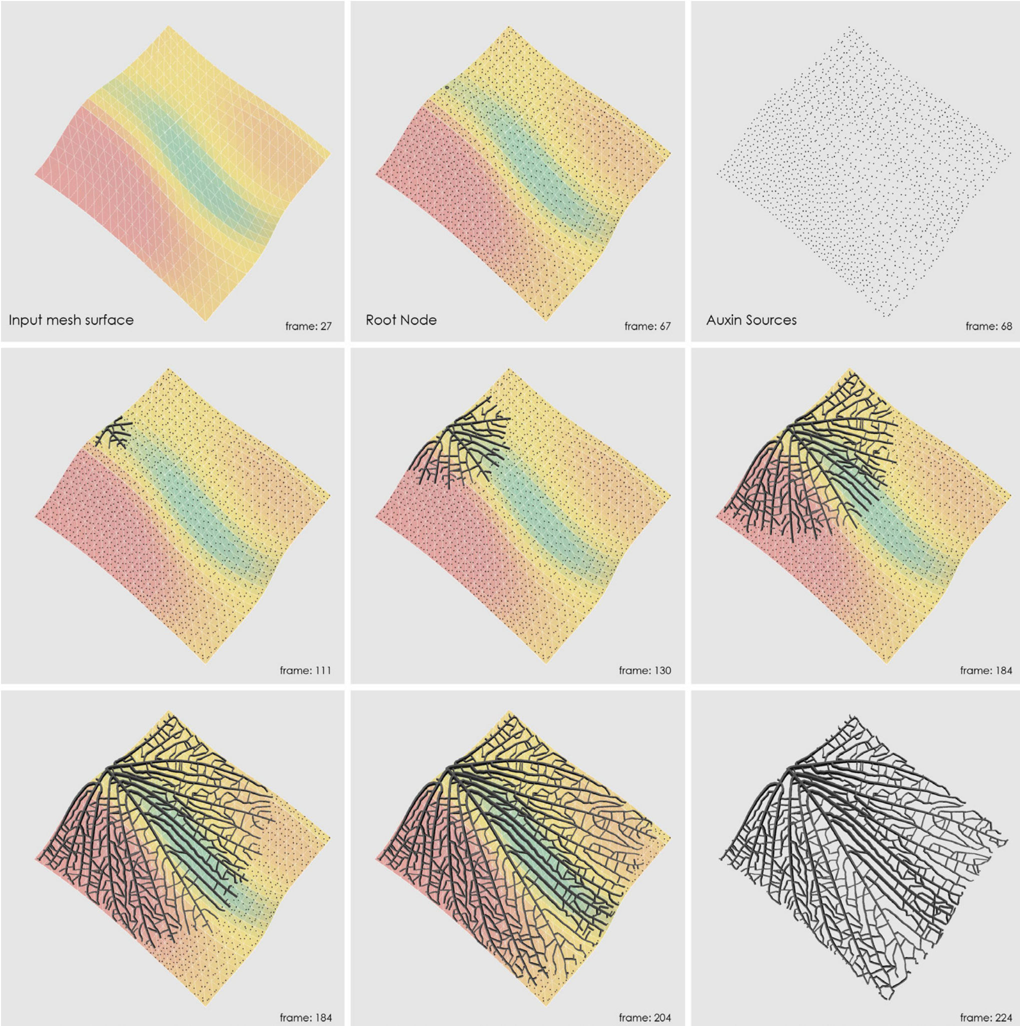


Figure 5
The leaf venation algorithm running on a 3d mesh surface. The input surface and the analysis data inform the distribution of auxin sources. The root node is placed by the user. The final geometry has local densities and corresponding distribution of vein nodes according to the analysis.

problem and integrates performance analysis directly to the computation of form.

EVALUATION OF GENERATIVE BUILDING ENVELOPE SYSTEMS

In a performance simulation system, a schematic approach defines how evaluations are quantified and integrated before another simulation is made (Becker, 2008). This schema provides a template for how computational tools are embedded in the process rather than establishing potential new connections following the analysis of design evaluation. On the other hand generative design tools act diagrammatic, providing various avenues for a project to be further

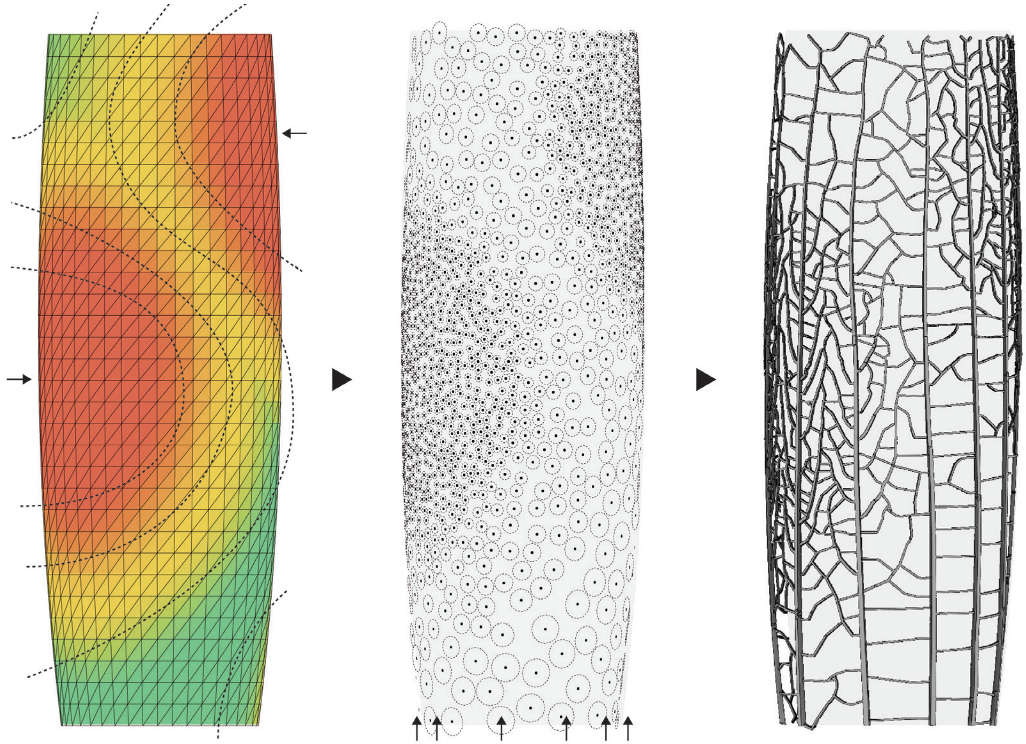


Figure 6
Leaf venation algorithm running on a building model. The input surface and the analysis data inform the distribution of auxin sources. Red areas inform denser auxin source placement. Multiple root nodes are placed by the user to facilitate simultaneous growth. The final geometry has local densities and corresponding distribution of vein nodes according to input.

developed. However, there is still a lack of integration concerning how these generative design processes and performance simulations could be connected at an early design stage (Grobman and Ruth, 2011).

The integration of various programming tools could help bridge the gap between analysis data and design by giving performative behaviors to system components during design development phase. This approach considers building elements as smart objects that can interact and change leading design in a developmental way. The leaf venation façade system presented in this paper is an example of how such process could be implemented. Since the algorithmic approach provides generative morphologies for design tasks, various performance criteria could be simultaneously tested providing different opportunities for development of a project. This system could be essential to connect the overall performance expectancy of a system and the local behavior of parts of a building. In this case the leaf venation patterns could pose a valuable approach towards the design of performative façade systems (Figure 6).

BIM INTEGRATION

Today performative façade systems highly rely on parametric tools that can be operated on various BIM tools. These programs enable efficient and seamless data exchange among participants of a project and provide modular parametric components to complex design solutions (Eastman et al., 2008). However these programs are still lacking customization options or generative tool development interfaces. As architects learn more programming interfaces they tend to develop their own tools for any specific problems. In many case these tools are hard to be integrated within BIM software since they are created outside the modeling environment.

The leaf venation patterns and the geometries that are produced for this paper represent an example of such problem. The mesh surfaces and the data that is used for the algorithm is generated in Rhino and Grasshopper. The mesh surfaces and data are imported into Processing to run the simulation. The generated venation patterns and geometries could be exported back to various BIM tools but these models would lack the consistency for the identification of individual parts for their further evaluation and manipulation. It will be essential to develop tools that can enable the integration of these technologies in BIM environments to provide innovative avenues for architectural solutions.

FUTURE WORK

The current implementation of the algorithm runs efficiently in two-dimensional mediums. To improve the three-dimensional implementation, the euclidean distances for auxin kill distances could be replaced by geodesic distance calculation. This will increase the computation time but will provide more reliable data and construction of venation patterns.

The articulation in the leaf venation pattern is proportional to the amount of triangle meshes used for the algorithm. In order to make the algorithm perform faster, lesser amount of triangles with more sources could be used. In addition, a balanced distribution of the auxin sources could be achieved by using a point relaxation method. This way the sources could be repelled away from each other before the simulation runtime to guarantee a uniform distribution of sources over the mesh.

CONCLUSION

Performance based design offers avenues where generative systems and computation could be used for architectural form-finding. Rather than using simulation for design evaluation and feedback, simulation could be directly used for form generation and variation.

This paper presented an approach for developing and testing generative design techniques of building envelopes. Using leaf venation patterns it is possible to construct a robust algorithm that can generate continuous and variable performative structures that have aesthetic qualities (Figure 7). While this system takes the performance criteria as a given parameter for design, the generated systems act to satisfy these needs through a responsive and interactive process. This way performance is considered as not a post-evaluation of a topological form or design. Instead, performance will be seen as a framework that defines the variable inputs that guide the behavior of an early generative design approach.

Since the morphology of the building components is achieved by growth, the system has self-organizing behavior in order to achieve structural outcomes. By using such methodology architects will be able to generate and test various iterations using simulations before deciding on the final product. This will change the schematic character of performance based design systems into a diagrammatic nature, showing alternative and dynamic design outcomes as the product of a single generative machine (Spuybroek, 2004).

REFERENCES

Becker, R 2008, 'Fundamentals of Performance-Based Building Design', *Building Simulation*, 1: 356–371.

Dengler, N and Kang, J 2001, 'Vascular patterning and leaf shape.' *Current Opinion in Plant Biology 4*, 1, 50–56.

Eastman, CM, Teicholz, P, Sacks, R and Liston, K 2008, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Architects, Engineers, Contractors, and Fabricators*, John Wiley and Sons, Hoboken, NJ.

Garcia, M 2010, *The Diagrams of Architecture*, Wiley, Chichester.

Goethe, JW von and Miller, D (ed) 1988, *Scientific Studies*, Suhrkamp, New York.

Figure 7
A rendering of the structural façade system generated by the leaf venation algorithm.

Goethe, JW von 1993, *The Metamorphosis of Plants*, Bio-Dynamic Farming and Gardening Association, Kimberton, PA. Translation of Die metamorphose der pflanze taken from the British Jurnal of Botany (1863). Rev. by Anne E. Marshall and Heinz Grotzke.

Grobman, YJ and Ruth, R 2011, 'Digital Form Finding: Generative use of simulation processes by architects in the early stages of the design process', *Respecting Fragile Places: 29th eCAADe Conference Proceedings*, eCAADe. Ljubljana, Slovenia: University of Ljubljana. Faculty of Architecture, pp. 107-115.

Grobman, YJ, Yezioro, A and Capeluto, IG 2007, 'Performance Based Form generation in Architectural Design - Using Performance Envelopes in a Generative Computer-Oriented Design Method', *Proc. of Tectonics Making Meaning International Conference.*

Prusinkiewicz, P and Lindenmayer, A 1990, *The Algorithmic Beauty of Plants*, Springer-Verla.

Runions, A, Fuhrer, M, Lane, B, Federl, P, Rolland-Lagan, A-G and Prusinkiewicz, P 2005, 'Modeling and visualization of leaf venation patterns'*, Acm Transactions on Graphics*, 24, no. 3, pp. 702-711.

Sachs, T 1991, 'Cell polarity and tissue patterning in plants', *Dev. Suppl. 1*, 83-93.

Spuybroek, L 2004, *Nox: Machining Architecture,* Thames & Hudson, New York.

Oxman, RE. , Roey, H and Shoham, BA 2007, 'Performative Design in Architecture', *Predicting the Future: 25th eCAADe Conference* Proceedings, pp. 227-234.

Thompson, DW 1992, *On Growth and Form*, Dover, New York.