Computational and Physical Modeling for Multi-Cellular Pneumatic Envelope Assemblies

Kathy Velikov, Geoffrey Thün, Mary O'Malley and Lars Junghans

Computational and Physical Modeling for Multi-Cellular Pneumatic Envelope Assemblies

Kathy Velikov, Geoffrey Thün, Mary O'Malley and Lars Junghans

This article describes recent research on the performative, formal and aesthetic potentials of multi-cellular pneumatic foil-based envelope systems for lightweight, responsive building skins able to control thermal insulation and air exchange with minimal amounts of energy and mechanical components. The prototype-based research involves the use of principles from biological examples of pneus, which inform the design of physical analogue models at an architectural scale. The process entails physical-computational feedback loops wherein physical performance findings are fed into computational design models for pneumatics and membranes, as well as modified energy models, in order to advance the predictive design capacities of simulation tools in designing such systems. In this process, material agency allies with computational agency to develop novel possibilities for dynamic pneumatic envelopes.

1. INTRODUCTION

The research described in this article is predicated upon the hypothesis that there is significant formal and performative innovation that can be advanced by exploring the possibilities of three-dimensional figural aggregation of nested pneu cushions with integrated kinetic capabilities for responsive performance. The aim of this work is to discover new models for lightweight, multifunctional, and light transmitting material systems, comprised of a singular composite material, capable of localized, variable control of thermal insulation, air exchange and human interaction (Figure 1).

▼ Figure 1: Installation of full-scale prototype of nested multi-cellular pneu array. (Photo: Kull, © Velikov/Thün 2014)

The formal, material and computational research in pneumatics for architectural applications was pioneered in the 1970's through the work of the Stuttgart Institute for Lightweight Structures (IL), under the directorship of Frei Otto. A *pneu* was defined by researchers at the IL as a medium enveloped by a membrane stressed in tension. Pneus were regarded as a fundamental material system to be explored by designers seeking to develop lightweight structures shaped by, and adaptive to, external forces. They were considered to be one of the basic structural principles of living organisms and were central to the IL's broader explorations on the intersections and between biology and building [1], [2]. This research aimed to advance knowledge on how biological forms and principles could inform the future of the built environment, and their advancements have continued to inform work today.

The late 1960's and early 70's witnessed a surge in inflatable structures, in both architectural and artistic practices [3], [4]. Pneus were recognized as being ideal for responsive architecture, due to their ability, in the words of Nicholas Negroponte, to "exhibit motor reflexes through simple controls" [5]. In the area of architectural pneumatics, the advances at that time were were primarily found in large-scale inflatable and air-supported structures. The possibilities of multi-cellular pneus for architectural applications, analogous to the compound membrane aggregates that appear more frequently in biotic systems, have, until recently, been relatively minimal [6], [7].

There has recently been a renewed interest in membrane-based architectures and pneumatic structures, spurred by recent advances in the material science of membranes and co-polymers, by new developments in lightweight textile and foil-based systems, by distributed and minituarized control systems, and by a maturing suite of computational tools for simulating nonlinear structural systems. On the material science side, the approval of ethylene tetrafluoroethylene (ETFE) for use in building applications in the late 1980's has fostered an accelerated refinement in pneumatic building skin systems [8], [9]. At a fraction of the weight of glass, ETFE foil assemblies have a much lower embodied energy, and this lightness has the potential to reduce overall building weight and material usage across multiple systems, improving the embodied energy performance of such structures [10], [11]. Unlike the long-span air supported structures of the past, contemporary ETFE envelopes are comprised of either individually inflated cushions or stretched foils assembled into insulating panelized building skins. The majority of contemporary ETFE research is focused on improving performance through additional layered films for thermal control, specialized coatings, switchable layer systems for shading, and integration of photovoltaics [12]. The body of work described in this article seeks to advance novel topologies for nested cellular pneu systems, and to combine these systems with dynamic components for modes of adaptation.

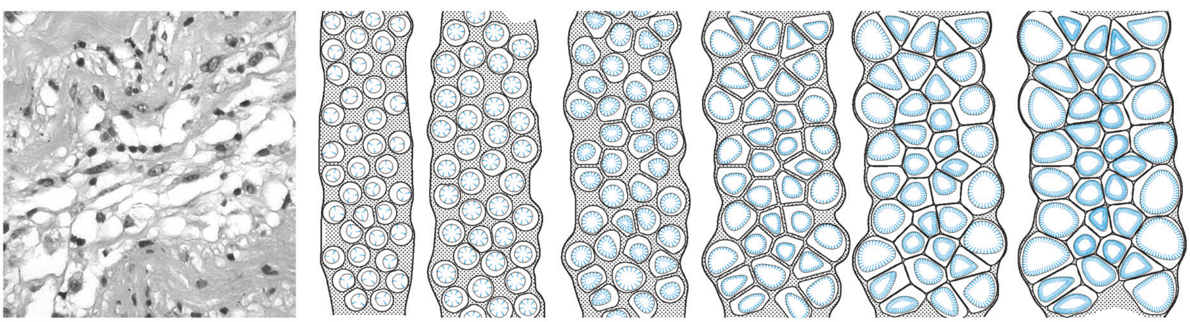
The non-linear and elastic properties of pneumatic structures make them notoriously difficult to simulate within a computational environment [13]. While it is possible to model inflation within a variety of software ranging from physics engines to animation programs, all current platforms have limitations in the extent to which they can reliably simulate a consistent relationship between deformations and real-world pressure or anticipate the behavior and effects of material collisions in the aggregate arrays [14]. The research described in the following article describes the iterative feedback that the authors have undertaken between digital and physical models in the development of full-scale prototype arrays and dynamic components. Also described is the development of a computational method for thermal simulation modeling of pneumatic figures – another area of research that requires significant advancement – and its verification though physical testing. Finally, we point to the scope of future research implicated by the initial investigations.

2. COMPOSITE PNEUMATIC SKINS

This research into composite pneumatic skins involved preliminary investigations into biological examples whose principles can be abstracted to inform film-based constructs. Biotic skins are often able achieve complex functions with minimal use of energy and resources through multifunctional material, organizational and geometric intelligence of differential membrane systems [15]. This work investigates two primary capabilities that present productive models for the development of architectural translations: variable thermoregulation (which has informed the investigations into cellular aggregation), and nastic movements (which has informed our investigations into nondirectional pneumatic motion systems).

Adaptation to severe changes in temperature is one of the most basic imperatives, biologically and architecturally. In some mammals, adipocytes (fat cells) can provide variable thermoregulation through the variation in the lipid content of their highly elastic exterior membranes [16] (Figure 2). Translating this principle into a material system, pneus might be programmed inflate and deflate to vary their capacity to thermally insulate across an aggregate assembly. Building skins might become 'chubby' and sealed in winter, 'skinnier' and more porous in summer. In order to explore this characteristic, an investigation was undertaken into possible geometries for co-dependent cellular aggregation within deep skin systems.

▼ Figure 2: Biological model studies for pneumatic thermoregulation. (Photo: Rosen 2008; Drawing: Velikov/Thün 2014)



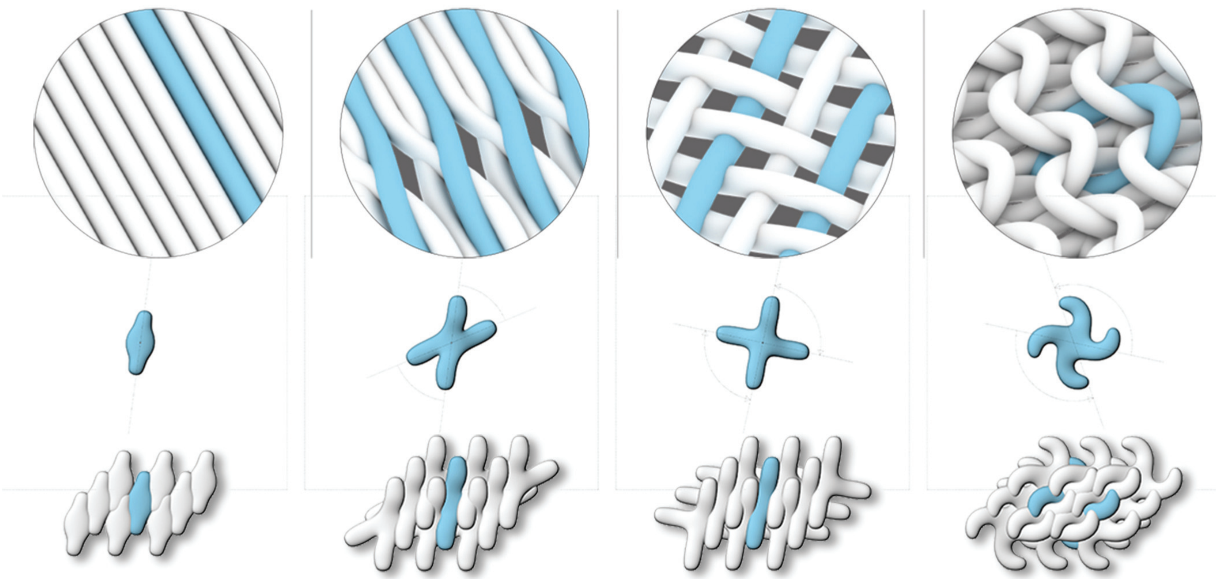
The most well-known aggregation geometries for pneumatic cells are the polyhedral tight packing structures derived from the inspection of the structure of foams, polycrystalline solids, living cells and soap bubbles [17].

Most commonly referred to as Weaire-Phelan structures, these may be topologically described as three-dimensional minimal surfaces whose Plateau borders form a continuous network [17]. However, in order to maintain contact pressure between the cells, a continuous exterior bounding wall or membrane is necessary for packed foam and bubble structures. One of our primary research questions was whether alternative and novel geometries for aggregates of pneu figures could be developed that maintain networked contact by alternate means.

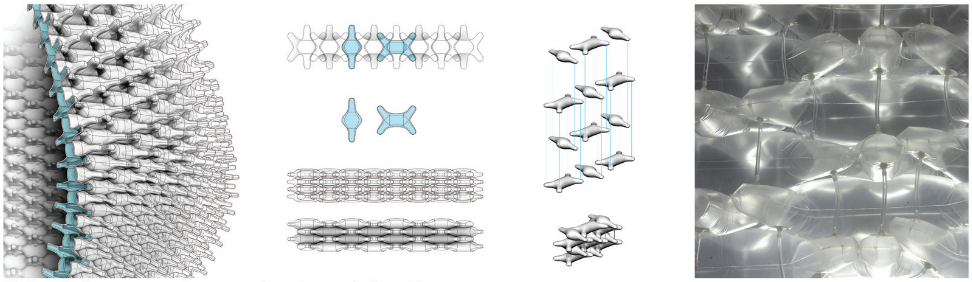
2.1. Array Development

The development of the nested, multi-cellular pneu skins began with the investigations into topologies of stacking, braiding, weaving, and knitting (Figure 3). These surface topologies were deconstructed into networks of interlocking primitives, such as S-figures, X-figures and Y-figures (Figure 4). The resulting assemblies behave much more like textiles than foam or packed bubble structures.

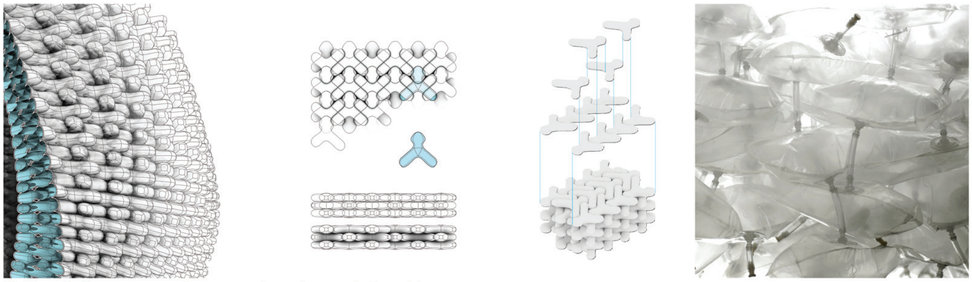
▼ Figure 3: Topology Studies: stack, braid, weave, and knit translated to nested interlocking units. (Velikov/Thün 2014)



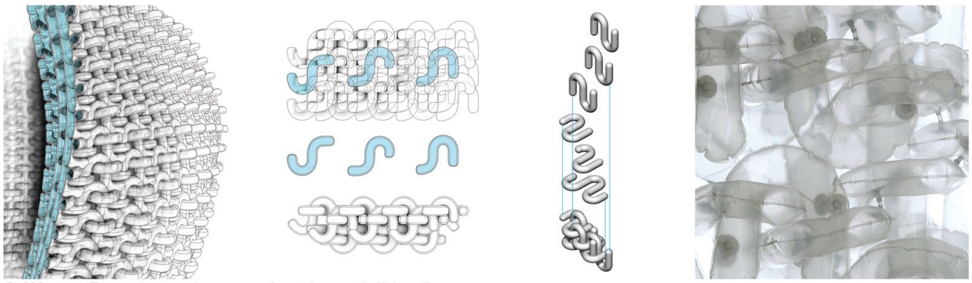
▶ Figure 4: Computational and physical prototype explorations of stack, weave, braid and knit topologies translated into various interlocking pneu arrays. (Photos and drawings: Velikov/Thün 2014)



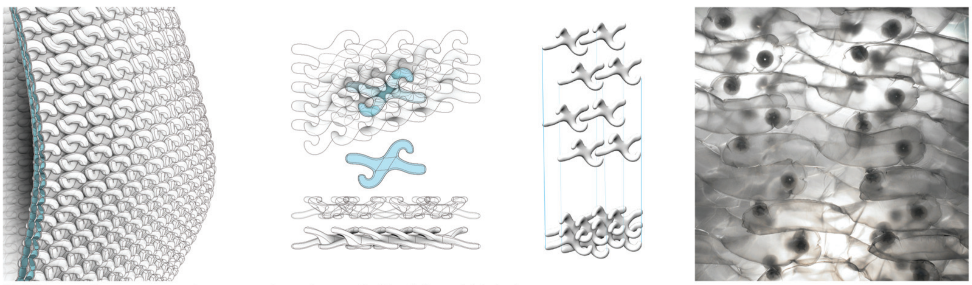
X-Stack Prototype: Aggregation through Stacking



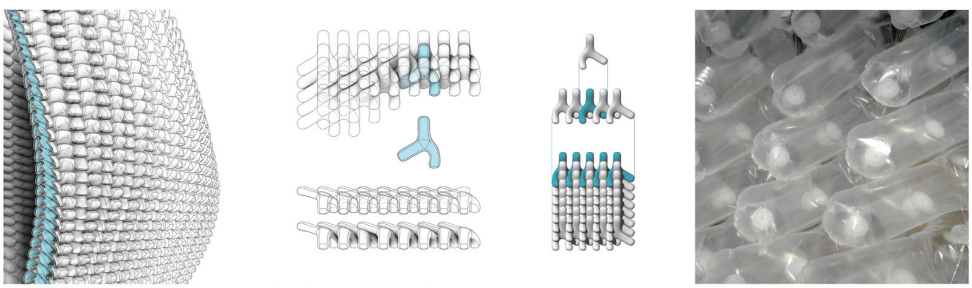
Y-Stack Prototype: Aggregation through Stacking



S-Weave Prototype: Aggregation through Weaving



X-Weave Prototype: Aggregation through Braiding / Knitting

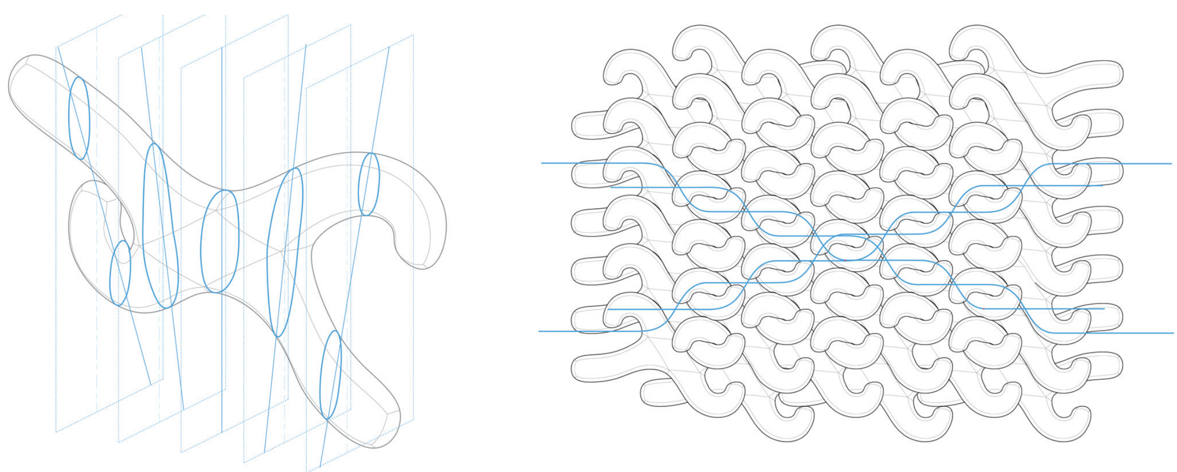


λ-Weave Prototype: Aggregation through Weaving

A heuristic process of testing and evaluation of the various arrays and their components determined which geometries held promise for further development. Arrays were iteratively developed as physical feedback informed the fidelity of the computational models and array models and their constituent figures were physically prototyped and evaluated through observations across a range of criteria assessing limits of geometrical configuration, deformation under pressurization, film uniformity at cushion edges, frequency of geometrically-induced stresses, valve location conflicts and replicability. Array geometry development was shaped by the physical constraints of materials and available methods of manufacture (the use of only two-dimensional contour-welded cell cushions as opposed to three-dimensional polyhedra), interconnection (via air valves and tubing) and suspension.

Weave arrays proved to hold the most promise. These share some qualities with both topological interlocking assemblies and with braid topologies. Topological interlocking is a design principle by which elements of a special shape are kept in place by kinematic constraints imposed through the shape and mutual arrangement of the elements [18]. This type of interlocking between cells is dependent on the cross section of individual cells continuously shifting in opposing directions relative to the centerline of the assembly cross-section (Figure 5). Such assemblies are able to maintain aggregation without fasteners, connectors, or binding agents, and figures can be designed to allow for interlocking between multiple parallel layers. While topological interlocking assemblies are typically composed as horizontal planes and rely on a rigid bounding perimeter to maintain the integrity of the assembly, this principle is helpful in developing geometries that lock together and create multiple insulating layers with a minimum number of elements. Braid theory also provides another logic for considering moments of component interlocking. The principles of braid groups – that strands must be continuous, must not intersect, and can only loop in a consistent

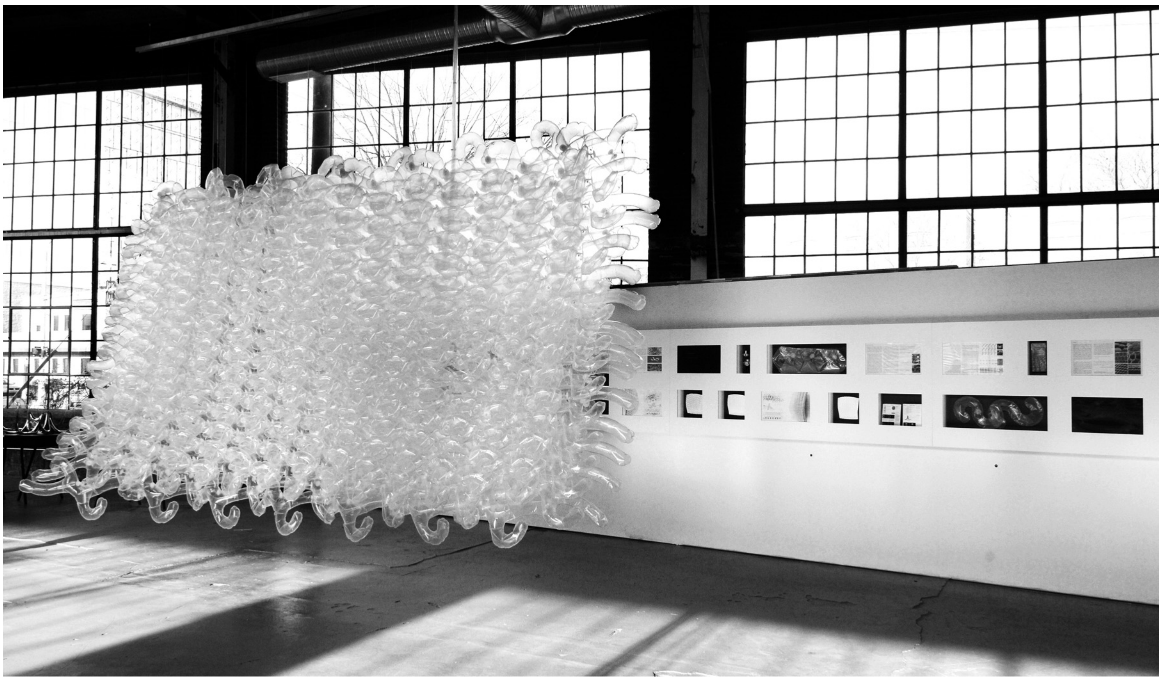
▼ Figure 5: Topologically interlocking assemblies are composed of units that shift around the centerpoint of the assembly through the cross-section of the figure (left). The interwoven curved arms of the X-weave can be understood as a repeating braid geometry (right). (Velikov/Thün 2014)



direction (i.e. strands cannot fold back up on themselves) – also apply to the logic of the pneu figures [19]. If individual figures are arrayed on a grid, the ordinates of the grid can be considered as individual strands, and by shifting the endpoints of these strands, new opportunities for looping units together can be identified.

The weave arrays also capitalized on the specific formal material capacity of pneus to deform during inflation, and make use of appendages that interlock when pressurized to produce an integrated self-reinforcing system. Once inflated, the interlaced weave topology combined with a pseudo-structural air tubing network is able to bind together to achieve a tightly nested envelope system. Of the arrays explored, the "X-Weave" was considered to be one of the most successful weave geometries as it was able to achieve a nested three-layer array through the simple weaving action of a single figure type, and was thus the array chosen for development into a full-scale prototype for a public exhibition of the research (Figure 6). Due to its geometric strategy, the front and rear sides of the array exhibit distinct formal characteristics (Figure 7).

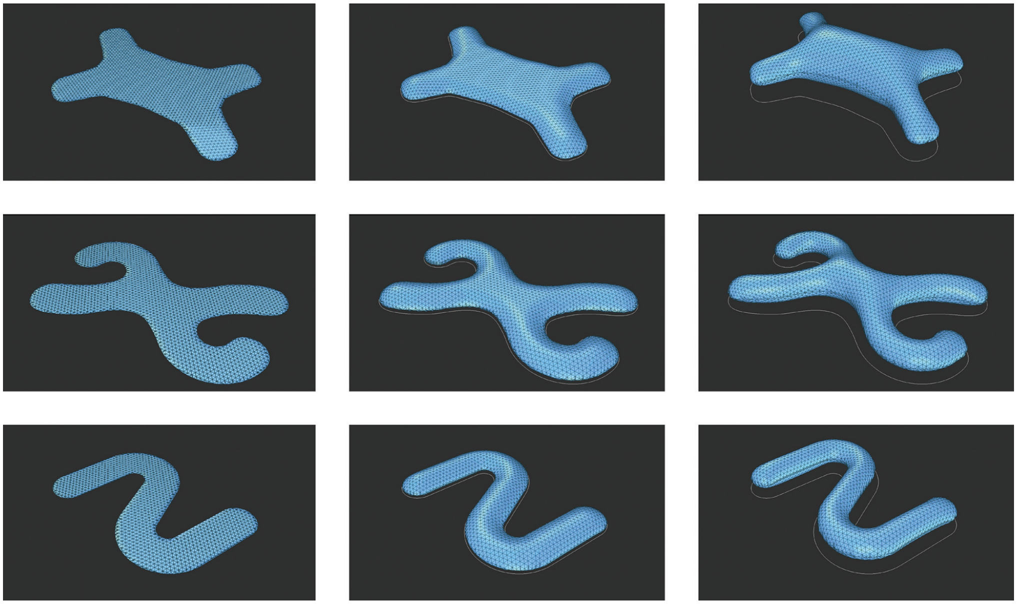
▼ Figure 6: Installation of a large X-Weave prototype array for public exhibition of first-phase design-research results. (Photo: Velikov/Thün 2014)



▲ Figure 7: Surface detail of X-Weave prototype array, opposite side. (Photo: Velikov/Thün 2014)

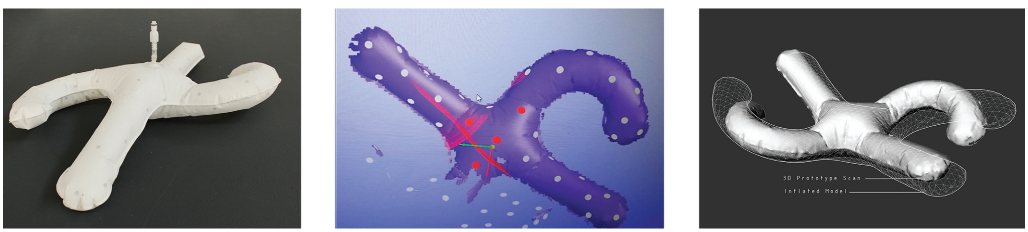
3. COMPUTATIONAL INFLATION MODELING

The research into multi-cellular pneumatic aggregation and nastic movement systems entailed a parallel body of research into combinatory approaches for computational simulation and fabrication of pneumatic models and assembly prototypes. In the prediction of the final inflated form of pneumatic figures, we experimented with both animation programs such as 3D Studio Max®, Maya® 3D (where pre-programmed 'material' options such as spring strength, curve density, damping, etc. are pre-adjusted to reflect real-world membrane material characteristics) and the Kangaroo plug-in for Rhinoceros® (whose stripped down physics engine allows the models to be more dynamic and interactive). The computational workflow that was ultimately pursued involved modeling pneu meshes in SmartForm, and simulating inflation with a customized Kangaroo definition (Figure 8). In order to verify the computational models, single cells were also physically prototyped, inflated, and 3-D scanned. The scanned prototype was compared to the digital model, and feedback from resulting variations was utilized to refine the definition parameters so that it could more closely simulate the final form of the inflated cushion figures (Figure 9). Although this process has been fairly successful in modeling individual pneu figures, the combined action of figure-to-figure collision, restraint, eccentric



▶ Figure 8: Cell inflation screenshots for various pneu figure types, using Kangaroo plug-in for Rhinoceros. (Velikov/Thün 2014)

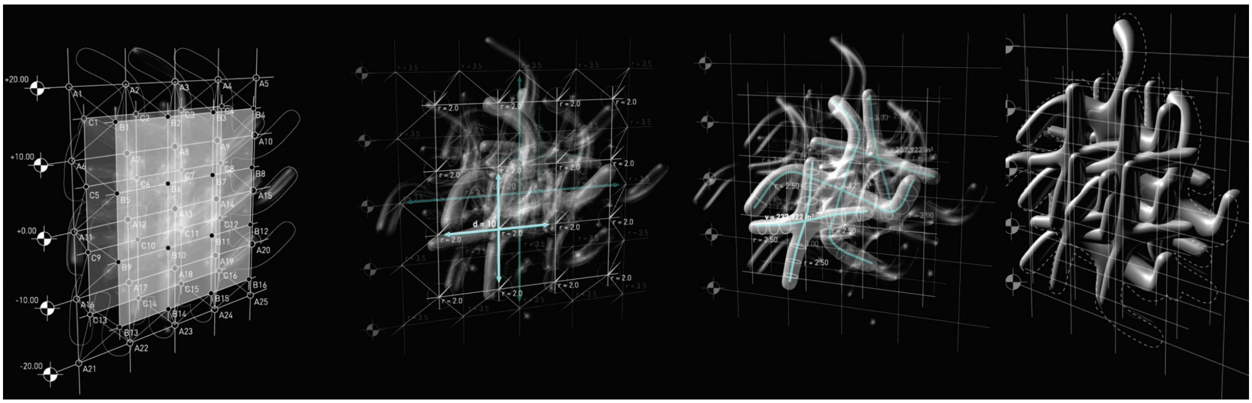
pressure and overall deformation characteristic of the array assemblies cannot be accurately predicted with our current computational methods. In response, we are examining the possibilities of skeletal, particle and agent based simulation techniques for the aggregate assemblies, however, this observation underscores the necessity for working iteratively between digital and physical models, and using a combinatory simulation approach in the development of this work.



▲ Figure 9: l-r: X-Weave figure prototype, spray painted solid (for scanner detection) and tagged with laser scanning positioning dots; Screenshot of laser scanning data constructing a digital model; Overlay of digital model and scanned prototype figure. (Velikov/Thün 2014)

Learning from the feedback between physical and digital prototyping, we also began to develop a refined set of principles and workflow using Maya 3D for how the interlocking unit geometry can be derived and assembled into deep, nested formations. Beginning with a series of grids, all relationships in the model were established at a basic organizational level: points and lines. At the grid intersections, nodes are were identified to which spheres were assigned. Each node extended four lines to its adjacent nodes which correlate to the units they will interlock with. In order to meet the desired level of interlock, each line was divided into a series of points, each of which received a directional weight with respect to the surrounding geometry. These lines were then extended along X, Y, and Z directions in order to establish mutual kinesthetic constraints between geometry. Once adjustments to the extensions were made, each line received a radial thickness, which was then blended to the sphere at its correlated node. When this logic was applied to all the nodes on the grid, the result was a thickened pneumatic textile-like structure (Figure 10). When this process was replicated with additional base grids, deep, nested, interlocking arrays at an infinitely variable thickness can be achieved.

▼ Figure 10: Video stills of deeply nested array modeling logic and geometry. (Velikov/Thün 2014)

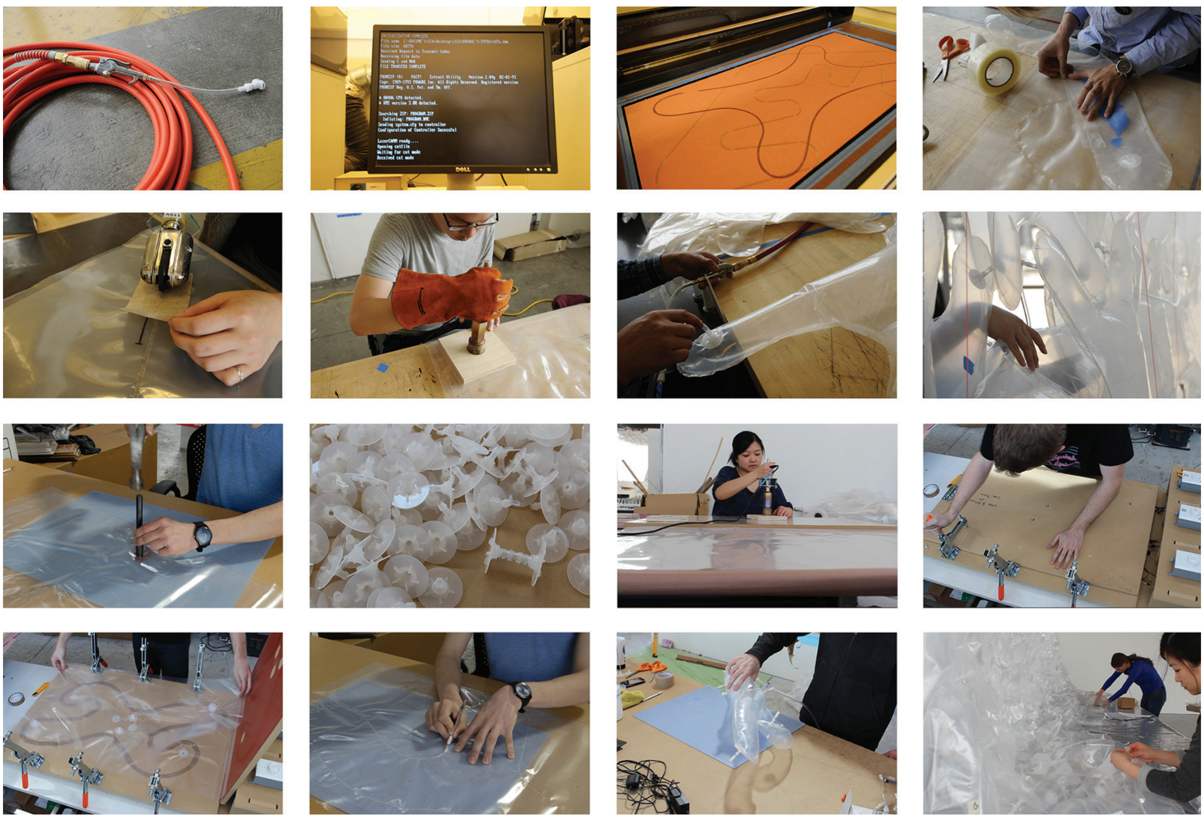


3.1. Physical Prototyping

Empirical knowledge gained through observation, testing and assessment of physical prototypes is an essential component of the design-research process. Prototype instantiations inform the fidelity between digital design and simulation tools and anticipated outcomes, allowing for refinement of the digital design environment. Such prototyping also reveals fundamental issues related to limitations of material and geometric combinations, spatial and material conflicts as well as coarse level insights into issues associated with manufacturing and assembly to be addressed early within the conceptual development of new propositions that are elusive within virtual design environments. Prototyping encapsulates the design space as a proving ground for methods of study as well as a generator for new vocabularies in material form and spatial performance [20].

Within contemporary industrial manufacturing settings, ETFE foil cushions are typically thermally welded using a large-scale impulse sealer to provide the specified combination of heat and pressure required to bond the foil edges [8]. This is, however, impractical for rapid testing of non-rectilinear geometries and differentiated cushion forms due to a combination of process limitations, set-up times and ready access to commercial equipment for researchers. In order to be able to undertake prototyping, testing and iteration of a multiplicity of cushion forms, two in-house methods of sealing the films were utilized: custom thermal contour welding films with a defocused CO2 laser cutter to test parametric variations on multiple geometries, and a custom clamshell heat press for higher volume production of repetitive unit types (Figure 11). In the physical prototypes, 4mil LDPE thermoplastic was used as opposed to ETFE due to cost and compatibility with available welding technology, yet similar material characteristics relative to thickness, stiffness and light transmission. Connections between the figures in both cases were achieved with off-the-shelf medical valves and clear PVC tubing, and we are now experimenting with custom 3-D printed components.

▼ Figure 11: Prototype manufacture sequences using laser-welding and heat press methods. (Photos: Velikov/Thün 2013-14)



4. ENERGY PERFORMANCE: COMPUTATIONAL AND PHYSICAL TESTING

While membrane-based envelope assemblies have the ability to create lightweight transparent envelope structures with improved embodied energy over glass, the thermal performance of these assemblies is fundamental in achieving the next generation energy efficient buildings. The hypothesis of this research is that multi-cellular pneu arrays will be able to achieve high thermal performance values due to their smaller cavity size (reducing internal convection), the multiple layers of cavities (as opposed to single cushion assemblies) and the reduction in frame components (which contribute to thermal bridging). Issues of overheating, which are also a problem for transparent building assemblies, while not addressed specifically in this research, can be mitigated by the self-shading created by multiple layers of cushions, and by shading applications on foil surfaces, such as electrochromic coatings [21].

The calculation of thermal performance for membrane-based cushion assemblies is an area of active research. Performance metrics published by industry leaders in ETFE applications list the center-of-cushion U-value as comparable to center-of-glass values published for low-e double-glazing systems [22], [23], [24]. However, several factors complicate a comparison based on static U-value alone. Energy is transferred across the thickness of a cushion more through convection and radiation than conduction, and the extent of energy transferred is highly contingent on both the size and orientation of the air cavity [25]. Due to the compounded effects of radiation and convection within the cavity, heat flux through a membrane cushion is also highly unsteady over time, making transient modeling a more accurate reflection of the actual performance of such systems [26]. As most software platforms for calculating energy performance of building systems do not account either for transient material properties or for complex geometries of individual units or assemblies, we are exploring alternate methods for predicting the energy performance of each pneumatic assembly through transient heat flow analysis and fluid dynamic simulations

Fluid dynamic modeling and transient analysis have been used in some studies to better understand the thermal behavior of ETFE cushions. Antretter et al (2008) validated a CFD model of a single two-layer ETFE cushion 4.75mm in diameter against an experimental roof installation. Kaufman et al (2013) calculated the transient U-value of an experimental wall installation over the span of one year. Dimitriadou and Shea (2012) studied a physical installation of a single ETFE foil over the course of two weeks to better understand the diurnal effects of long wave radiation transmission [25], [26], [27]. However, these studies do not account for assemblies that consist of more than two layers of foil or multiple adjacent cushions. As a result of the inherent layered configuration of aggregate pneus assemblies, such composite membranes necessitate assessment of the thermal effect of multiple adjacent cushions and the transfer of heat through multiple cell chambers.

We are currently developing a dual simulation modeling approach utilizing TRNSYS to simulate heat flow across a section of the assembly over time and FLUENT to model the convection within the cushion cavities, with comparative hot box tests for physical validation of the simulations.

Due to limitations of both the simulation software and the physical experiment, in all cases the tests were performed with somewhat simplified models to isolate the thermal performance of cushion thickness and quantity alone. Issues related to infiltration and radiation were not taken into account during the tests.

4.1. TRYNSIS Modeling

A heat flow model was produced to try to understand the relationship between the thickness of a cushion assembly and the resulting U-value. By observing heat flow over time against a baseline material, the thermal resistance could be calculated. Because of geometric limitations within the program, the tested variables of the assembly were limited to cushion thickness and number of cushion layers. To represent a system that approximated the pnues assembly, the technique involved modeling multiple cavities as adjacent zones within TRNSYS. The depth of the zones and the total number of zones was varied throughout the testing.

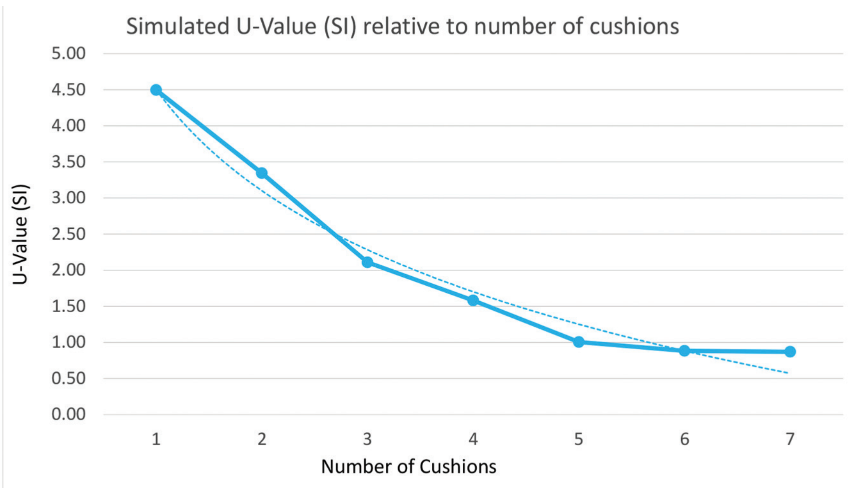
A customized material was inputted into TRNSYS to replicate the characteristics of ETFE foil. Because of the thinness of the material and the low thermal conductivity, the thermal capacity of the material was too small to be taken into consideration and the foil was defined as "massless". The material (tilted FOIL) was instead assigned a resistance of 0.001 m2 K h/kJ, calculated from properties taken from ETFE foil, including a density of 1700 kg/m^3, a specific heat of 2000 j/kg-K, a thermal conductivity of 0.238 W/m-K, and a thickness of 100 microns

Two types of wall assemblies were then defined using the ETFE material: 1) A wall composed of only a single layer of foil to represent outermost cushion edges, and 2) A wall composed of two layers of foil directly in contact to represent the surfaces of the cushion in contact. Individual zones were then defined to be 1m x 1m in height and width, with a starting depth of 100mm. The major 1m^2 faces were assigned the foil wall conditions, and then established as either adjacent or external walls as required. All other surfaces were defined as internal walls and assigned the default pre-defined TRNSYS materials of INTWALL and INTFLOOR construction, functioning as adiabatic surfaces.

Simulations were run for assemblies ranging from 1 to 7 zones, reflecting assemblies with 1 to 7 cushion layers. All models were set up so that the exterior surface faced west (though solar loads were not taken into consideration), and an additional zone (the "interior" zone) on the east side of the assembly, constructed as 1m x 1m x 1m, provided the regulated interior condition. Again, all non-adjacent zones are modeled as internal and adiabatic. The initial temperature of the interior zone was established at 30°C; all other initial temperatures were established at 20°C. The model did not include heating, cooling, infiltration, lighting, or internal gains. A custom weather file was imported into the model that maintained a constant external temperature of 23°C, a constant humidity of 50% and constant radiation levels of 1000. Simulations were run with 0.01 hour time step for 87 hours. Outputs of results included the air temperature of each individual cavity and the interior zone, as well as surface temperatures for the front and back of all of the cushions.

Results were analysed by identifying the time period when the interior temperature dropped 1°C (from stabilized 26.0°C to stabilized 25.0°C), and determining the time required to complete that temperature drop (in seconds) and examining these results against the average difference in the external and internal surface temperatures throughout the experiment. Simulated results indicate that an air-tight four cushion assembly could be expected to have an SI U-value of 1.58 (Figure 12).

▼ Figure 12: Results of simulated heat transfer using TRNSYS. The dotted line indicates control case curve and solid line illustrates simulated thermal performance for each additional layer of 100mm deep cushion (Velikov/Thün 2014).



CONTROL CASE						
Test No	Time (s)	Int Surf Temp	Ext Surf Temp	Δ Surf Temp	Given R-value (SI)	Calculated constant
1	135,792.00	25.39	23.09	2.30	0.88	0.000002818

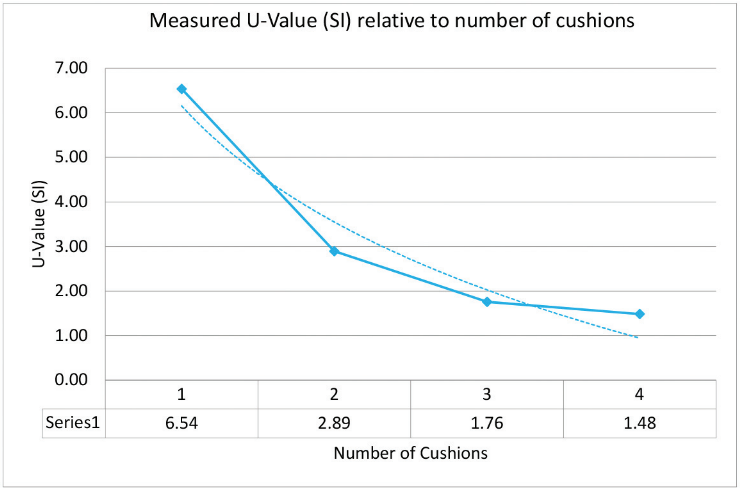
4" CUSHION							
Cushion #	Time (s)	Int Surf Temp	Ext Surf Temp	Δ Surf Temp	Constant	Calc R-val (SI)	U-val (SI)
1	75,168.00	24.81	23.76	1.05	0.000002818	0.222415	4.50
2	98,244.00	22.86	21.78	1.08	0.000002818	0.299000	3.34
3	123,660.00	25.06	23.70	1.36	0.000002818	0.473924	2.11
4	155,916.00	24.71	23.27	1.44	0.000002818	0.632695	1.58
5	179,208.00	25.18	23.21	1.97	0.000002818	0.994866	1.01
6	199,008.00	25.18	23.16	2.02	0.000002818	1.132825	0.88
7	207,108.00	25.16	23.19	1.97	0.000002818	1.1497518	0.87

4.2. PHYSICAL VERIFICATION

To provide validation for the transient thermal model tests, physical tests were performed on cushion assemblies using a thermal chamber, referred to as the "hot box". The hot box had an interior dimension of roughly 1m^3 with five of the six surfaces of the box composed of 150mm thick SIPS panels, and one surface left open to house the test material (Figure 13). Test panels were inserted into the opening and clamped against gasketed cleats inside of the box to minimize air infiltration around the frame.

▲ Figure 13: Photograph of hot box set up used for physical thermal testing. Test panels were inserted into the opening and clamped against gasketed cleats inside of the box to minimize air infiltration around the frame. Thermocouples record the interior of the box, the surface temperature of the most interior surface of the cushion assembly, the surface temperature of the most exterior surface of the cushion assembly, and the exterior ambient temperature 300mm away from the cushion assembly. (Photo: Velikov/Thün 2014)

A control test was performed first with a known material, a 1m x 1m x 0.0254m thick extruded polystyrene rigid insulation panel (Owens-Corning Foamular 150, SI U-value 0.88) to establish a baseline of energy exchange over a constant area. The test was then repeated multiple times with several inflated cushion assemblies of 100mm thickness, arranged in assemblies ranging from 1 to 4 cushions deep. Cushions were composed of heat-welded LDPE for ease of construction. The geometry of the cushions was simplified from the for the purposes of testing; cushion panels were built as simple rectangles with straight welded seams at 160 mm intervals to limit inflation to a 100 mm thickness. The welded seams were not continuous, but had gaps in their length to allow air passage to the full cushion. In multi-cushion assemblies, pleats were offset so the inflated cushions would nest together and limit gaps between cushion layers. Each cushion assembly of one through four layers was tested a total of four times, and results were



◀ Figure 14: Results of physical heat transfer test. Dashed is curve of control case and solid line illustrates measured thermal performance for one to four layers of 100mm deep cushions. (Velikov/Thün 2014)

averaged. The physical heat transfer tests indicated that an airtight four-cushion assembly could be able to achieve a U-value of 1.48 (Figure 14).

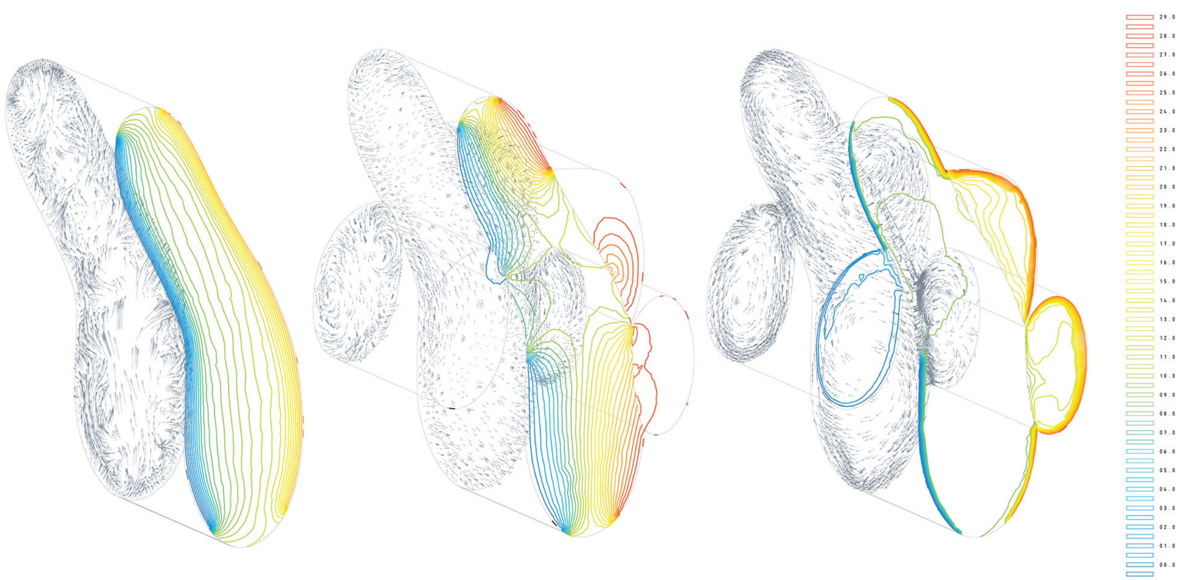
Though the thermal resistance values calculated from the simulations showed some correlation to the values derived from physical tests, in all cases, the simulated tests demonstrated significantly longer time spans to drop 1°C than the physical tests. A number of factors could account for this discrepancy, particularly the possibility of air infiltration during the physical experiments (which the transient heatflow model did not account for) and the effects of convection. In both the simulated and physical test results the relative benefit to thermal resistance of additional layers decreased after a number of cushions, indicating that the assembly would eventually reach a saturation point of transferrable energy. While the transient heat flow simulations indicated a flattening of the thermal resistance curve between five and six cushions deep (between U-1.0 and U-0.88), the physical experiments indicated that the relative benefit to thermal resistance of additional layers would become negligible between three to four cushions in depth (between U-1.76 and U-1.48), suggesting a limit state to effective assembly thickness for design.

4.3. FLUID DYNAMIC STUDIES

To further understand the effect that air flow has on energy transfer in the assembly, fluid dynamic studies were undertaken using the FLUENT module in ANSYS. Though these models have not yet provided quantifiable explanation for the effects of convection or air infiltration, they have afforded some study of the impacts of geometry and figure-to-figure contact on convection within the pneu cushions.

As with both the thermal transfer simulations and the physical tests, the complex geometry of the nested pneu system was simplified for clarity in the fluid dynamic simulations. Exemplar section cuts were taken through the pneu X-Weave assembly, showing the range of figure adjacency, layer quantity, and individual cushion thickness and overlap within the weave. Five section cuts were taken which represented conditions that repeated throughout the array. These sections were then extruded 50 cm to create enclosed volumes that could be inputted into ANSYS and meshed. Due to limitations on the licensing of ANSYS, the mesh resolution was limited to a relatively coarse level of refinement, with one surface node roughly every 20mm^2. All of the figures were drafted as closed volumes, but in each figure, a very small section of one of the end surfaces (roughly 10mm^2) was defined as an outlet surface to prevent over-pressurization of the cavity due to air expansion resulting in calculation error. These outlets were created in non-contact surfaces so the flow of air would not directly affect adjacent cushion figures. Surfaces of the figures that came into contact with other figures were defined as interface boundary conditions, where the two surfaces in contact were defined as a coupled wall. All other surfaces were defined as the ETFE boundary condition.

To simulate convection within the cavities of the wall assembly, 3-dimensional simulations were performed where the thermal properties of opposing cavity surfaces were defined to have a 30°C temperature difference. This was intended to reflect a condition where the assembly would be used for a building envelope assembly in a climate with extreme cold temperatures. During these simulations, the surfaces identified as "exterior" were defined to have a 273K (0° C) constant temperature, and the surfaces identified as "interior" were defined to have a 296K (26° C) constant temperature. The temperature differences between the two surfaces created a convective whorl within the cavity (Figure 15).



▼ Figure 15: Results from simplified CFD simulation models. The models demonstrate (Left) the internal convection of a single pneu figure, (Center) the internal convection of multiple layered pneu figures not thermally coupled, and (Right) of multiple layered pneu figures thermally coupled. In each case, a temperature of 0°C has been applied to the outside boundary surfaces, and a temperature of 30°C has been applied to the inside boundary surfaces. (Velikov/Thün 2014)

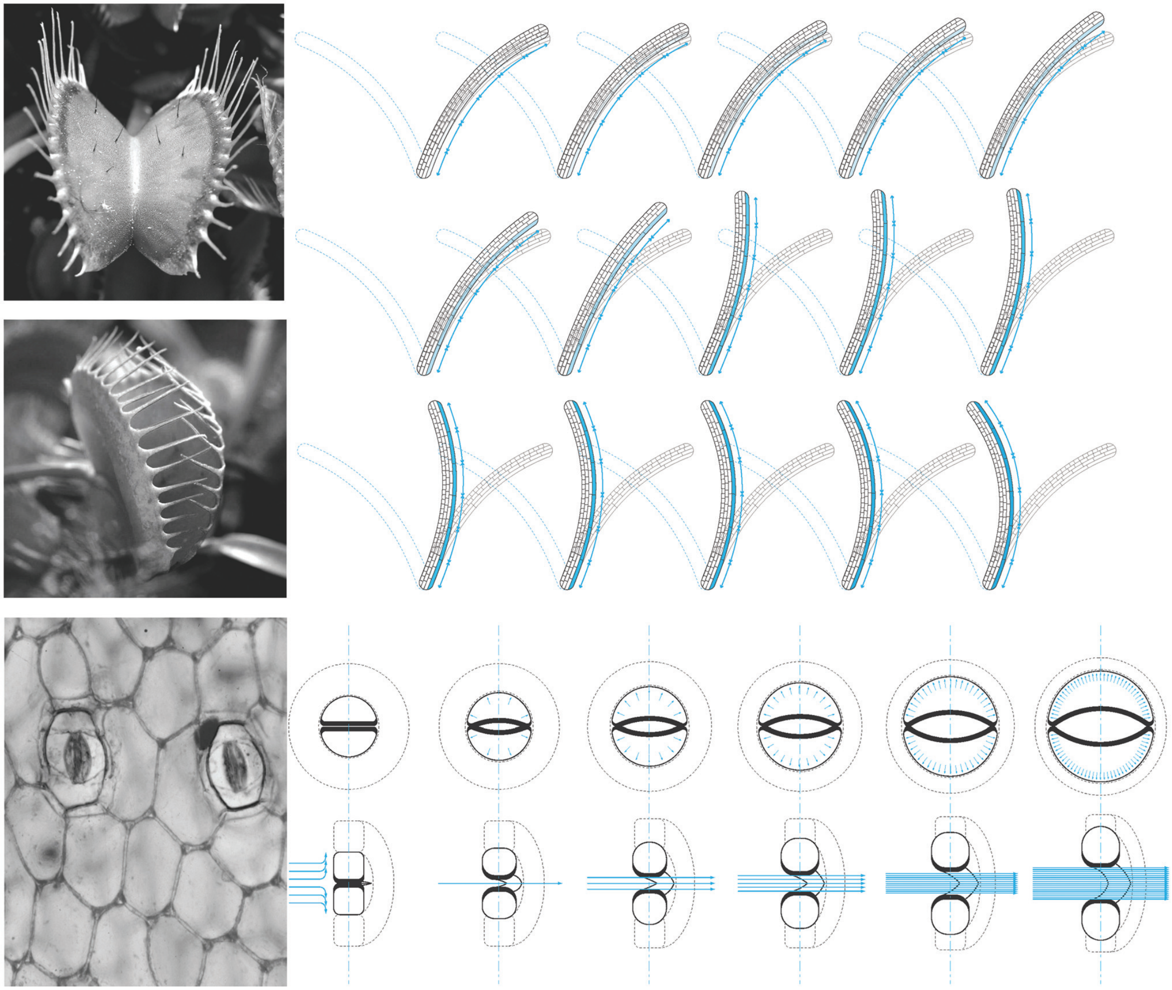
Theoretically, this consistent movement of air within the individual cushion figures, transferring heat between the two surfaces, would be detrimental to the thermal resistance of the assembly, but we do not have quantifiable results of how this convective airflow would impact the overall performance.

These simulations provided insight into how convection drove airflow within the individual chambers of the assembly relative to their geometry under constant conditions. We have not yet developed a satisfactory model for studying the transient effects of a fixed quantity of energy exchange, so we have not yet replicated the conditions of the transient heat flow simulations and the physical experiments. Future research would include further exploration into time-based heat transfer in fluid dynamic models, as well as if and how to quantify air infiltration relative to assembly density and thickness.

5. NASTIC MOVEMENTS

It is a characteristic of pneumatic systems to deform, sometimes quite radically when under pressure. This stream of research addresses the question of motion behaviors and related geometries for pneu figures. Pneumatic motion systems are currently an active area of research in the field of soft robotics. These systems are primarily developed to support specialized autonomous kinetic tasks and are based on biological models such as muscular hydrostats [28]. For architectural envelope systems, a wider range of individual functionalities may be desirable and achieved through the combination of numerous discrete functions within a larger array assembly, more appropriately modelled on the operations of biotic skins. These may include systems of apertures for air exchange or kinetic components for active cooling or shading functions, or the maximization or minimization of surface area for example.

Nastic movement is a term that refers to physical, non-directional responses of plants to stimuli. In contrast to the complex skeletal-muscular system of movement in animals, this mode of movement occurs through a unified action resulting from turgor (water pressure) changes within specific cell geometries. In most plant species, efficient gas exchange across the entire plant is critical for effective photosynthesis and respiration. The stomatal complex controls the exchange of air between the leaf and the atmosphere with a high degree of granularity, while also adjusting to minimize water loss [29]. Studies of the Venus flytrap (Dionaea muscipula) leaf, whose movements (thigmonasty) occur more rapidly and radically than in other plants, have demonstrated that the double-curved geometry of the leaves could be responsible for the speed and force of closure [30]. These principles demonstrate sophisticated models of adaptation with low energetic cost, and have shaped our experiments with geometries for pneumatic actuation (Figure 16).



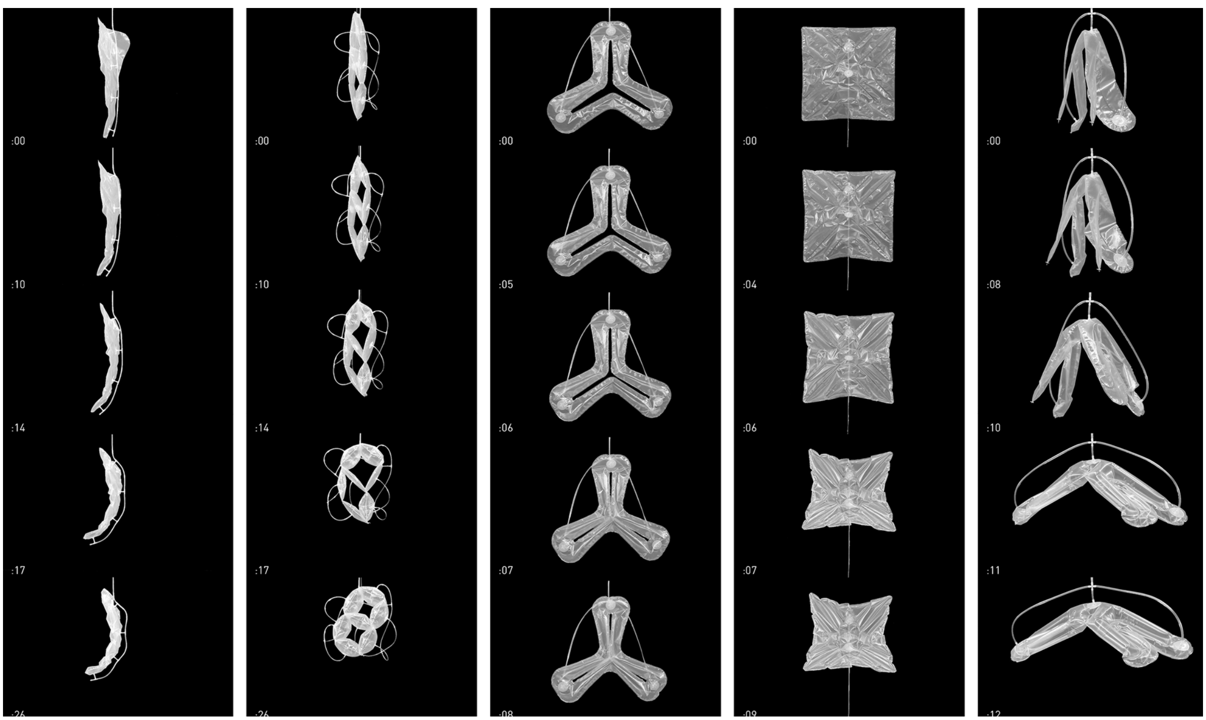
▲ Figure 16. Biological model studies for pneumatic nastic movement (upper) and aperture control (lower). (Photos: Venus Flytrap closed: Snyder, 2011 © Exploratorium; Venus Flytrap open: Elhardt 2006; Stomata: Caan 2013; Drawings: Velikov/Thün 2013).

Nastic movements for architectural pneusystems builds upon the research developed at the IL on 'convertible pneus' between 1974-1976. The IL identified multiple typologies of biological convertible pneus, and several techniques for their design and construction as film-based inflatable structures [31]. For contour welded cushions, these techniques include the introduction of indentations or pleats in the membrane to alter chamber size, strategically restraining structure inflation through indentations, locating maximum volumes at opposing terminal positions of extension to induce stiffening, the introduction of asymmetric loads to induce directional movement, and use of multi-figured pneumatic structures to achieve maximum flexibility and formal kinetic range. A significant characteristic identified is the changing cross-section of pneus while deforming under pressure and the relationship between variable cross-sections relative to the overall motion of a structure [31].

Our research efforts translate these fundamental operational techniques into a range of pneus for application in architectural envelopes. Nastic movements offer a model for aperture control within a packing system of variably sized pneus that constitutes an alternate model to frame-reliant façade operation in buildings for variable air flow, while limiting thermal bridging elements. Paired with integrated sensing and processing for distributed control, airflow may be tempered to precise local environmental demand response, minimizing pressure on high-energy centralized systems while eliminating the need for a complex of mechanical actuators.

Our experiments began with a bottom-up methodology that entailed the development of a primary vocabulary of nastic geometries and behaviors. These were classified into basic behaviors that describe the typology of motion produced by the individual pneu figure when pressurized over time. Terms such as curling, opening, squeezing, cupping, and kicking were used to define the nature of desired differentiated actions produced (Figure 17). For each behavior, multiple geometries were tested and evaluated, and success was placed on maximization of gross displacement, replicability of action over multiple actuations, range of motion and reversibility of movements. The figures developed exhibit a range of operational characteristics that can in future be either be utilized in isolation within static arrays, or in combination to produce more complex operational outcomes.

▼ Figure 17: Motion sequences of selected nastic motion figures developed. l-r: curling, opening, squeezing, cupping, and kicking forms. (Photos: Velikov/Thün 2014)



Within our ongoing work, these active and variable figures will become a fundamental performative "grammar" for more sophisticated composite models to be integrated within the aggregate arrays to achieve specific changes either within the field of the system (e.g. an aperture) or as an actuator within the system (e.g. to introduce a force that alters other figure-to-figure relations).

6. CONCLUSION

Advances in foil-based material systems, digital design and computational tools for performance simulation, and the uptake of design-research methods privileging iterative prototyping practices have produced a context to suggest re-visitation of the pneu as a model for dynamic and responsive envelope systems. This paper presents a body of research work that has been taken across a range of interdependent streams of investigation undertaken by the authors at the University of Michigan to develop a vocabulary of geometries, performance characteristics, material details, actuation capabilities and prototyping techniques with iterative feedback from each stream of work informing the others in a bottom-up method of exploration. Motivations to pursue such research are multiple and aim to couple the potential of these systems for variable thermal insulation and high light transmission with low embodied energy and non-mechanical component actuation towards new models of energy-efficiency and response in the built environment. Subsequent phases of the research will develop and prototype more complex assemblies, combining multiple functions and performances within an integrated system, primarily comprised of air and membranes. This will include further refinement of seam, joint, hinge and air supply details that can accommodate the various forms of the aggregate geometries in full-scale envelope applications, as well as exploration of hybrid structural systems, and more definitive physical testing of thermal performance criteria across full scale installations.

ACKNOWLEDGEMENTS

Previous versions of portions of this paper have been published in "PneuSystems: Cellular Pneumatic Envelope Assemblies," *ACADIA 2014: Design Agency, Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*, 2014, 435-444, and in "Nervous Ether: Soft Aggregates, Interactive Skins," *Leonardo Journal* 37(4), 2014, 344-351.

Project Team: Eric Meyer, Nick Safley, Christina Kull, Dan McTavish, Wiltrud Simbuerger, John Hilmes, Michael Sanderson, Yunzhi Ou, Dr. Satinder Singh Baveja.

Funding and Support: University of Michigan Taubman College Research Through Making Grant; University of Michigan Office of Research Small Projects Grant; UpJohn Research Initiative Grant from the Board Knowledge Committee and College of Fellows of the American Institute of

Architects; University of Michigan Rackham Spring/Summer Research Grant; Social Sciences and Humanities Research Council of Canada; SMC Corporation of America Detroit Branch.

REFERENCES

1. Burkhardt, B. ed., *IL6 Biology and Building I,* Institut für Leichte Flachentragwerke (IL), University of Stuttgart, Stuttgart, 1973.
2. Bach, K. Bereiter-Hahn, J., Gutman, W.F., Helmcke, J-H., Nachtigall, W., Otto, F., Raccanello, R., Schaur, E., Schill, R., *IL9 Pneus In Nature And Technics*, Institut für Leichte Flachentragwerke (IL), University of Stuttgart, Stuttgart, 1977.
3. Herzog, T., *Pneumatic Structures,* Verlag Gerd Hatje, Stuttgart, 1976
4. Ducasse, M., *The Inflatable Moment: Pneumatics and Protest in '68*, Princeton Architectural Press, New York, 1999.
5. Negroponte, N., *Soft Architecture Machines*, MIT Press, Cambridge, 1975.
6. Gharleghi, M. and Sadeghy, A., Adaptive Pneus, reForm( )-Building a Better Tomorrow in: *Proceedings of the 29th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*. Chicago, IL: The School of the Art Institute of Chicago, Chicago, 2009, 110-117
7. Hasdell, P. Pneuma: An Interminate Architecture, or Toward a Soft and Weedy Architecture, in: Tilder, L. and Bolstein B., eds. *Design Ecologies: Sustainable Potentials in Architecture*, Princeton Architectural Press, New York, 2009, 92-113.
8. Knippers, J., Cremers, J., Gabler, M. and Lienhard, J., *Construction Manual for Polymers and Membranes*, Birkhäuser, Basel, 2011.
9. LeCuyer, A, *ETFE: Technology and Design*, Birkhäuser. Basel, 2008.
10. Chilton, J. C., Pezeshkzadeh S. A., and Afrin. S., Effect of Cushion Geometry and Configuration on the Embodied Energy of ETFE Foil Construction, in: Bletzinger, K.-U., Kröplin B., and Oñate E. eds., *International Conference on Textile Composites and Inflatable Structures: Structural Membranes,* CIMNE Munich, 2013, 332-339.
11. Monticelli, C., Campioli A., and Zanelli. A., Environmental load of ETFE cushions and future ways for their self-sufficient performances, in: *Evolution and Trends in Design, Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium*. Editorial Universitat Politécnica de Valencia, Spain, 2009, 754-766.
12. Cremers, J., Energy Saving Design of Membrane Building Envelope, in: Oñate, E., Kröplin B., and Bletzinger K.-U., eds. *International Conference on Textile Composites and Inflatable Structures: Structural Membranes,* CIMNE, Barcelona, 2011,148-155.
13. Maffei, R., Luchsinger R., and Zanelli. A., Design tools for inflatable structures, in: Oñate, E., Kröplin B., and Bletzinger K.-U., eds. *International Conference on Textile Composites and Inflatable Structures: Structural Membranes,* CIMNE, Barcelona, 2011,175-187.
14. Skouras, M., Thomaszewski, B., Kaufmann, P., Garg, A., Bickel, B., Grinspun, E., Gross, M., Designing Inflatable Structures in: *ACM Transactions on Graphics* 33(4), Article 63, July 2014. DOI = 10.1145/2601097.2601166 http://doi.acm.org/10.1145/2601097.2601166.
15. Vincent, J., Biomimetics of Skins, in: Favret E., and Fuentes N., eds., *Functional Properties of Bio-Inspired Surfaces: Characterization and Technological Application*, World Scientific Publishing, London, 2009, 3-15.
16. Montie, E., Blubber Morphology in Wild Bottlenose Dolphins, *Journal of Morphology* 269, 2008, 496–511.

17. Weaire, D., and Hutzler. S., *The Physics of Foams*, Clarendon Press, Oxford, 1999.

18. Estrin, Y., Dyskin, A.V., Pasternak, E., Topological interlocking as a material concept, *Materials Science and Engineering*, C 31(6), 2011, 1189-1194.

19. Chiodo, M., *An Introduction to Braid Theory*, Honours Graduate Thesis, Department of Mathematics, University of Melbourne, 2005.

20. Coyne, R.D., Rosenman, M.A., Radford, A.D., Balachandran, M., and Gero. J.S., *Knowledge-Based Design Systems*, Addison-Wesley, Reading, 1990.

21. Azens, A., Avendaño, E., Backholm, J., Berggren, L., Gustavsson, G., Karmhag, R., Niklasson, G.A., Roos, A., Granqvist, C.G., Flexible foils with electrochromic coatings: science, technology and applications, *Materials Science and Engineering*, 119(3), 2005, 214-223.

22. Guardian Industries, Sunguard Superneutral, http://www.eu.en.sunguardglass.com/ToolsandResources/TechnicalLibrary/Product Literature/index.htm [02-06-2014]

23. Vector-Foiltec. Texlon, Thermal Properties, http://vector-foiltec.com/en/downloads/technical-papers.html [11-12-2012]

24. Poirazis, H., Kragh, M., Hogg, C., Energy modelling of ETFE membranes in building applications in: *Eleventh International IBPSA Conference*, Glasgow, 2009, 696-703.

25. Antretter, F., Haupt, W., and Holm. A., Thermal Transfer through Membrane Cushions Analyzed by Computational Fluid Dynamics in: *8th Nordic Symposium on Building Physics in the Nordic Countries*, Lyngby, Copenhagen, 2008, 347-354.

26. Kaufman A., Sedlbauer K, Sieder, M., Wärmetechnische Besonderheiten von Membrankissenkonstruktionen, [Thermo-technical characteristics of membrane cushion constructions], *Bautechnik,* 90(7), 2013, 395-401.

27. Dimitriadou, E., Shea, A., Experimental Assessment and Thermal Characterization of ETFE Foil in: *Atiner's Conference Paper Series, No. CON2012-0145*, Athens Institute for Education and Research, Athens, 2012, http://www.atiner.gr/papers.htm [05-23-2014].

28. Trivedi, D., Rahn, C. D., Kier, W. M. and Walker, I. D., Soft robotics: Biological inspiration, state of the art, and future research, *Applied Bionics and Biomechanics*, 5(3), 2008, 99-117.

29. Carpenter, K. J., Stomatal Architecture and Evolution in Basal Angiosperms, *American Journal of Botany,* 92(10), 2005, 1595-1615.

30. Forterre, Y., Skotheim, J. M., Dumais J. and Mahadevan. L., How the Venus flytrap snaps, *Nature*, 433, 2005, 421-425.

31. Bubner, E., Burkhardt, B., Denner, J-F., Kurzweg, R., von Lieven, A., Otto, F., Papakostas, G., Schaur, E., van Schoor. B., *IL12 Convertible Pneus*, Institut für Leichte Flachentragwerke (IL), University of Stuttgart. Stuttgart, 1976.

Kathy Velikov[1], Geoffrey Thün[1], Mary O'Malley[2] and Lars Junghans[3]

[1]University of Michigan Taubman College of Architecture and Urban Planning
RVTR Inc.
305 E. Liberty St. Ann Arbor, MI 48103, USA

kvelikov@umich.edu; gthun@umich.edu

[2]Foster + Partners
22 Hester Road, London SW11 4AN

momalley@fosterandpartners.com

[3]University of Michigan Taubman College of Architecture and Urban Planning
2000 Bonisteel Blvd. Ann Arbor, MI 48109, USA

junghans@umich.edu