Material Systems

A Design Approach

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Abstract: This paper describes and reflects upon the results of an investigative project which explores the setting up of a material system – a parametric and generative assembly consisting of and taking into consideration material properties, manufacturing constraints and geometric behavior. The project approaches the subject through the construction of a logic-driven system aiming to explore the possibilities of a material system that fulfills spatial, structural and performative requirements concurrently and how these are negotiated in situations where they might be conflicting.

Keywords: Generative design; design tool development; material systems.

Introduction

In recent years, it is as though a new paradigm has emerged within contemporary architecture, a paradigm that seems to abandon the Post-modern concerns for appearance and instead seeks to construct an architecture justified by its performance. Parameters like construction, structure, assembly, economy, and environment has become important inputs for the generation of architecture and now implemented from the very beginning of the design process; meaning that the traditional top-down process of form-making, where the architect is seen as the genius creator, is shifting towards a bottom-up logic of form-finding, where the architect is seen more as a controller of processes (Hensel and Menges, 2006).

Working with this new performative approach to architecture calls for a reconsideration of the design process and the tools, both analog and digital, needed to work with multiple parameters simultaneously.

The logic inherent in materials

With the introduction of a material system that includes geometric behavior, manufacturing constraints, assembly logics and material characteristics, Michael Hensel and Achim Menges try to “promote an understanding of form, material and structure not as separate elements, but as complex interrelations in polymorphic systems” (Hensel and Menges, 2006). They argue, that through the setup of a parametric computational model, a large number of variable inputs can be negotiated simultaneously, thereby challenging common processes of optimization that emphasize the most efficient performance of a single variable for the least amount of material, as well as finally outmoding the more traditional relations of form and material achieved in analogue design processes.

The central tenet of a material system is the development of a high degree of integration between
design and performance: a system capable of adapting to varied performance requirements through the modulation of the system’s inherent geometrical and material parameters, while remaining within the limits of chosen production technologies.

The computational framework
To be able to work with a material system that deals with these complex interrelations - comprising different parameters, restrictions and characteristics inferred from the material explorations - a computational framework has to be set up. This framework has to be open and extendable and most importantly parametric, so as to be able to deal with the geometric relationships between different parameters.

This computational framework, based on the logics of the material system, will be able to integrate the possibilities and limitations of fabrication, and the self-forming behavior and constraints of a chosen material. Through evaluation of the material, it will be possible to inform the framework step by step with a series of parameters, restrictions and characteristics. This will include the specific material and geometric behavior on the formative processes, the size and shape constraints of involved machinery, the procedural logistics of assembly and the sequences of construction. In other words this will ensure that any morphology generated within the computational framework can be materialized without contravening with any of the fabrication logics thereby avoiding the need for post-rationalization of the design.

A material systems case study
In order to explore this approach to material systems it was set up as the main theme for a master thesis project carried out at the Digital Design program at Architecture & Design, Aalborg University, Denmark. The Architecture & Design faculty is known for its problem-based approach to the design process and as this project sought to construct a logic-driven system with the aim of exploring the potentials of a material system fulfilling spatial, structural and performative requirements concurrently, the implications of choosing this approach meant a “…shift away from programme as design-defining towards design as programme-evolving.”(Hensel and Menges, 2006).

This shift greatly affected the design process of the project. The objective was not to impose a pre-defined form onto a programme, but rather to tease out or elicit the emergence of a changing form from a flow that has its own intrinsic behavior.

Membranes
Having seen a great potential in the utilization of membrane structures, both with respect to its material performance and self-organizational behavior, these were chosen as the underlying basis for an exploration into material systems, or one could say, into membrane systems.

Looking at the structural aspect of membranes an important aspect is that they only transmit tensile forces and therefore belong to the form-active tension systems. This fact entails that membranes, according to the applied forces, take shape into minimal surfaces. This is not to be understood as the construction of minimal surfaces, but rather that the shape of a membrane is found through its self-organizing behavior – as the state of equilibrium of the internal and external forces.

Transferring this knowledge to form-finding experiments, the shape of a membrane structure can be found by applying differentiated forces and then utilizing the self-organizational behavior of the membrane to derive the resulting shape. Such experiments not only depend on extrinsic forces but also on the tension of the membrane itself; both having an influence on the final state of the relaxed membrane geometry.

The experimental setup
Membrane systems are form-active tension systems, which mean that they transmit only tensile forces and take shape according to the applied forces. As
a result of this, membrane systems must be form-found, utilizing the self-organizational behavior of membranes under extrinsic influences. To be able to work with this kind of form-finding approach it was important to construct an experimental setup that would allow for the introduction of tensile forces, or constraining control points, capable of collecting or transmitting the tensile forces of a membrane in tension.

A solution to the experimental setup was found in the construction of an acrylic box: a rectangular box consisting of five acrylic plates, all with a series of holes drilled so as to create a point grid with five centimeter spacing. With standard fishing line and regular elastic fabrics membrane patches could be strung up inside the acrylic box and be visually assessed from all angles. Assigning a coordinate system to the box also enabled an extraction of the various control point coordinates, making a smooth transition from the physical membrane experiments to any CAD software; thereby facilitating further explorations.

Utilizing an existing dynamic relaxation script for Rhino, developed by David Rutten, this form-finding process could also be carried out digitally. Dynamic relaxation is a finite element method which, based on the positioning of boundary control points and the specific elasticity of the membrane, settles a digital mesh into equilibrium by performing iterative calculations.

Initial experiments with the membrane material was carried out in both the analog and the digital domain and dealt with the technical aspects of cutting and mounting membrane patches, observing how membranes react when exposed to varying tensile forces, as well as identifying the parameters present within the membrane system. These initial observations, which were based on the setting up of several different membrane geometries and configurations, lead to the conclusion that the membrane system consisted of four basic parameters: the size of the membrane patch, the geometry of the patch, the number of control points connected to the patch, and the spatial placement of these control points.

The physical acrylic box and the dynamic relaxation script enabled a continuous shift between carrying out experiments with the membranes in the physical and in the digital domain. One of the advantages of this constant shift can be exemplified through the experiments carried out with regards to tensile forces. When setting up the surface relaxation process in Rhino one has to input the level of tensile forces for the membrane so as to determine the elasticity of the material. Altering this parameter, while simultaneously keeping the control points at the same position, changes the geometric expression of the membrane; an experiment that would require a series of different materials with varying elasticity had this to be conceived with the physical setup. This would be a time consuming task involving the re-mounting of different materials within the acrylic box, but a simple and fast manoeuvre within the digital software.

Exploring parameters
To ensure that coherency was present within the material system and to ensure that it utilizes the inherent potentials of the membrane, these parameters was explored and investigated. Throughout this exploration all the relationships between parameters, limitations concerning materials or production, geometrical behavior, etc. was added to or updated in an always growing Rhino Script, ensuring that each observation was stored in the code of the material system, or to be exact, in the computational framework (Figure 1).

One of the parameters that were explored was the one controlling the ‘number of control points’ and with this the focus was on the behavior of the membrane system when a membrane patch was added a varying number of control points. These experiments were initiated through the use of the acrylic box, where one ‘control point’ was equal to a fishing line being attached to a piece of fabric and then pulled through one of the holes of the acrylic box and fastened. What became obvious from
observing the results of this experiment was that increasing the number of control points resulted in the potential for additional geometrical definition and more curvature of the membrane patch. Here it’s important to note that there is only a ‘potential’ for more geometrical definition and curvature given that another parameter, ‘spatial placement of attachment points’, also has an effect on this outcome.

Critically observing the outcome of every experiment showed to be an important factor when exploring a material system. New potentials might appear when systematically experimenting with one parameter at a time, or when setting up a relationship between two different parameters. For instance, while exploring the parameter ‘number of control points’, a potential was seen in subdividing this parameter into ‘attachment points’, being the point where the membrane is connected to the fishing line, and ‘control points’, being the point where the acrylic box is connected to the fishing line. This opened up for the possibility of manipulating the ratio between these two parameters, which had previously been a fixed 1:1 ratio, enabling for instance the opportunity for a membrane patch to connect two of its own attachment points to each other, creating more diversity to the geometrical configurations of the membranes.

**Component-host setup or inheritable genetic code**
When setting up a matrix of identical membrane patches, where only the outermost objects have a control point connecting them to the context/acrylic box and the others only connected to the neighboring membrane, one can introduce the concept of a
component-host setup. In this configuration the flow of information runs from the host and down to the individual component. This hierarchical relationship means that a manipulation of the control points belonging to the host affects the placement of the attachment points of the component. We can now talk about manipulating the membrane system globally, as changing the placement of the control points for the host will have a global effect as it changes the placement of all the attachment points belonging to the component as well. This effect, or way of direction the flow of information within the system, was tested through various physical and digital setups and although a huge potential, but also a to some degree foreseeable outcome, was recognized in the construction of a system capable of generating differentiated sub-environments throughout its span, the potential of finding other ways of constructing the flow of information were investigated.

With inspiration taken from the Von Neumann Architecture - a concept that deals with a system where the first component holds the rule, or ‘genetic’ code, of how to manufacture a new component based on its own existence – one could instead setup a system where the population of components was controlled by an initial rule that was subsequently passed on to the next component. (http://www.zyvex.com/nanotech/selfRepJBIS.html#vonNeumannArchitecture: Jun 2009). Within such a setup the information will run from one component to the next and the designer will not have the opportunity to directly manipulate the population on a global level, but will only take part in the construction of the initial rule-set.

Investigations were made on the setting up of growth-rules and how to incorporate this line of thought into the membrane system, leading to several experiments within the acrylic box featuring different populations of identical membrane patches informed by various growth rules. Transferring the observations made from these experiments to the rhino script/computational framework, the computational power could be utilized to construct more complex growth rules dealing with even more parameters, but still informed/restricted by the parameters and values extracted from previous experiments. Reflecting on the outcome of these genetically inspired experiments it was concluded that by informing the material system through these inheritable generative rules one would obtain a higher degree of focus on the setting up of the inner logics rather than the external form and still be able to inform the material system through the use of contextual-based inputs.

A contextual independent structure
During the process of constructing the material system the possibility for less attachment points between the membrane system and the context were seen as a potential for making the structure more independent of the physical context, but still very contextually informed and –adaptive. Exploring this potential resulted in the introduction of a frame system, consisting of structural beams configured as a rigid triangular bi-pyramid. This new frame component was constructed on the basis of several physical prototypes all based on the idea of having a structure with no need for contextual support which at the same time could act as the support structure for the membrane components.

Pursuing this idea of a combined membrane-frame system entailed that the computational framework had to be reconfigured so as to consist of and be capable of negotiating between to interrelated sub-systems. It also called for a rethinking into how one system informs the other and thereby how the flow of information should run within the computational framework. For instance it was clear that because the membrane patch was physically linked to the corners of the frame component, any change made to the frame would affect the membrane, thereby placing the frame system higher up in the internal hierarchy than the membrane system.

Performance
From the beginning of this exploration into material systems the aim has been to explore the shadowing
performance of a membrane system, not to obtain a maximum shadowing effect, but to generate a system with the potential of creating more differentiated and locally adjustable shading.

During experimentations with the membranes configuration within the bi-pyramid frame it was noticed that a membrane, spanned within the frames five corner points, had the potential of adjusting to local requirements by repositioning itself within the frame. Investigations into the possible effects of this repositioning of the membrane patch revealed that differentiated effects regarding shadowing were obtainable.

To simplify the task of computing the degree of shading the membrane patch was considered as being defined by two of the six sides comprising the frame and that these sides were fully ‘covered’ by the membrane (Figure 2).

From this abstraction, or simplification, it was simply to calculate the difference in degrees between the normal vector of each of the frame’s sides and the angle of the rays emitted by a digital representation of the sun. The smaller the difference, the closer the frame side would be at being perpendicular to the sun, and the larger the area will be for creating shade. Selecting the two sides with either the smallest or the largest difference in degree would result in the component shading as much or as little as possible, respectively. The only rule that needed to be enforced in this decision-making process is that the two chosen sides only share one joint, as this would ensure that the desired membrane geometry could be strung between the two sides.

These explorations of the membrane’s environmental performance revealed, that utilizing the membrane’s potential to reposition itself within the frame, would enable the membrane system to perform local environmental modulations with regards to differentiated shadow patterns. In other words, this enabled the material system to use contextual parameters, as well as the designer’s desire for differentiated shadow intensities over a given area, as inputs for guiding the evaluation processes that control the repositioning of the membrane.

As these processes could be described in a series of logical steps they were both converted to an
algorithm and implemented into the rhino script/computational framework. The only thing lacking in this procedure is an input that can inform these evaluating processes, for instance telling the system to choose minimum or maximum shading for each individual membrane, and so on.

**A material systems implementation**

Having obtained a computational framework with restrictions and behaviors extracted from various experiments it was necessary to define a method for guiding and informing the system. From those behaviors detected throughout the explorations it was uncovered that certain parametric manipulations yield certain desired effects and recapitulating on these potentials a number of different parameters were in need of an input so as to determine or guide their behavioral effects (see figure 3).

The final stage of the material system was setup in such a way that it could be informed, or guided, by a series of points, lines and numeric values, all drawn or entered through the Rhino-interface. For instance, the parameter representing the flow of people, which had both an attractive and repelling effect on the placement of each successive frame component, was informed through the placement of a curve.

More important though was the construction of a decision-making procedure that would enable the computational framework to successfully make decisions, when these were based on several, on often conflicting, inputs. This scenario existed for instance in the recurring procedure involving growth direction, where a new frame had to be attached to one of the three sides of the existing frame, requiring an evaluation procedure taking into account the position of the existing frame, the direction towards the sun, the force and placement of a number of attraction points, the flow of people, a height limit etc. Introducing a scoring chart it was possible to let the designer choose, for instance, how much influence the flow of people should have on the growth of the frame system, or from which three-dimensional point the first frame would originate.

**Conclusion**

Throughout the exploration of the material system it was informed in a step by step manner which ensured that the observed behaviors were extracted from the experiments and explorations of both the physical prototypes and the digital tests. This allowed for further modulation of the material system enabling additional differentiations that remained coherent with the already revealed behaviors and established restrictions. But, although the final stage of the material system was capable of generating different assemblies, based on hereditary information residing within each successive component, a number of issues would still need to be dealt with in a further exploration into material systems.

It is evident that in order to setup a system capable of generating useable architectural constructions it is necessary to incorporate both assembly logics and structural analysis. Doing so will also enable the material system to generate outputs with an even higher complexity as it would then be negotiating between even more restrictions. On way of implementing this structural analysis could be through the implementation of adaptive growth. At the final stage of the material system each individual component only had the “knowledge” of itself and its own position in the system, but if one were to construct the system so that a component also has knowledge of the previous component it will gain the ability to adapt through a re-evaluation and re-configuration
of the previous components. Implementing this ability within the material system would make it possible to e.g. re-dimension the beams on all existing frame components following the generation of a new component, thereby re-configuring the structural support to fit the needs of the continuously growing assembly. As when “hacking” into the code containing the relaxation script, as mentioned earlier, this could be done by re-using an existing code containing a finite element procedure.

Another subject of interest is the act of selecting parameters. One of the limitations of the material system lies in the number and type of parameters that are embedded to the system. One could for instance argue that the material system treated in this paper would not make sense without a parameter dealing with wind loads, as this factor plays an important role in the construction of a physical membrane construction, but as when adding all the existing parameters, adding wind to the list would only be a matter of further development, making working hours the main limitation.

When talking about parameters, and which and how many to incorporate, one might turn towards the writer and philosopher Manuel DeLanda and his writings about genetic algorithms, where he argues that there’s an important difference between CAD designers and breeders: “Unlike someone manipulating evolution in the realm of biology, where one starts from the beginning with a fantastically productive phylum or body-plan (the body-plan of the vertebrates, for instance), in the virtual realm one does not have an abstract architecture full of potential, but must create one.” and concerning the role of the designer he states that: “…he or she must be able to create novel abstract architectures or body-plans…” (DeLanda, 2002). Following DeLanda, it is the creation of the body-plan, or in this case the computational framework, which is of most importance. Reflecting on the work made in the material system case study, it is evident that the computational framework has not been advanced to a state that is rich enough to generate virtual structures that are structurally capable of being placed in the physical world and bearing loads. To create true evolutionary forms, on the basis of the instructions gathered within the computational framework, one will have to see this set of instructions as genes or as the DNA of the form, and additionally be capable of setting up a system that allows for mutations to take place within this DNA.

References