Biomimetic performance

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ABSTRACT: Making sure buildings perform responsibly is a key issue today, in part due to our global environmental crisis. “Humanities footprint first exceeded the Earth’s total bio-capacity in the 1980s; this overshoot has been increasing since then.” (Living Planet Report, 2008) Nature is the ultimate in performance-orientated design so it is no wonder that attention is finally being paid to its processes. This paper discusses research from the 2011-2012 academic year at the University of Arizona, where investigation was centered on the principles of natural systems, biomimetics (the abstraction of natural principles into design). The overriding goal of one particular project was to renegotiate the interface between the built and natural environment.[1] This developed in a conceptual and literal sense with material research into the area of porous cellular ceramics and concrete. Controlling the density (the ratio of solid to void space) allowed for a unique material to develop, whose properties could be tightly controlled to environmental criteria. Testing focused on thermal properties, compressive strength and evaporative cooling. The material was ultimately incorporated into an evolutionary, digital design proposal whose form was optimized with the incorporated material research.

KEYWORDS: Material science, biomimetics, porosity, computation.

1.0 INTRODUCTION

Biomimetics is the study and application of biological principles as essential design parameters. This study goes beyond a metaphor; it is not about mimicry, but about understanding the nature of the material itself. In the English speaking world the term, biomimetics has appeared as equivalent to the German, bionik, coined by Otto Schmidt in the 1950’s. On the website of the German Bionik Network, bionik is defined as the, *decoding of inventions of animate nature and their innovative implantation in technology.* The Center for Biomimetics at the University of Reading, England defines biomimetics as *the abstraction of good design from nature*. Negotiating design and performance with engineering and fabrication is one of the central topics of architectural discourse today. Driving this is a growing awareness of how important the subjects of ecology and sustainability are, of which nature is obviously a successful model to aspire to. Although buildings and biological organisms are both subject to the same physical laws, from gravity to carbon cycles the connection goes beyond conventional scientific relationships. The interest in biomimetics is not just about being performative in a technical sense, it also relates to the larger issue of humanity’s relationship to the natural world. Gregory Bateson discusses this phenomenon in *Mind and Nature*, “We are parts of the living world” but “most of us have lost that sense of unity of biosphere and humanity which would bind and reassure us all with an affirmation of beauty” (Bateson 1979). Part of the following design goal was to re-establish these connections between humans, mind and body and the natural world.

2.0 POINT OF DEPARTURE

Arnim von Gleich et al. in their book, *Potential and Trends in Biomimetics* have identified three main strands of developments in biomimetics, these are; functional morphology (form and function), biocybernetics, sensor technology, robotics and nanobiomimetics. In many cases some of these strands merge. In addition to the three strands of development they also distinguish 3 levels of learning from nature:

> Learning from the results of evolution (hook‐and-loop fasteners, the aircraft wing, etc.), learning from the process of evolution (optimisation techniques, evolutionary optimisation strategy (e.g., Evolutions-technik, see Rechenberg/Schwefel), genetic algorithms, etc.), and finally, learning from the success principles of evolution (closed loop economy, adaptability, etc.) which is the third and most abstract level (von Gleich et al. 2009, 24).

Generally the more areas that are covered imply a richer approach. Natural systems are complex, so reductive designing will not get us to where we need to be, at the same token complexity for complexities sake is not the solution either. Nature is constantly adapting whereas most buildings are static in every sense of the word. How literal does this adaptability need to be? Sometimes moving parts can just add to the complexity of a project without much gain. Generally, if sustainability is a true goal then as many passive design moves and systems should be employed as a first step in the design process.

Reyner Banham has documented in his book, *The Architecture of the Well-Tempered Environment*, that as technology developed (e.g. air conditioners) it has increased our ability to control our environment which has generally led to a separation of the inside from out. This happens often without any relationship to a particular climate or region. Ironically, technology today is generally seen as the solution to the world's environmental problems. That being said the need for computation to study and model this complexity is paramount. John Frazer, a pioneer in the use of computers in architecture has written that,

> The modelling of these complex natural processes requires computers, and it is no coincidence that the development of computing has been significantly shaped by the building of computer models for simulating natural processes. Alan Turing, who played a key role in the development of the concept of the computer (the Turing Machine) was interested in morphology and the simulation of morphological processes by computer-based mathematical models (Frazer 1995, 13).

Michael Weinstock, Founder and Director of the Emergent Technologies Master's Program at The Architectural Association, London has stated that,

> Material is no longer subservient to a form imposed upon it but is instead the very genesis of the form itself (Weinstock 2012, 104).

Today with increasing technological tools, these environmental and material properties can be incorporated as parameters into the digital model. Achim Menges, Director of the Institute for Computational Design at the University of Stuttgart has worked for the last decade on how to generate a design approach related to performance and specific physical materialization. He has stated,

> Computation, in its basic meaning, refers to the processing of information. Material has the capacity to compute. Long before the much discussed appearance of truly biotic architecture will actually be realized, the conjoining of machine and material computation potentially has significant and unprecedented consequences for design and the future of our built environment (Menges 2012, 16).

3.0 APPROACH

It was important to have a design approach with the material properties being the key driver. Porous materials were selected as conceptually they have the potential of blurring the boundary between inside and out – the human built environment and the natural world outside. Also, the research showed that,

> a close analysis of materials found in nature reveals that most of them have a cellular structure and thus contain a significant amount of porosity, which plays a key role in optimizing their properties for a specific function (Scheffler and Colombo 2005, xix).

The specifics of the porosity and what this meant architecturally was what the research intended to analyze. Initially ceramics was the chosen material as it is a fairly conventional building material with some research data available in its porous form. According to Paolo Colombo, porous ceramics,

> display a rather unique combination of properties, such as low density, low thermal conductivity, low dielectric constant, low thermal mass, high specific strength, high permeability, high thermal shock resistance, high porosity, high specific surface area, high wear resistance, high resistance to chemical corrosion and high tortuosity of flow paths (Colombo 2006, 110).

Most of the following research was conducted by a single Master's student, Nicholas Johnson.[2] The author was chair of his thesis committee. Some of the earlier work with ceramics was developed with some additional undergraduate assistance in an elective by the author on biomimetics. Initial research showed that there are three common methods of creating porous soft materials. The first option, *Replication*, involves an application of foam slurry to a template that is burnt out during firing. The second option is *Direct Foaming,* which is usually developed through physical agitation and the third option is *Pore Burn Out*, which incorporates additive materials, usually in the form of beads or particles. The Replication option was initially selected as it seemed to be the easiest method to obtain uniform results. The templates chosen ranged from soft sponges to various examples of pre-manufactured foam. Samples were created by soaking the particular template in a clay slurry, then air drying, then kiln firing to burn out the template and form the ceramic (Fig. 1)

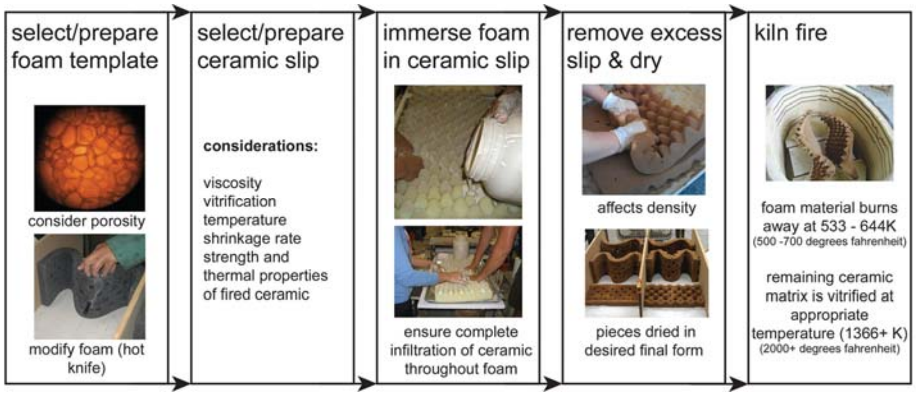


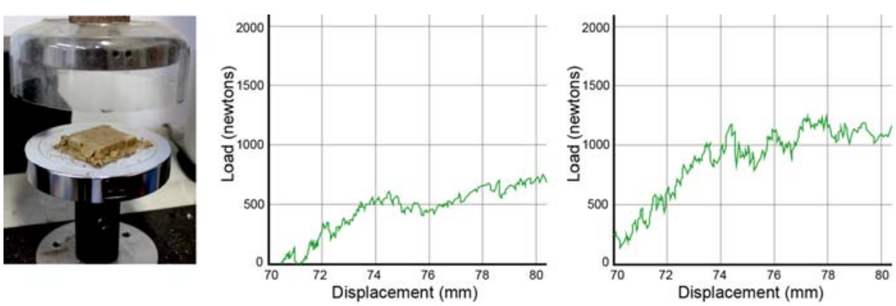
Figure 1: Process of Replication to make cellular ceramic. Source: (Johnson 2012)

The project began with the relationship between three critical properties, which were researched and tested: density, water holding capacity (relating to the degree of porosity, surface area and interconnectedness of cells), and structural capacity (compressive strength). Various samples were made with different densities by adding more or less ceramic material to the foam template. Despite a difference in weight between the two samples of 35%, the difference in porosity is only 2%, and the difference in the percentage of water volume to void volume is only .02%. This suggests that increasing the amount of ceramic material has only a limited negative affect on the water holding potential of the block. Thermal surface temperature testing confirmed this (Table. 1). Finally, compressive strength was tested using a method of crush testing on the Instron machine. These tests showed that while ceramic density may not have a significant effect on the evaporative cooling ability of the cellular ceramic it does have a significant effect on the structural capacity. The sample with the greater density (B) had almost double the compressive capacity of the lighter sample (A) (Table. 2).

Table 1: Results of surface temperature testing with saturated samples, A and B. Source: (Johnson 2012)

	STATIC AIR	Initial	AMBIENT AIR	5 min	10 min	15 min	DIRECT AIR	5 min	AMBIENT AIR	5 min	STATIC AIR	5 min	10 min	
A		291		289	288	286		283		286		286	287	Ambient Air: 296 K (73 deg F) 18% humidity. All measurements in kelvin
B		291		290	288	286		284		286		286	287	
Dry		296		296	295	295		294		295		295	295	
		MAX				MAX		MAX		MAX			MAX	

Table 2: Results of Instron compressive tests. Sample A (left) and B (right). Source: (Johnson 2012)



Even though these results looked very promising with regards to using porous ceramic as an evaporative cooler, it was decided to move away from ceramics and the replication process. The energy consumption of the firing process and the toxicity of the burn-out material seemed to be a contradiction to the overall goals of the project. The reliance on the template material was also seen as a restriction as we were limited by the range of existing materials. For these reasons the possibilities of using cellular concrete was then evaluated.

In situ direct foaming was selected to get a greater variety of options. Richway Industries (http://www.richway.com) provided the foam generator and foaming agent. The resulting porosity (and related properties) depends on 1) the properties of the concrete mixture (raw materials, ratios, and additives), 2) the quality of the wet foam (affected by water purity and concentration of foaming agent) and 3) the ratio of foam added to the concrete slurry (density).

If the material was going to be effective as an evaporative cooler then it was critical how the material interacts with water. The cellular ceramic was effective because it could absorb water and also retain it within its cellular structure. With the foam concrete, one issue became the nature of the edge condition – it needed to be cellular and open to enable the water to enter. This edge is affected by the formwork and the pouring and curing processes. Additionally the degree of permeability is dependent on the density of the final product, which is controlled by the amount of foam added to the mix (Fig. 2).

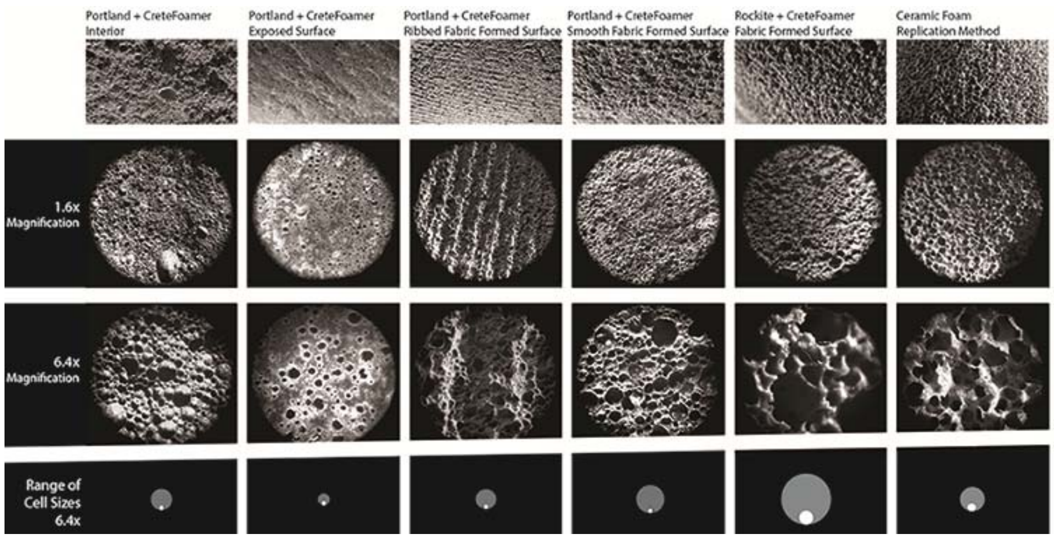


Figure 2: Microscopic Images of various samples using various material compositions and forming techniques. Source: (Johnson 2012)

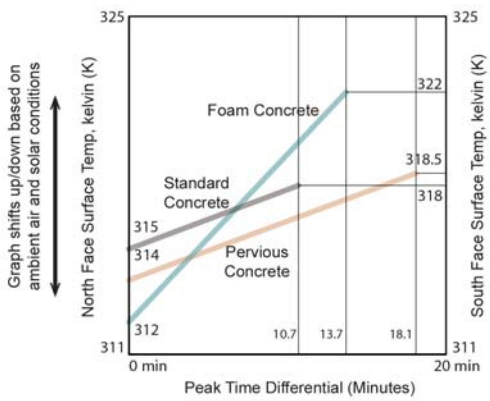
Obviously the desire for increased porosity needed to be balanced with its structural stability. Testing showed that the potential to hold water was dramatically reduced near a threshold of 0.8 g/cm3 (50 lbs/ft3). This corresponds to a compressive strength of less than 6,205 kPa (900 psi) (based on established density and compressive strength data found on the cretefoamer website).[3] The data showed that in its most effective water holding range, the foam concrete cannot be used as a structural material. This led to two possible options - the first one being that it could be conceived as a cladding material requiring a structural frame. The second option, which was selected, was to research the possibility of it becoming part of a hybridized material with another material whose properties would complement the properties of the foam concrete. Pervious Concrete was ultimately selected to be this second material. Part of the reason for this selection was the fact that the two materials are essentially made from the same range of materials and can therefore have a similar construction process. The other determining factor was pervious concrete's high density and structural capacity. It has a macro-porosity compared to the micro-porosity of foam concrete which means that although it could provide the desired structural properties it is not an effective evaporative cooler, as water flows through it instead of being stored.

4.0 THE DESIGN PROCESS AND FINDINGS

Various tests were implemented on the created samples so that specific data could be incorporated into the digital modeling process along with environmental data. Foam and Pervious concrete are not new materials, so there is existing data in many areas. Their potential use as an evaporative cooler is new and undocumented though. The tests were broken down into ones that could establish issues of thermal performance (time lag, performance/thickness ratio, effects of shading/solar exposure) and evaporative cooling (thermal effects of saturation). The evaporative cooling tests were conducted outside and in the College's wind tunnel facility. Samples were saturated and then allowed to dry in the wind tunnel, under various conditions, while data was collected on both sides of the material.

The results of the material research and testing showed that foam concrete is an effective insulator, has a high evaporative cooling efficiency, a low permeability, and a low compressive strength. Whereas pervious concrete is effective as a thermal mass, it has a lower evaporative cooling efficiency, a high permeability, and a high compressive strength. These properties led to a design strategy which would utilize the foam concrete for insulation and evaporative cooling while the pervious concrete would be used as a thermal mass and the structure (Table 3).

Table 3: Summary of surface temperature results for foam, pervious and standard concrete. Source: (Johnson 2012)



The design project's site was to be in Tucson, Arizona in the Sonoran Desert in the southwest United States. The Sonoran desert is generally categorized as a hot, arid region. Barrel Cacti, African Termite Mounds and Mining Bee's Nests were studied for their ability to survive in desert conditions. Desert species have formal criteria that relate to self-shading and orientation as well as material qualities that allow for expansion and contraction during dehydration, they also have insulative and reflective properties. In the case of the Mining Bee vents to the nest are lined with clay walls with a high water content allowing for evaporative cooling. Each example optimizes passive strategies in order to gain comfort. The passive design strategies that had been identified for their positive response in regulating comfort in hot, arid climate zones were evaporative cooling (due to low humidity), high thermal mass (due to extreme heat and solar energy), night ventilation (due to large diurnal temperature shift), comfort ventilation, shading, and in the winter time, direct solar gain.

Initially a simple pavilion-like dome structure was chosen for its minimal surface properties and because of its more fluid environmental exposures. One of the issues raised was questioning what the acceptable levels of comfort should be and whether these should be specifically related to individuals, time of day and year or a particular climate rather than a one size fits all. Comfort and health, like sustainability in general goes beyond a physical issue, it extends to environmental, social, economic and psychological areas.

The first step in the design process was to mold the form of the initial dome shape in an specified way relating to the basic material functions outlined in the schematic design (Fig. 3)

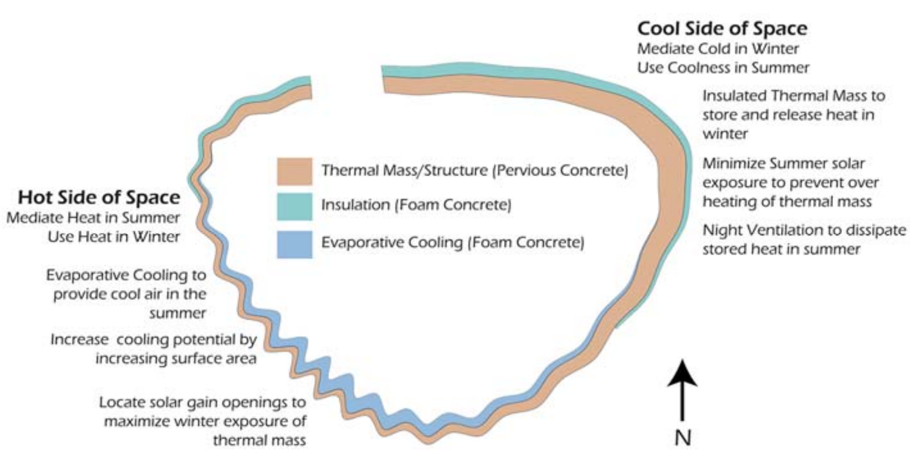


Figure 3: Schematic plan showing placement of foam and pervious concrete. Source: (Johnson 2012)

The digital model was given a wide range of potential formal deformations relating to solar radiation. The goal was to minimize solar radiation on the north side in the summer (to further cool that zone) and maximize solar radiation on the southwest side in the winter to allow for solar gain. An opening was also optimized which would allow the sun to enter in winter to charge the thermal mass of the floor and the north wall. Formal iterations were generated by inputting parameters into Galapagos, a software plug-in for Robert McNeel's Rhinoceros software, developed by David Rutten. Design iterations were then sent to Autodesk's Ecotect for summer and winter solar radiation analysis. The data was then brought back in to Galapagos to determine its relative success or failure and then it generated the next iteration and so on (Fig. 4)

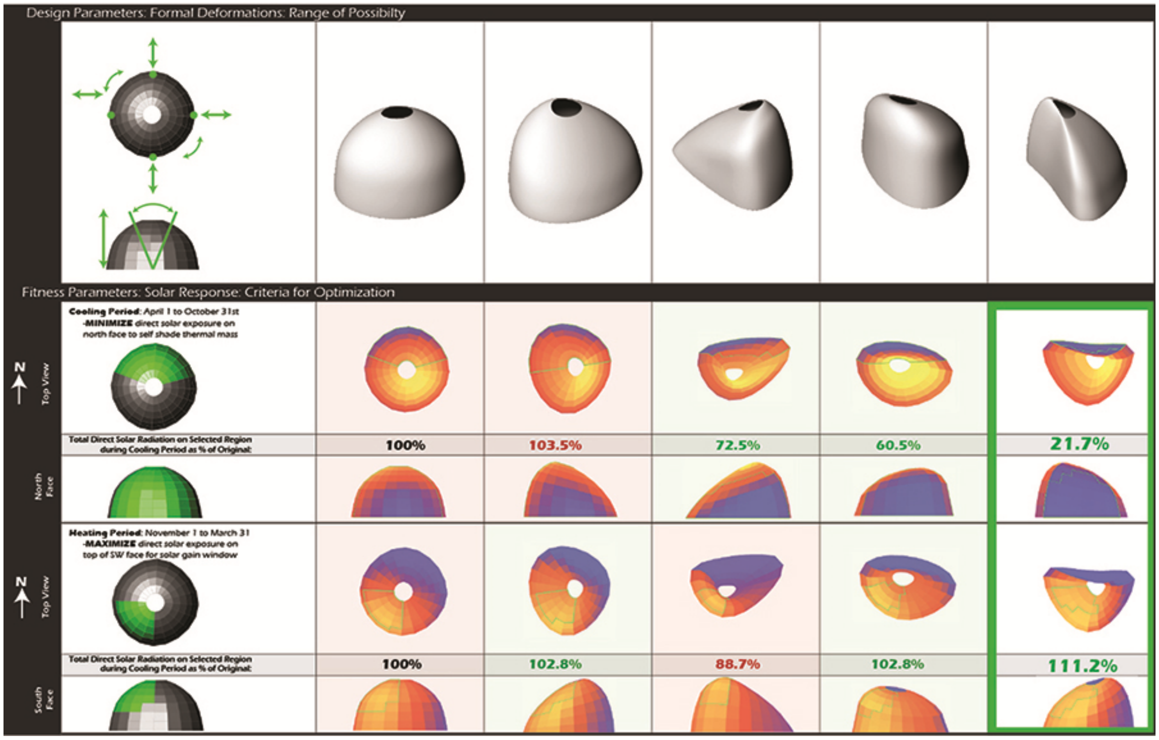


Figure 4: Results of digital optimization process relating to solar radiation. Source: (Johnson 2012)

The next step in this process dealt more directly with the material properties themselves. The goal was to determine the optimal material thicknesses throughout and also optimize the size of the openings. This was accomplished by inputting specific material performance data into the parametric model and again using Galapagos to generate formal iterations which were then fed into Ecotect to get solar gain data. This was then incorporated into mathematical equations within the model that related material properties and thicknesses with environmental data. These equations calculated Thermal Time Constant (TTC)[4] which should be maximized year round, and Diurnal Heat Capacity (DHC)[5] which should be maximized in the winter for heating. These fitness parameters were balanced and the results helped generate the next iteration in Galapagos (Fig. 5).

Due to time constraints, this was the last step in the design process. In an ideal world the next step would be to optimize the evaporative cooling function and maximize its effect on the form. It was noted that formally there would probably have been a difference if all the operations had run concurrently too. Although the computer is calculating the design iterations, there is still control of the parameters which are in the designer's hands. The goal was not to design the form, but to design the system that would generate the best form based on the design criteria for the specific environment where it exists. The various software tools are still in the early stages of development, so the process is sometimes slow and clunky, although developing daily.

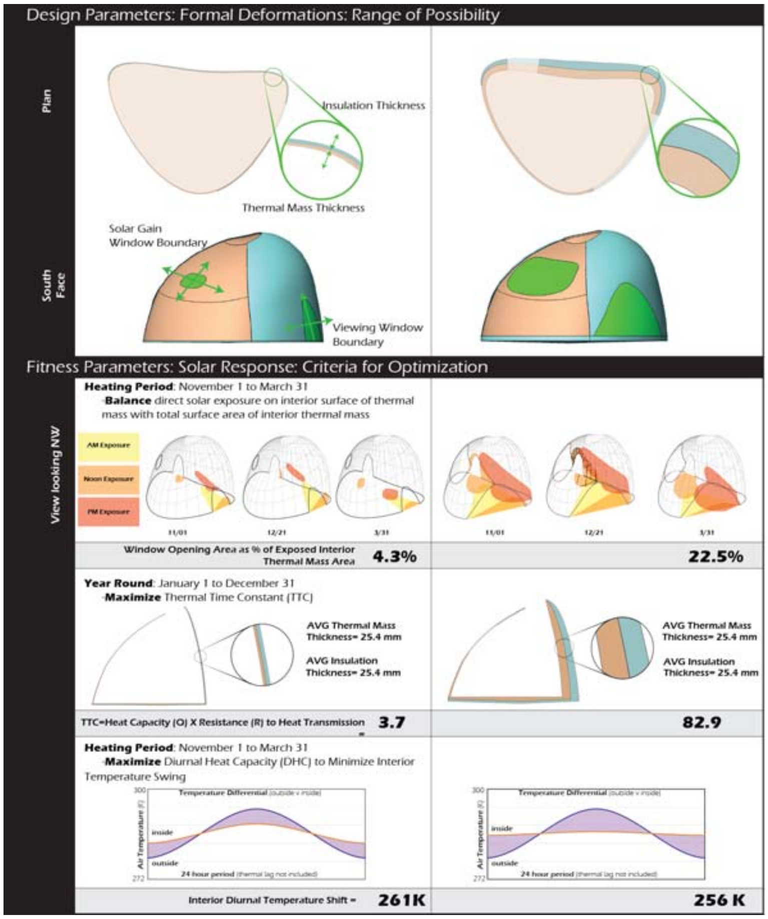


Figure 5: Results of digital optimization process relating to material thickness and direct gain openings. Source: (Johnson 2012)

5.0 CONCLUSION

It was apparent throughout that understanding performance and attempting to emulate the natural world is a complex task indeed. This particular example emphasized materiality as a design driver, but obviously it is crucial to be multi-faceted in order to see the issues holistically. This relates to the idea that as humans we need to become more integrated with nature in a literal sense, which has vast implications for traditional levels of comfort, on which much of our often static performance criteria is based upon. Humans need to be a bit more willing to adapt to living in certain climates rather than expecting environmental systems to manage everything.

The material research showed that there is significant potential for these materials to be developed for arid regions as an evaporative cooler. Specifically, it was assumed that water would be added to the system depending on the exterior conditions. To optimize the system further a mechanical fan would be placed at the top to draw the air through the small holes and through the space. It was realized that a further development of an adaptive shade structure would really improve the results too, but this was not executed in any level of detail due to time constraints. Beyond the specifics of this project there is also a more general potential for the optimization and hybridization of materials so they are used more intelligently and sparingly related to their specific properties in a given location.

One of the other and perhaps most applicable aspects of the project is the use of the computational design process itself. Digital design applications are a given today and with the advancements in Building Information Modeling (BIM) we are starting to see more data and information incorporated into our digital models. The thrust to make our virtual world have more materiality is obviously growing, but these aspects as design drivers are still in their infancy. Using the computational power of computers is crucial in developing our designs to be more reflective of the natural world as there are many behaviors and forces to integrate which are never static. Our digital models, although virtual simulations, are getting more and more sophisticated about modeling environments in live ways and thus becoming less abstract. It is a real positive to be able to immerse ourselves in these virtual realms in the hope that our built projects, which take large investments of time, energy, materials and money, will be smarter, more comfortable on multiple levels and not necessarily more expensive because of it. John Frazer has stated,

> It must be re-iterated that this exploration and resolution cannot be carried out symbolically, at an abstract level. The forming of material is the process of calculation, mapping and resolution of differences. The information thus gained is not absolute knowledge about either the world or form. It is relational; not a measure of either participant in the dialogue, but a measure of the dialogue itself. (Frazer, 1995, 117)

ACKNOWLEDGEMENTS

I would like to acknowledge the other members of Nicholas Johnson's Thesis Committee; Nader Chalfoun, Larry Medlin and Beth Weinstein. It is important to also thank Professor Emeritus Alvaro Malo, who began this process with Nicholas Johnson as the lead of the Master's Program of Emerging Material Technologies at the University of Arizona.

ENDNOTES

[1] The project mentioned was Nicholas Johnson's 2012 University of Arizona Master's Degree Thesis, "Renegotiating the Interface between the Built and Natural Environments."
[2] Some of the following text is cited from Nicholas Johnson's 2012 University of Arizona Master's Degree Thesis, "Renegotiating the Interface between the Built and Natural Environments." Johnson is also cited for all figures and tables with some small graphic and title changes by the author. Consistent changes by the author were made in units of temperature (Fahrenheit to Kelvin).
[3] Cretefoamer. "Cellular Concrete Technical Information," http://www.cretefoamer.com/index.html?page=TechInfo1
[4] Givoni, *Climate Considerations in Building and Urban Design*, 133-135.
[5] Jones and Wray, "Simplified Methods," in *Passive Solar Buildings*, 194-195.

ERRATUM

Erratum added on October 18th 2014 to clarify Nicholas Johnson's contributions to the paper. Changes consisted of adding endnotes i and ii and listing Nicholas Johnson's University of Arizona Master's Degree Thesis as a cited reference.

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