HIGH PERFORMANCE PRECAST FACADE PANELS

Finding A Better Building Envelope

LANA SHIHABEDDIN / JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

Identifying the Problem

Technological advancements in the production of building, structural, and infrastructural components, suggests advanced manufacturing techniques will allow these components to address issues including construction speed, structural performance, combinatorial material efficiencies, and economics of production. A key building element able to benefit from these technological advancements and meet the demands of current urban growth is the development of a more intelligent and responsible building envelope.

Statistics show that 40% of U.S. energy is consumed in residential and commercial buildings, with 51% of that energy going toward heating and cooling of the spaces directly related to the facade of the building. The performance criteria of an effective building envelope is to be the protective layer around a building possessing the qualities of a thermal and moisture break, structural stability, wind and impact resistance, locally acclimated to environmental conditions, and provide the aesthetic expression of the building. It is one of the most direct methods to develop a more efficient, sustainable, and economically feasible means to address the pressing needs of rapid urbanization and the performance criteria associated with more intelligent and responsible design. A key component toward developing a more advanced building envelope is the utilization of a precast concrete cladding system, particularly the further advancement of precast concrete sandwich panels. The development of Ultra-High-Performance Fiber-Reinforced-Concrete (UHP-FRC) has made it possible to investigate the extent of a stronger, lighter, and more durable precast concrete sandwich panel.

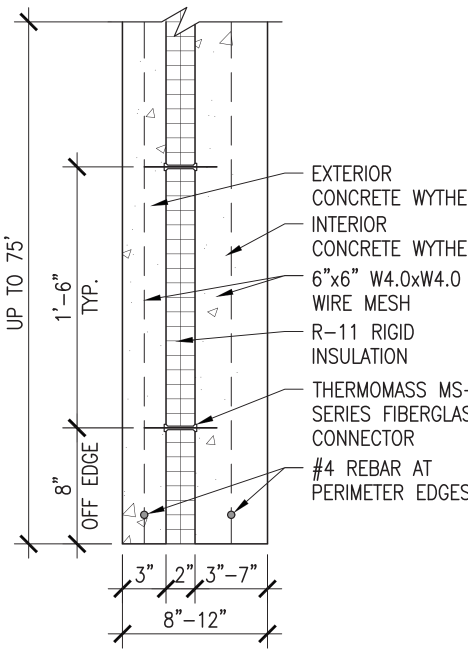
Question

Utilizing the material properties of Ultra-High Performance Fiber Reinforced Concrete (UHP-FRC) to design and fabricate a precast cladding system what are the performative strengths over traditional precast concrete cladding systems and how can we begin to add secondary performative value that utilizes these strengths?

Hypothesis

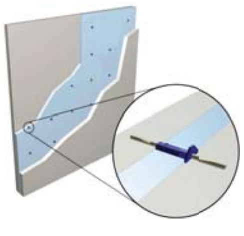
Using UHP-FRC in precast sandwich panels for facade applications we can develop a sandwich panel that is thinner, lighter, more durable, structurally and thermally optimized, and is able to be fabricated through a sustainable means in both time and materials.

INDUSTRY STANDARDS OF PRECAST SANDWICH

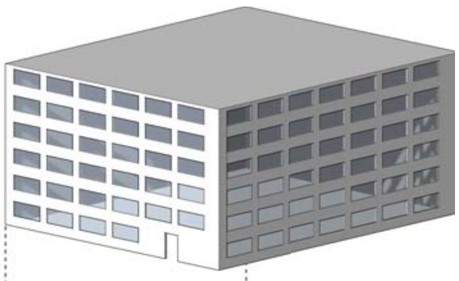


Sectional Detail
Typical Sandwich Panel

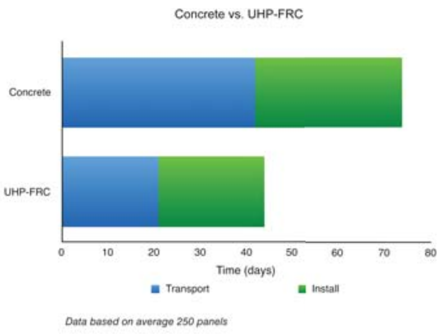
Typical Sandwich Panel



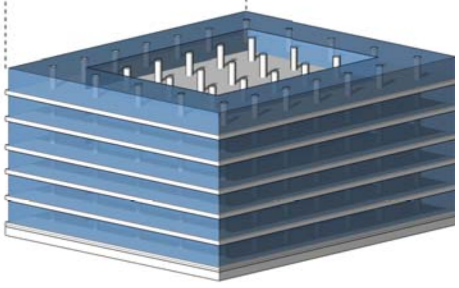
3D Diagram Thermomass MS-T Ties



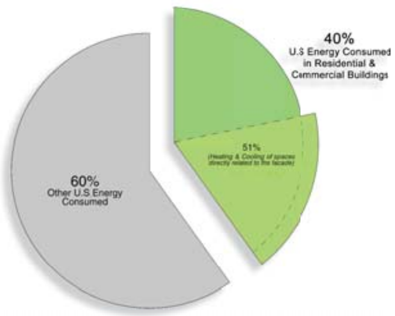
Building Envelope



Graph of Panel Delivery Comparison



Graph of the Spaces Directly Related to the Building Envelope



Graph of U.S. Energy Uses

TYPICAL SANDWICH PANEL FABRICATION METHOD

Formwork is Assembled and Prepped

Steel Reinforcement is Laid in Place

After the First Wythe is Poured and Scraped

The Second Wythe Pour

Scraping the Backing Wythe to Achieve an Even Finish

Precast Sandwich Panels on Site Ready to be Installed

HIGH PERFORMANCE PRECAST FACADE PANELS

Part I: Methodology

LANA SHIHABEDDIN / JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

Panel Objectives:

1. Lighter

2. Thinner

3. Equally Rigid

4. Higher/Equal R-Value

5. Solar Heat Gain

6. Reusable Formwork

Phase I: *Industry Baseline*

Investigate the current industry standard of constructing a pre-cast sandwich panel and cast a 3'x3' panel according to typical dimensions, assembly details, and fabrication techniques. Establish data points of the weight, compressive strength, bending strength, panel thickness, and thermal conductive and radiant properties of the panel as a baseline comparison.

Phase II: *UHP-FRC Baseline*

Investigate the material advantages of UHP-FRC as a pre-cast sandwich panel and cast a 3'x3' sandwich panel with similar compressive properties using appropriate dimensions for UHP-FRC and the same technique minus steel reinforcement. Establish data points of weight, compressive strength, bending strength, panel thickness, and thermal conductive and radiant properties to compare against baseline.

Phase III: *Structurally & Thermally Optimized*

Investigate the UHP-FRC panel assembly as hybrid composite/non-composite sandwich panel. Investigate the options for a monolithic pour to create a hollow core structural wythe. Digitally design a structurally optimized connection grid and geometry within the backing wythe while minimizing thermal bridging. Investigate the conductive and radiant thermal properties of the hybrid assembly.

AGENDA METHODOLOGY

Existing Advantages
- Insulation Included
- Inherent Weather Barrier
- High Impact Resistance
- "Simple" Install
- "Fast" Fabrication
- Higher Quality Control

−

Existing Disadvantages
- Thick & Heavy
- Material Amount for structurally rigidity
- Travel Restrictions

+

Research
- UHPFRC Application
- Self-Shading Surface
- Component Assembly
- Re-usable Formwork

=

Optimized Facade System

MATERIAL PROPERTIES

UHP-FRC Attributes	Dense Particle Packing	Specific Particle Ratio	Steel Fiber Reinforcement
Function	Greater Strength per Volume ↓	Greater Flowability ↓	Greater Ductility ↓
Panel Advantage	**Stonger** **&** **Lighter** *(per PSI)*	**Cast Thinner** **&** **More Detailed Geometry**	**More Durable** **&** **Greater Tensile Strength**

THERMAL PROPERTIES

Heat flows through the building envelope by two means of heat transfer; conduction and radiation.

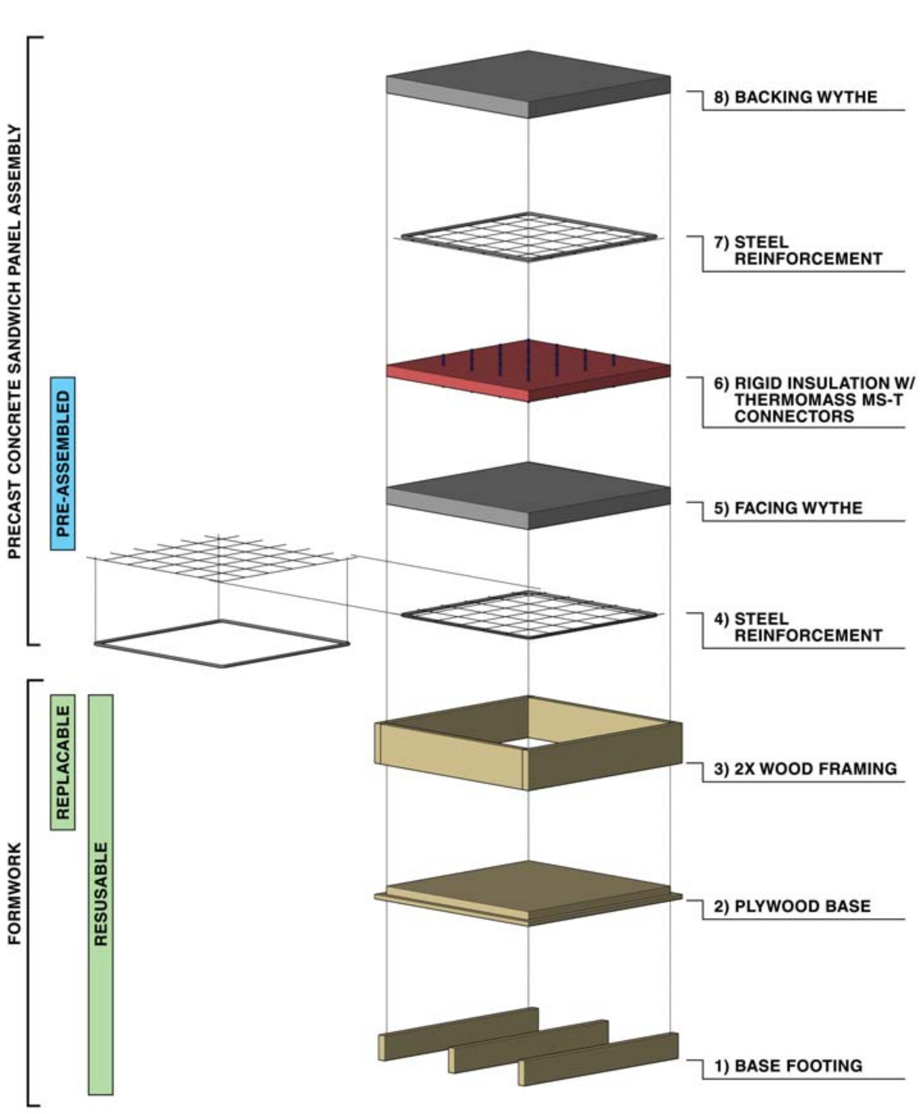
RADIATION is the heat transfer by electromagnetic radiant heat energy through space from one body to another without affecting the space in between. Radiant heat transfer to a body and its surrounding temperature depends on the absorptivity (A), transmissivity (T), and reflectivity (R).

CONDUCTION is the flow of heat through the substance due to a difference in temperature on two sides of the substance. Conduction is typically associated with the flow of heat through solids, but it can also happen through liquids and gases.

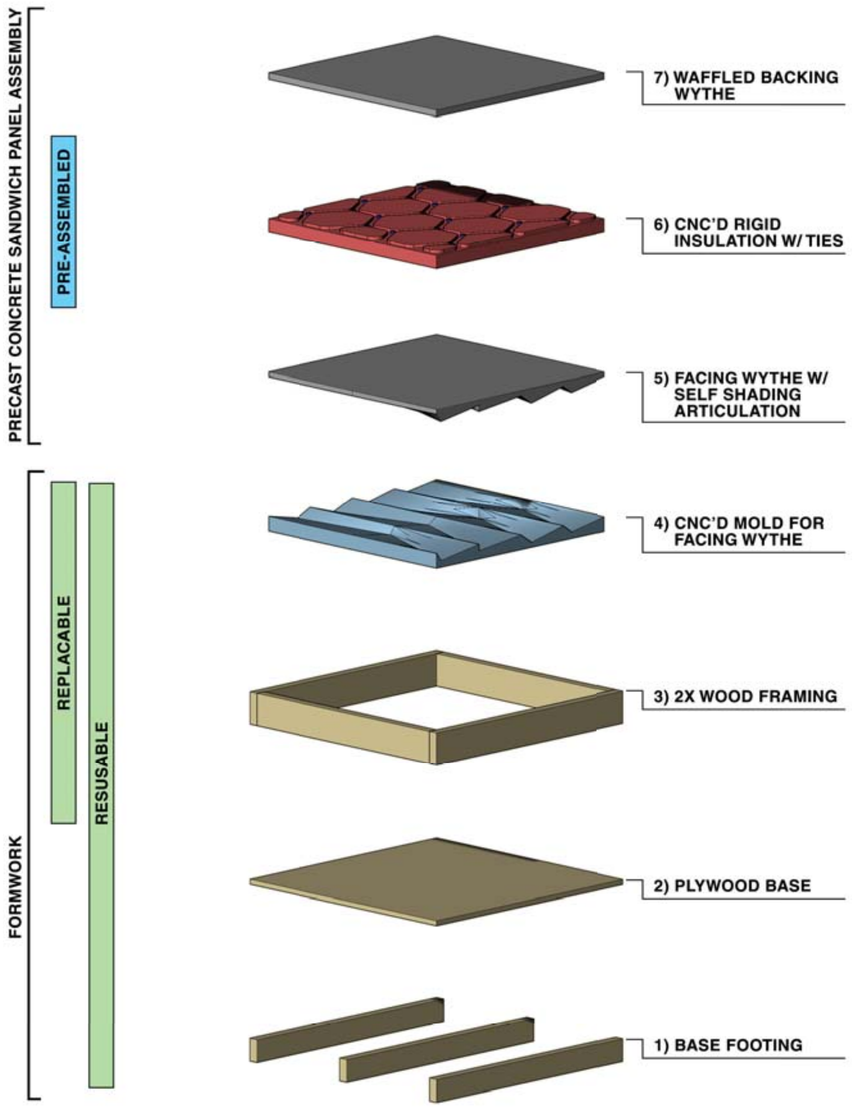
Jason Vollen EcoCeramic Research

Biomimetic Self Shading

STANDARD ASSEMBLY & CASTING



UHP-FRC ASSEMBLY & CASTING

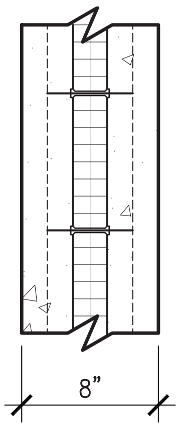


HIGH PERFORMANCE PRECAST FACADE PANELS

Part I: Phases of Design Research

LANA SHIHABEDDIN / JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

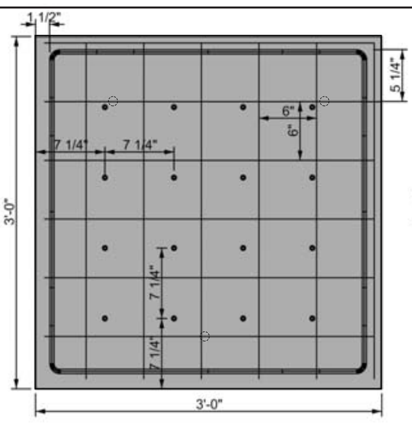
PHASE I



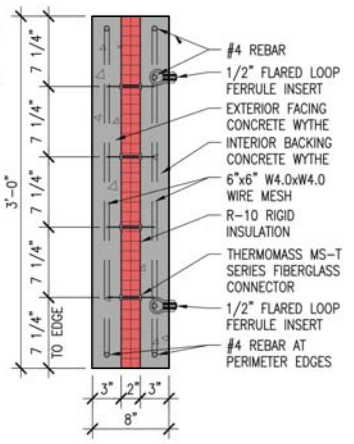
Phase I establishes the industry standard of a pre-cast sandwich panel. In collaboration with Gate Pre-cast and Thermomass, a typical non-composite assembly is chosen to cast a 3’x3’ panel. The assembly consists of a 3” facing wythe, 2” EPS rigid insulation, and a 3” structural backing wythe.

Gate Pre-cast provided their standard 7-sac Portland Cement mix for both the facing mix having a compression strength of 5,000 psi and the backing mix with a typical compression strength closer to 7,000 psi. Each wythe is structurally reinforced with 6”x6” wire mesh for cracking resistance attached to #4 (1/2”) re-bar around the parameter and through the ferrule loop inserts for tensile reinforcement. The ferrule loop inserts are exposed on the back of the panel as lifting points and tie points for display.

Thermomass MS-T Ties are used to tie the two wythes together connecting through the foam while limiting the amount of thermal bridging. Industry standard allows the spacing between the connectors to be a typical 18”, but the outermost connectors must be within 8” of all panel edges. Given the edge requirement and to support the panel evenly the ties are arranged in a 4x4 grid equally spaced at 7-1/4”.



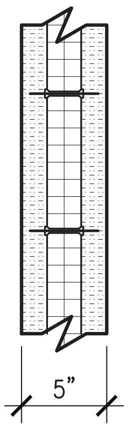
FRONT



SECTION

COMPRESSIVE STRENGTH:	R-VALUE:	DIMENSIONS:
5000 PSI	10 Conduction Heat Transfer Through the Panel (Q_T): **15.26 Btu/hr**	Width: **36”** Height: **36”** Thickness: **6”** Weight: approx. **650 lb**

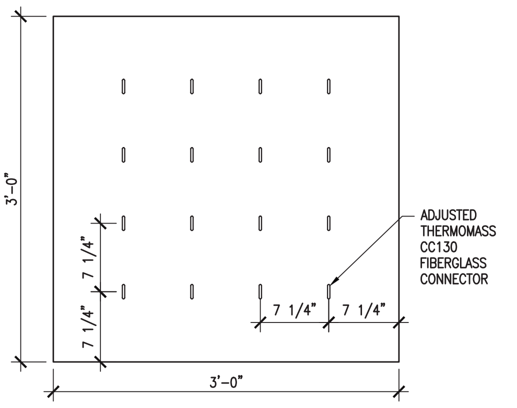
PHASE II



Phase II establishes a UHP-FRC sandwich panel baseline that is comparable to industry standard panel cast in phase I. Given the compressive strength of UHP-FRC a comparable non-composite assembly is made. The cast is a 3’x3’ panel consisting of a 1-1/2” facing wythe, 2” EPS rigid insulation, and a 1-1/2” structural backing wythe.

Thermomass CC-130 ties are used to tie the two wythes together connecting through the foam while limiting the amount of thermal bridging. The ties extend 1-1/2” from the insulation which were needed to be cut down on each end to avoid protrusion through the face. Industry standard allows the spacing between the connectors to be a typical 18”, but the outermost connectors must be within 8” of all panel edges. Given the edge requirement and to support the panel evenly the ties are arranged in a 4x4 grid equally spaced at 7-1/4”.

To cast the sandwich panel form work is designed as a reusable assembly of a plywood base and dimensional lumber framing. In order to allow the desired panel thickness based on the width of dimensional lumber the four 2x6’s, had to be cut down to 5”. All the inside surfaces are sealed with polyurethane and waxed to help release the concrete when cured. For the base a 1/4” sheet of plastic is placed to provide a smooth facing surface.



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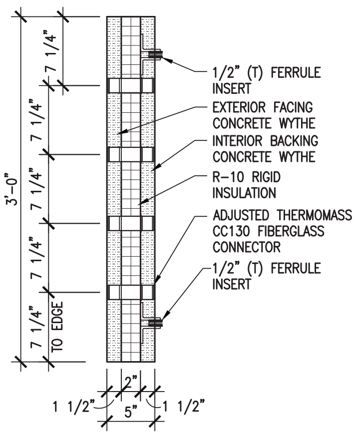
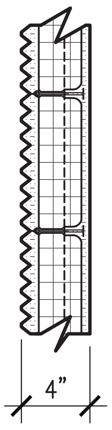


SECTION

COMPRESSIVE STRENGTH:	R-VALUE:	DIMENSIONS:
25,000 PSI	10 Conduction Heat Transfer Through the Panel (Q_T): **20.47 Btu/hr**	Width: **36”** Height: **36”** Thickness: **5”** Weight: approx. **325 lb**

PHASE III

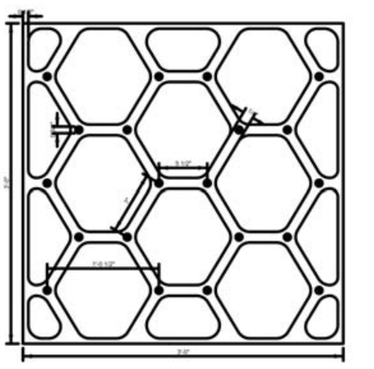


Phase III introduces thermal performative qualities utilizing UHP-FRC. It combines the baseline standard casting methods discussed in phase I and II. The introduction of thermal performance is done in two separate parts, the surface articulation, and an increase in the overall rigid insulation.

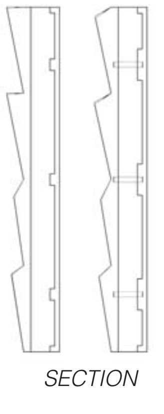
The final phase utilized CNC milled foam as the casting mold for the facing wythe. A similar process for the wood framing formwork as previously done was followed. In order to prep the foam for casting, it was sealed utilizing a latex sealant as well as wax to ensure release.

The CNC’d rigid insulation had the pre-inserted connector ties to prepare for the waffled back wythe. The hexagonal grid allowed for the structural back wythe to have the waffle form to minimize connections and continue to create a solid 1/2” concrete surface.

The pouring process similar to before was pouring the facing wythe on top of the CNC mold followed by the rigid insulation which already consisted of the connector ties, tying both front and back wythes. Once the foam was set in place the threaded bolts were used as an anchor.



FRONT



SECTION

COMPRESSIVE STRENGTH:	R-VALUE:	DIMENSIONS:
25,000 PSI	R1=13 R2=10 Conduction (Q_T): Q_T1=***14.33 Btu/hr*** Q_T2=***11.86 Btu/hr***	Width: 36” Height: 36” Thickness: 4” Weight: *approx.* **250 lb**

HIGH PERFORMANCE PRECAST FACADE PANELS

Part I: Optimization of Structural Wythe

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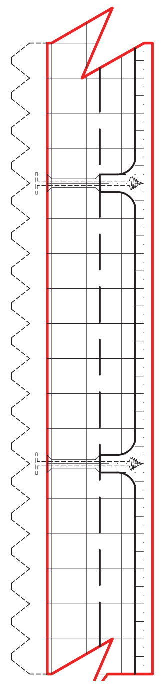
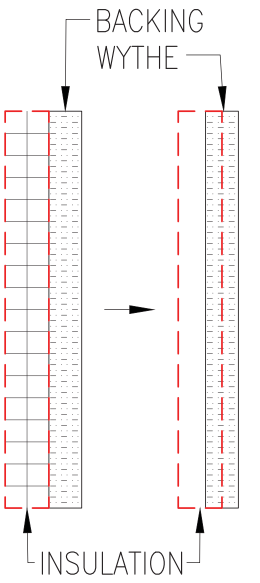


Phase III introduces the opportunity to discover the full potential of using UHP-FRC for sandwich panels in a facade application. Pushing the limits of thinness and thin casting requires the need to resolve the issue of impact resistance perpendicular to the plane of the panel. The fibers help resist bending as an intrinsic property of the material. However, testing the limits of just how thin we can cast while maintaining structural rigidity allows the investigation of the relationship of material properties, geometric arrangement, and nodal connections.

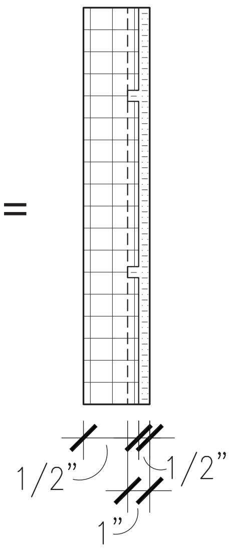
The primary goal for the backing wythe is to investigate how to infuse the insulation into the backing wythe. Doing so allows the potential for greater thermal performance and further lightens the panel. Two options for creating this hybrid backing wythe are investigated as a Waffle and a Hollow Core.

Searching for a geometric means to reinforce the thinness of the backing wythe a series of square grid, diagrid, and hex grid are analyzed. The grid study is to find the arrangement that minimizes the number of nodal connections, maintains an acceptable max length distance between nodal connections, and minimizes material. With the hex grid satisfying these requirements further investigations for the hollow core option look at the potential of further strengthening the wythe with simple misalignments of the grid and the effect of a hyperboloid connection between the two grid layers.

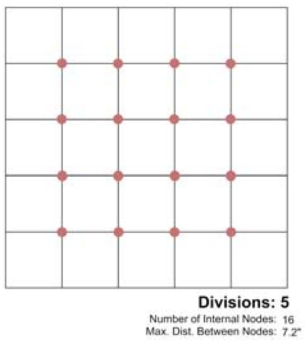
A final decision to cast a Waffle backing wythe was made after determining the Hollow Core would require an injection casting process and therefore not integrate directly to industry standards.



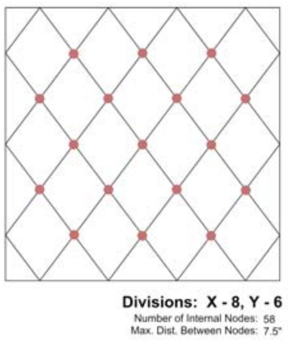
Insulation into Strucural Wythe Diagram



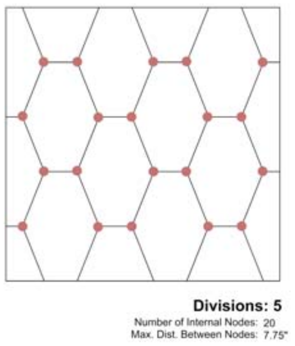
Hybrid Backing Wythe Section



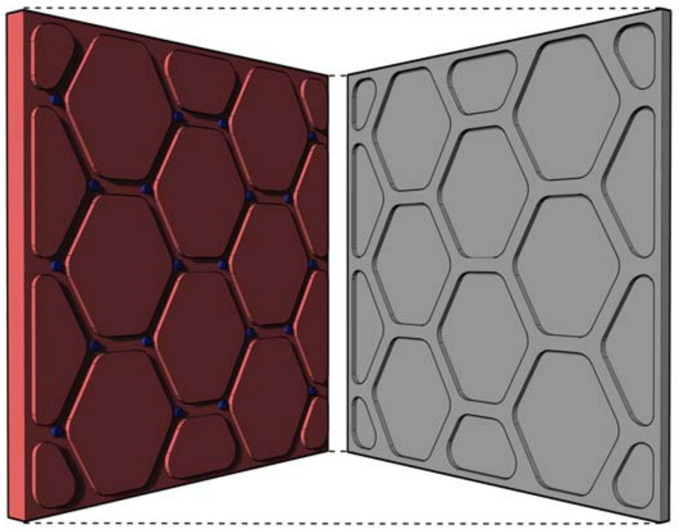
Divisions: 5
Number of Internal Nodes: 16
Max. Dist. Between Nodes: 7.2"



Divisions: X - 8, Y - 6
Number of Internal Nodes: 58
Max. Dist. Between Nodes: 7.5"



Divisions: 5
Number of Internal Nodes: 20
Max. Dist. Between Nodes: 7.75"



CNC'd Rigid Insulation (Mold for backing wythe)

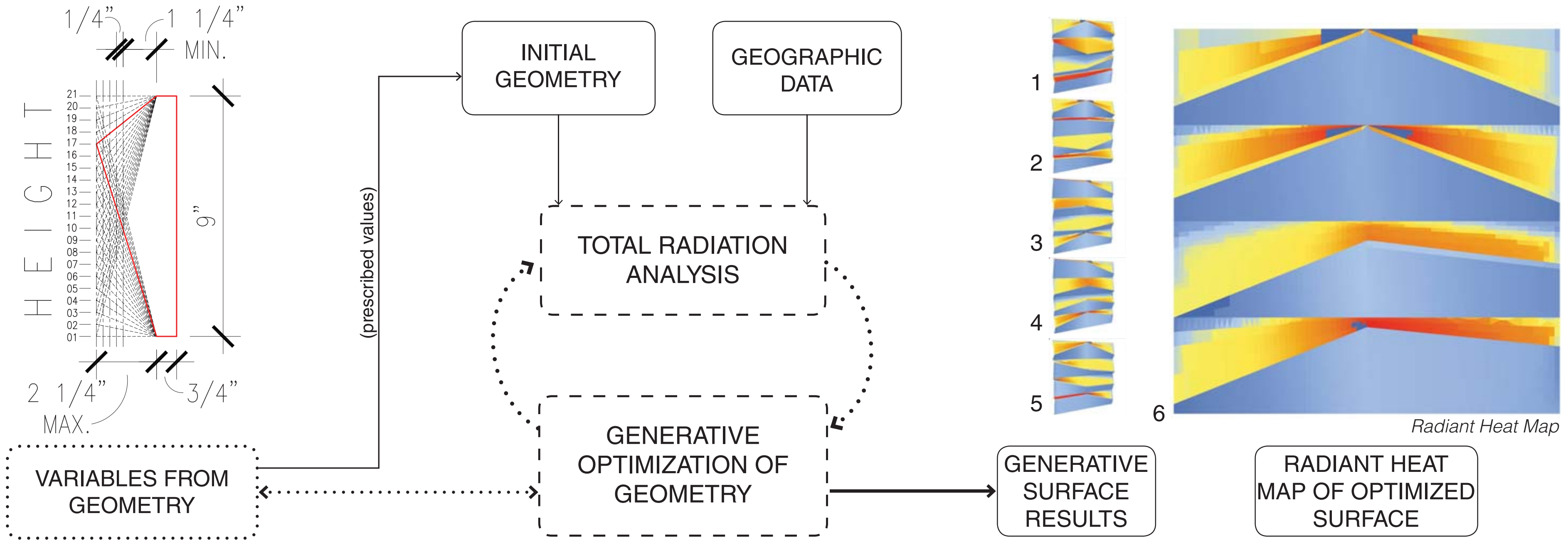
Waffled Backing Wythe

THERMAL PERFORMANCE

CROSS-SECTION
TO MANIPULATE

COMPUTATIONAL
WORK FLOW

RESULTING SELF-SHADING
ARTICULATED SURFACE



INITIAL GEOMETRY

GEOGRAPHIC DATA

TOTAL RADIATION ANALYSIS

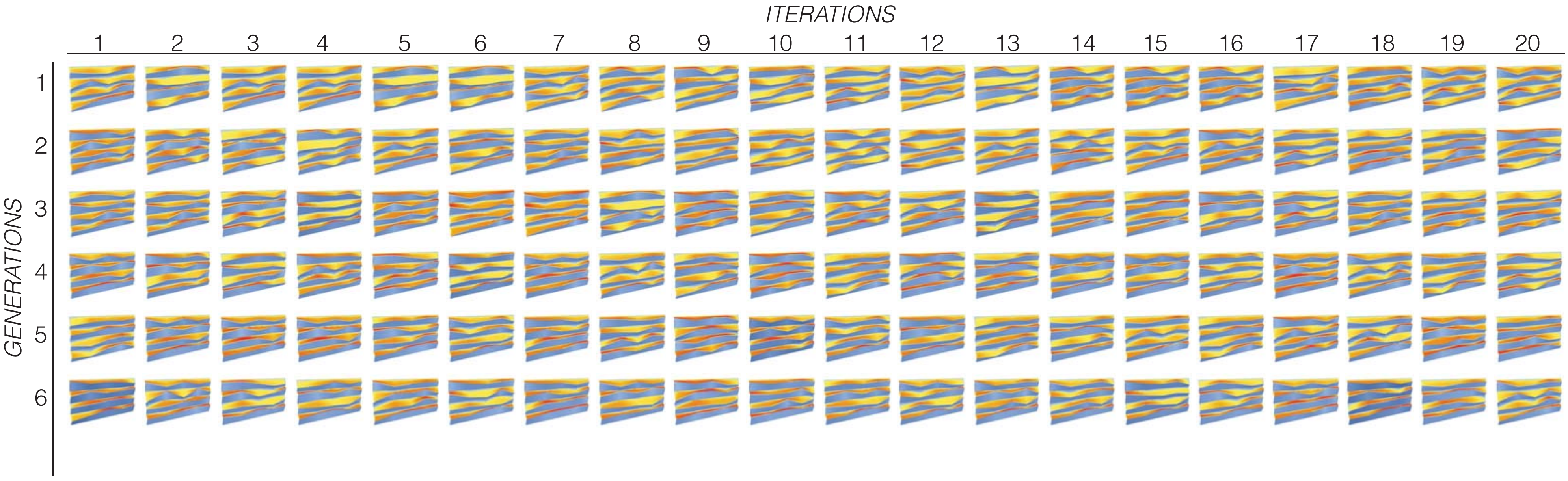
GENERATIVE OPTIMIZATION OF GEOMETRY

VARIABLES FROM GEOMETRY

GENERATIVE SURFACE RESULTS

RADIANT HEAT MAP OF OPTIMIZED SURFACE

Radiant Heat Map



HIGH PERFORMANCE PRECAST FACADE PANELS

Part I: Testing of Bending Strength

LANA SHIHABEDDIN / JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

In order to test and compare the structural performance of the different panels, a 3-point flexure test was performed on each panel to determine their respective strength in bending. A pin and roller set up was used and sensors were calibrated to record the load deflection.

The results show that the industry standard panel initially cracked at a low weight compared to both panels 2 and 3 despite both of the Ultra High Performance panels being much thinner. Both the standard panel and the initial Ultra High Performance panel were able to take more load than the final Ultra High Performance panel. However it is important to note that this 3rd panel was only slightly weaker than the other two despite being quite a bit thinner. This can likely be attributed to the waffle pattern of the structural backing wythe which was able to more evenly distribute the load throughout the panel despite being only an inch thick.

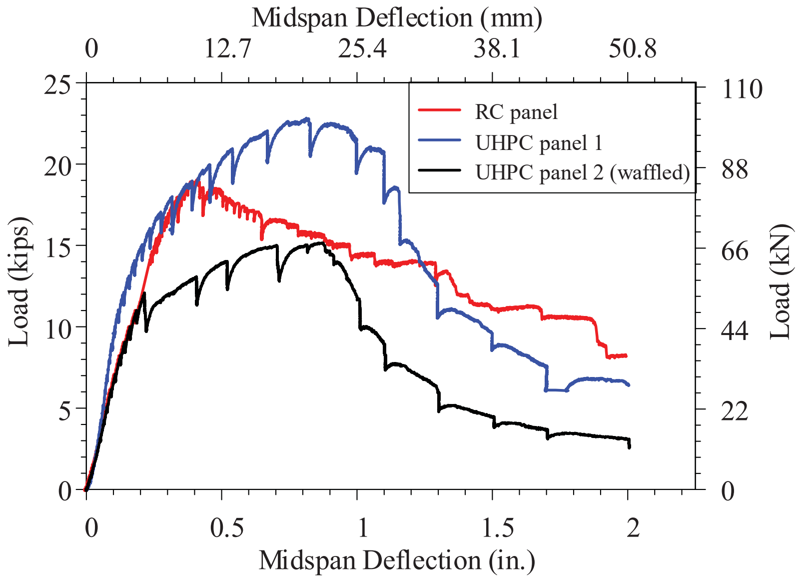
Testing Set-Up

Panel 1, 2, & 3 After Structural Testing

STRUCTURAL TESTING DATA

PANELS	STRUCTURAL WYTHE THICKNESS	OVERALL THICKNESS	INITIAL CRACK (KIPS)	PEAK LOADING (KIPS)	WEIGHT (LBS)
PANEL 1					
LOAD VS THICKNESS	3"	8"	5.8	19	676
	1.93 KSI/6.3 KSI	.725 KSI/2.38 KSI			
PANEL 2					
LOAD(KIPS) ÷ WYTHE THICKNESS	1 1/2" 12.66 KSI/15.2 KSI	5" 3.8 KSI/4.56 KSI	19	22.8	338
PANEL 3					
LOAD(KIPS) ÷ WYTHE THICKNESS	1"	4"			
	12.8 KSI-15.15 KSI	3.2 KSI/3.79 KSI	12.8	15.15	233

PANEL 3 VS. TRADITIONAL	6.5 TIMES STRONGER	3 TIMES LIGHTER	1/2 AS THICK



PANEL 1

Cracking at Loads

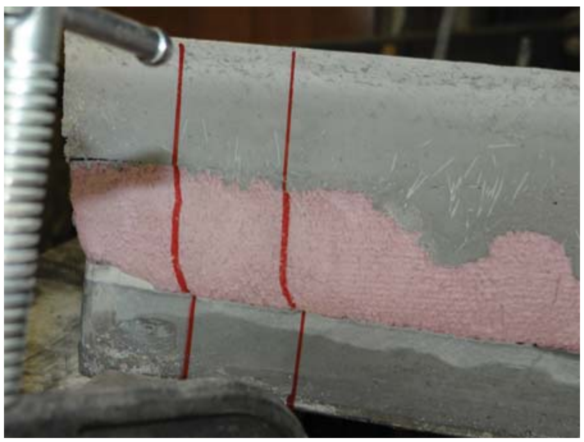
Main Failure Crack

Shear in Panel

PANEL 2

Cracking at Loads

Main Failure Crack



Shear in Panel

PANEL 3

Cracking at Loads

Main Failure Crack

Shear in Panel

HIGH PERFORMANCE PRECAST FACADE PANELS

Part II: Implications of Net-Zero Strategies

JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

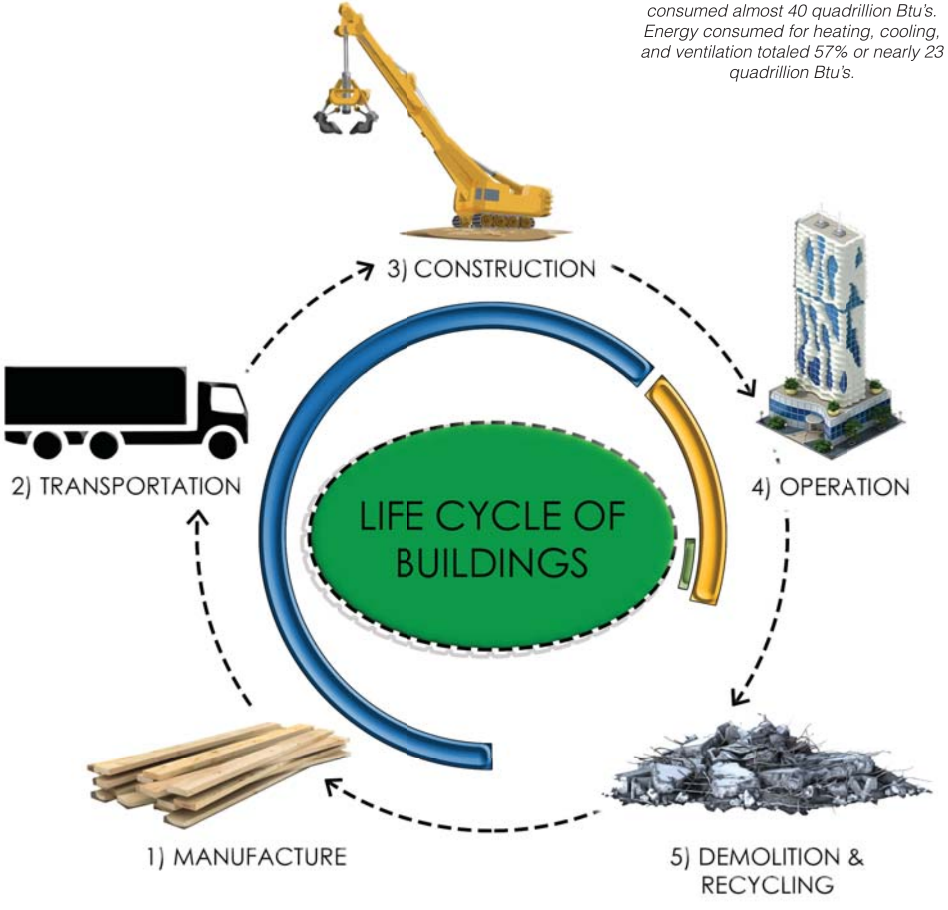
Research Questions

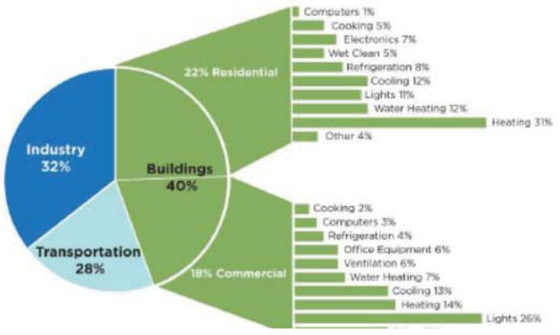
1. What are the performative parameters necessary to achieve a Carbon Neutral / Net-Zero building envelope utilizing UHP-FRC in a self-shading pre-cast sandwich panel façade system?
2. How can we optimize the panel's face to reduce heat transfer and self-shade in accordance with its environment?

Research Hypothesis

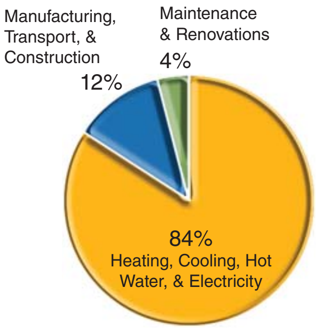
Extending the research of UHP-FRC in a performative façade application from the Fall of 2015, we can further assist the parameters required of Net-Zero buildings through the development of an advanced pre-cast concrete sandwich panel as a holistic building envelope design that is both thermally & structurally optimized, and is able to be fabricated through a sustainable means in both time and materials. These advances effect the construction process and overall life cycle of a building providing the potential to reduce Co2 emissions, other GHG's, costs of construction, costs of building operation, and ultimately providing a practical and economically viable solution to sustainable development of our built environment.

** Residential and commercial buildings consumed almost 40 quadrillion Btu's. Energy consumed for heating, cooling, and ventilation totaled 57% or nearly 23 quadrillion Btu's.*





Energy Consumption in the US
Source: 2007 DOE Buildings Energy Data Book



Typical Building Energy Usage
Source: World Business Council

1. Reduction of GHG

2. Higher R-Value

3. Solar Heat Gain

4. Net Zero System Implementation

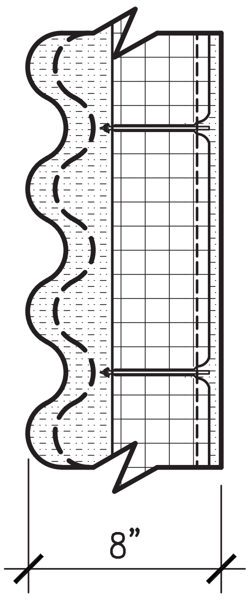
Phase I: *Optimized Panel for Net-Zero*

Investigate design opportunities to thermally optimize the facing wythe surface for a more sinuous surface type for self shading. Investigate the parameters associated with the building envelope able to assist sustainable strategies like Carbon Neutral and Net-Zero. Identify specific performance criteria to optimize the composition and structure of the panel with the optimized surface articulation for self shading to cast a 3'x3' panel prototype.

Phase II: *Architectural Implementation*

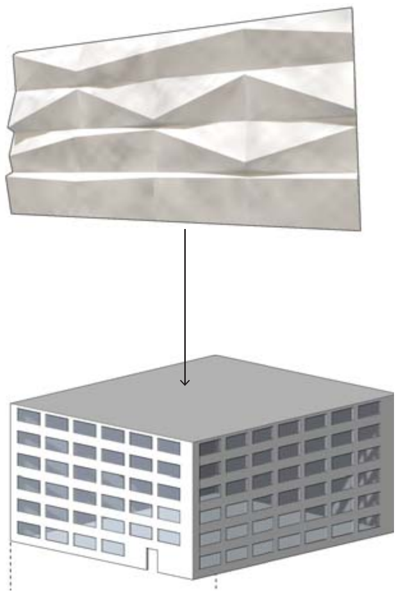
Take a standard building type and redesign it using High Performance Facade panels to create a case study that analyzes the impact these panels could have on cost and operation of typical buildings.

Phase IV



Optimized Net-Zero UHP-FRC Precast Sandwich Panel

Phase V



Architectural Case Study System Implementation

HIGH PERFORMANCE PRECAST FACADE PANELS

Research Components

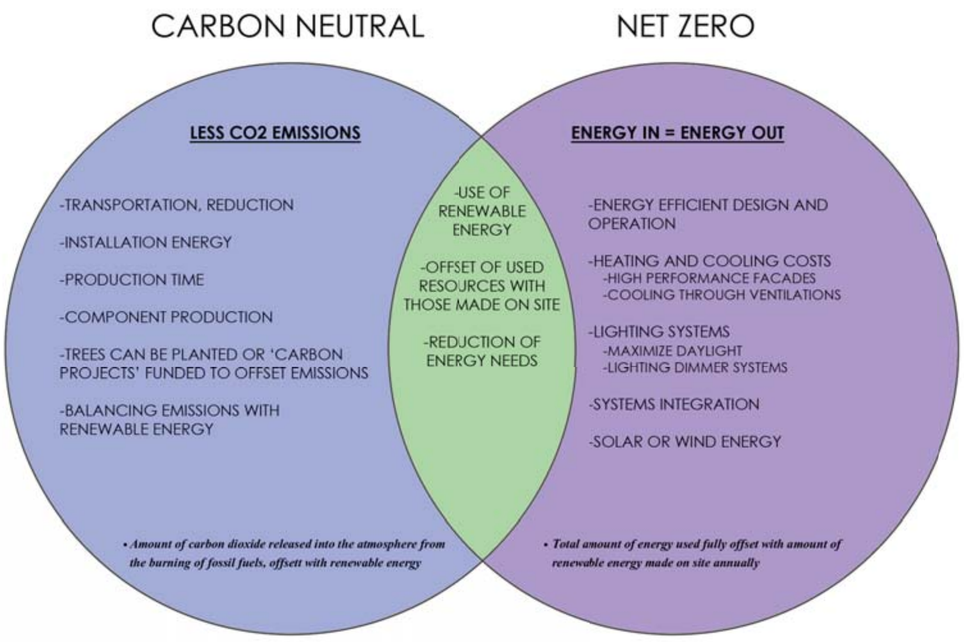
JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

Sustainable strategies such as Net Zero and Carbon Neutral attempt to reduce carbon dioxide emissions and electricity use through the implementation of programs and strategies that help to reduce output in these areas.

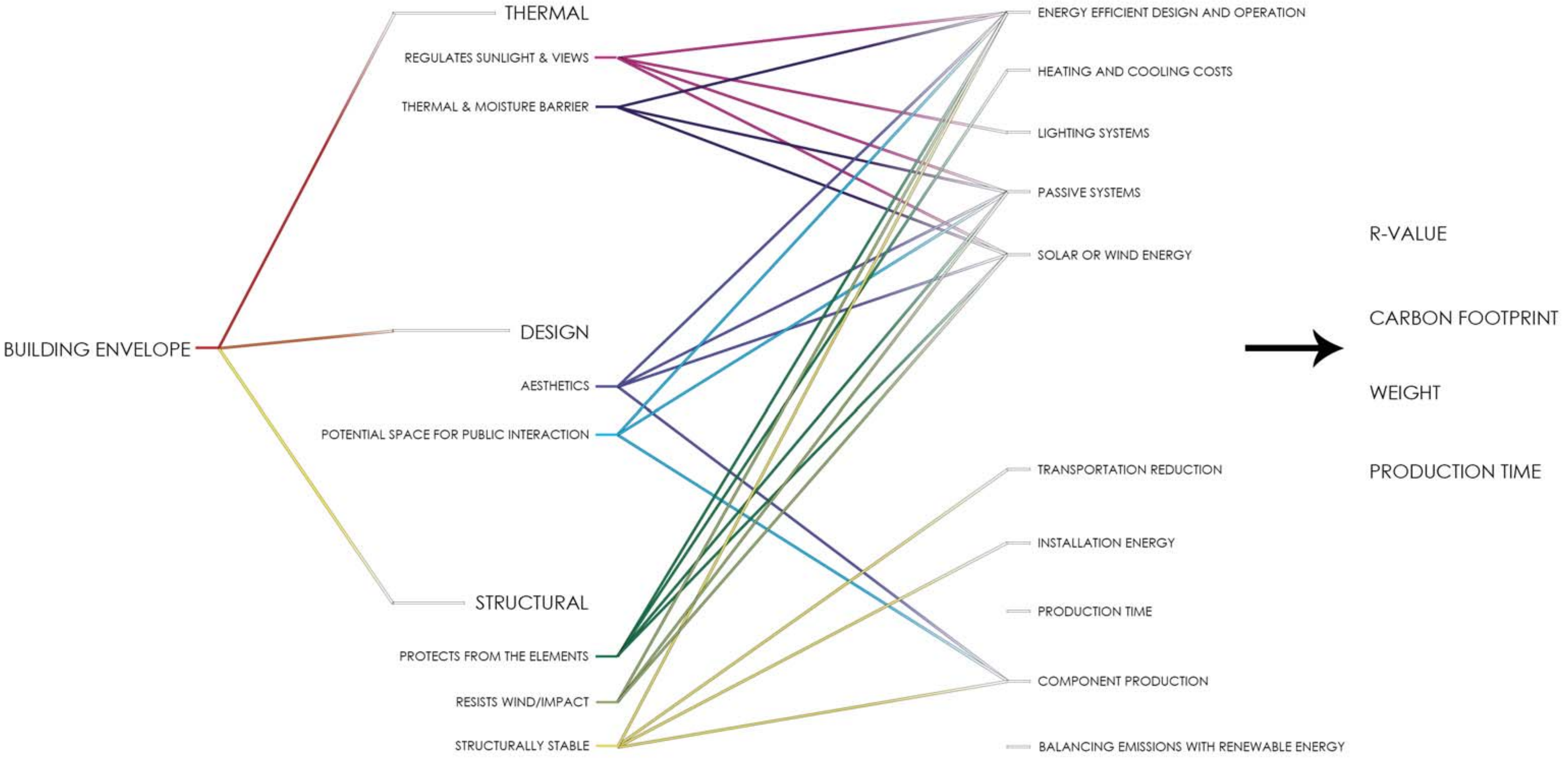
Carbon Neutral strategies look to reduce the amount of carbon dioxide released into the air by everything from the manufacturing of components to the installation and lifespan of these components. This is done through reducing emissions in transportation, installation, and production of components as well as offsetting emissions by planting trees, funding carbon projects, and balancing these emissions with renewable energy.

Net Zero strategies attempt to reduce the amount of electricity a building requires, generally only once a building has been completed and is already in operation. Strategies to reduce this energy need include designing energy efficient components and systems, implementing high performance facades and natural ventilation to reduce heating and cooling needs, maximizing daylight to reduce lighting electricity, and harnessing solar or wind energy to produce renewable energy for the building to use.

In the interest of using a building envelope to help Net Zero and Carbon Neutral strategies, what would this envelope need to accomplish in order to assist these strategies?

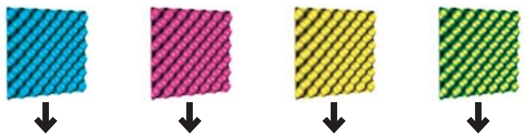


BUILDING ENVELOPE AND PERFORMANCE RELATIONSHIPS

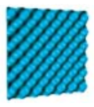


SURFACE DESIGN

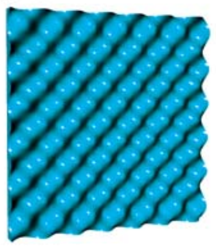
Surface Articulation Inventory



FILTER BASED ON TOTAL AVERAGE RADIANCE



OPTIMIZED FOR MAX SHADING FOR LOCATION & ORIENTATION



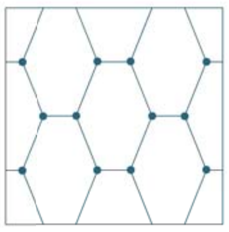
COMPOSITE DESIGN

R-Value

Insulation Thickness

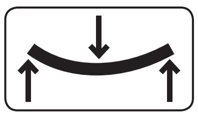
Thermal Conduciton Analysis

Connector Arrangement



STRUCTURAL DESIGN

Testing Results



VS.

Regional Wind Load

Refinement of Structural Waffle

Digital Simulation (Karamba)

Optimized Structural Wythe

HIGH PERFORMANCE PRECAST FACADE PANELS

Self-Shading Surface: Macro Articulation

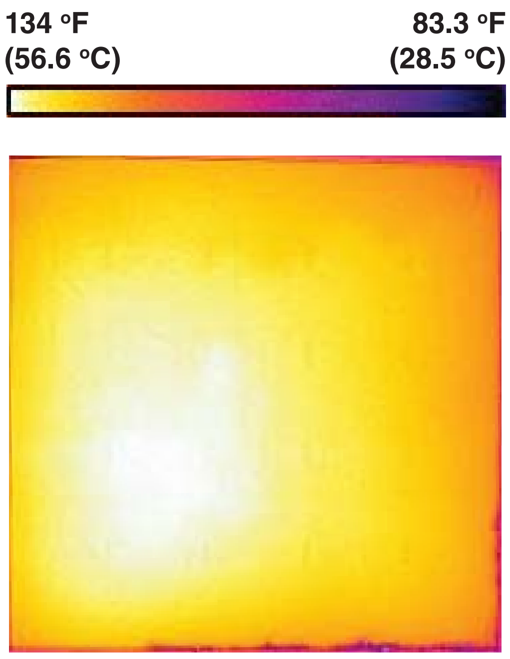
JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

Self shading surfaces are an attempt to reduce solar heat gain and therefore reduce heat transfer. This system is investigated to determine its effectiveness on an insulated UHP-FRC concrete panel. Compared to a typical flat panel self shading may provide thermal performance able to further assist sustainable building strategies. The simulation data below provides the parameters of the study that remain consistent through out the studies.

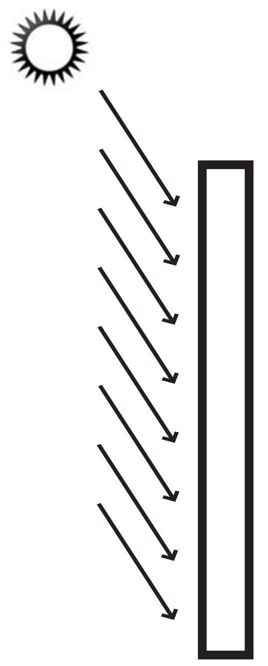
Simulation Data

Location:	Dallas, Tx
Sim. Period:	Day, 12 pm - 3pm
Orientation:	South
Exposure %:	100%
Avg. Outside Temp.:	84.5 °F (29.2 °C)

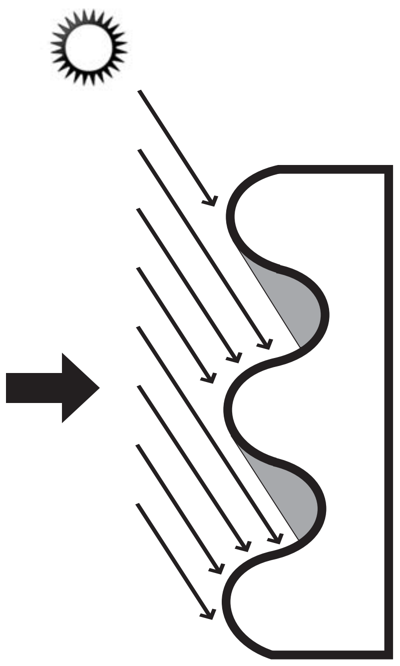
*Starting surface temp. is assumed the same as outside temp.



Heat Map of Flat UHP-FRC Panel



Flat Exposure Diagram

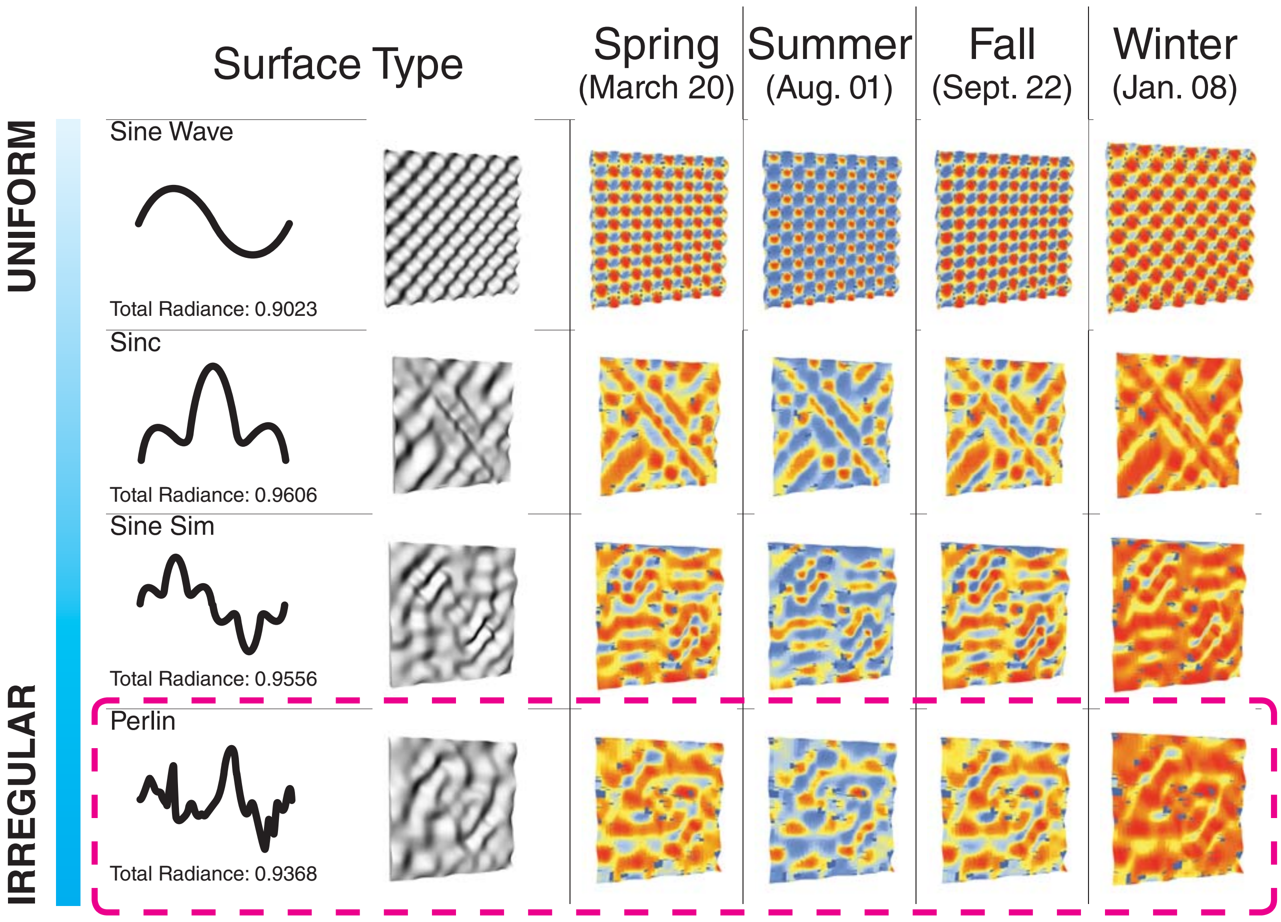


Self-Shading Exposure Diagram

SURFACE DESIGN INVENTORY

An inventory of macro surface articulations are made to investigate the performative self shading result for a different sinuous surface. Grasshopper and Rhino are used to generate the geometries and analysis. Designed on the premise of uniform to irregular, each surface is created from a manipulation of a point grid with attractor points. The distance is fed through calculations measuring the distance between the grid which makes the surface and the attractor points. These values are then fed through each of the graph types of a Sine Wave, Sink Wave, Sine Sim, and Perlin wave. Each graph type creates a different surface type.

Each surface type is then analyzed for radiance in a given location for a set period of time. Each season is analyzed separately to determine its effectiveness year round and given an average total radiance. These results help to determine which sinuous surface provides the most shading.



CHOOSE & FINE TUNE DESIGN TYPE

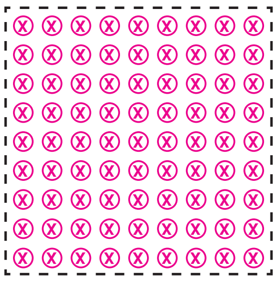
Based on the results from the radiance analysis the Perlin type is chosen. The Perlin design performs comparably well to the uniform articulation of the Sine Wave but provides an array of final articulation options. The next step is to fine tune the method of creating a surface utilizing the Perlin type.

To fine tune the surface and in addition to providing self-shading performance the method for generating the final result must fulfill three primary functions:

1. The design method must be repeatable.

2. The final surface must have an anticipated result, not a random result.

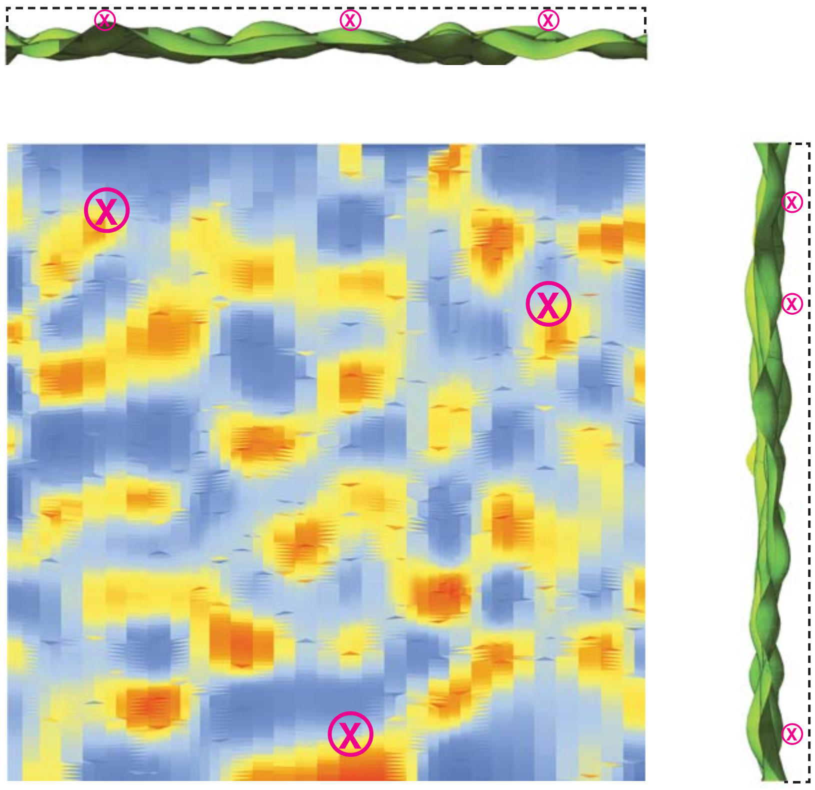
3. The generating script must provide a level of variability to create different results.



1. Identify Surface Points

2. Identify Variable Points

3. Fine Tune Perlin Graph



HIGH PERFORMANCE PRECAST FACADE PANELS

Self-Shading Surface: Macro Optimization

JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

To determine the optimal surface articulation requires the analysis of thousands of options provided from the fine tuned design type. In order to narrow down the list a generative solver within Grashopper called Octopus is used. Utilizing computation Octopus changes then reads what it is solving for, changes geometry variables, and reads what it is solving for again. This process is repeated within the guidelines set by the designer. The results are plotted on a 3d point graph.

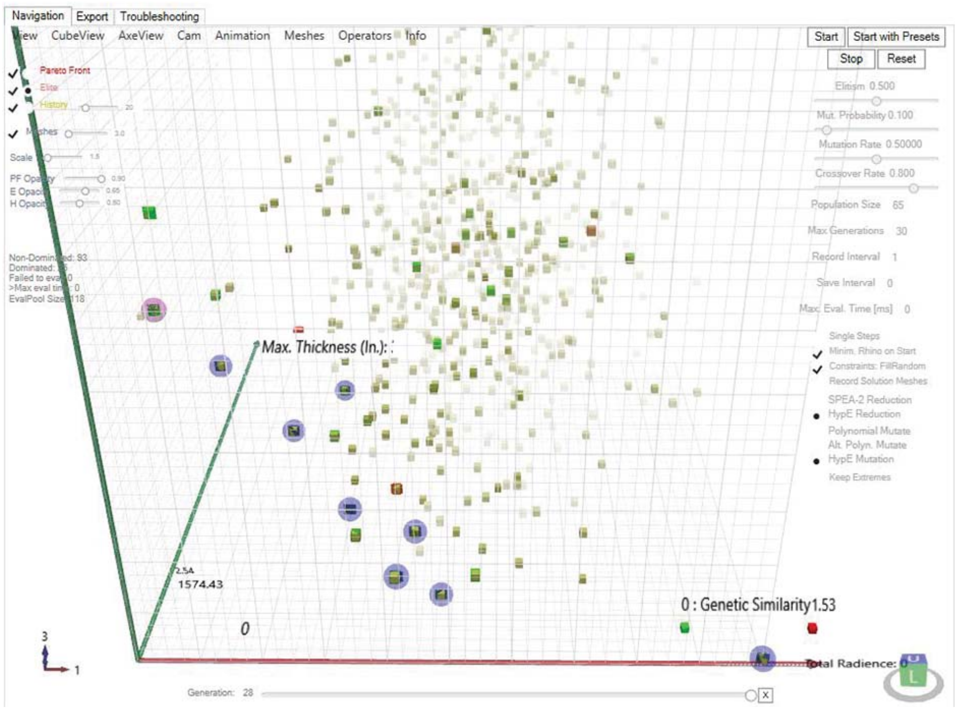
Octopus is set to solve for the least amount of radiance on the surface, total volume created by the surface articulation, and minimizing the thickest moment in the articulation. The simulation is set to run thorugh 29 generations with 65 iterations within each generations.

Generative Solver Settings:

Solve for least amount of...

1. Radiance
2. Volume
3. Max. Thickness

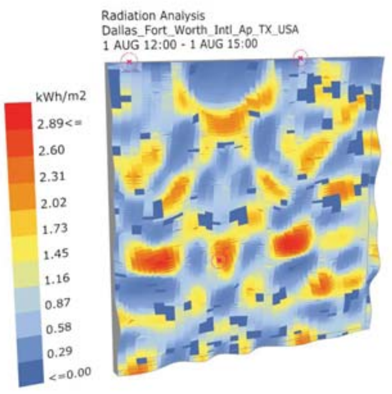
Run for 29 generations with 65 iterations per generation.


Elitism 0.500
Mut. Probability 0.100
Mutation Rate 0.50000
Crossover Rate 0.800
Population Size 65
Max Generations 30
Record Interval 1
Save Interval 0
Max. Eval. Time [ms] 0
Generation: 28

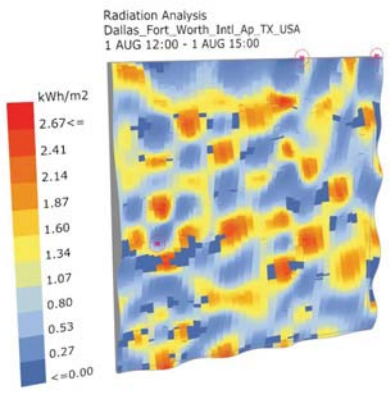
3D Point Graph of Optimization Results
Prefered settings highlighted in purple.

PREFERED OPTIMIZATION RESULTS

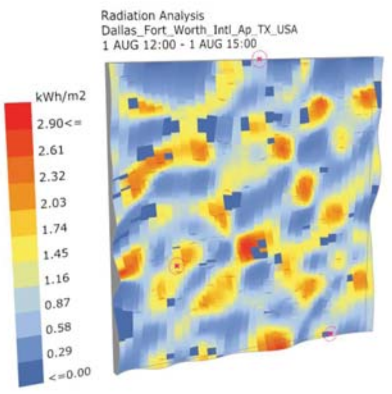
A



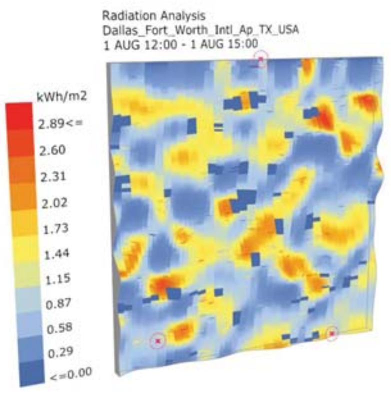
B



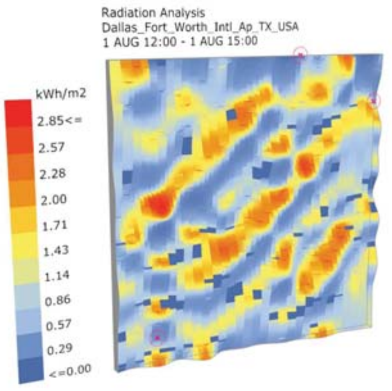
C



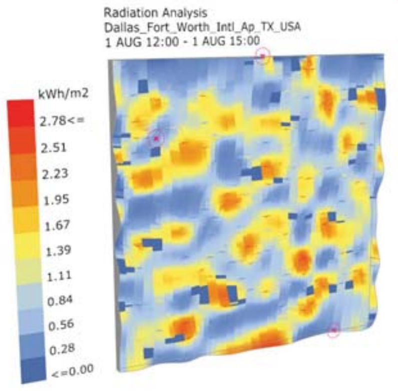
D



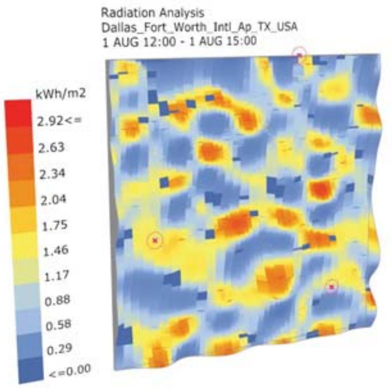
E



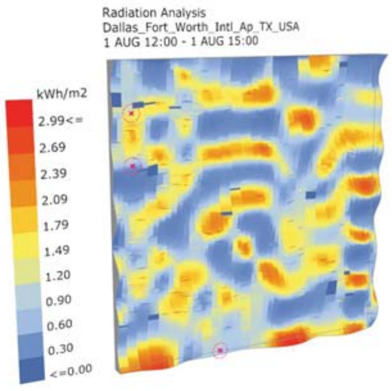
F



G



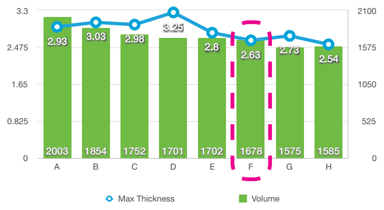
H



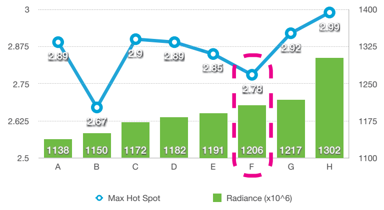
ANALYSIS OF RESULTS & CHOSEN SURFACE

Analyzing the resulting data from the prefered option surface F is chosen. The preferred options include the best performer of each category and others close to them. Cross referencing thickness, volume, and radiance values surface F is not the best at any one category, but rather best overall.

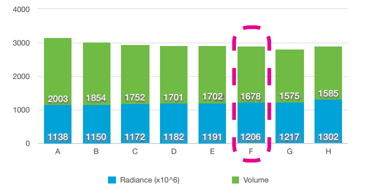
Thickness v. Volume



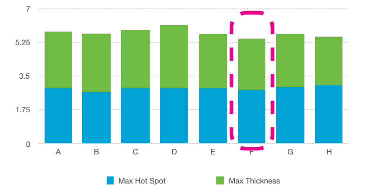
Total Radiance v. Highest Radiance



Total Radiance v. Volume

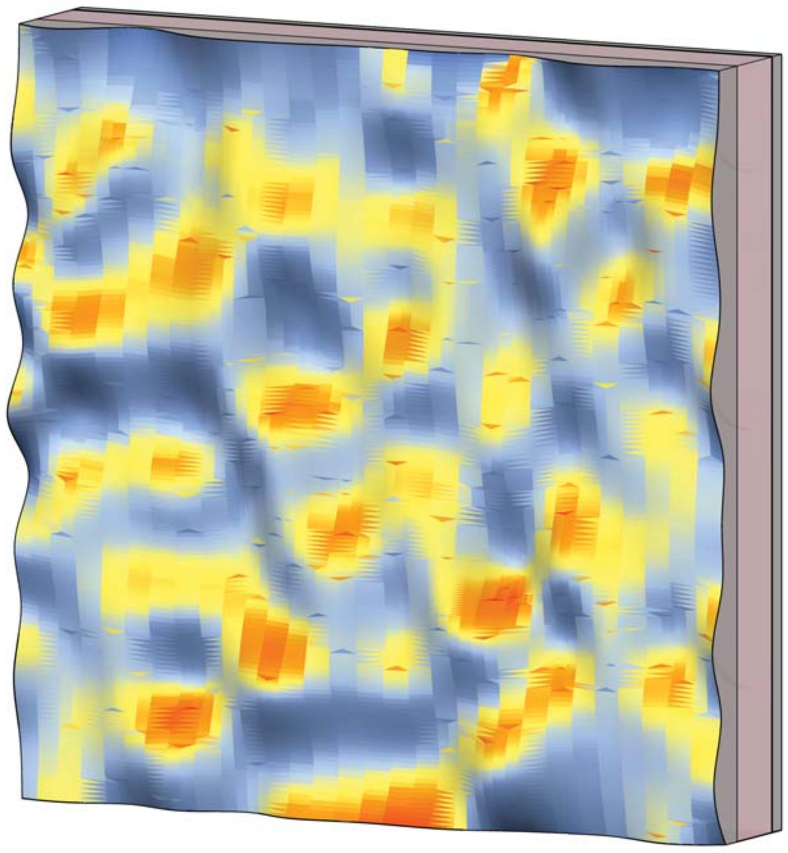


Max. Thickness v. Highest Radiance



Self-Shading Surface: Macro Articulations

Surface Option	Radiance (x10^6)	Max Hot Spot	Max Thickness	Volume
A	1138	2.89	2.93	2003
B	1150	2.67	3.03	1854
C	1172	2.90	2.98	1752
D	1182	2.89	3.25	1701
E	1191	2.85	2.80	1702
F	1206	2.78	2.63	1678
G	1217	2.92	2.73	1575
H	1302	2.99	2.54	1585



Panel 4 w/ Optimized Self-Shading

HIGH PERFORMANCE PRECAST FACADE PANELS

Panel Thermal Analysis

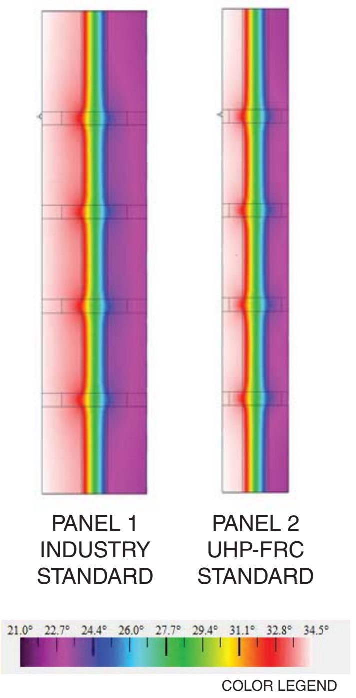
JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

Higher R-Value is the primary factor to reduce the thermal heat transfer through the building envelope. Supplying thicker rigid foam insulation provides a direct increase of the envelopes R-Value, but to a point. The composite design of our research sought to answer four main questions.

1. How does heat flow through the panel?
2. What R-Value should the panel be?
3. What, if any, effect does a self-shading surface have on conduction through the panel?
4. Can self-shading help reduce the need for significant insulation thickness?

Digital analysis techniques and softwares are used to investigate the potential heat flow through the panel. THERM is a program designed to study the two dimensional section of any assembly of materials. It operates by outlining the physical geometry, assigning material type to the geometry, and identifying the inside and outside temperatures.

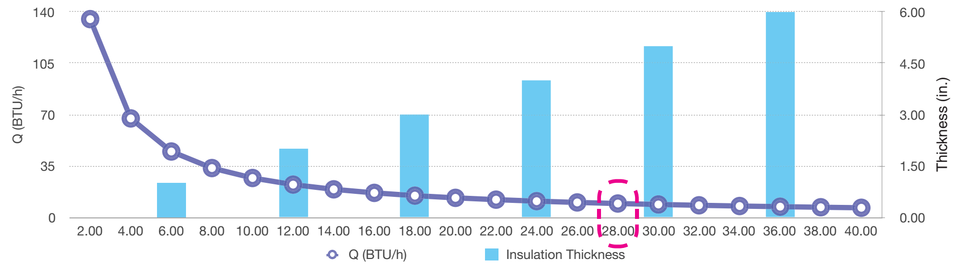
THERM models


PANEL 1 INDUSTRY STANDARD

PANEL 2 UHP-FRC STANDARD

COLOR LEGEND

Insulation Conductivity/R-Value/Thickness



The proper R-Value of a facade panel is a combination of code requirements and desired efficiency in thermal performance. In a sandwich panel the rigid insulation is the primary thermal barrier. Typical XPS or EPS insulation has an R-value of 5 per inch. Polyisoacanurate has an R-value of 6 per inch, but costs a little more. The key benefit of using Polyisoacanurate is the dramatic decrease in GHG's produced during manufacturing, lowering the carbon footprint of the panel.

The thickness to R-value of insulation is not a scalar function. The benefit of thermal performance eventually levels off making extra thick insulation a waste of money. The graph above shows the relationship of thermal conduction performance Q (BTU/hr) to R-Value and it's relative thickness. Examination of this relationship shows an average benefit of factors at 4" of insulation to have an R-value of 24.

RADIANT HEAT EFFECT ON THERMAL CONDUCTION

Conduction Formula: $Q_T = A_s U(T_H - T_C)$

Q_T= conduction/heat transfer rate, A_s= Surface Area, U= conductive value, T_H-T_C= Tempurature difference of either side of specimen

Stefan-Boltzmann Law: the total energy radiated per unit surface area of a black body across all wavelengths per unit of time (j) is directly proportinoal to the fourth power of the body's thermodynamic temperature. A body that does not absorb all incident radiation (grey body) emits less total energy than a black body and is characterized by an emissivity (є < 1). The formula to solve for irradiance from a grey body is,

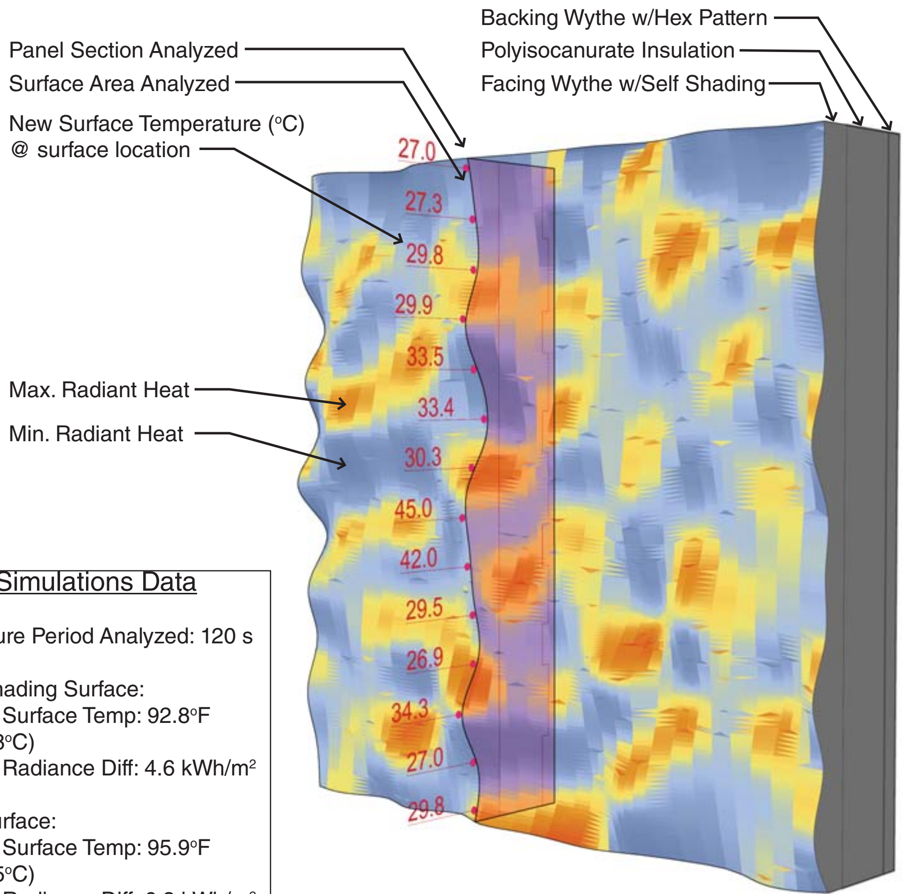
$$j = \epsilon \sigma T^4$$

j= irradiance (kWh/m²), є= emissivity,
б= Stefan-Boltzmann Constant, T= Surface Temp. in Kelvin

We can reorder the formula to solve for the new surface tempurature for a given amount of radiance over a period of time,

$$T = \sqrt[4]{\frac{j}{\epsilon \sigma}}$$

This allows us to determine the new surface tempurature after being exposed to the radiant heat energy after a given period of time. Therefore allowing the determination of surface tempurature to a specific location on the panel.



Simulations Data

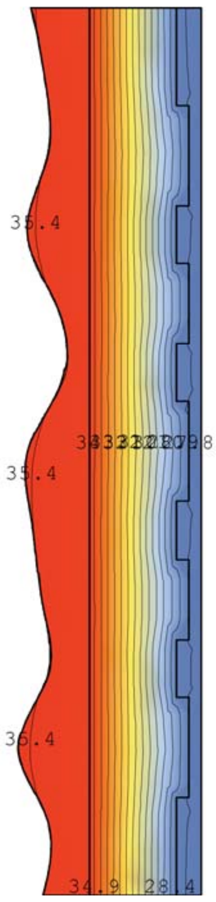
Exposure Period Analyzed: 120 s

Self Shading Surface:
- Avg. Surface Temp: 92.8°F (33.8°C)
- Avg. Radiance Diff: 4.6 kWh/m²

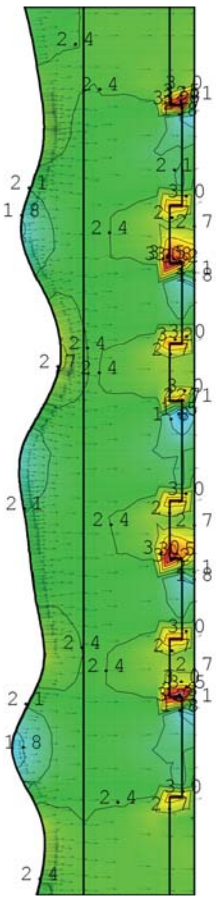
Flat Surface:
- Avg. Surface Temp: 95.9°F (35.5°C)
- Avg. Radiance Diff: 6.3 kWh/m²

THERM STUDIES OF THERMAL HEAT TRANSFER

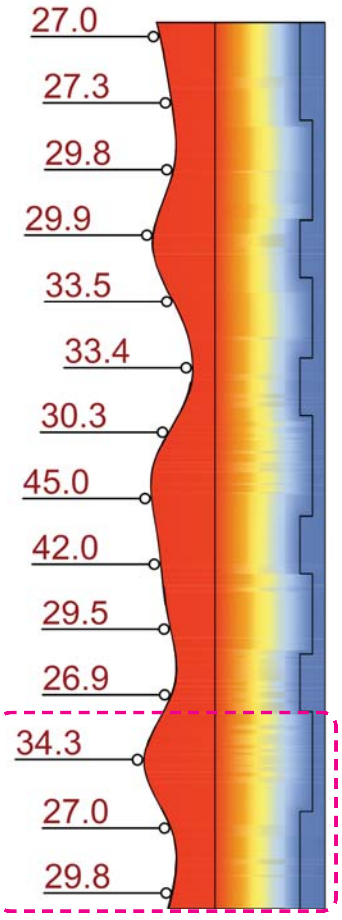
Using the two dimensional analysis software THERM the conduction and heat flux within the panel is analyzed. From these analysis it can be determined the primary effectiveness of each material in the panel assembly. The gradient of the heat map represents the heat resistance within. Heat flows from hottest to coolest, therefore the simulation requires an outside and inside boundary at given temperatures. This is problematic in determining the effectiveness of self shading. Self shading changes the surface temperature at any given point on the surface. Therefore to study the effectiveness of self shading on heat transfer individual sections need to be analyzed with the appropriate surface temperatures.



Normal Heat Transfer Diagram



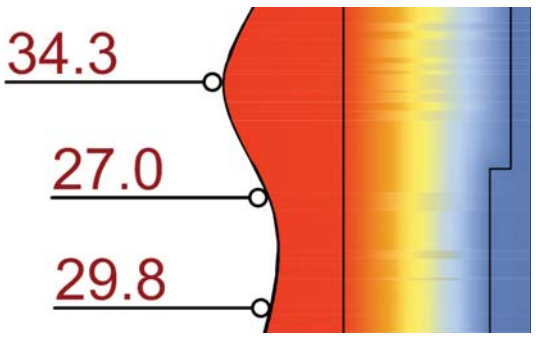
Heat Flux Diagram



Overlayed Heat Transfer Diagram w/ Individual sections at different temps.

Individual sections are identified within the grasshopper/rhino model according to the surface area and location analyzed. They are then organized into a series of 9 categories guided by the range of total radiant heat hitting the surface. These sections are analyzed through THERM separately then with the Normal Heat Transfer Diagram. This overlay shows a change in the moment of equilibrium toward the face of the panel.

This shift provides evidence, however subtle, that self shading may provide some assistance to reducing heat transfer and possibly allow for thinner insulation.

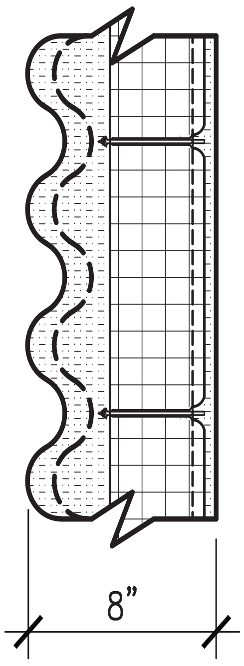


Overlayed Heat Transfer Diagram Detail

HIGH PERFORMANCE PRECAST FACADE PANELS

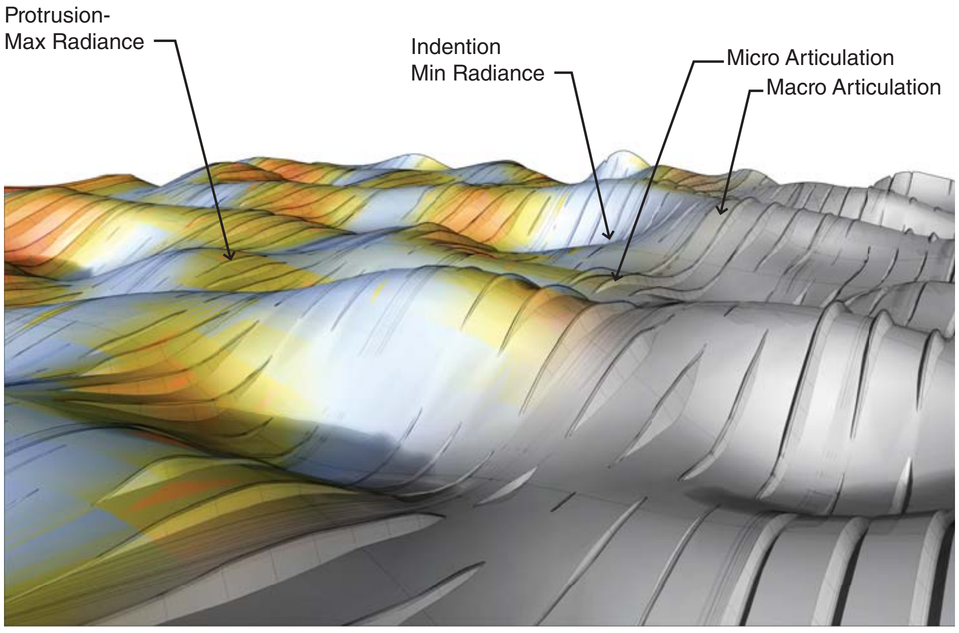
Panel 4: Micro-Articulation and Fabrication

JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

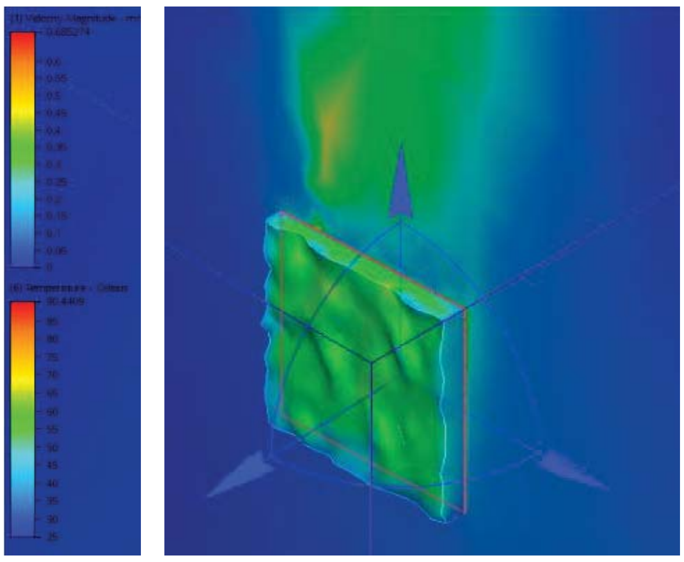


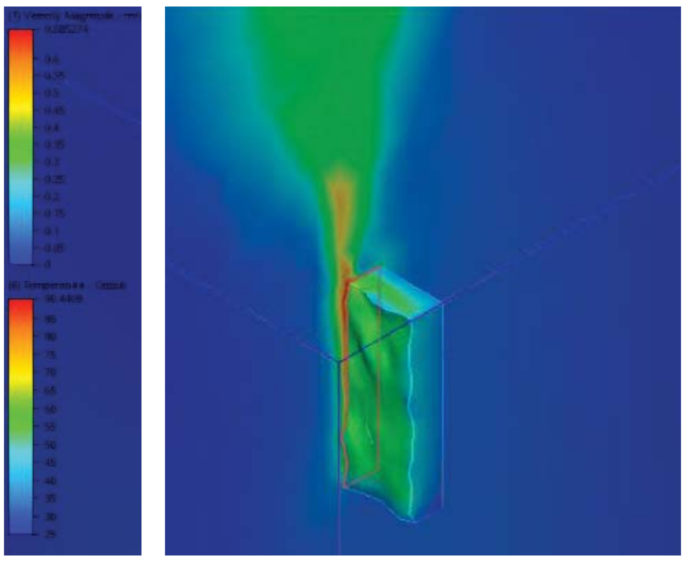
The final design and fabrication of panel four focuses on the development of micro articulation of the panel and the process of casting a 3’x3’ prototype.

The use of radiance is used to influence the development of the surface articulation on the macro scale as well as the micro scale. A series of studies including a CFD Analysis, computational fluid dynamics, to simmulate the effect of wind on convection in removing heat from the surface. The results found a slight increase of wind on the panel.



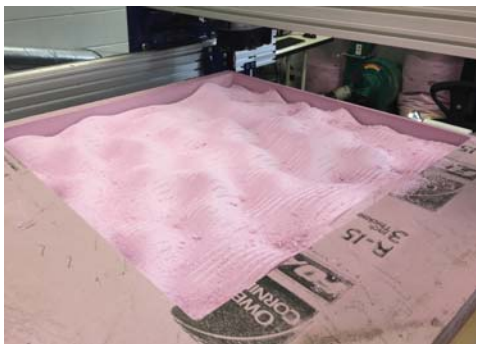
UHP-FRC ASSEMBLY

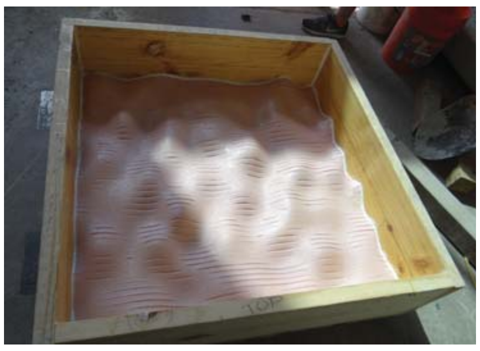


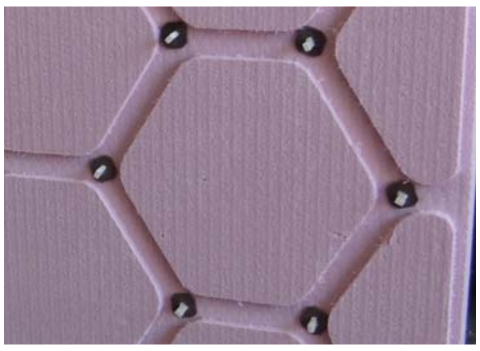


FORMWORK ASSEMBLY & CASTING

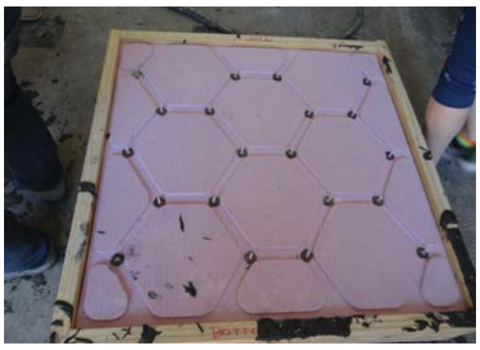

CNC MILLING WAFFLE WYTHE


CNC MILLING FACING MOLD


SURFACE ARTICULATED MOLD


INSERTED CONNECTOR TIES


POURING OF FACING WYTHE


RIGID INSULATION IN PLACE


POURING OF STRUCTURAL WYTHE


THREADED BOLT INSERTS


PANEL AFTER FORMWORK PULLED

UHP-FRC PANEL RESULTS SUMMARY

DIMENSIONS:

WIDTH: ***36”***
HEIGHT: ***36”***
THICKNESS: ***8”***
WEIGHT:
approx. ***450 lb.***

COMPRESSIVE
STRENGTH:

25,000 PSI

HIGH PERFORMANCE PRECAST FACADE PANELS

Cost and Life Cycle Analysis

JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

In investigating Net Zero and Carbon Neutral strategies in relation to concrete facade panels, we implemented advanced materials such as UHP concrete and polyiso insulation board. There is evidence that these types of materials contribute to the lowering of GHG emissions with comparable or enhanced performance. However, these materials tend to be more expensive than their standard ccounterparts. This raises the question of the true cost of sustainability.

Working with industry practitioners, we were able to determine the relative cost of a 10' x 30' concrete sandwich panel made with both UHP and standard methods and compare the two. Among the factors included were the cost of the materials, the sizing of the HVAC system needed according to the performance of each panel, and the sizing of the structure needed according to the weight. Analyzing all these factors allowed us to determine not only an up-front cost for things like material, transport, and installation, but also a cost over time based on the operation of the building.

The data revealed that, although the up-front cost of materials is higher in a UHP panel, there is a savings in transport, installation, and steel structure as well as a significant savings in the reduced sizing necessary in the HVAC system and therefore reduced energy consumption of the building over time. This makes this type of panel feasible for long-term, energy demanding construction.

STANDARD PANEL

10'x30' Panel Weight: 22,500 lb Volume: 150 ft³

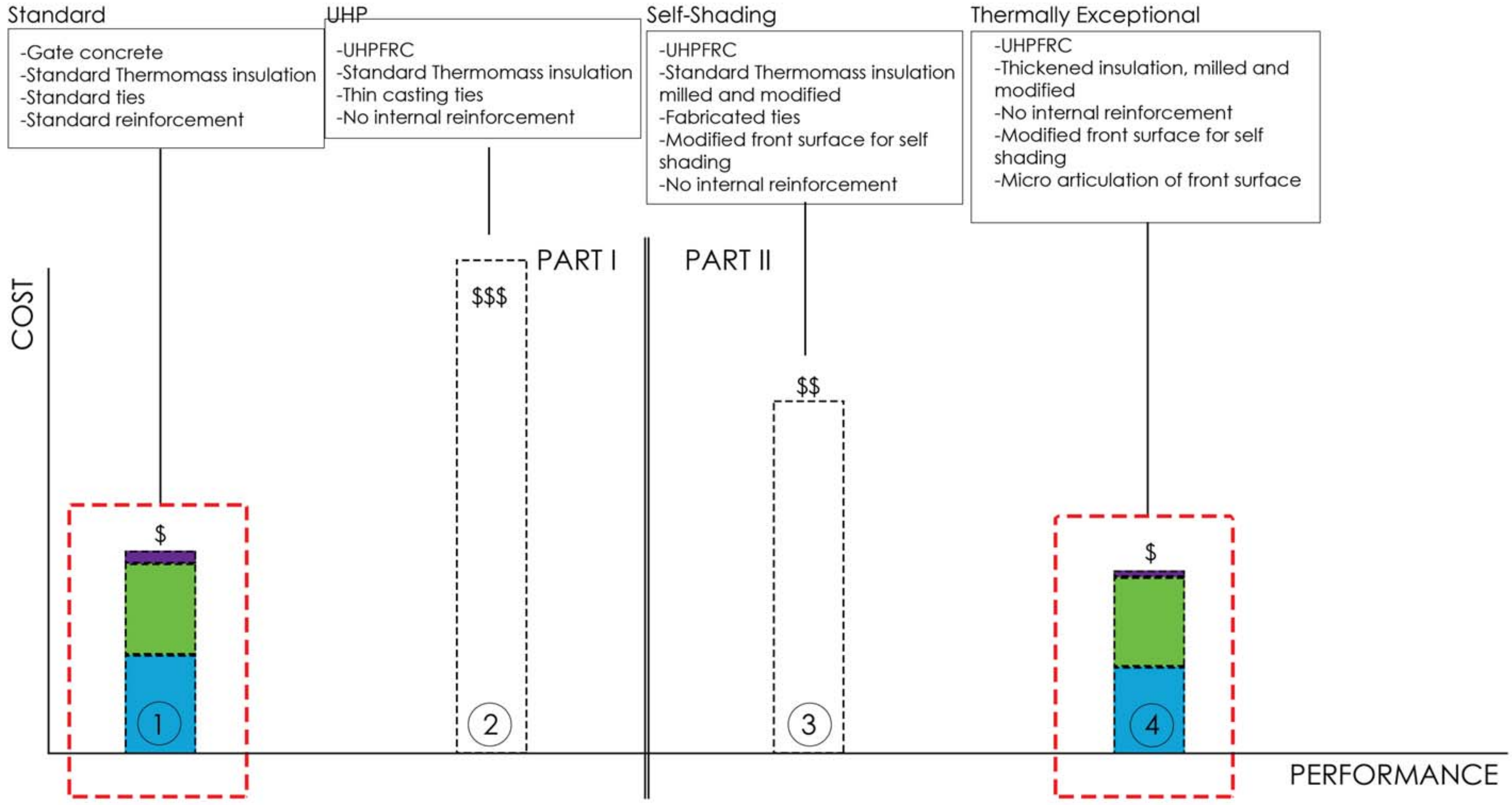
Panel Production	Standard Concrete: $100/yd³	10'x30' Panel: $555		**Material Cost-Per Panel: $1,987**
	XPS Insulation: $1.40/yd²	10'x30' Panel: $420		
	Reinforcement: $0.75/lb	10'x30' Panel: $1,012		
Panel Installation	Labor: $56,640/month	Misc. Equipment: $5,000/month	OH/P @ 15%: $21,996	**Install Cost-Per Panel: $1,405**
Crane (80 ton)	$25,000/month	Assembly/Breakdown: $60,000	Total: $168,636/ 120	
Transport	$7.50/mile From UTA to site: $165	1 panel per trip		**Transport Cost-Per Panel: $165**
				Total Cost-Per Panel: $3,557

UHP PANEL

10'x30' Panel Weight: 8,700 lb Volume: 58 ft³

Panel Production	UHP Concrete: $500/yd³	10'x30' Panel: $1,075		**Material Cost-Per Panel: $1,777**
	Polyiso Insulation: $2.34/yd²	10'x30' Panel: $702		
	-	-		
Panel Installation	Labor: $56,640/month	Misc. Equipment: $5,000/month	OH/P @ 15%: $20,496	**Install Cost-Per Panel: $1,309**
Crane (40 ton)	$15,000/month	Assembly/Breakdown: $60,000	Total: $136,640/ 120	
Transport	$7.50/mile From UTA to site: $165	2 panels per trip		**Transport Cost-Per Panel: $82.50**
				Total Cost-Per Panel: $3,168

COST COMPARISON

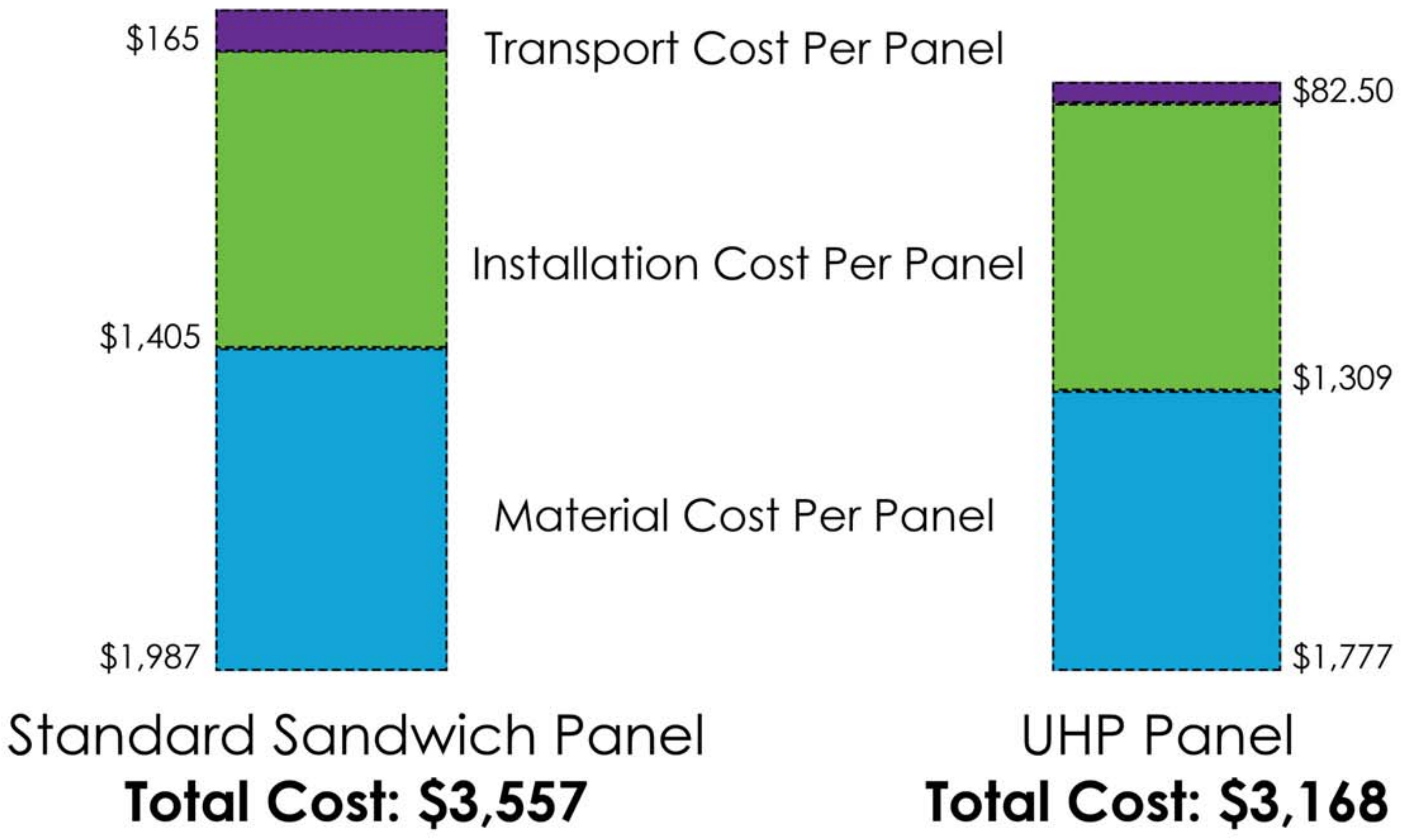


Standard
- -Gate concrete
- -Standard Thermomass insulation
- -Standard ties
- -Standard reinforcement

UHP
- -UHPFRC
- -Standard Thermomass insulation
- -Thin casting ties
- -No internal reinforcement

Self-Shading
- -UHPFRC
- -Standard Thermomass insulation milled and modified
- -Fabricated ties
- -Modified front surface for self shading
- -No internal reinforcement

Thermally Exceptional
- -UHPFRC
- -Thickened insulation, milled and modified
- -No internal reinforcement
- -Modified front surface for self shading
- -Micro articulation of front surface



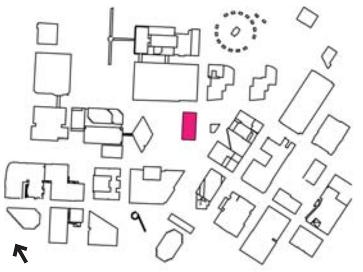
HIGH PERFORMANCE PRECAST FACADE PANELS

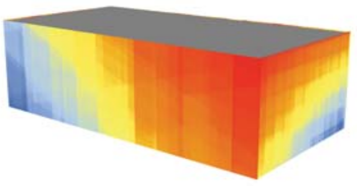
Environmental Analysis

JONATHAN ESSARY / HALIMA AREVALO / SAMANTHA RICHARDSON

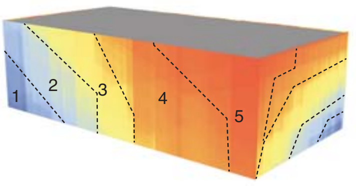
An environmental analysis was conducted using Rhinoceros to determine the effect the panels would have in a specific context. A structure was placed in Dallas and oriented among the built environment. A simulation was then run to determine the efficiency of the panels and the way the buildings around it contributed to or detracted from this efficiency throughout the year.

This analysis painted a clearer picture as to where panels with deeper macro articulation would be most useful and where flatter panels would be sufficient. This kind of information can begin to inform the number of panel variations that would be necessary to outfit a specific facade and therefore the number of different molds that would need to be produced per building. This too can help contribute to a better understanding of the relative cost of this kind of panel in terms of formwork.





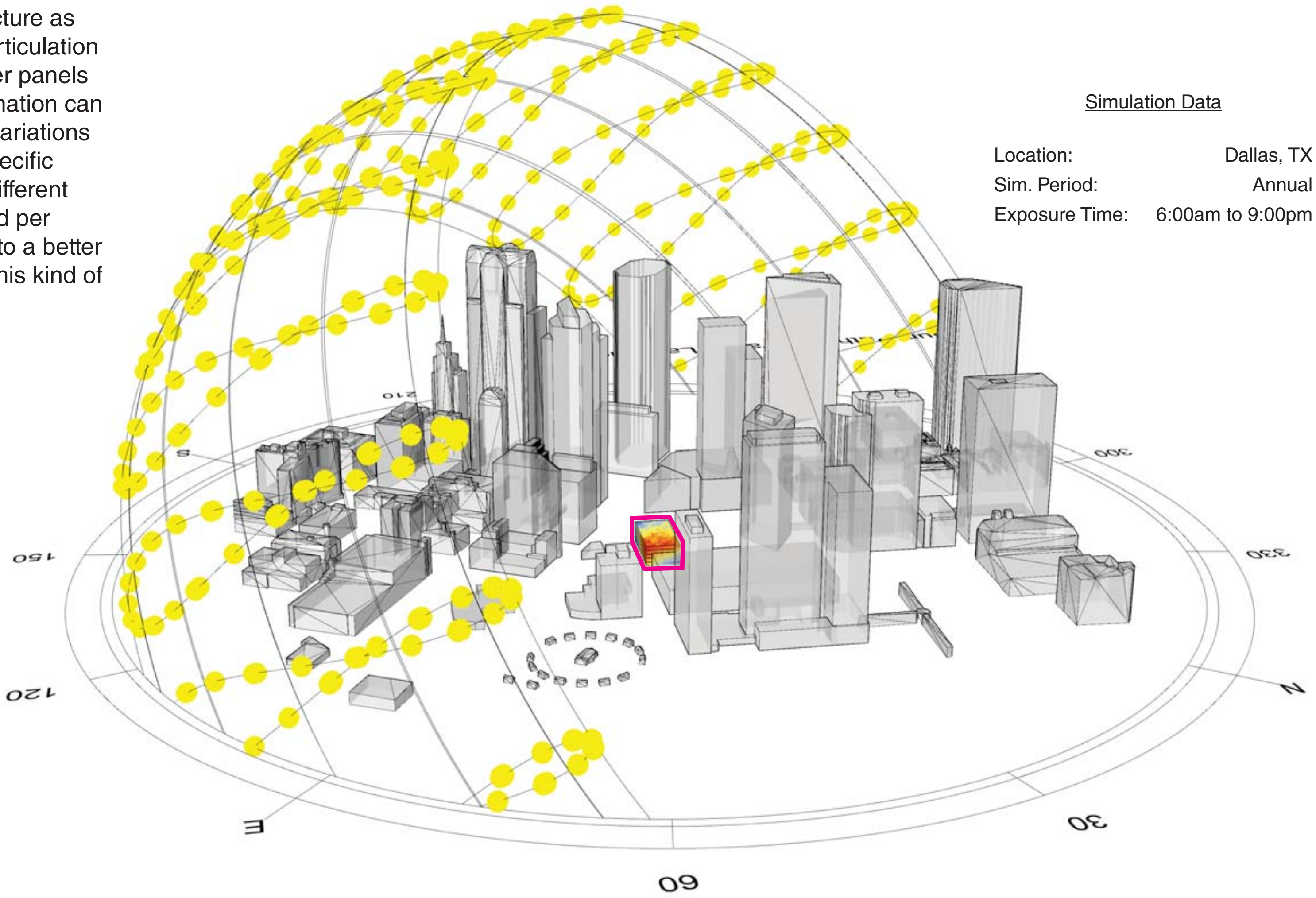
Full Resolution Building Radiation



Radiation Regions

Simulation Data

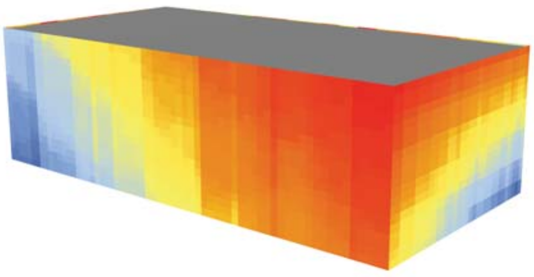
Location:	Dallas, TX
Sim. Period:	Annual
Exposure Time:	6:00am to 9:00pm



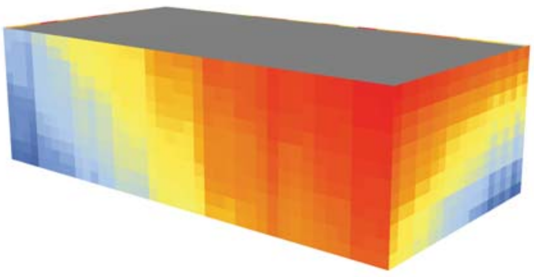
Annual Solar Path Diagram

COMPONENT DISTRIBUTION

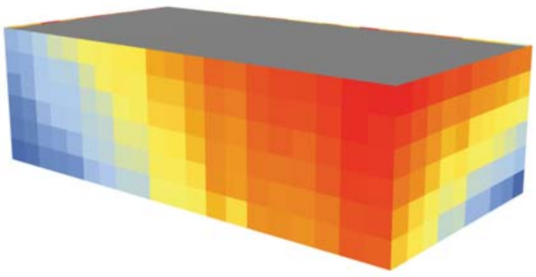
Fabrication Strategies



3' x 3' Resolution



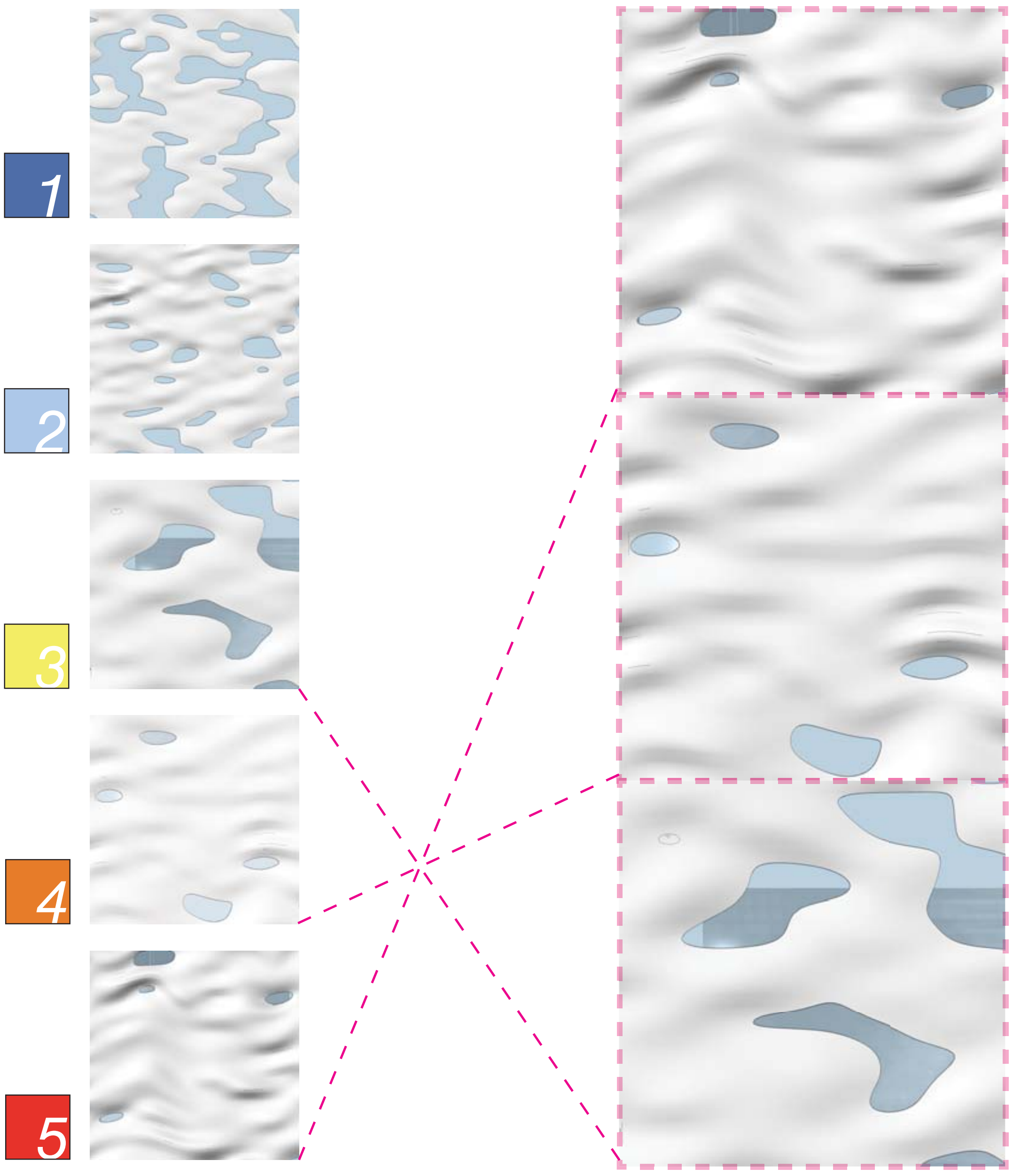
5' x 5' Resolution



10' x 10' Resolution

Modules

Component



Full Scale Component 10' x 30'