THERMAL PERFORMANCE ISSUES OF GLAZING FACADES AND THE USE OF ENVIRONMENTAL PARAMETERS IN EXTERIOR SHADING DEVICE DESIGN

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INTRODUCTION

While many architects in the 20th century saw nature as an adverse factor to be excluded at all cost, the vast majority of today's architectural profession sees its future in the interplay and balance between the natural and built environments. The current trend of green design, which has established itself as the prominent paradigm of the last decade, seeks to establish a functional interface between the natural and the built environments and in doing so to improve building performance[1].

An equally important trend today is the wide-spread integration of software and numerically-controlled fabrication technologies in architectural design and construction processes. Digital fabrication techniques have transformed the methodology of design and have fostered a reciprocal relationship between the processes of design and making.

The above two trends offer designers and engineers a renewed opportunity to combine qualitative and quantitative research methods in harnessing the potential of computing and digital fabrication to better address emergent environmental demands on the built environment.

THERMAL PERFORMANCE ISSUES OF FACADES

In the United States buildings consume 40% of primary energy[2] and 72% of electricity consumption[3]. The majority of the electricity demand is lighting (almost 20%) and heating and cooling (36% and 8%). Each of these energy demands is closely related to the *building envelope*, and can be decreased with efficient envelope design. The building envelope, a.k.a. *building façade* or *building skin*, is the most important subsystem of the building, serving as the link between all other components of the building system (structure, technical services, and the interior walls of the building).

In 2011, the total energy consumption for lighting in commercial buildings was 3.2 quadrillion *Btu*[4] while the total end use energy consumption of lighting in residential buildings was 2.17 quadrillion Btu[5]. Of the combined 5.37 quadrillion Btu that the residential and commercial sectors have used for lighting, 25% can be attributed to the energy gains and losses related to *fenestration*[6] elements, i.e. 1.34 quadrillion Btu, which is being used to offset undesirable energy gains and losses related to doors, windows, fenestrations elements and others, usually deployed as part of building envelope design. This number represents 13.6% of the 39.38 quadrillion Btu consumed by the entire residential and commercial sectors in 2011 taken together. The potential for energy savings through targeted fenestration design is significant.

DESIGN APPROACH

This research pursues the development of an algorithmic design for a façade shading component that utilizes model data from site conditions as a means to mitigate the adverse effects of solar heat gain on energy demand. The positive effect of solar heat gain during the cold season will be given consideration at subsequent stages of the project and will not be a part of the design criteria outlined here.

Present day parametric design software enables environmentally derived data to be incorporated seamlessly into the design process and be taken into account in the form-generation of building envelope components. The parametric modeling tool Grasshopper ®, a plug-in for the 3-dimensional NURBS[7] modeling software Rhinoceros™, enables the design process to become more flexible and responsive by the interactive integration of environmentally driven parameters.

The general term, commonly in use today, of *parametric design* refers to defining a form through the interplay of geometrically defined objects and sets of parameters that describe the relations that geometry must maintain. Thus geometry can be described by a series of rules, each of which may relate to a wide number of parameters[8].

Using a specifically written in Grasshopper® parametric design algorithm, this research project will produce a design for a building envelope component, which is able to provide full shading over a pre-determined period of time, in addition to providing optimal surface for rain water shedding, as well as optimal porosity to allow for natural light penetration and ventilation. The 3-dimensional structure will be processed for construction using Rhinoceros™. The geometry will be transferred into CAD[9] software, such as Autodesk AutoCAD Architecture 2012, from where it can be processed for construction. At a subsequent stage a CNC-router will be used to produce a prototype of the optimized building envelope component.

The Importance of Shading Systems

When designing energy efficient buildings, solar *radiation*[10] can be a blessing and a curse. On one hand, energy from the sun can be harnessed through solar passive design and as a renewable energy source using photo-voltaic systems; on the other hand, solar radiation represents the largest source of heat gain in buildings[11], which can demand significant amounts of energy to keep a building cool.

A transparent east south or west facing building skin without shading devices is fully exposed to direct *insolation*[12] and is especially problematic. Efficient design of shading devices is imperative in climates where the exterior temperatures exceed the desired indoor temperature for extended periods of time. Direct sun light has smaller impact on exterior walls than on exterior fenestration due to the latter's significantly higher thermal mass and inertia. Shortwave and long wave radiation, i.e. *energy*, is absorbed easily by exterior walls and is released at night, and thus mediating the impact of extreme changes in outside temperature. Solar insolation heats up the interior through energy *transmittance*[13] thought the façade and the roof of a building. Not all of the energy gets transmitted; most of it gets absorbed by the material. The amount of *absorption*[14] depends on the properties of the material and its color. Glass, on the other hand is almost transparent to radiation[15]. Solar insolation directly heats up the interior surfaces and is the main contributor to heat gain. One strategy to mitigate this is by introducing reflective coating, whose increased effectiveness results in coloration and reduced transparency - leading to reduced visual properties and quality of experience. With regard to visual quality the use of shading to protect the window area from direct insolation yields better results.

Shading Types

Shading devices can be systematized according to orientation and according to location. In regards to the first, most shading devices are oriented vertically or horizontally. In addition, either can be located on the interior of the glazing, in line with the glazing, and exterior to the building envelope. There is a high variety of shading devices on the market, yet of all can be said that internal shading devices are the least desirable since they act as radiators, having absorbed the short wave radiation and converted it to long wave radiation. Internal shading devices heat up the interior surfaces and the space between the window and the device through radiation and air convection. They should be rather classified as *glare control devices*[16].

Shading installed within the window unit or fenestration system are of less interest in regards to efficiency of retrofitting and improving the energy performance of existing envelopes as their use requires the replacement of the fenestration component and their significant upfront cost in material and labor may be prohibitive in most cases. Similar concern can be attributed to various screens integrated with the building envelope, etched glass, ventilated curtain walls, operable shutters, and automated manipulators.

External shading on the other hand can be designed with precise local conditions in mind and installed without disruption of building occupancy and in a variety of configurations. Weather conditions, such as air temperature swings, humidity, UV radiation, precipitation, and wind, can lead to higher production and installation costs as well as concerns for durability and maintenance.

In evaluating which shading device is most appropriate for a given situation, one must take into account its geographic location, its orientation with regard to the sun, and its performance with regard to the degree of visual contact as well as the degree of shading they provide throughout the year. The latter two criteria usually are seen to work against each other. A high amount of provided shading may lead to a low degree of visual contact and, conversely, a high degree of visual contact may result in poor shading performance.

Preliminary Design Parameters

For the purposes of testing our design approach we have selected a case study building of ubiquitous type, construction, and occupancy.

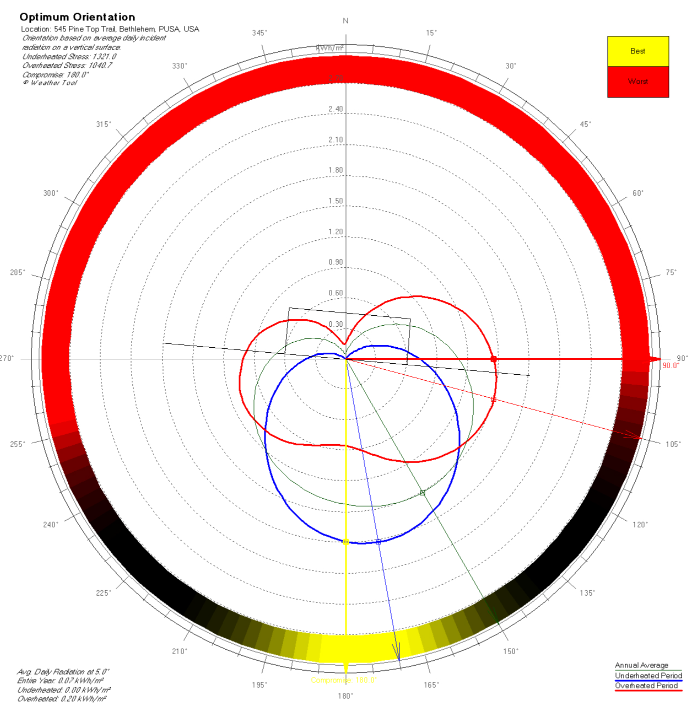

Figure 1. Optimum orientation, Weather Tool 2011, Autodesk Inc. 2010

The case study building is located in the Lehigh Valley, Pennsylvania, USA. Built in 1959, it is a single family residence with a rectangular perimeter, concrete block ground floor, light wood frame main floor construction, concrete slab foundation, wood joist floor and a flat EPDM roof. The building is oriented with its long side in the North-South direction and its shorter sides in the East-West directions. However, the East and West facing facades are 77% glazed, while only 12% of the North and South facades are glazed. Further, the building's latitude is 40°39'50"N (40.66°), longitude is 75°22'0"W (-75.37°), and altitude is 116.0 m; its North and South elevations are oriented 5.24° N[17]. The climate during the hot summer months form mid-June until mid-August is classified as *warm humid*.

The most undesirable orientation for glazing is towards those portions of the sky in which the sun is low in its daily path, usually towards the East and West. The best orientation for a vertical surface is when there is the most solar radiation during the underheated period and least during the overheated period. An analysis of the case study location leads to the conclusion that the worst case scenario is for east-facing glazing at 15 degrees from true east, based on average daily incident radiation on a vertical surface, Figure 1. The glazing façade in question is facing at a near 5.25° degrees from true East[18], which identifies it as most needing a shading solution.

For small buildings, the ratio of exterior building skin to interior floor area is relatively large[19], which means that substantial part of occupation occurs in close proximity to daylight sources such as windows and skylights. The main challenge for the designer is to control the quality of light and to avoid excessive sun exposure of the interior.

Shading Criteria

At thermal comfort zone[20] set at thermal neutrality, we have the maximum daily *DBT*[21] exceeding the upper limit of the comfort zone, 78.8°F, without more than a day interruption for the period of June 19 – Aug 22. For the general purposes of this project we exclude the single day bellow comfort day of July 12, Figure 2.

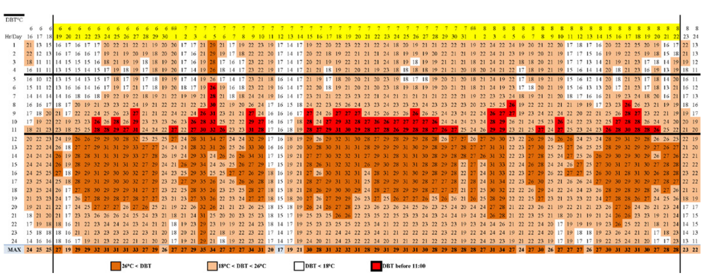

Figure 2. Hourly Dry-Bulb Temperatures, June-August (in degrees, Celsius)

During that period the impact of incident solar radiation on the building and its interior has an added undesirable effect on cooling demands. The maximum DBT for that period is on July 4, 35°C, at 16:00 Hr. Characteristic hourly values of temperature, direct radiation, sun azimuth, and sun elevation for the beginning and end of the period in which the DBT is above the comfort zone, June 19 and August 22, are gathered from weather data available from U.S. Department of Energy[22] and formatted in Weather Tool 2011[23].

Of significance to our design are only those values with respect to the strictly facing east façade. We must eliminate from this dataset all values before sunrise and after the sun's rays are no longer hitting directly the façade, i.e. when the south façade is facing the sun and the east façade is in shade. Keeping in mind that our east façade is oriented at 5.24° N, the range of azimuth (Az) needs to be bigger or equal to the azimuth at sunrise and less or equal to 185.24°N. Adjusted to the closest hour, for which weather data is available, 84 data points represent the DBT values of direct exposure to solar radiation. Those are between the hours of 5:00 and 11:00. (Figure 2, in red). Figure 3 plots all 84 1-hour periods, for which we have recorded information. Their polynomial distribution is $El = F(Az) = -0.0102\ Az^2 + 2.9548\ Az - 149.33$, with $R^2 = 0.8496$[24].

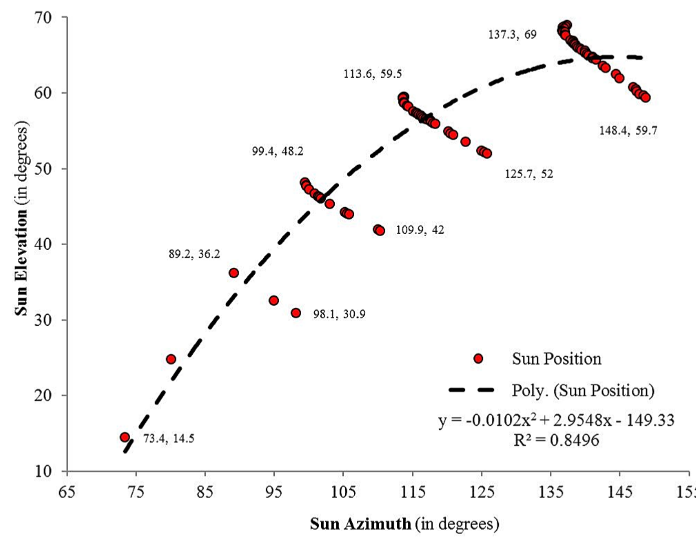

Figure 3. Sun Position (Elevation and Azimuth), and adjusted polynomial distribution curve.

The above data represents the sun positions, expressed in the solar coordinates of elevation (El) and azimuth (Az) for the previously described time period and will serve as external parameters in the design of our exterior shading device.

ARGUMENT FOR FIXED GEOMETRY

With our predominantly east facing façade a fixed system will not perform well throughout the whole day as the altitude of the sun is much lower and sun light will pass directly under most horizontal shading systems[25].

To overcome this problem one strategy is to use a movable solar shading system. This strategy would introduce computer controlled fins that follow the path of the sun. Achieving this level of control, however, is relatively expensive and dependent on mechanical and electronic devices. By introducing a sufficient number of units of varied geometry we can achieve similar amount of control with fixed shading devices. Varied fixed geometry combines the efficiency of movable shading systems with the affordability of conventional fixed shading devices. Our use of digital fabrication machines pre-conditions low production cost to unit variability ratio.

UNIT DESIGN

The initial design is mainly comprised of two planar surfaces – one is active and is configured in a plane perpendicular to the direction of the sun (Figure 3-A, points 1-3-4-5). This surface actively reflects and absorbs the solar radiation and mitigates the majority of the solar stress on the shading system. The other type of surfaces is inactive – it is positioned at 90° to the active surface, or parallel

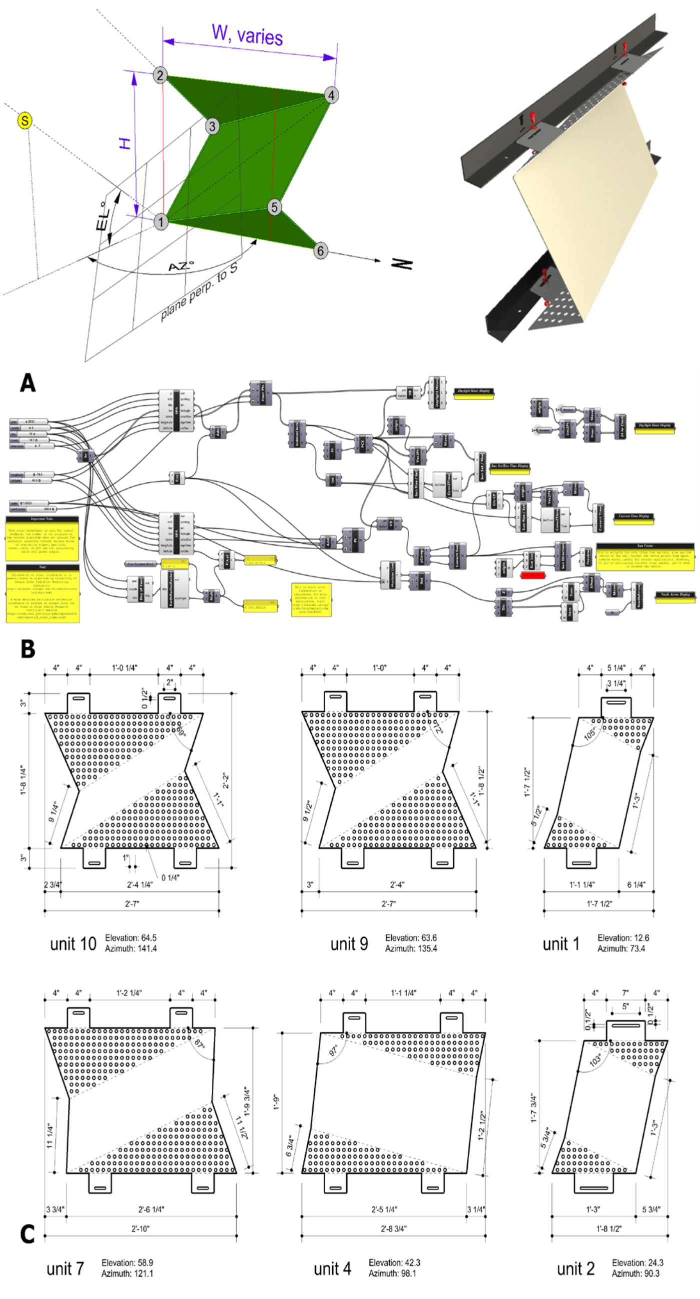

Figure 4. A - Geometric definition of variable shading unit; B - screen capture of Grasshopper algorithm; C - Sample of 6 unrolled flat units.

to the direction of the sun, and has little, if none, exposure to direct solar stress. It however performs inactively by absorbing, *reflecting*[26] and *transmitting*[27] indirect radiation from the exterior environment or adjacent shading devices. The designed unit maintains a clear opening that is a result of the Sun's altitude and azimuth. The unit design is developed in the algorithmic modeling tool Grasshopper® and interactively integrates environmental parameters, such as geographic altitude, longitude, and latitude, daily and hourly sun position, and geometric variables, such as desired unit height and orientation, Figure 4-B.

The unit design allows for a varied active and inactive surface orientation as a function of El and Az, and variable width as a function of the unit's' height. Our east facing glass façade has dimensions of 8"-0" high by 24"-0" wide, or 96"x288". There are two sets of parameters that control the optimum number of units required for covering the entire 96"x288" area of the façade. One is the already explained dependency of the shading unit geometry on the solar azimuth and elevation. The other is the length of each unit and the total sum of unit lengths which are parametrically linked to the desired unit height. If the proposed shading device utilizes six 16" high rows of units the total length of all units need be 6 x 24 feet, which is 144 linear feet, or 1728 inches.

Using a specifically written in Grasshopper®, a plug-in for the 3-dimensional NURBS modeling software Rhinoceros™, parametric design algorithm, we generate 84 unique shading units based on the 84 previously established unique solar coordinates (Az, El). We compute that their total length exceeds the above linear 144 feet (288 Inches) of shading units. After a series of trials and errors we conclude that the optimum approach is to balance the number of available units to the sum of their respective heights and widths.

By entering the polynomial distribution from Figure 3 in Grasshopper®, we get a redistribution of the 84-point dataset to the following 12 points, whose total width, regardless of their order, is 287.962774 inches, Table 1.

Data point	1	2	3	4	5	6	7	8	9	10	11	12
El.	12.6	24.3	34.1	42.3	49.1	54.6	58.9	61.7	63.6	64.5	64.6	64.5
Az.	73.4	82.2	90.3	98.1	105.8	113.5	121.1	128.5	135.4	141.4	146.2	148.7

Table 1: Redistributed data points

These 12 points were used to produce 12 units. Each corresponds to the pair of altitude and azimuth values from Table 1. The unit's consist of a single flat folded surface where the inactive area is perforated for increased porosity. Figure 4-C shows a six of the 12 units unrolled flat and dimensioned for fabrication.

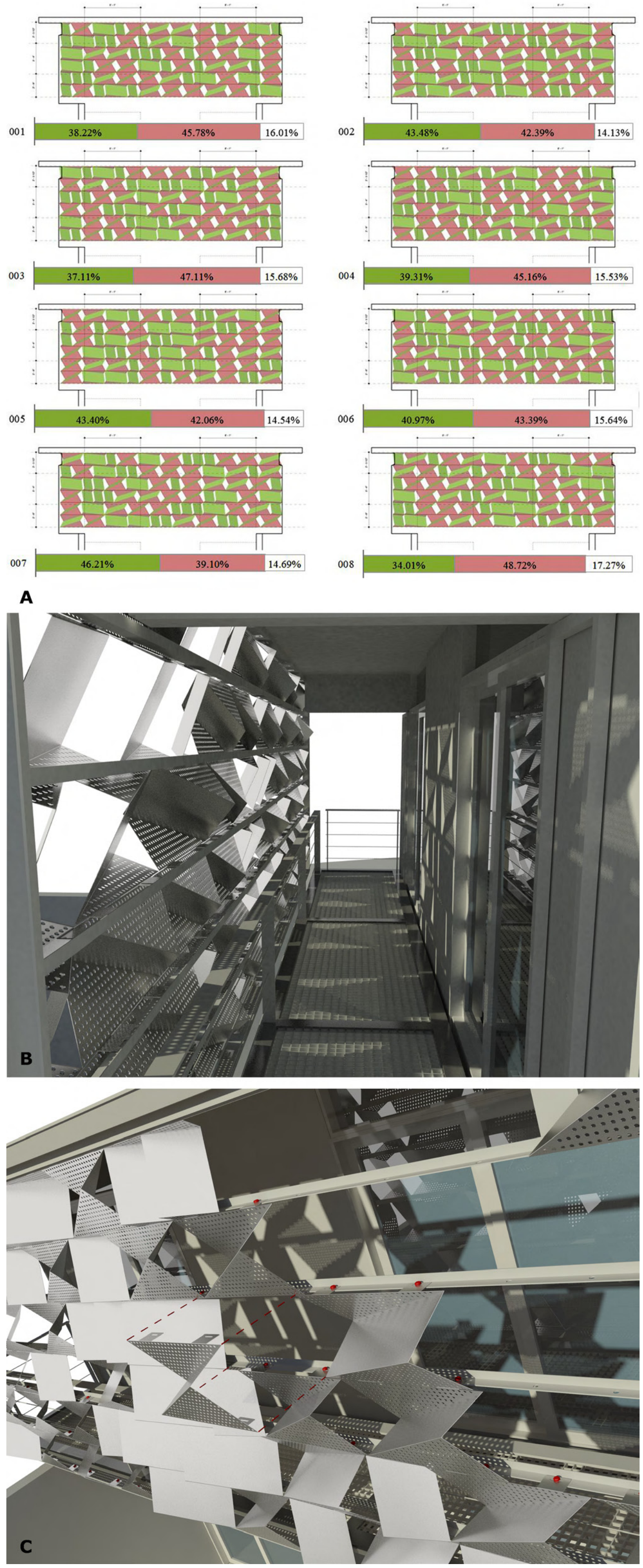

Figure 5. A - Opacity Study, 8 of 96 possible combinations shown, compared with respect to percentage of opaqueness, partial openness, and full openness over the areas of the façade where the windows are located; B and C - Views of shading design.

There are almost 480 million permutations of 12 units in a row (12! = 479001600) - a number which previously would have been prohibitive for use by the designer but with the help of scripting and computing a series of combinations are generated in which each of the 12 units is utilized once on each row and that number is reduced to 567 unique series of non-repeating 12 units and no repeating sequences in each row. These 576 rows form 96 sets of 6-rows/ 12 unit designs.

Degrees of Visual Porosity

Each of the series is evaluated with respect to percentage of opaqueness, partial openness, and full openness over the areas of the façade where the windows are located, Figure 5-A. The combination with highest percentage of openness is chosen for the prototype proposal, Figure 5-B, C.

CONCLUSION

This paper so far has outlined a method of analysis and design that takes into direct consideration environmental parameters, such as sun position and hourly and daily radiation and temperature values. We, however, refrain from claiming that incorporating environmental parameters is sufficient to achieving sensible design. The merit of the final design should only be seen in context of the process that generated it. While introducing shading can play an active and important role in mitigating the negative effect on solar gains during the hot months of the year, the use of the proposed shading device is warranted only during the times of year when the outdoor temperature is above comfort levels. This design method would be more effective in more extreme climates than the one chosen here, where the hot season is extensive and year-round. Further research would be required in optimizing the shading device for maximum solar gains in winter, particularly in cases of being used in colder climates.

Additionally, the building occupancy type, residential, was chosen arbitrarily. The commercial building sector's contribution to the overall demand is projected to increase faster than any other sector, and take over the electricity demand of the residential building sector by 2013[28]. In reflection of this trend our further design and study will be applied to an office building type.

It is important at this stage in the project to assert that energy-consumption reducing design criteria are only a part of the demands on the building professions and the consumers to evolve towards a more sustainable future. However, we firmly believe that performance in architecture is a formal property born from a process that simultaneously sites artifact geographically, culturally, critically, as well as engages the process of formal generation and development. This project prioritizes the dependency of design on the site, such as orientation, time, and sun position, program and structure. The emphasis on this dependency is the structuring and organizing principle for the generation and modification of form.

ENDNOTES

1. Millard, Bill. *Designing the Building-Landscape Interface*, Architect, July, pp56-62, 2011.
2. U.S. Energy Information Administration (2008), EIA Annual Energy Outlook
3. U.S. Energy Information Administration, http://www.eia.gov/oiaf/aeo/tablebrowser/
4. A *British thermal unit* (Btu) is a measure of the quantity of heat required to raise the temperature of 1 pound of liquid water by 1°F at the temperature that water has its greatest density (approximately 39°F).
5. U.S. Energy Information Administration (2011), EIA Annual Energy Outlook
6. *Fenestration* is any opening in a building's envelope including windows, doors and skylights. National Fenestration Rating Council, www.nfrc.org/fenestrationfacts.aspx
7. *Non-Uniform Rational B-Splines* (NURBS) are mathematical representations of 3-D geometry that accurately describe a wide range of curves, surfaces and solids, http://www.rhino3d.com/nurbs.htm
8. Boza, Luis Eduardo. *Parametrics, Performance and (Pre) Fabrication*, 2008 UMass Wood Structures Symposium and 2008 ACSA Northeast Fall Conference Proceedings, (2008, pp.277-279).
9. Computer Aided Design (CAD)
10. A propagation of electromagnetic *energy* through space. This process is to be distinguished from other forms of energy transfer such as *conduction* and *convection*. http://amsglossary.allenpress.com/glossary/search?id=radiation1
11. Ecotect solar radiation training package
12. *Insolation* - solar radiation on the surface of the Earth. This term has been generally replaced by *solar irradiance* because of the confusion of the word with *insulation*. http://rredc.nrel.gov/solar/glossary/gloss_i.html
13. *Transmittance* is the fraction or per cent of a particular frequency or wavelength of electromagnetic radiation that passes through a substance without being absorbed or reflected. Glossary of Solar Radiation Resource Terms, http://rredc.nrel.gov/solar/glossary/gloss_t.html
14. *Absorption* is when energy is captured by a substance, reducing the amount available. http://rredc.nrel.gov/solar/glossary/gloss_a.html
15. Bader, Stefan. Professional Report: *High Performance Façades for Commercial Buildings*, University of Texas at Austin, p 9, 2010
16. Ibid., p10.
17. Google Earth, Google Inc. 2011
18. Determined from Earth System Research laboratory, NOAA Solar Calculator, http://www.esrl.noaa.gov/gmd/grad/solcalc
19. Allen, Edward, and Joseph Iano. 2012. The architect's studio companion: rules of thumb for preliminary design. New York: Wiley.p 144
20. This environmental temperature range is subjectively determined but generally it is assumed to be 18.0°C to 26.0°C at relative humidity of 40-65%.
21. *Dry-bulb Temperature* (DBT) - air temperature measured with a thermometer, similar to *ambient temperature*, to be distinguished from *wet-bulb temperature* measured by a *psychrometer* to determine relative humidity. http://rredc.nrel.gov/solar/glossary/gloss_d.html
22. pps1.eere.energy.gov/buildings/energyplus/ weatherdata/4_north_and_central_america_wmo_region_4/1_usa/USA_PA_Allentown-Lehigh.Valley.Intl.AP.725170_TMY3.zip
23. Weather Tool ™ 2011, © 2010 Autodesk, Inc.
24. R-Squared is a statistical term saying how good one term is at predicting another. If R-Squared is 1.0 then given the value of one term, you can perfectly predict the value of another term. Generally, a higher value of R-Squared means that you can better predict one term from another, http://www.trade-ideas.com/Glossary/R-Squared.html.
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27. U.S. Energy Information Administration (2011), EIA Annual Energy Outlook, http://www.eia.gov/oiaf/aeo/tablebrowser/.