Associative Design for Building Envelopes'

Sun Control and Shading Devices

by

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ABSTRACT

In geographical locations with hot-arid climates, sun control in buildings is one primary problem to solve for the building envelope design. Today's technological advances in building science bring with them the opportunity to design dynamic façade systems for sun radiation control and daylighting. Although dynamic systems can become an attractive visual element, they can be costly and challenging to maintain for building owners. Alternatively, fixed solar-shading systems can be designed to create dynamism in the façade of the building, while providing similar functionalities for sun control.

The work presented in this project focuses on the use of a visual scripting editor for modeling software, Grasshopper, to develop a *Solar Control Visual Script* that evaluates building envelope surfaces with planar and non-uniform rational basis-spline (NURBS) forms and provides projections for fixed sun control systems. The design platform of Grasshopper allows individuals with no experience or prior computer coding education to build up programming-like capabilities; this feature permits users to discover new design possibilities within flexible frames that can contribute to the overall design being pursued, while also having an environmental response.

The *Solar Control Visual Script* provides minimum sizing geometries that achieve shading in openings at a particular date and time of the year. The model for this method of analysis makes use of three components to derive the appropriate values for the projections of shading geometries: typical meteorological year (TMY) data, irradiation isotropic equations and shading profile angles equations for vertical and tilted surfaces.

Providing an automatic visual of generated geometries uncovers the opportunity to test several model forms and reiterates the analysis when modifying control parameters. By employing building science as a set of environmental parameters, the design outcome bears a dynamic form that responds to natural force conditions. The optimized results promote an efficient environmental design solution for sun control as an integral alternative into the building envelope.

ACKNOWLEDGMENTS

There are many people that I would like to thank sincerely for their support during the evolution of this journey.

My sincere gratitude to my thesis committee: Prof. Harvey Byan, for being a genuine advisor during my time at ASU, not only by encouraging me throughout my thesis work but also by making me aware of what needs to be done to contribute towards better built environments; Prof. Jason Griffiths, for your support on bridging the gap between science technicalities and design, and sharing your interest in digital technologies; and Prof. Michael Kroelinger, for your commitment to keeping me grounded during my thesis and nourishing my interest on daylighting topics.

Advancing my thesis would not have been possible without lecturer David Newton. David, your passion for digital information, parametric design and guidance contributed greatly to my work.

Solar geometry algorithms and equations may seem easy, but when they are applied to non-traditional surfaces it results in a complex paradigm; my gratitude to professors Marlin Addison, Agami Reddy and Muthu Ramalingam for your engagement in conversations about this topic.

My appreciation to the architects Wendell Brunette, John Kane and Jeff Stanton for dedicating time to discussing their buildings, which have set a direction for implementing state-of-the-art technologies for sun control systems. Thank you for sharing valuable project information.

During my student life at ASU I have encountered dear friends and classmates; all of you in one way or another have contributed to my work.

My special appreciation to my friends: Andrea, Nasim and Supriya; who helped me throughout this journey and always offered me encouraging words.

Dad, Mom, brothers and sis, THANK YOU from my heart for your support and for keeping up with me and my always busy schedule. I love you!

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INTRODUCTION

Overview

Actual concerns for the natural environment and climate change obligate professional disciplines related to the built environment to explore innovative design solutions. These solutions must attempt to achieve an acceptable level of human thermal comfort in buildings while minimizing energy consumption. Thus, it is essential that architectural solutions in building design respond to the use of passive strategies prior to selecting and adopting any active systems that support thermal comfort in buildings.

One prime solution is the proper design of the building envelope that responds effectively to solar radiation control. Climate and thermal analysis and control are fundamental initial steps in the design process due to the importance of solar heat gain and loss in buildings, which can cause overheating or underheating respectively. Therefore, this matter should be considered in the early stages of building design.

While incident solar radiation in buildings needs to be regulated through the envelope to reduce the use of mechanical systems for cooling and heating, proper daylight strategies have to be integrated into the envelope design to decrease the use of artificial lighting systems, thus reducing energy consumption in buildings.

Solar radiation control is not a new approach in architectural solutions. In ancient times, Greeks focused the development of their cities on solar availability.

Previous work done by Olgyay and Olgyay (1957), Mazria (1979) and Brown (1985) set a framework for passive design strategies, analysis and calculations for shading elements in buildings to minimize overheating. The increased availability of efficient glazing and heating and air conditioning systems in building construction during the 1980's resulted in the neglect of the application of passive systems for sun control in design solutions: The glass and steel typology in architecture prevailed under the technological systems' advance. These events have made architecture dependant on the development of more proficient mechanical systems as well as on improvements in

glazing materials, lighting systems and controls to provide efficient energy performance in the built environment.

In office buildings, for instance, the energy consumption of the mechanical and lighting systems is among the top energy end-uses according to the U.S. Environmental Information Administration (EIA). In 2003, cooling, heating and lighting represented 64% of the site electricity consumption in office buildings in United States. Cooling and heating represented 13% and lighting 38% (EIA, 2009).

At the beginning of my Masters program, I read the article by the architect Mazria "It's the Architecture, Stupid!". Having a degree in architecture myself, I felt uncomfortable and intimidated by the title, but as I read the article further, I agreed with the author. Mazria writes: "Most people don't understand what architects really do and most architects don't have a deep understanding of the relationship between architecture and the natural environment" (2003, p. 49). He argues that architecture has the answers to the challenge of reducing the energy and climate crisis.

I believe that the end result of any crisis throughout history has been transformation. We are developing among ourselves a deeper awareness that each action we perform has its consequences; by realizing that, we are changing. We are recognizing that design, an intrinsic human activity, affects nature; thus we have initiated a conversation to provide responsible architectural solutions for the built environment, solutions that not only protect humans, but also nature.

In 2005 the American Institute of Architects (AIA) released the 2030 Commitment; its goals are to raise professional awareness of, dedication to and leadership in environmentally safe design and construction practices. The Commitment emphasizes that the largest energy reductions can be achieved through design (2030 Architecture, 2011). Parallel to this, in 2006 the AIA became the first adopter of the 2030 Challenge, a program developed by the non-profit organization Architecture 2030 led by Edward Mazria. Since 2002 the leaders of this organization have worked to publicize the program and find new adopters that support the organization's mission:

Architecture 2030's mission is to rapidly transform the U.S. and global Building Sector from the major contributor of greenhouse gas emissions to a central part of the solution to the climate change, energy consumption, and economic crises. Our goal is straightforward: to achieve a dramatic reduction in the climate-change-causing greenhouse gas (GHG) emissions of the Building Sector by changing the way buildings and developments are planned, designed and constructed (Architecture 2030, 2011).

Design professionals are constantly exploring innovative methods and systems that reduce energy consumption in buildings. Architectural design practice is becoming more conscious of regional climates and reduction of the buildings' carbon footprint. Thus, understanding the science behind each solution that comprises Architecture, Environment, Design and Technology is essential.

Indeed there are many research lines that we can pursue; my choice is to investigate those that address the building's connectivity to the external environment: The building's envelope.

A significant part of the heat gain or loss in buildings relates to the inappropriate assembly composition and design of the building's envelope. It is understood by building designers that envelopes that respond to the climate conditions will lower energy consumption. However, this is not always set in practice.

In Phoenix, Arizona, a hot-arid climate zone, the building envelopes' overheating is a problem of greater concern than underheating. Shading the envelope can assist in resolving this issue. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) states that if the envelope is fully shaded from the outside the reduction of solar heat gain can be as much as 80% (ASHRAE, 2005, p. 30.44). However, this fact is overlooked by most designers.

In today's digital age, design and architecture are making use of computational tools, such as computer aided design (CAD), building information modeling (BIM) and simulation software to conceptualize and produce building design solutions. Design

tectonic exploration has moved from the Cartesian planar forms to complex ones. We, as designers, are leveraging from computer software tools to produce buildings with non-Euclidean geometries. I consider that this "morphogenetic" concept has its beginning in 1980 with the Guggenheim Museum Bilbao by Frank O. Gehry. We observed with this project a transformation in the building envelope design. But how do these new typologies respond to the natural context? Can we combine the thrill of the technological advances and the architectural morphological changes with the use of solar geometry and thermodynamics knowledge to have architecture that is accountable to the environment?

Digital tools can aid us in producing performative solutions that carefully balance (throughout the process of iterations) the elements involved in architectural design. With the use of software programs for simulation, analysis and fabrication, the design for solar envelopes and shading devices aiming to reduce solar radiation while harvesting daylight have great potential; not only could they respond to energy use performance but also enhance the building's skin aesthetic perception.

This research contributes to the subjects of solar control, heat gain reduction and daylighting through the use of shading envelopes for hot-arid climate conditions. In addition, it aims to provide a simple tool that assists in the building envelope design while taking into consideration the external forces of solar patterns.

Data drawn from the exercise of optimizing the envelope analysis can be used as the input for energy simulation analysis in that design stage or later phases.

Problem Statement

During the last 20 years, technological advances in computer aided design and drafting (CADD) have been significant. Computer software for architecture began as a computer aided drafting (CAD) tool, developed as a design tool for rendering, visualization and fabrication. Today, a great number of available computer software programs use parametric features and allow geometries to link dimensions and variables within and with other geometries; this process generates an associative design. This thesis will address how associative design and parametric software can be used in early stages of design to formulate a responsive building envelope by establishing a process for analyzing levels of solar radiation and for calculating shading element sizes for sun control in a building envelope.

Research Geographical Area

The present research will focus on the hot-arid climate zone of the Sonoran Desert, in particular the city of Phoenix, Arizona.

Research Goals

Shading envelopes and sun control systems are being analyzed as an aid to achieving the following:

1. Reduce heat gain in buildings while decreasing the energy consumption of the building by reducing heating and cooling energy
2. Attempt maximization of daylighting
3. Allow exterior views
4. Permit natural ventilation
5. Provide an aesthetic dynamism in the building envelope

Qualitative and Quantitative Aspects

The aim of this research is to explore and address the following research questions:

Qualitative Aspects

- What are the benefits of the use of parametric software for design of shading devices and what tools are available to use during the conceptual design phase?

- How can the design of parametric shading for building envelopes be linked to energy simulation software?

- Are non-mechanical shading devices in building envelopes better suitable for hot-arid climates than mechanical shading devices?

Quantitative Aspects

- How can shade devices be optimized for different building skins?

- How can the design process for shading devices be streamlined?

Significance

It is important that the architectural community understand that the performative response of the building envelope to the environment is as much a critical issue as the aesthetic aspects. An attentively designed building skin needs to be supported not only by architects that foster a traditional design practice but also by avant-garde architects and designers leading the digital age in architecture.

Although there are many problems to be solved when designing a building, the envelope synthesizes the relationship of internal and external forces that craft a building, hence the value of providing a balanced response that can help to define the character of the building.

Understanding the process for shading device calculations can be unclear. The use of a visual interface to generate solutions would encourage architects and designers to approach multiple iterations and make decisions regarding the building envelope's geometry in early stages of design.

BACKGROUND LITERATURE

Introduction

There were several subjects in which my research was done to set the theoretical framework for this thesis. The following are the most relevant.

Geographic Conditions

Phoenix is located in the Southwest of the United States in the Salt River Valley in central Arizona in the northeastern reaches of the Sonoran Desert.

Phoenix's geographical coordinates are 33°27' North, 112°4' West and it lies at a mean elevation of 1,117 feet.

The topography of Phoenix is generally flat, except for the mountains surrounding the city.
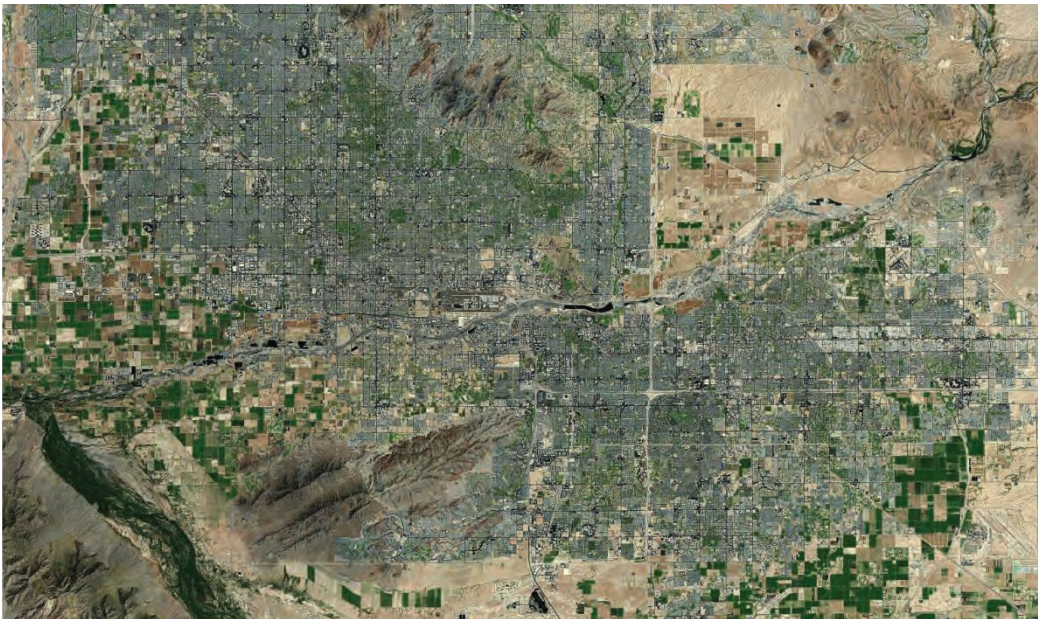
Figure 1. Aerial Image of Phoenix, AZ (Google Maps. 2011).

Climate Conditions

To ensure a positive environmental design outcome, it is important to understand the climate conditions of the particular site where a building will be designed or perhaps redesigned. There are several tools that increase understanding of the climate factors involved in a geographical area.

Climate Consultant. It is among the tools available for analyzing climate conditions in a specific location by using the location's EnergyPlus Weather (EPW) data file from the EnergyPlus Weather Data of the U.S. Department of Energy web site. This software provides applicable passive principles as Design Guidelines for the EPW file in use. The Design Guidelines that apply specifically to Phoenix's climate indicate that the most important principle is to provide window overhangs, designed accordingly for this latitude; or operable sunshades (that extend in summer and retract in winter) that can reduce air conditioning required. Refer to Appendix A for a complete list of Design Guidelines.

Temperatures. *Figure 2* illustrates the monthly temperature chart from Climate Consultant for Phoenix, AZ. The temperature ranges between 36°F in winter season to 110°F in the summer months. Between April and October the mean temperature is above the human thermal comfort temperature zone.
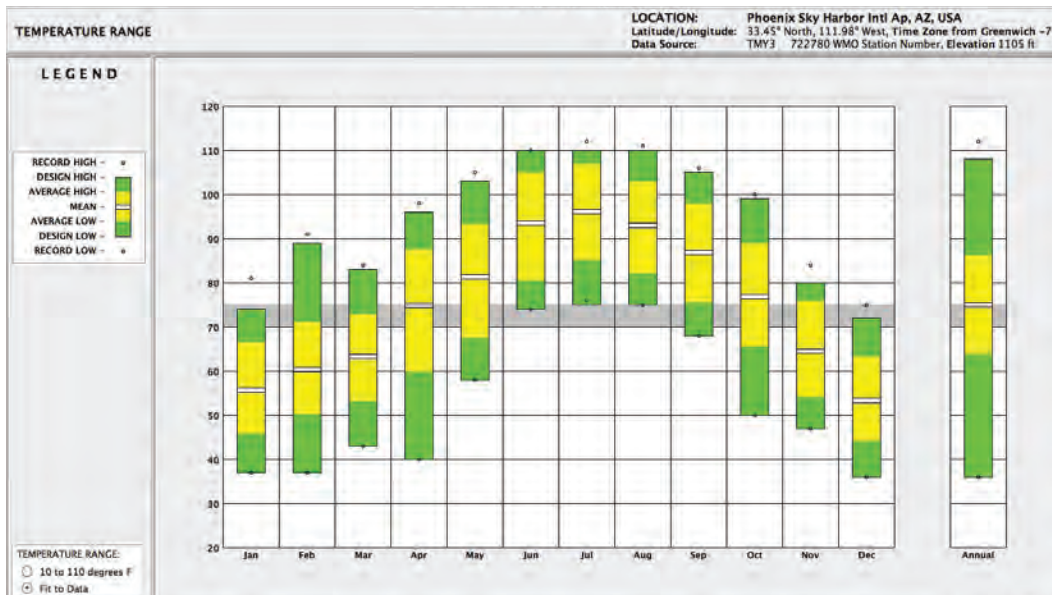
Figure 2. Temperature Ranges Phoenix, AZ.

Human Thermal Comfort. One of the important goals in building design is to achieve acceptable thermal comfort for building users. Thermal comfort is defined by ASHRAE as "that condition of mind that expresses satisfaction with the thermal environment" (ASHRAE Standard 55). High temperatures in Phoenix, AZ will require a type of mechanical system in buildings to supply cooling air, even if reducing heat gain with shading devices.

When design mechanical equipment, it is necessary to set temperature targets complying with human thermal comfort. For people dressed in normal winter clothes, effective temperatures of 68°F to 74°F, with measured 50% relative humidity is considered a comfort set point. For people dressed in summer clothes the comfort zone is between 73°F to 79°F (Climate Consultant, 2011).

Psychrometric Chart. A psychrometric chart graphically represents the thermodynamic properties of moist air and is used to verify dry bulb temperature, the additional requirements of moist air and necessary change in air temperature to reach the comfort zone target. Phoenix climate conditions are 5.5% within the comfort zone target (*Figure 3*) only 483 hours from the total hours of the year.
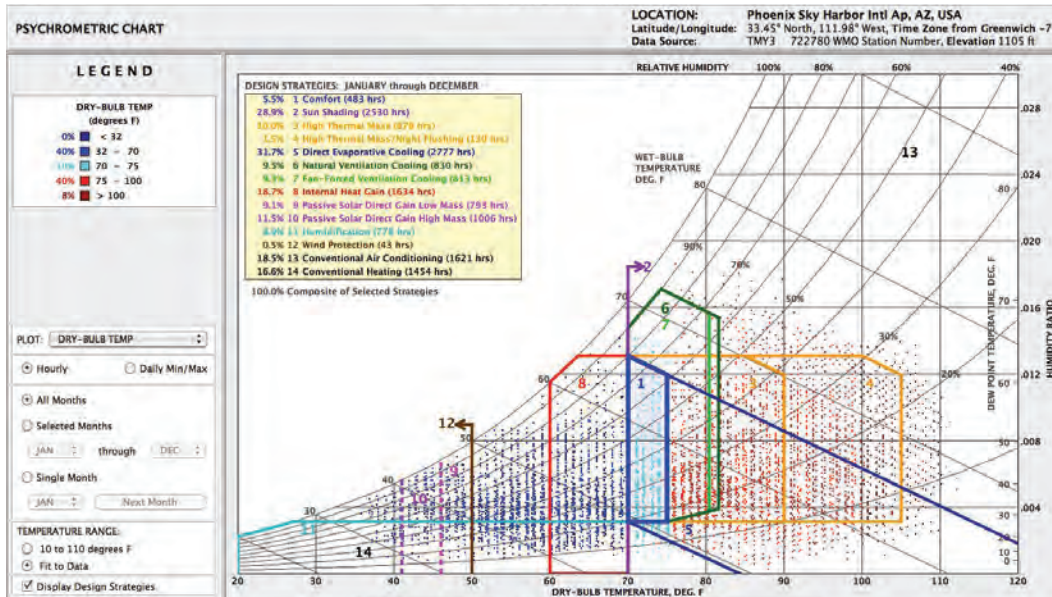
Figure 3. Phoenix, AZ Psychrometric Chart.

Typical Meteorological Year Data. The typical meteorological year (TMY) data set files are actually the base for Climate Consultant and many other energy simulation software programs. A typical meteorological year data set provides hourly meteorological values that characterize conditions at a specific location over a long period of time, such as 30 years; it is not designed to provide meteorological extremes.

TMY data has natural diurnal and seasonal variations and represent a year of typical climatic conditions for a location. The data sets are derived from the 1961-1990 and 1991-2005 National Solar Radiation Data Base (NSRDB) archives. TMY3 files are the most current, since they are based on recent and accurate data. The TMY3 are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. Because they represent typical rather than extreme conditions, they are not suited for designing systems to meet the worst-case conditions occurring at a location.

The TMY3 data sets were produced by the Electric Systems Center of the National Renewable Energy Laboratory (NREL) under the Solar Resource Characterization Project, which is funded and monitored by the U.S. Department of Energy's Energy Efficiency and Renewable Energy Office.

Calculations for Solar Profile Angles, Profile Angles for Shading Geometries and Solar Irradiance

In the same way solar radiation is needed as a source to produce renewable energy in buildings for systems such as solar photovoltaic panels, solar heaters and solar water heaters; buildings should also be protected from unwanted radiation. Detailed analysis of the solar geometry angles is a viable tool for determining if a building's form should receive projections for sun control on openings upon its geographical location and the project's configuration on site.

To determine solar profile angles, solar irradiance and shading elements' profile angles, several methods can be used: Analytical Method, Graphical Method and Computer Software.

Analytical Method. Mathematical equations are used in this method to determine sun profile angles or solar geometry at a given geographical location based on its latitude and longitude, date and time of the year. Also solar radiation levels can be calculated based upon the surface's relative angle to the solar angles and its own tilt angle.

Solar Profile Angles. Equations for the solar profile angles are compiled in the 2005 ASHRAE Handbook Fundamentals, section F31. Fenestration. Table 1 includes these equations and *Figure 4* illustrates the respective angle geometries that correspond to the equations.

Table 1

2005 ASHRAE Handbook Fundamentals Solar Profile Angles Equations

		Equations	*Remarks*
1	Equation of Time (ET)	$ET = 9.87 \sin 2(b) - 7.53 \cos(b) - 1.5 \sin(b)$	$(b) = 360\,(n\text{-}81)\,/\,364$ n = day of the year (1 to 365)
2	Declination (δ)	$\delta = 23.45 \sin \{[360\,(284+n)\,]\,/\,365\}$	n = day of the year (1 to 365)
3	Apparent Solar Time (AST)	$AST = LST + ET/60 + (LSM - LON)\,/\,15$	LST = Local Solar Time LSM = Local Standard Meridian LON = Longitude
4	Hour Angle (H)	$H = 15\,(AST - 12)$	
5	Solar Altitude (β)	$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta$	L = Longitude
6	Solar Azimuth (Φ)	$\cos \Phi = (\sin \beta \sin L - \sin \delta)\,/\,(\cos \beta \cos L)$	
7	Surface Solar Azimuth (γ)	$\gamma = \Phi - \Psi$	Ψ = Surface Azimuth
8	Incident Angle (θ)	$\cos \theta = \cos \beta \cos \gamma \sin \Sigma + \sin \beta \cos \Sigma$	Σ = Surface tilt angle from the horizontal plane
		$\cos \theta_H = \sin \beta$	Σ = 0°, when the surface is horizontal
		$\cos \theta_V = \cos \beta \cos \gamma$	Σ = 90°, when the surface is vertical
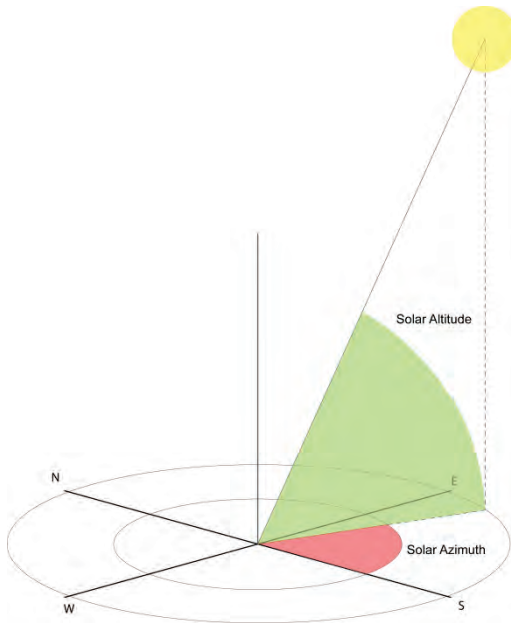
Solar Angles
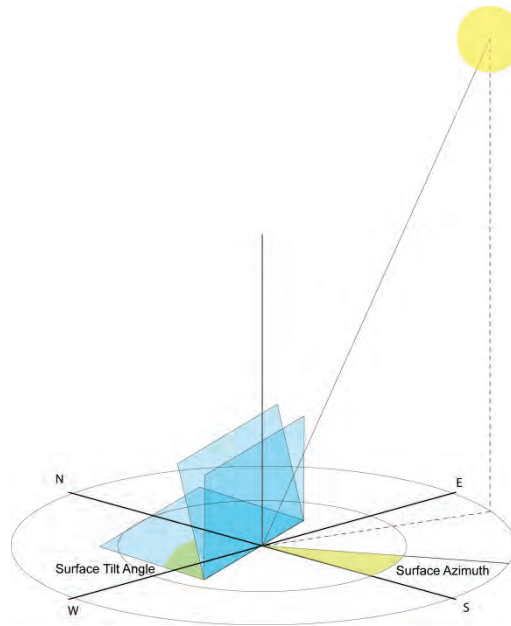
Surface Solar Angles
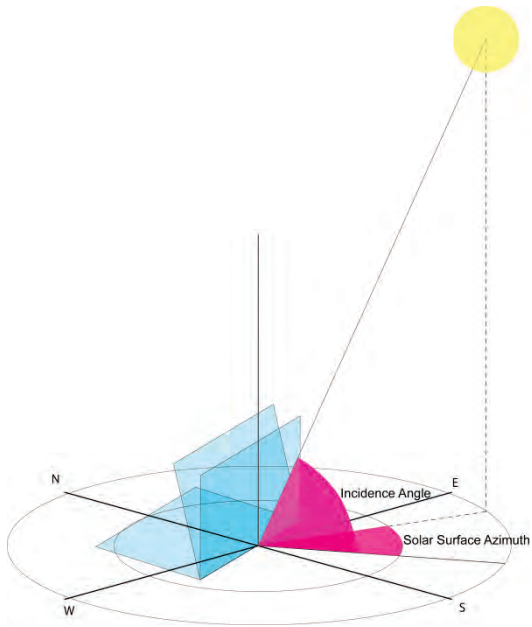
Solar and Surface Angles

Figure 4. Solar Angles and Surface Solar Angles.

Profile Angles for Shading Geometries. The calculation for the sizes of member projections for openings can be done by using the equations offered in this manual, and as indicated in Table 2.

Table 2

2005 ASHRAE Handbook Fundamentals Profile Angles Equations

		Equations	*Remarks*
9	Vertical Projection Profile Angle (P_V or Δ)	$\tan \Delta = \sin \gamma \cos \beta / \cos \theta$	$|\theta| < 90°$
		$\tan \Delta_H = \sin \gamma / \tan \beta$	For horizontal surfaces, for all γ
		$\Delta_V = \gamma$	For vertical surfaces, $90° > |\gamma| > 270°$
10	Horizontal Projection Profile Angle (or Ω)	$\tan \Omega = (\sin \beta \sin \Sigma - \cos \beta \cos \gamma \cos \Sigma) / \cos \theta$	For tilted surfaces, when $|\theta| < 90°$
		$\tan \Omega_H = (\tan \beta / \cos \gamma)$	For horizontal surfaces, when $90° < |\gamma| < 270°$
		$\tan \Omega_V = (\tan \beta / \cos \gamma)$	For vertical surfaces, when $90° > |\gamma| > 270°$
11	Length of Vertical Projection (P_V)	$P_V = W / \tan \Delta$	W = Opening width
12	Length of Horizontal Projection (P_H)	$P_H = H / \tan \Omega$	H = Opening height
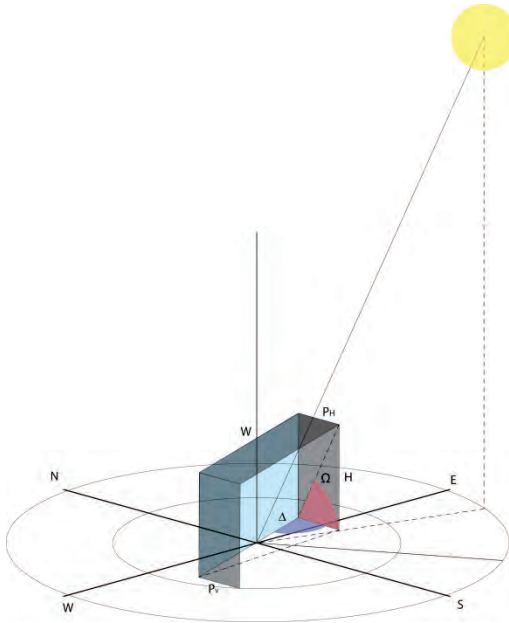
Shading Geometry: Vertical and Horizontal Projections

Figure 5. Profile Angles for Shading Geometries.

Solar Irradiance

ASHRAE. Similar equations for solar irradiance are found in the 2005 ASHRAE Handbook Fundamentals, section F31. Fenestration. Calculations for the irradiance values on surfaces are done utilizing the Clear Sky approach. The equations offered in this manual are compiled in Table 3.

Table 3

2005 ASHRAE Handbook Fundamentals Solar Irradiance Equations

		Equations	Remarks
13	Direct Normal Irradiance (E_{DN})	$E_{DN} = [A / [\exp(B / \sin \beta)]$	Values for A and B vary during the year (Table 7 ASHRAE, section 31.14)
14	Surface Direct Irradiance (E_D)	$E_D = E_{DN} \cos \theta$	
15	Ratio, Vert/Horiz Diffuse (Y)	$Y = 0.55 + 0.437 \ \cos \theta + 0.313 \cos^2 \theta$ $Y = 0.45$	For $\cos \theta > -0.2$ For $\cos \theta \leq -0.2$
16	Diffuse Irradiance (E_d)	$E_d = CYE_{DN}$ $E_d = CE_{DN} \ [(1 + \cos \Sigma) / 2]$	For vertical surfaces For surfaces other than verticals
17	Ground-Reflected Irradiance (E_r)	$E_r = E_{DN} (C + \sin \beta) \ \rho_g [(1 + \cos \Sigma) / 2]$	
18	Total Surface Irradiance (E_t)	$E_t = E_D + E_d + E_r$	

Isotropic Equations for Solar Irradiation on Tilted Surfaces. For calculating the total solar irradiation values on tilted surfaces, the necessary three irradiation components are: Direct normal irradiance, diffuse horizontal irradiance and global horizontal irradiance (Kreider, 2005). These three components' values can be obtained from the TMY files and the related equations are indicated in Table 4.

Table 4

Isotropic Solar Irradiance Equations for Tilted Surfaces

		Equations	Remarks
19	$I_{global\ plane}$	$I_{direct} \cos \theta + I_{diffuse} F_{sky} + I_{global,\ horiz} \rho_g F_{ground}$	$\rho_g = 0.2$ No snow $\rho_g = 0.7$ Snow
20	F_{sky}	$(1 + \cos \Sigma) / 2$	
21	F_{ground}	$(1 - \cos \Sigma) / 2$	

The direct solar irradiance is multiplied by the incidence angle to translate the irradiance values from the ground plane to the surface. The F represents the fractions of the radiation from the sky and ground due to the surface's tilt. And ρ_g represents the reflectivity of the ground, normally 0.2 for when snow is absent and 0.7 when snow is present.

Graphical Method. This type of method is based on the use of charts that are drawn for different latitude locations. They help to determine the solar irradiation, shading masks and shading percentage based upon the type of shading element. One of them is the sun path chart, which is based on the position of the sun throughout the year for the given latitude in respect to each month of the year and each hour of the day. Solar radiation calculators and shading masks are other available charts. The diagrams normally have a central and a base axis that help designers to locate the façade and then determine the solar radiation amount at that location and if the direct sunlight is being blocked.

Computer Software. The geometrical and analytical methods have been translated to the use of computer software. The mathematical computer models can now calculate the solar radiation received at specific locations in a building design model and also determine its thermal performance; using computer software for shading calculations is normally an evaluative process. This means that the size of the opening is given to the software and then a result of the shading percentage is calculated, thus its efficiency and performance. A sample of this type of software is Solar Tool under Autodesk Ecotect Analysis.

Solar Control and Shading

  Olgyay's Approach. Aladar Olgyay and Victor Olgyay made important
contributions in their 1957 book *Solar Control and Shading Devices*, which discusses the
role of shading devices as architectural elements, provides technical information for the
fundamentals of design on solar control in buildings, proposes a method for practical
applications, and includes an extensive array of architectural buildings examples.

  Among the basic concepts to understand are:

1. The number of daylight hours available and

2. The hours above comfort heat levels

  The use of sun path diagrams and overheated period charts for the geographic
location of the building help to determine when shading is needed.
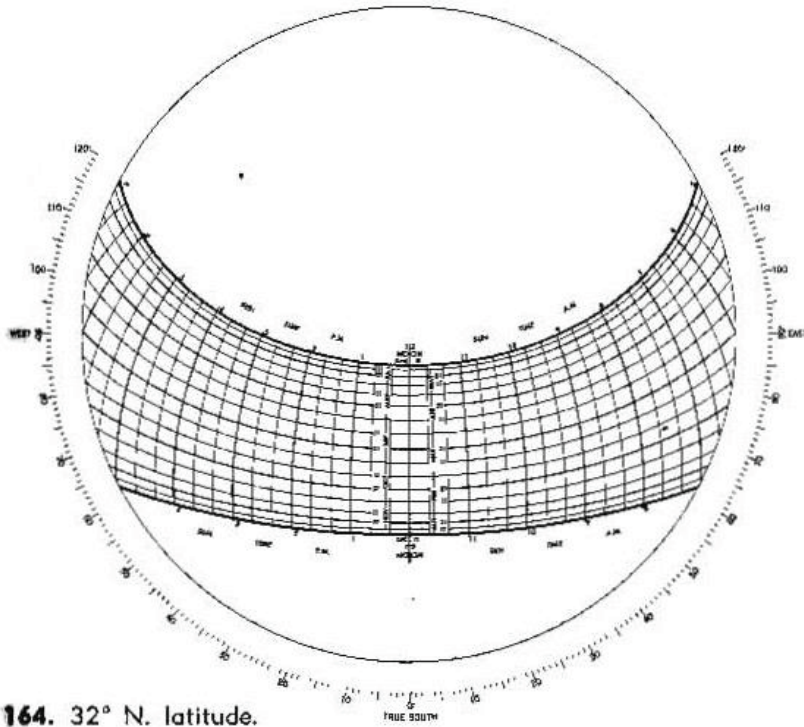
164. 32° N. latitude.

Figure 6. Sun Path Diagram (Olgyay and Olgyay, 1957).
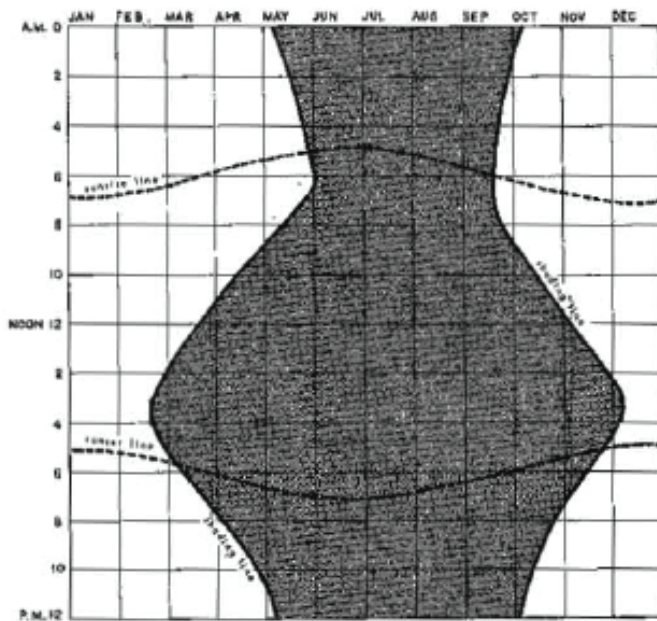
169. Phoenix, Arizona, 32° N. latitude.

Figure 7. Overheated Period Chart (Olgyay and Olgyay, 1957).

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Mazria's Approach. In his 1979 book *The Passive Solar Energy Book,* Edward

Mazria lays out a series of concepts and information to design a passive solar building.

Among the techniques the book provides is a new visual approach to the Solar Chart and

Shading Mask previously developed by Olgyay to calculate horizontal overhangs and

vertical fins for sun control in buildings.
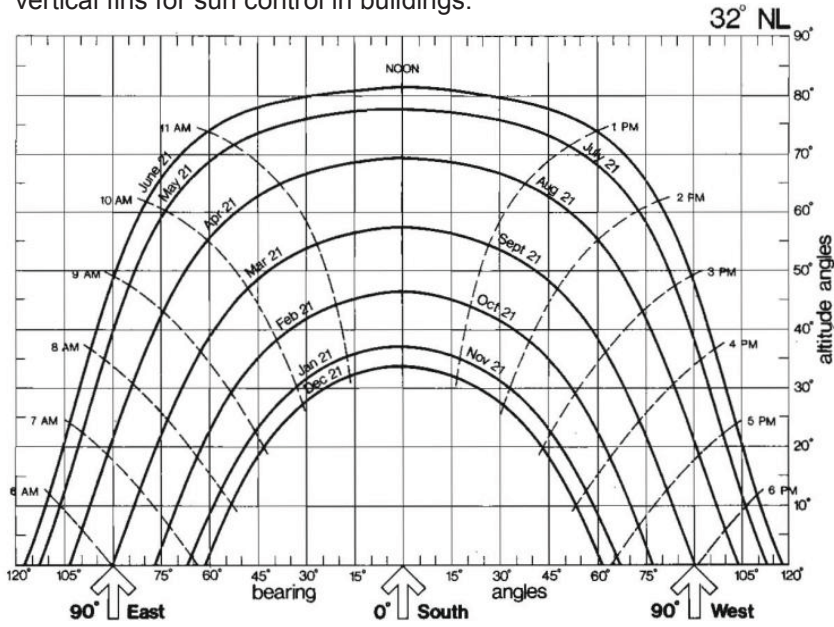
Figure 8. Sun Path Diagram (Mazria, 1979).
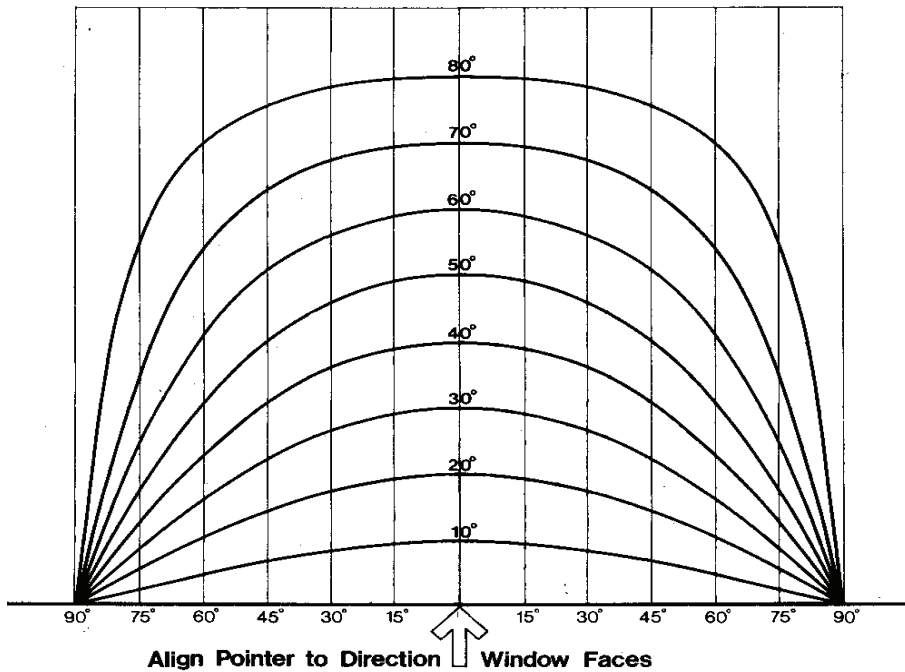
Figure 9. Shading Calculator (Mazria, 1979).

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Brown and Dekay's Approach. Later on in 1985, G. Z. Brown and Mark Dekay organized their book *Sun, Wind, & Light* by architectural elements at three scales:

a. Building groups,

b. Individual buildings and,

c. Building parts

Each scale highlights sustainable design strategies with building examples and practical design tools. Under building parts, strategy 98, Daylight-Enhancing Shades and strategy 99, External Shading, establish methods for calculating vertical and horizontal shading devices.

Shading Systems Types

The work done by Olgyay and Olgyay (1965) established the ground level to attain knowledge for basic concepts related to Solar Responsive Architecture. Their book *Sun Control and Shading* devices offers a detailed classification of the different systems and applications. Among the shading device types for sun control that architects have available for use are:

- Overhangs.

One of the simplest devices, an overhang is a continuation of the roof and provides shade to the envelope.

- Sun screens.

A waved material, either fabric or metal, will serve to block a percentage of solar radiation while letting another percentage pass through and another to be reflected.

- Fins or Vertical Louvers.

This system helps to reduce direct solar gain when low solar angles are present.

- Horizontal Louvers.

Recommended for East, South and West elevations.

- Egg Crates.

This system combines horizontal and vertical louvers.

Energy Use in Buildings

The properties of a building envelope can relate directly to lighting and cooling energy use. While the percentage of openings on walls can determine the level of daylight on the interior spaces, it can also contribute to solar heat gain if openings are not protected nor have high performance glazing for reducing unwanted solar irradiance.

ASHRAE Handbook Fundamentals claims that one of the most effective ways to reduce the solar load on fenestration is to intercept direct radiation from the sun before it reaches the glass. It calculates that any fenestration in the envelope that is fully shaded from the outside can have a reduction of solar heat gain of as much as 80% (ASHRAE, 2005). Hence the importance of research on building envelope design towards a balanced result between adequate levels of daylighting to reduce lighting systems use and shading systems to decrease solar heat gain. It is understood that the thermal properties of the envelope assembly of materials also contribute to reduce solar heat gain; however this matter is not studied under this present work.

Also Olgyay notes that "the most sensitive single element of the structure is the window area. Its positioning for winter and solar control during summer produce the largest effect on heat flow balance" (Olgyay, 1963, p.152). Certainly solar control in buildings is important, as it is the understanding of how this task can be achieved by the use of adequate shading geometries.

Solar control in buildings not only helps to define an energy balance in the envelope, also it can contribute to the reduction of lighting systems by harvesting available daylight. Thus this can contribute to the reduction of electricity consumption. In commercial buildings, lighting and cooling are two of the major consumers of electricity (EIA, 2009). From the information collected by CBECS in 2003, 38% of the electricity used by the inventory of buildings included in their survey was consumed by lighting and 13% by cooling (*Figure 10*). Lighting represents the highest end use among all other end users.

Site Electricity Consumption
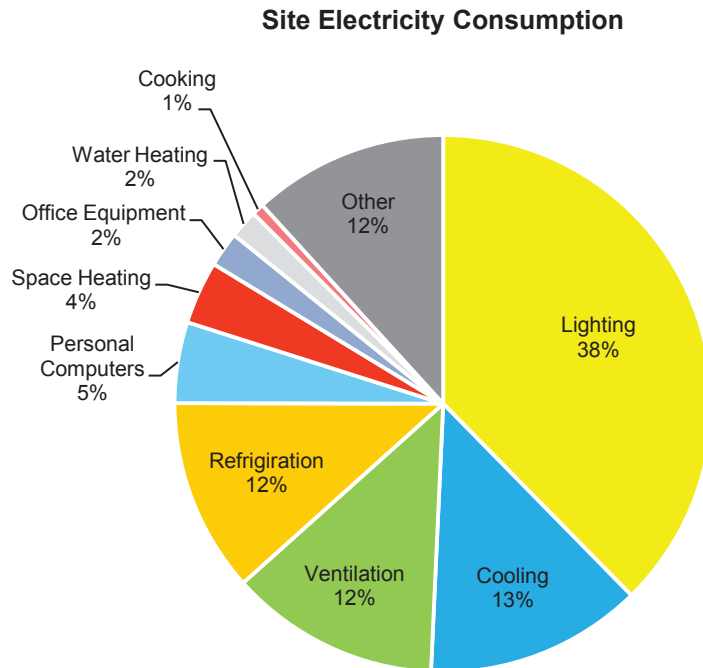
Figure 10. Site electricity by end use based on U.S. Energy Information Administration, 2009.

Local energy use. According to the Department of Energy in 2009 Arizona's energy expenditure per person was $2,662.45. Arizona ranked 50th among all the states. Under energy expenditure Arizona ranked 46th, using 64,699 kilowatt hours per capita. (DOE, 2011). Local governments acknowledge the importance of energy reduction in buildings, among them City of Phoenix has committed different programs that leading towards a more sustainable city. Some samples of these programs are Energize Phoenix, Urban Form and Tree and Shade Master Plan. This last one was presented in 2010 and it "provides the framework for creating a healthier, more livable and prosperous Phoenix" and even though the program target is the renewal of the city's "trees, urban forest and engineered shading structures," it recognizes that by doing this, the city reduces carbon footprint, energy costs and address the urban heat island effect.

Computer Aided Architecture and Software

There have been many changes in architectural practice since Ivan Sutherland wrote Sketchpad in 1963. His development opened the door to computer-aided design and drafting (CADD), computer graphics and graphic user interface. Departing from Sutherland's 2D-vector-based drafting program, computer applications have advanced to a point where drafting and design systems are able to model 3D solids and surfaces by applying dynamic mathematics. In Negropontes' book *Soft Architecture Machines,* he highlights the prospective influence computers may have in human life and his specific interest in architecture:

> … I adopted the position that, if computers were to aid the evolution of architecture, they would have to be a class of machines that (we could generally agree) exhibited intelligent behavior. I took the stance that computer aided architecture without machine intelligence would be injurious because the machine would not understand what it was aiding (Negroponte, 1975, p.33).

Step by step, the development of computer software for architectural design applications is leading towards more virtual and dynamic applications that not only relate to the user but also to the environmental response. Since the 1980's, software developers have started to introduce in CADD software parametric design controls, which has opened a variety of possibilities in architectural practice. Furthermore, energy analysis and behavior in building modeling have become more relevant; software companies and researchers are constantly developing better ways to improve the flow process from CADD or BIM software to simulation software.

Associative Design

When I attended architecture school I experienced the transition from hand drafting to CAD. It was at that point that I perceived an endless world of opportunities; since then, the constant changes and new developments in building modeling software have escalated exponentially. These changes have aided the complexity of the design process, in which many layers of information need to be considered and analyzed

carefully to provide a solution to a design problem or several ones. Building envelopes are now exposing that complexity. With the use of software tools available, it is possible to create dynamic geometries and respond to different layers of information. These layers can relate to each other and to the geometry; if one changes, it will affect the whole geometry or parts of it. This design is "Associative."

Associative Modeling as Khabazi explains:

It relates to a method in which elements of design being built gradually in multiple hierarchies and at each level, some parameters of these elements being extracted to be the generator for other elements in the next level and this goes on, step by step to produce the whole geometry… Basically this method of design deals with the huge amount of data and calculations and happens through the flow of algorithms (Khabazi, 2010, p.3).

In his recent book *Parametric Architecture with Grasshopper*, Tedeshi (2011) defines associative modeling as "the ability of the algorithm to weave complex relations among objects, and generate mutually linked geometries." He points out that "the main algorithm's result is not the specific geometry but the system of relations (nodes) between input and output that become dynamic geometrical connections."

Parametric Design

…Parametric design enables the recognition of patterns of geometric behaviour and related performative capacities and tendencies of the system. In continued feedback with the external environment, these behavioral tendencies can then inform the ontogenetic development of one specific system through the parametric differentiation of its sub-locations (Hensel, Menges, 2008).

In brief, parameters help to define an object's form when modeling. By applying parameters, the history that has defined the model can be seen. This can easily inform us about the number of parts, objects or entities that are interconnected and work together to give birth to a new geometry. A model can have one parameter or as many as hundreds and because of the relationship amongst each of them, they are dependant. "A

parametric model can be considered as a dynamic system of relations among different

objects" (Tedeshi, 2011, p.17).

Since the early 1980's the development of parametric software has been growing

in the building and design industry. Table 5 indicates the most commonly used

parametric software used for design and construction.

Table 5

Parametric Modeling Software List.

Software	Description
CATIA	Computer Aided Three-dimensional Interactive Application. It is a CAD/CAM/CAE platform developed by Dassault Systems. Originally developed in 1977 (then known as CATI) to assist aircraft manufacturing.
SolidWorks	Released in 1995. This 3D-CAD software was conceived as an affordable software for Windows system. Currently owned by Dassault Systems.
Rhinoceros | Grasshopper	Released in 1998, Rhinoceros was developed by Robert McNeel & Associates. Specializes in 3D modeling (NURBS) free-forms and its plug-in, Grasshopper, is a parametric modeler. Several other plug-ins are available.
Generative Components	Introduced by Bentley Systems in 2003. This software is used with 3D solid modeling to provide parametric capabilities.
ParaCloud | GEM	Generative Design Software that acquires data from Microsoft Excel to create parametric models. It is compatible with Rhino, Maya, 3DS Max and Sketch Up among others. It was launched in 2008.
ArchiCAD	Launched by Graphisoft in 1987, this BIM-CAD software is able to create parametric 3D objects, which can be represented either in 2D or 3D-ways.
Revit	A BIM-CAD software that has Architectural, Structural and MEP specific versions and in which specific models can merge into a centralized one. It was acquired by Autodesk in 2002.
Digital Project	BIM-CAD Software based on CATIA v5, developed by Gehry Technologies and launched in 2004 as an effort to bring together AEC industry.

Generative Algorithms

An algorithm is a procedure for solving a mathematical problem (as in finding the greatest common divisor) in a finite number of steps that frequently involves repetition of an operation (Merriam-Webster, 2011). Designers are employing algorithms in parametric design to help them to control modeled objects' properties and solve geometrical conditions of complex objects. Furthermore, the use of genetic algorithms involves optimization of the model geometry by utilizing an established pair of variables (or genes) that auto-process their combined information in a repetitive mode to solve a problem. Khabaki (2010) states in his description of generative algorithms, the opportunities on using these recent available tools: "The horizon is a full catalogue of complexity and multiplicity that combines creativity and ambition together."

Rhinoceros and Grasshopper

Rhinoceros (Rhino) is a software program developed by Robert McNeel & Associates and specializes in 3D modeling non-uniform rational B-spline (NURBS) free-forms. Rhino was officially released in 1998 and its development is on-going. This modeling program is gaining acceptance among different design disciplines (architecture, structural engineering and industrial designers) because it is diverse, easy to learn and use, and has a powerful set of multiple add-ons and plug-ins available. The Rhinoceros capabilities for modeling are notable, but some plug-ins, like Grasshopper, establish a powerful design instrument to conceptualize.

Grasshopper aids Rhinoceros in building geometric forms using *Generative Algorithms*, and requires no previous knowledge or programming or scripting. Its interface allows for scripting to create parametric modeling. In addition, Grasshopper is very visual, a characteristic that most designers appreciate. It brings the opportunity to develop either simple or complex parametric routines that can be applied to solving design problems while visualizing solutions simultaneously. This becomes an important tool for architectural design problem solving. McNeel provided a description of this plug-in:

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Grasshopper is a way for designers to look at design problems as a set of sophisticated relationships and to map those relationships graphically and programmatically into a system that allows them to interactively visualize alternatives. At first Grasshopper was very simple but, based on user feedback, it now allows for very complete systems, including the ability for expert users to extend the system with C# and Visual Basic components (AEC/McNeel, 2009).

The Grasshopper editing platform is currently available at no cost for users who are interested on generative modeling of simple or complex objects that require defined control in their geometry (McNeel, 2010). To date, Grasshopper is a work-in-progress tool and has not been released officially.

Even though a prior knowledge of computer programming may not be necessary, an overall understanding of available components and the types of connectivity among them is required. Tedeshi (2011) sets a clear distinction on the type of components that Grasshopper's interface has available. *Figure 11* shows this distinction; while some components perform actions, others, referred as "parameters" storage data. This data can be a numerical value or geometry and either can be data specifically given by the user (persistent data) or can be data that is retrieved by the connection of one or more parameters (volatile data). *Figure 12* shows a sample of typical numerical and geometrical parameters, as well as action components in Grasshopper's interface.
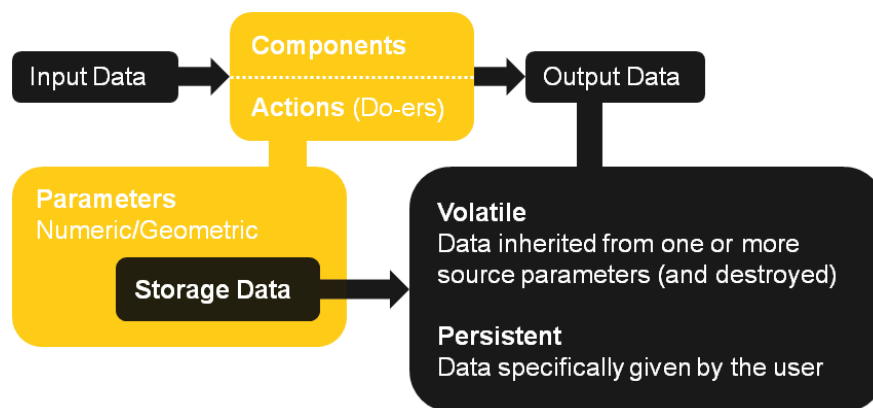
Figure 11. Grasshopper's components and parameters functions.
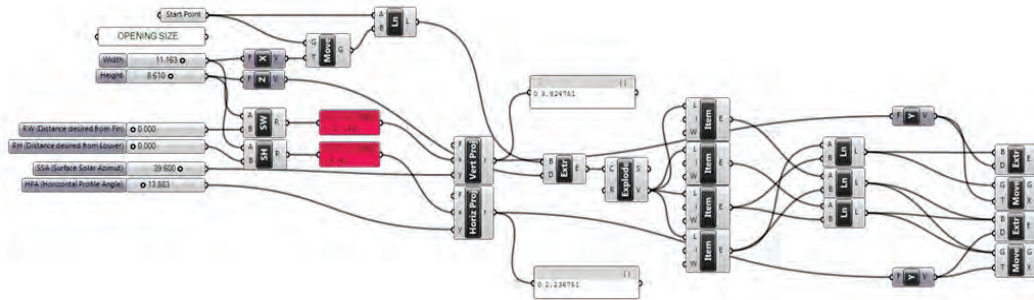
Figure 12. Grasshopper Sample of Parametric Model.

Solar Angles Scripts. In 2009 Ted nGai developed a Grasshopper parametric

model to provide irradiation on surfaces created under the Rhino modeling program. The

model provides the vector of the sun at any location, date and time of the year. Several

main components, which are the core of the application, are developed under the

VB.NET component of Grasshopper. These components set the calculations for the solar

profile angles, the day of the year, the earth radius factor (earth-sun distance), the

conversion of time and the sun's vector. The sun vector, if used in calculating incident

solar angles, then the vector needs to be reversed on direction. The model also

calculates solar irradiation values on the surface or surfaces selected, although nGai

(2009) states that "solar irradiance is only used for visual feedback; the number is not

accurate as the current algorithm does not account for radiation reduction through

various kinds of scattering (vapor, particle, ozone, etc)." The calculation of solar

irradiance is based on the *Simple Solar Spectral Model for Direct and Diffuse Irradiance*

on Horizontal and Tilted Planes at the Earth's Surface for Cloudless Atmospheres from

the National Renewable Energy Laboratory (NREL). However, it includes for its

calculation only the first two components from the direct irradiance equation (22) in Table

6: $H_{o\lambda}$ and D.

Based on the equations from NREL, the direct irradiance on a surface normal to

the direction of the sun at ground level for wavelength λ is given by the equation (22)

shown in Table 6.

Table 6

Simple Solar Spectral Model for Direct and Diffuse Irradiance

		Equations	Remarks
22	$I_{d\lambda}$	$H_{o\lambda}\, D\, T_{r\lambda}\, T_{a\lambda}\, T_{w\lambda}\, T_{o\lambda}\, T_{u\lambda}$	$H_{o\lambda}$ = Extraterrestrial irradiance, 1367 W/m^2
23	D	$1.00011 + 0.034221 \cos\varphi + 0.00128 \sin\varphi$ $+ 0.000719 \cos 2\varphi + 0.000077 \sin 2\varphi$	φ = day angle in radians
24	φ	$2\pi\,(d-1)/365$	d = the number of the day in the year (from 1 to 365)

The parameter $H_{o\lambda}$ is the extraterrestrial irradiance at the mean earth-sun distance for wavelength λ, a constant of 1367 W/m^2. D is the correction factor for the earth-sun distance given by Spencer (1971).

$T_{r\lambda}$, $T_{a\lambda}$, $T_{w\lambda}$, $T_{o\lambda}$ and $T_{u\lambda}$ are the transmittance functions of the atmosphere at wavelength for molecular (Rayleigh) scattering, aerosol attenuation, water vapor absorption, ozone absorption, and uniformly mixed gas absorption, respectively.

All the transmittance parameters are not included in solar direct irradiance calculation from nGai's parametric script model. Likewise, the diffuse irradiance is not included. The direct irradiance on the horizontal surface (ground) is obtained by multiplying $I_{d\lambda}$ by the cosine of the solar zenith angle. The direct irradiance on the surface of analysis is obtained by multiplying the direct irradiance of the horizontal on the ground by the normal angle of the surface. The solar incidence Grasshopper definition is included in Appendix B, with a detail documentation of the VB.NET scripts.

METHODOLOGY

Objective

This work intends to identify a process to automate the execution of tasks for creating geometries that respond to sun control and have adaptation capabilities to streamline the geometry's efficiency as a shading "fixed system." The process is assisted by visual scripting and parametric design to create a definition that attempts to fully shade assumed openings over a selected building envelope responding to the climate conditions of Phoenix, AZ. The work includes but is not limited to horizontal projections, vertical projections and other custom solutions. A secondary goal for this thesis project is to set a comparison between fixed shading systems and dynamic systems.

Scope of Work

The background literature supported the information needed for the development and research portion of this thesis methodology. The work is divided in four parts: the analysis of the TMY3 data set for Phoenix, the definition for the *Solar Control Visual Script*, the analysis of Euclidian and NURBS building envelopes geometries, and the study of local buildings with dynamic solar control devices to help define pros and cons of fixed and dynamic systems.

Section 1 – TMY3 Data Set Analysis. The data set from the TMY3 file for Phoenix is read using a worksheet in Excel and values are arranged to obtain for each month of the year average hourly temperatures in Fahrenheit degrees. Originally the TMY3 file provides temperature values in Celsius degrees. Similarly, the average hourly values for each month for global horizontal irradiance, direct normal irradiance and diffuse horizontal irradiance are obtained. The values in the TMY3 data set are given in W/m^2 and conversion to $Btu/h\text{-}ft^2$ is done.

After defining these values, they are tested against pre-established parameters for temperature and irradiation, meaning that temperatures are filtered by temperature limits for overheating, comfort and underheating periods as shown in Table 7; direct normal irradiation levels are filtered by the value of 200 $Btu/h\text{-}ft^2$, assuming values over

this amount are considered to be overheated surfaces. Then the results of average hourly temperatures and direct normal irradiation are layered over. By layering these two parameter values, the hours and months in which high temperatures and high irradiance values overlap define a numerical domain in which sun control is needed for the building envelope. This numerical domain is implemented on Section 2 – Solar Control Visual Script.

Table 7

Temperature parameters for setting overheating and underheating periods.

Period	Temperature
Overheating	> 75°F
Comfort	< 75°F and > 65°F
Underheating	< 65°F

Section 2 – Solar Control Visual Script. Grasshopper, one of the plug-in software for Rhinoceros, is the program used to formulate the visual script for the associative design to resolve shading geometry projections based on the sun's path of travel. Rhinoceros 4.0 Service Release 9 and Grasshopper Version 0.8.0052 are the software versions used.

The associative design for the *Solar Control Visual Script* is divided in several portions to calculate:

A. The solar path and vector (based on nGai's Grasshopper definition).

B. The solar irradiation values by retrieving the values from the Excel TMY3 file.

C. A series of sub-surfaces that are based on the analysis of the main surface acting as the building envelope and on a selected grid pattern. These sub-surfaces represent the geometry for the openings in the envelope.

D. The profile angles for each of the sub-surfaces to draw their opening sizes that respond to irradiation levels.

E. The size of projections for shading geometries over the sub-surfaces.

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Figure 13 indicates the overall *Solar Control Visual Script* flow chart as described in the previous paragraph.

Figure 13. Grasshopper Solar Control Visual Script Flow Chart.

Part A of the visual script is based on the *Solar Incidence Definition* by Ted nGai (2009). From this definition, the portions related to the solar path and the calculation of sun's profile angles are implemented into the *Solar Control Visual Script*. In order to have a congruent model analysis that applies the equations from ASHRAE *Handbook Fundamental*s, several modifications to nGai's definition are established:

The first one changes the calculation of the *sun azimuth angle. The Solar Incidence Definition* measures the azimuth angle from North and with no distinction between negative and positive values. Based on ASHRAE *Handbook Fundamental*s, to calculate solar profile angles, the azimuth angle is measured from South and azimuth angles between South and East are considered negative values and between South and West are considered positives values (ASHRAE, 2005).

The second modification is the *irradiation values* calculation for the surfaces. The calculation is based on the analysis of the data set obtained from the TMY3 file, instead of the solar constant of 1367 W/m^2 or 433 Btu/hft^2 from the World Radiation Center's 1985 standard extraterrestrial spectrum (Wehrli, 1985). This is with the goal of using measured data from the particular city's location where the building envelope is designed.

The third modification is the change of the solar vector's direction to be able to calculate a correct incidence angle between the solar vector and the normal vector of the surface.

Part B of the *Solar Control Visual Script* calculates the global irradiation values (defined in *Section 1*) by extracting values automatically from the TMY3 Excel spreadsheet into the Grasshopper interface. An instruction under a VB.NET component in Grasshopper takes the input data from Excel starting from an assigned column and row that relates to the month and hour selected in the definition for analysis, and then it retrieves the global horizontal, the direct normal and the diffuse horizontal irradiance values to calculate the global irradiation value.

Part C evaluates the surface based upon the selection of a predetermined grid pattern geometry that lays out the openings' configuration on the building envelope. This

portion was built using as a base a Grasshopper definition explored under the Digital

Ecologies course on spring 2011 lectured by David Newton at Arizona State University.

Part D determines the openings' sizes in relation to the amount of irradiation by

assigning a correlation between the irradiation values drawn from the global irradiance

calculation and a maximum and a minimum offset from the established grid geometry.

The surfaces with high irradiation values are linked to maximum offsets resulting in

smaller size openings, while surfaces with low irradiation values are linked to minimum

offsets resulting in greater opening areas.

Part E calculates the geometrical components projections to determine

overhangs, vertical fins and egg crates by using the Analytical Equation Methods profile

angles based on *2005 ASHRAE Handbook Fundamentals* and which are mentioned in

the *Background Literature* section.

Section 3 – Analysis of Euclidian and Complex Geometries. The Solar

Control Visual Script is tested in several surfaces to experiment the outputs, making a

clear differentiation among two different building envelopes for analysis:

1. Euclidean Geometry based on planar elements, and

2. Complex Geometry based on NURBs

Solar Control Visual Script is simplified for the Euclidean Geometries.

Section 4 – Shading systems: Fixed versus Dynamic. This section describes

the use of fixed shading systems and compares it with dynamic systems used under the

climate conditions of Phoenix. Three local buildings that incorporate into their

architectural design mechanically operated shading devices are illustrated:

1. Burton Barr Central Library

2. Temple Transportation Center

3. Papago Park Center

Research Limitations

This thesis work is based only on the data retrieved from local solar incidence for a proposed building envelope. Solar thermal mass in the building envelope is neither considered nor accounted for in the development of the parametric definition. Daylighting levels, an important subject directly related to sun control and shading devices, have not been included as part of this research. Glazing type in openings, which can also contribute to the reduction of solar heat gain, has not been included in the development of the definition.

RESULTS

TMY3 Data Set

      Temperature. The analyzed temperature results from the TMY3 data set for Phoenix are shown in Table 8. The hours of the day during which temperatures are above 75°F, the overheating period, occur from the months of April to November; the highest registered average temperature values in this period of time occur between 3 and 4 p.m. The overall highest average temperature is 106.6°F on July at 4 p.m.

Table 8

Average Hourly Temperature, TMY3 for Phoenix, AZ.

Hour	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	51.1	55.7	59.1	68.5	75.7	87.4	91.2	88.3	81.6	71.6	59.7	49.2
2	50.3	54.4	57.7	66.5	73.6	85.7	89.6	86.6	80.5	70.1	58.4	48.2
3	49.3	53.5	56.2	64.4	71.6	84.4	88.3	85.8	79.2	68.8	57.4	47.5
4	48.4	52.7	55.1	62.8	70.2	82.6	86.9	84.4	78.0	67.5	56.3	46.5
5	47.5	51.9	54.2	61.6	68.9	81.4	86.2	83.3	76.8	66.7	55.7	45.7
6	46.9	51.4	53.8	60.5	67.8	80.9	85.8	82.5	76.3	66.2	54.9	45.3
7	46.7	50.9	53.7	61.5	70.1	82.8	86.9	82.8	76.5	65.9	54.6	44.8
8	46.7	52.0	56.1	66.4	74.1	86.3	89.4	85.8	79.2	69.0	56.1	45.3
9	49.8	55.0	59.8	71.3	78.2	90.0	92.7	89.3	83.0	73.3	60.3	48.5
10	53.7	58.4	62.9	75.6	81.4	93.6	95.7	92.6	86.5	77.2	64.5	51.8
11	57.3	62.2	65.5	78.7	84.6	96.7	98.5	95.3	89.8	81.0	68.1	55.1
12	60.1	65.2	67.8	81.2	87.2	99.1	101.1	97.6	92.5	83.9	70.9	57.7
13	62.0	67.4	69.4	83.5	89.3	101.5	102.9	99.4	94.9	86.1	73.1	59.9
14	64.2	69.2	70.8	85.1	91.3	103.0	104.7	100.9	96.6	87.8	74.3	61.5
15	65.7	70.0	71.6	86.5	92.3	103.9	105.8	101.7	97.7	88.4	75.5	62.6
16	65.9	70.5	72.3	87.1	92.3	104.2	106.6	102.3	97.6	87.7	75.3	63.0
17	65.6	70.0	72.1	86.3	92.0	103.8	106.1	102.5	96.5	86.3	74.0	61.9
18	62.7	68.1	71.2	85.1	91.1	102.8	104.0	102.0	95.2	83.5	70.7	59.5
19	60.6	65.3	69.4	82.6	89.1	100.5	101.9	100.1	92.3	80.9	68.4	57.2
20	58.2	63.4	67.2	80.1	86.2	97.7	99.7	97.7	89.8	78.6	65.9	55.0
21	56.4	61.6	65.3	77.0	82.4	95.2	95.9	95.1	87.3	76.9	64.3	54.0
22	54.9	60.0	63.4	74.4	80.6	92.8	96.1	92.6	86.0	75.3	63.0	52.5
23	53.5	58.7	62.0	72.4	79.3	90.8	93.9	91.1	84.3	74.2	61.7	51.2
24	52.5	57.6	60.5	70.8	77.7	89.3	92.9	89.5	82.6	72.9	60.4	50.0

Month

Hour

■ Underheating Period > 65°F
□ Comfort Period < 75°F and > 65°F
■ Overheating Period > 75°F

Direct Normal Solar Irradiance. Table 9 indicates the hours during each month in which the average direct normal irradiation values are greater than 200 Btu/h-ft^2. These are presented between 9 a.m. and 5 p.m; however, these values reoccur more from 10 a.m. to 4 p.m., starting in April and ending in November.

Table 9

Average Hourly Global Horizontal Irradiation in Bth/h-ft^2. TMY3 for Phoenix, AZ.

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6	0.0	0.0	0.0	0.7	13.3	21.7	8.9	0.3	0.0	0.0	0.0	0.0
	7	0.0	0.0	10.4	66.4	111.4	126.0	76.1	66.5	37.1	22.1	1.3	0.0
	8	5.5	40.0	112.3	170.1	179.1	183.6	139.6	147.8	136.5	138.5	78.0	26.3
	9	114.9	137.1	152.3	223.0	213.4	217.2	160.8	188.0	196.3	195.3	177.8	137.6
	10	169.5	182.7	188.9	241.8	241.1	240.1	192.9	209.2	224.1	219.3	214.7	181.4
	11	186.4	206.2	205.1	259.8	237.5	252.2	219.3	210.9	242.9	230.1	231.3	207.5
Hour	12	191.4	218.7	213.8	255.0	242.5	260.3	233.7	234.0	245.3	235.1	232.2	216.4
	13	214.6	214.4	198.1	248.3	245.2	259.1	226.9	236.5	257.7	239.8	234.8	210.2
	14	206.5	199.8	195.6	248.8	244.2	263.7	229.9	233.4	246.1	235.2	233.7	218.6
	15	207.2	190.5	190.9	233.9	228.6	251.6	225.6	219.8	240.8	210.3	219.9	199.0
	16	172.8	170.3	190.8	210.6	229.1	233.9	228.4	219.2	222.9	152.7	183.9	182.4
	17	180.4	143.2	172.9	184.0	198.0	208.2	189.1	203.7	181.7	142.6	119.8	147.3
	18	59.6	68.6	127.8	139.4	168.7	175.9	136.9	159.3	124.0	43.8	19.5	0.0
	19	0.0	2.8	26.6	44.8	85.2	109.0	51.8	63.7	20.4	0.1	0.0	0.0
	20	0.0	0.0	0.0	0.1	5.2	15.8	7.7	0.3	0.0	0.0	0.0	0.0
	21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

■ I direct > 200 Btu/h-ft2

Overlay of Temperatures and Solar Direct Normal Irradiance. By layering these two data sets, the hours and months in which high temperatures and high irradiance values overlap are identified and simplified in a linear range. In this case, the acknowledged values range from 10 a.m. to 4 p.m. from April to October. This numerical range is assigned to the parameters in the *Solar Control Visual Script*. Table 10 below indicates the overlap with a shaded area.

Table 10

Overlay of overheating temperatures and direct irradiance values > 200 Btu/hft^2

						Month						
Hour	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	51.1	55.7	59.1	68.5	75.7	87.4	91.2	88.3	81.6	71.6	59.7	49.2
2	50.3	54.4	57.7	66.5	73.6	85.7	89.6	86.6	80.5	70.1	58.4	48.2
3	49.3	53.5	56.2	64.4	71.6	84.4	88.3	85.8	79.2	68.8	57.4	47.5
4	48.4	52.7	55.1	62.8	70.2	82.6	86.9	84.4	78.0	67.5	56.3	46.5
5	47.5	51.9	54.2	61.6	68.9	81.4	86.2	83.3	76.8	66.7	55.7	45.7
6	46.9	51.4	53.8	60.5	67.8	80.9	85.8	82.5	76.3	66.2	54.9	45.3
7	46.7	50.9	53.7	61.5	70.1	82.8	86.9	82.8	76.5	65.9	54.6	44.8
8	46.7	52.0	56.1	66.4	74.1	86.3	89.4	85.8	79.2	69.0	56.1	45.3
9	49.8	55.0	59.8	71.3	78.2	90.0	92.7	89.3	83.0	73.3	60.3	48.5
10	53.7	58.4	62.9	75.6	81.4	93.6	95.7	92.6	86.5	77.2	64.5	51.8
11	57.3	62.2	65.5	78.7	84.6	96.7	98.5	95.3	89.8	81.0	68.1	55.1
12	60.1	65.2	67.8	81.2	87.2	99.1	101.1	97.6	92.5	83.9	70.9	57.7
13	62.0	67.4	69.4	83.5	89.3	101.5	102.9	99.4	94.9	86.1	73.1	59.9
14	64.2	69.2	70.8	85.1	91.3	103.0	104.7	100.9	96.6	87.8	74.3	61.5
15	65.7	70.0	71.6	86.5	92.3	103.9	105.8	101.7	97.7	88.4	75.5	62.6
16	65.9	70.5	72.3	87.1	92.3	104.2	106.6	102.3	97.6	87.7	75.3	63.0
17	65.6	70.0	72.1	86.3	92.0	103.8	106.1	102.5	96.5	86.3	74.0	61.9
18	62.7	68.1	71.2	85.1	91.1	102.8	104.0	102.0	95.2	83.5	70.7	59.5
19	60.6	65.3	69.4	82.6	89.1	100.5	101.9	100.1	92.3	80.9	68.4	57.2
20	58.2	63.4	67.2	80.1	86.2	97.7	99.7	97.7	89.8	78.6	65.9	55.0
21	56.4	61.6	65.3	77.0	82.4	95.2	95.9	95.1	87.3	76.9	64.3	54.0
22	54.9	60.0	63.4	74.4	80.6	92.8	96.1	92.6	86.0	75.3	63.0	52.5
23	53.5	58.7	62.0	72.4	79.3	90.8	93.9	91.1	84.3	74.2	61.7	51.2
24	52.5	57.6	60.5	70.8	77.7	89.3	92.9	89.5	82.6	72.9	60.4	50.0

Overheating Period > 75°F

I direct > 200 Btu/h-ft2

Solar Global Irradiance. Table 11 represents the collection of data values that are drawn automatically from Excel to Grasshopper by a VB.NET component in order to calculate the global irradiation values on a surface.

Table 11

Compilation of hourly average irradiation values.

Hour	JAN GHI	DNI	DHI	FEB GHI	DNI	DHI	MAR GHI	DNI	DHI	APR GHI	DNI	DHI	MAY GHI	DNI	DHI	JUN GHI	DNI	DHI	JUL GHI	DNI	DHI	AUG GHI	DNI	DHI	SEP GHI	DNI	DHI	OCT GHI	DNI	DHI	NOV GHI	DNI	DHI	DEC GHI	DNI	DHI
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	1	0	6	13	4	8	22	6	3	9	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	10	0	19	66	11	39	111	17	47	126	19	32	76	18	18	67	10	13	37	9	4	22	1	0	1	0	0	0	0
8	0	5	0	12	40	7	34	112	13	75	170	23	104	179	31	110	184	32	86	140	32	72	148	23	61	137	24	42	138	16	18	78	9	1	26	0
9	32	115	12	57	137	22	91	152	33	149	223	34	170	213	44	176	217	45	143	161	51	138	188	39	128	196	37	97	195	23	69	178	20	39	138	13
10	83	169	25	112	183	35	150	189	45	210	242	47	233	241	52	239	240	56	206	193	65	201	209	56	190	224	47	154	219	35	123	215	32	86	181	24
11	122	186	35	159	206	43	194	205	51	261	260	52	271	238	64	283	252	60	259	219	70	246	211	72	237	243	52	200	230	49	162	231	37	127	207	32
12	151	191	45	188	219	45	225	214	57	287	255	61	296	243	67	311	260	61	298	234	77	285	234	72	265	245	60	223	235	52	182	232	42	150	216	35
13	174	215	48	202	214	54	225	198	63	292	248	67	308	245	71	317	259	63	305	227	83	300	237	78	280	258	58	229	240	51	190	235	45	155	210	39
14	164	206	47	193	200	58	226	196	70	283	249	63	300	244	71	312	264	60	299	230	80	289	233	76	262	246	59	214	235	50	176	234	42	154	219	40
15	145	207	42	168	191	53	195	191	58	250	234	63	263	229	68	281	252	60	270	226	71	249	220	66	230	241	53	173	210	47	143	220	36	123	199	35
16	99	173	34	128	170	45	168	191	55	202	211	60	221	229	55	228	234	52	231	228	57	209	219	54	178	223	45	124	153	54	91	184	28	89	182	32
17	67	180	27	75	143	29	115	173	42	135	184	45	153	198	43	170	208	46	161	189	44	149	204	38	110	182	32	61	143	21	36	120	15	48	147	26
18	5	60	2	23	69	13	65	128	36	68	139	27	92	169	30	105	176	33	86	137	27	81	159	26	48	124	20	9	44	4	6	19	4	0	0	0
19	0	0	0	2	3	1	2	27	1	15	45	10	29	85	15	42	109	19	31	52	20	21	64	12	8	20	6	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	3	5	2	7	16	5	3	8	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

GHI - Global Horizontal Irradiance

DNI - Direct Normal Irradiance

DHI - Diffuse Horizontal Irradiance

Parametric Visual Script

The following paragraphs describe the series of outputs for the *Solar Control Visual Script* in Grasshopper. This flow is established to create a dynamic process for calculating irradiation values and determining the shading elements' dimensions to fully shade an opening. Since the flow is an associative design, the first three steps here can be followed in any order and the results will not be affected (i.e., assigning the surface geometry for the building envelope, choosing a pattern for the surface or selecting the month and time for the analysis of the solar profile angles are interchangeable steps).

Surface for Building Envelope. In this step, the surface that acts as the building envelope is set in Rhinoceros and then assigned to the Grasshopper geometry button. A series of grid parameter components in Grasshopper give the opportunity to assign a design pattern to the surface; custom grids or patterns can be assigned as well, though, this thesis work only includes the typical components for grid patterns available under Grasshopper's user interface. The grid pattern chosen is by default created on the XY plane of the Rhinoceros workspace and, by connecting a component to analyze surfaces, the grid pattern geometry is re-parameterized into the surface geometry working as the building envelope. This selected grid pattern can either simulate a full curtain glass system or function as a grid to create a series of offsets representing the openings on the building envelope to be analyzed for shading. By doing this, the whole surface is divided into sub-surfaces that follow the grid pane, which will aid in analyzing smaller portions of the overall surface's geometry.

The resulting offset geometry can be associated with the solar irradiance values striking the surface and then it responds to its sizing according to the maximum and minimum values of irradiance. *Figure 14* and *Figure 15* indicate the geometries inputs and resulting outputs for these steps. Appendix D, Section 3 illustrates the portion of the *Solar Control Visual Script* that corresponds to this section.

Input: Selected Surface Geometry
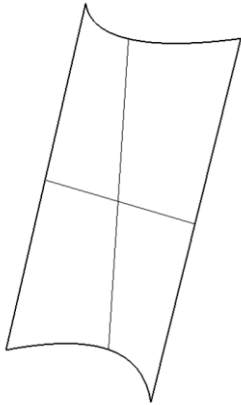
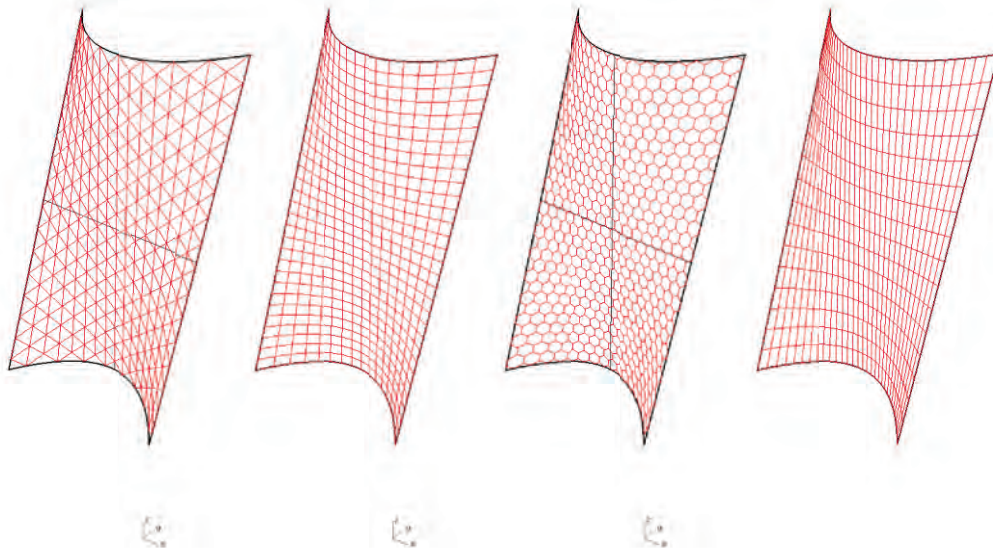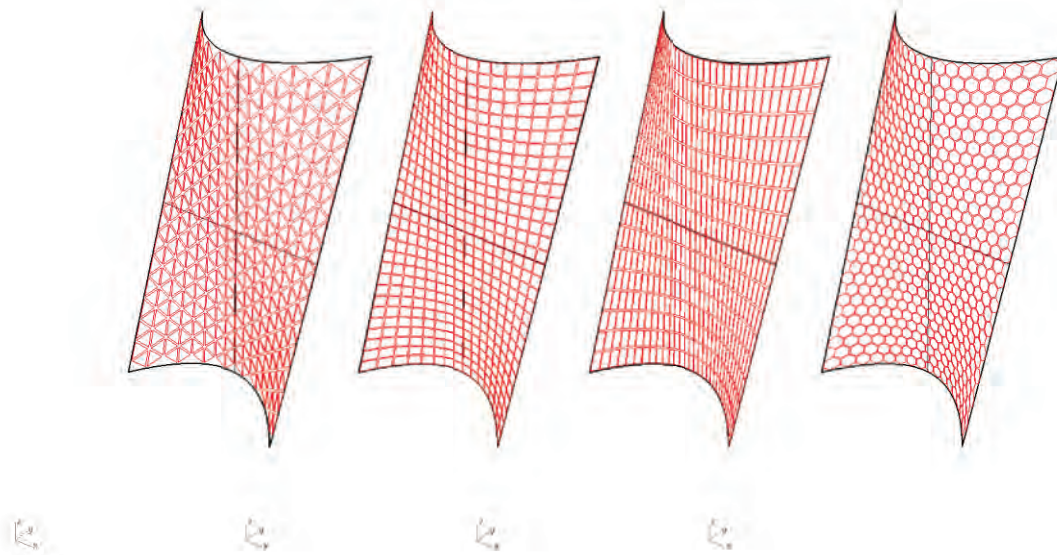Output: Re-parameterized Grid Patterns on Selected Surface

Figure 14. Visual Script. Assigned surface for analysis and various options for grid patterns on surface.

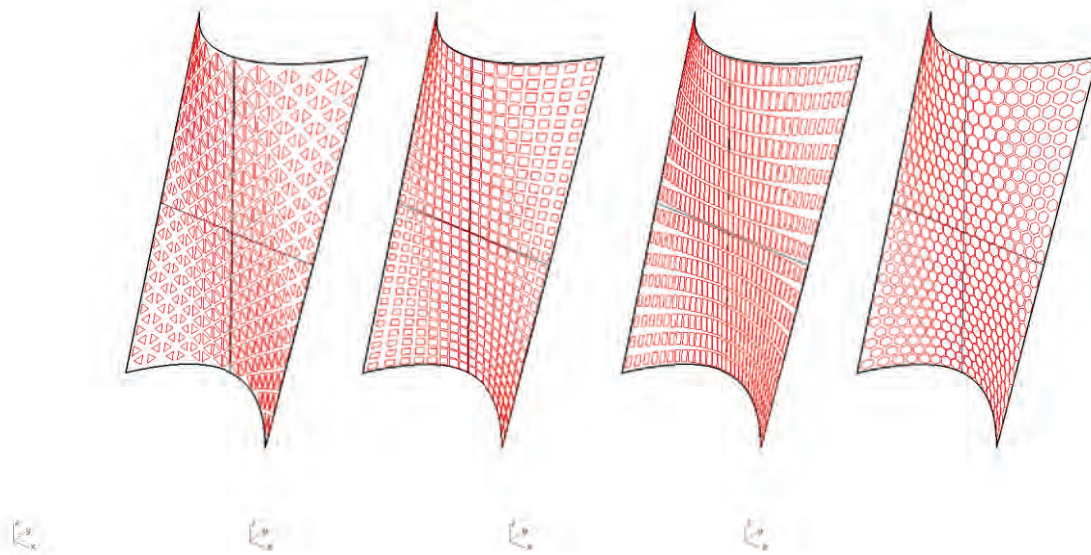Output: Custom Offset

Output: Offset Based on Irradiance Values

Figure 15. Visual Script. Resulting Geometries based on offsets from grid.

Month and Hour Parameters. Based on the set of values derived from the TMY3 data set analysis, the *month* slider component of the *Solar Control Visual Script* has a numerical domain from 4 to 10 corresponding to the array of months between April and October. Likewise, the *hour* slider component has a numerical domain from 10 to 16 corresponding to the hours in the day when shading is needed. By choosing a particular date and time from the two slider parameters, the solar path and solar vector are drawn automatically for that particular input data selection. *Figure 16* shows a visual sample of the solar path and the solar vector created on Rhino workspace for June 21 and December 21 at 2 p.m. Appendix D, Section 1 illustrates the overall portion of the *Solar Control Visual Script* that generates the Solar Path and Solar Vector.
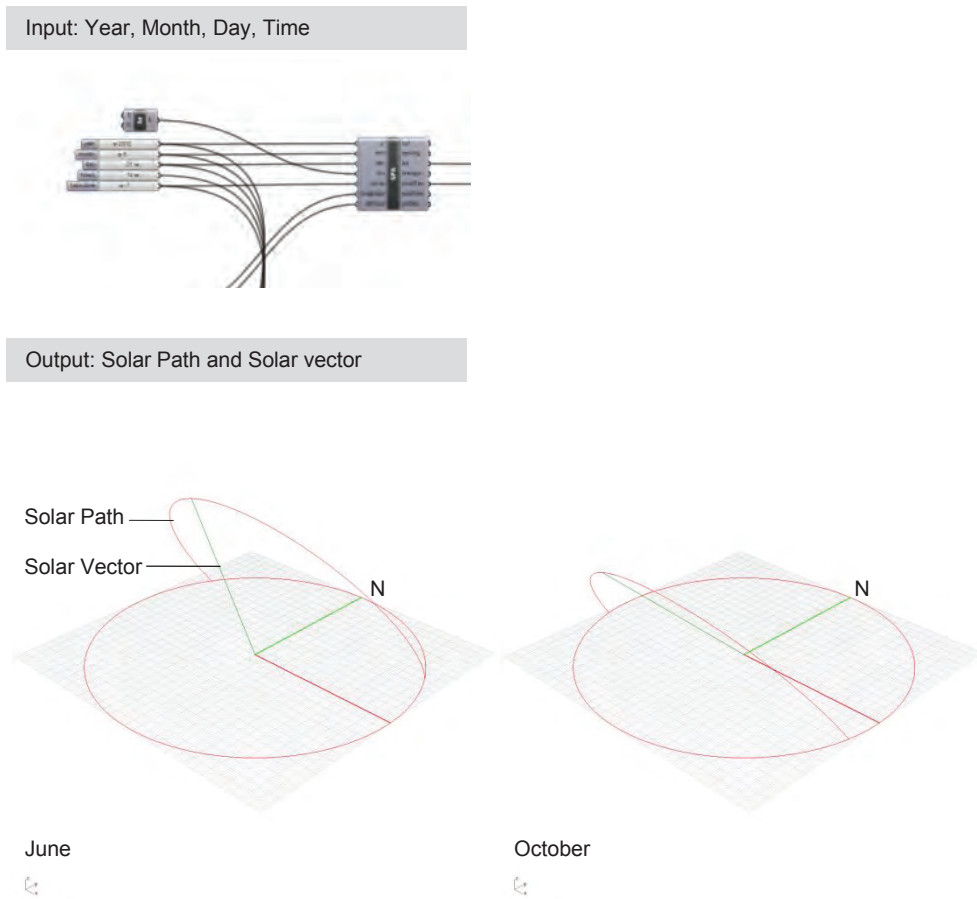
Figure 16. Visual Script. Sample of Solar Path and Solar Vector.

Solar Irradiance Value on Surface. The input values for solar GHI, DNI and

DHI from the Excel spreadsheet are plugged automatically into the Grasshopper

definition to calculate the Global Irradiance at all the sub-surfaces or assumed openings

of the selected surface. This portion of the *Solar Control Visual Script* outputs the

numerical irradiation values for all the sub-surfaces. These values are calculated in Btu/h-

ft^2. This portion of the script also displays a color gradient indicating the intensity of

irradiation values: Red for higher values and blue for lower values. *Figure 17* indicates

the output display for a grid pattern with no offsets and for a set of offsets on the

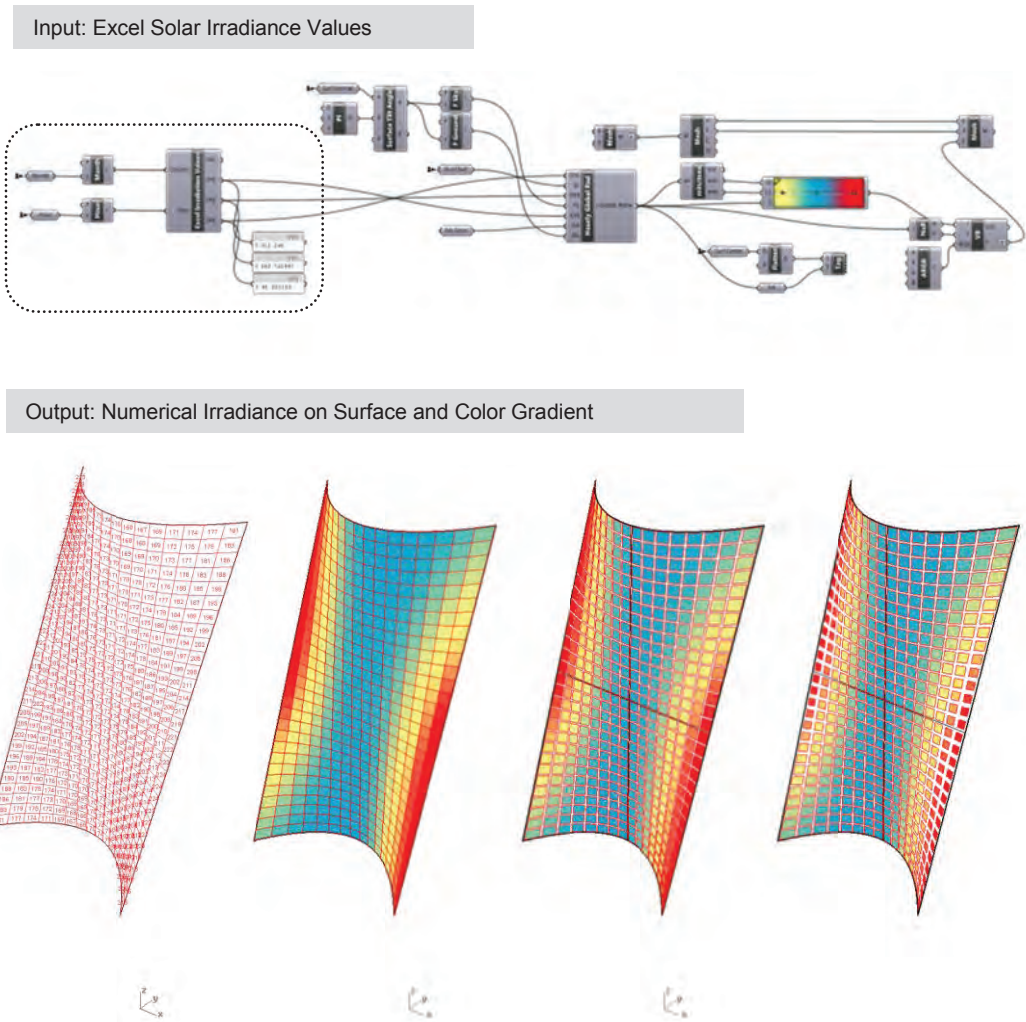geometry responding to the irradiation values on the surface at a particular month and

time.

Input: Excel Solar Irradiance Values

Output: Numerical Irradiance on Surface and Color Gradient

Figure 17. Visual Script Output. Solar irradiance values and color gradient display.

Sub-surfaces Analysis. The sub-surfaces, which represent the openings in the overall surface, are analyzed individually to determine the normal vector to the surface, solar surface azimuth, tilted angle and incidence angle. The output data for these parameters then becomes the input data for calculating the shading projection either as a horizontal plane, vertical plane or as an extrusion of the sub-surface's edge for the opening if this option is selected. The resulting geometries are shown

Figure 18 for April, July and October on the 21st day of the month at 2 p.m.; it corresponds to a scheme in which the sub-surfaces are determined by an offset from the grid pattern and which is based on the irradiance values that hit the sub-surfaces. Appendix D, Section 4 illustrates this portion of the *Solar Control Visual Script*.

Output: Extrusion of Openings for Shading

| April-2pm | July-2pm | October-2pm |
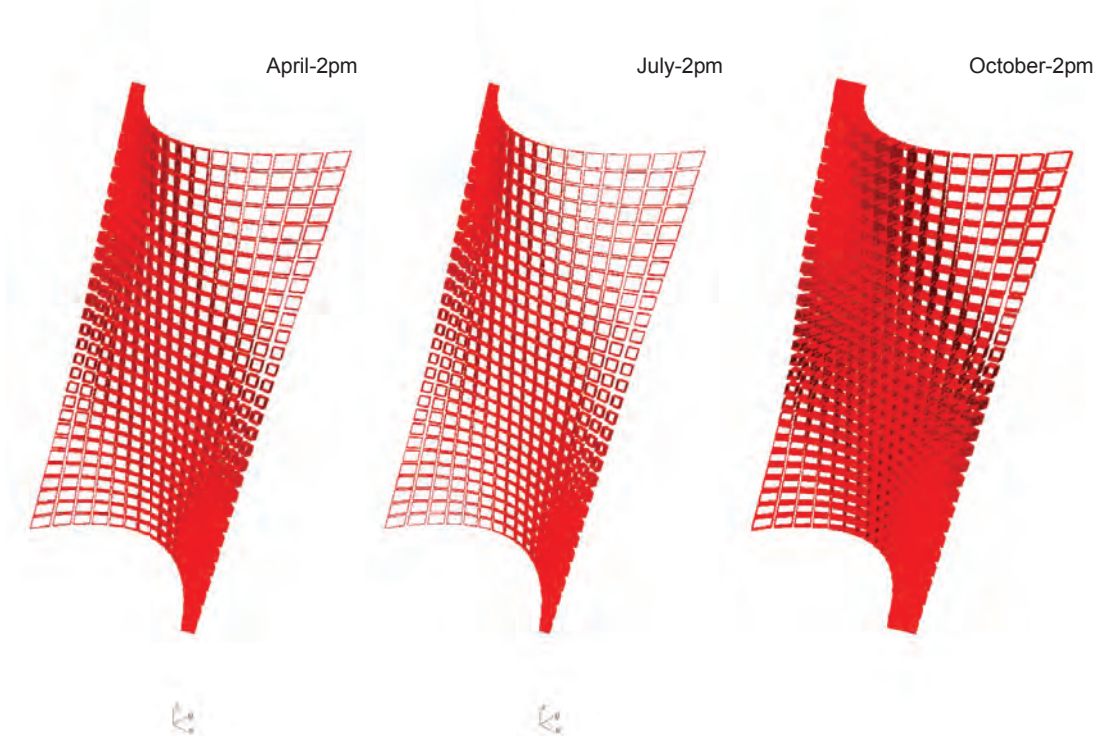
Figure 18. Visual Script Output. Analysis of surface's profile angles and generation of shading geometry.

Euclidean and Complex Geometries

The Solar Control Visual Definition has a variant to calculate surfaces that are based on the Euclidean planes. The previous definition described corresponds to NURBS geometries only.

Shading Systems: Fixed versus Dynamic

Fixed Shading Systems. Where sunscreens are fixed, they can become major, multifunctional architectural features. Because they result in articulation of the building façade, sunscreens also add diversity and richness to a building's appearance, as well as differentiation useful to orientation (Knowles, 1981, p.184).

Fixed façade elements for shading systems need to be designed responding to the particular building elevation in which they are placed. There is a great array of materials that can be utilized to provide fixed systems; among them are coated fabrics, concrete, wood, and steel. However, since the main topic for this thesis does not revolve around materiality, it will not be discussed further but it is important to mention that based upon the type of material chosen and the proximity to the building, the radiation coming from the system can affect the heat gain in the building.

The use of fixed elements for shading devices is a challenge when trying to respond to lower sun angles for East and West elevations, since they need to resolve direct radiation affecting not only the building envelope but also the working plane in which the building occupants perform their tasks. By resolving this, the designer can avoid high levels of glare that can be uncomfortable and affect productivity. One way to resolve this is to target sub-surfaces from the overall surface that relate to the visual plane of the occupants' work plane and respond with a specific design for these conditions responding to the lower solar angles.

Dynamic Shading Systems. The three architectural local buildings selected from the Phoenix Metro area: Burton Central Library, Tempe Transportation Center and Papago Park Center have received the attention of the local architectural community

because of their holistic focus on environmental design, energy efficiency and conservation. These projects illustrate the client or the architect's innate interest in incorporating a dynamic sun control system as part of the building envelope with the goal of not only reducing solar heat gain but also setting the lead on adopting available system technologies that respond mechanically to solar control.

Burton Barr Central Library. Built in 1995, this building provides shading devices for sun control and glare located on the North and South façades. The North façade has a fixed array system of external vertical fins, and it is just cited here as a reference. The South glazed façade was designed for a computer controlled horizontal perforated aluminum louver system. The design goal for this system was to improve solar control – heat and glare – during winter months. Due to improper functioning, however, this system on the South elevation was disconnected soon after the building was opened to the public (Brunette, 2011). Refer to Appendix E for overall building information.

Tempe Transportation Center. The Tempe Transportation Center was completed in 2008. It was originally designed to implement a mechanical Solar Veil Shading system for sun control 15 feet apart from the curtain wall glazing system in the southeast elevation, though, several months after the building was occupied the system stopped working properly. A replacement system was implemented in January 2012 with fully retractable aluminum horizontal louver modules that are controlled from the interior of the building. Refer to Appendix F for overall building information.

Papago Gateway Center. This building construction was completed in 2008. A major design feature of the building is the photo-sensitive operable louver system on the East, South and West exposures. The system's goal is to provide substantial motorized solar shades while ventilating and reducing glare on those façades. The devices are perforated aluminum louvers, designed with 27% openness. There are over 2000 individual louvers, which are organized in 200 banks of 10 louvers each. In the energy simulation performed during the design phase of the building, the expected reduction in

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the percentage of solar heat gain (SHG) was 80%, but this included other efficient

envelope items besides the louvers.

Prior to choosing the automatic system, the designers considered a fixed system

for exterior shading. However, due to the typology of the building and the client's desire

to have a strong statement in regard to sustainability and new technology, a dynamic

system prevailed over a fixed system. Refer to Appendix H for overall building

information.

Comparison of Systems. The type of exterior sun control system is an

important point to study for most buildings, in particular for those that are located in

extreme environments similar to Phoenix's climate and with clear sky predominance. The

implementation of a mechanical sun control system has to be studied precisely by

including an analysis of several items in relationship to the particular environment in

which the system will be placed:

1. Solar Geometry

2. Extreme Temperatures

3. Irradiance Levels

4. Relative Humidity

5. Wind Patterns

6. Dust Concentration on Air

7. System Materials

8. Appropriate Mechanisms

Most mechanically operated systems require a high level of maintenance,

making it a complicated task for the owner and maintenance operators of the building to

keep these systems functioning properly. The use of a combined passive system for

exterior shading and active solution in the interior for glare control can be an option. By

doing this, the active system is minimized only to target the building occupants' working

planes and view areas while the passive portion of the system serves to mitigate solar

heat gain over glazing façades. Table 12 illustrates the cost for two of the projects

mentioned in this section.

Table 12

Project's Shading Systems Cost Data

Building	Project Cost	Shading System Cost	Percentage from Total Cost
Burton Bar Central Library	$28M	$.35M	1.3%
Papago Gateway Center	$62M	$3 M	5%

CONCLUSIONS

The results of this research provide a path on how to facilitate the design of sun control elements in buildings in early stages of design by the use of visual scripting and weather data available to the designer.

Solar Control Hours

Based on the average hourly temperature and average hourly total irradiation from the weather data analysis and the constraints on temperature and irradiance values given (75°F and 200 Btu/hr-ft2, respectively), the period of time in which solar control for building envelopes located in Phoenix, Arizona applies is from April to October, from 10 a.m. to 4 p.m. For winter months it is acceptable to let sun radiation contribute to reduction of heating loads. However, it is important to note that future studies are needed to take into consideration the use of balance point temperatures and cooling degree days to further refine the number of solar control hours needed for Phoenix location. Another point to consider is that this study is restricted solely to the envelope and further steps need to be taken to set a framework and interact with a whole-building energy analysis.

By having parameters in the visual script associated with the Excel TMY3 data it is easy to adjust or modify a set of new targets for overheating periods and irradiance levels for alternative analysis. The study is set for climate conditions in Phoenix, Arizona; the flexibility of the script, however, can be easily set for another geographical location by changing the TMY3 file.

Visual Scripting

Grasshopper's platform design allows individuals with no previous computer coding training to explore programming-like capabilities and to discover new design possibilities within flexible and powerful frames that can contribute to the overall design that is being pursued and to resolve design problems.

The work-table that Grasshopper offers is transparent and very flexible. Because the user is able to visualize the definition as it continues developing, a debugging system can be created with the use of the note pads, and running tests can be done "on the go."

The use of parametric systems provides tools that can be applied in the early stages of design to analyze shading envelopes and provide responsive solutions. By using an associative design to manipulate geometries responding to climate data, the design exploration for shading devices can be optimized. The script is set to analyze geometries and execute the actions implemented in the visual script over the geometry. This setting makes it possible to exchange or modify the base geometry for new ones. The design process for shading devices is then streamlined. The designer has the opportunity to manipulate not only the time of the year and the day, but also to work in custom geometrical solutions by, for instance, retrieving vertical projections or edge openings projections.

Recently developed software tools under the Grasshopper interface facilitate the link to energy simulation under Rhinoceros. This additional plug-in software is DIVA Thermal and Daylight Analysis. The first one runs EnergyPlus software to generate thermal calculations and the second, DIVA Daylight, runs Daysim for evaluation of daylighting in interior spaces. This add-on contributes to the performance analysis of building geometries within the same software with no need to export the file to another software sources.

Software that is open source, such as Grasshopper, gives the design community an opportunity to participate actively and provide feedback to the program developers, thus permitting a constant evolution of the software with a grounded base in responding to user issues. It has led developers of other modeling software to implement similar visual scripting tools (e.g., Autodesk Vasari/Dynamo).

Efficiency of Systems

Climate-responsive-envelope design is critical in extreme climates, even in internal load dominated buildings in which internal sources of heat are the primary issues. Non-mechanical shading devices in building envelopes are more suitable for hot-arid climates than mechanical shading devices when the project budget might not permit the expense of a dynamic system.

Mechanically operated shading systems in any climate represent long-term high maintenance for building owners. The installation of these systems in hot-arid extreme climates can signify a challenge for the operating mechanisms within the system. For example, if systems are not concealed, dust in the air can contribute to deteriorate the efficiency and increase the maintenance of the mechanisms. These systems, however, have great benefits:

1. Algorithms and sensors can make this type of system very efficient.

2. Dynamic façades represent a platform for the advancement of technologies in building systems for architecture.

When the reduction of the solar heat gain on the building's envelope is accomplished, the cooling loads are reduced and then the adequate sizes for mechanical equipment can be set efficiently; thus the energy consumed by equipment will be less.

Aesthetic Factors

While this research looks into the application of parametric systems to achieve automated solutions for 100% fully shaded openings on a building's envelope with the goal of reducing energy, there is also an additional layer that is beyond this thesis work. That layer is the architecture's visual expression, which is instinctive from the use of geometrical patterns and provides vitality along the envelope and creates dynamism that brings a special character to the building.

In most cases, as result of the use of parametric design in the conceptualization of building envelopes, the systems that emerge from this process can provide variations of light and shade on the planes or curvature as well as visual richness. The task of designing efficient building envelopes does not to have to split from providing more formal expressions; shading devices, when they are integrated into the building envelope, can accomplish very dynamic aesthetic language.

Future Work

Future research work can include several subjects:

A new path of the study can result by analyzing solar control geometries for mid-rise buildings in response to solar envelopes and the effect of shading cast from surrounding buildings, a parallel work-frame based on Ralph Knowels' research work.

Under the subject of Daylighting, an analysis of the impact of shading geometries in interior spaces can be researched further, including device's material characteristics: reflectivity, absorption and transmittance. The analysis of fixed shading systems can be designed with the goal of providing a balance between access of daylight and reduction of heat gains in a building.

For Energy Modeling, a process for the modeling of complex shading geometries in energy simulation programs can be delineated. Also, a review of the capabilities other plug-ins as DIVA can be analyzed, as well as the flexibility for working among more robust software for whole building energy simulation.

Digital Fabrication has an important application in building design; the use of associative design, supported by environmental parametrics, material properties and mass customization is opening new ways of work in architecture. How could solar control and shade systems be designed to take advantage of the opportunities that digital fabrication brings? This is a good path for exploration, not only at the scale examined in this study in which the shading geometries were derived from the edges of the assumed openings, but also at a smaller scale. For instance, window screen designs and patterns can respond to solar parameters… "This newfound ability to generate construction information directly from design information…is what defines the most profound aspect of much of the contemporary architecture" (Kolarevic, 2003).

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APPENDIX A

DESIGN GUIDELINES FROM CLIMATE CONSULTANT FOR PHOENIX, AZ

DESIGN GUIDELINES FROM CLIMATE CONSULTANT FOR PHOENIX, AZ

       The following is the list of design guidelines that Climate Consultant recommends and that apply specifically to the climate of Phoenix, Arizona, starting with the most important first:

1. Window overhangs (designed for this latitude) or operable sunshades (that extend in summer, retract in winter) can reduce or eliminate air conditioning.

2. On hot days ceiling fans or indoor air motion can make it seem cooler by at least 5 degrees F (2.8C), thus less air conditioning is needed.

3. An evaporative cooler can provide most or all of the required cooling capacity (thus reducing or even eliminating the need for an air conditioner).

4. Minimize or eliminate west facing glazing to reduce summer and fall afternoon heat gain.

5. Traditional homes in hot dry climates used high mass construction with small well shaded openings operable for night ventilation to cool the mass.

6. For passive solar heating, face most of the glass area south to maximize winter sun exposure, but incorporate design overhangs to fully shade in summer.

7. Raising the indoor comfort temperature limit will reduce air conditioning energy consumption (raise thermostat cooling set-point).

8. Use light colored building materials and cool roofs (with high emissivity) to minimize conducted heat gain.

9. Good natural ventilation can reduce or eliminate air conditioning in warm weather if windows are well shaded and oriented to prevailing breezes.

10. Traditional homes in hot windy dry climates used enclosed well shaded courtyards, with a small fountain to provide wind-protected microclimates.

11. A radiant barrier (shiny foil) will help reduce radiated heat gain through the roof in hot climates.

12. Locate door and window openings on opposite sides of building to facilitate cross ventilation, with larger areas facing upwind if possible.

13. High Efficiency air conditioner (at least Energy Star) should prove cost effective.

14. In very hot dry climates, earth sheltering or occupied basements benefit from earth cooling in summer (it stays near average annual temperature).

15. A whole-house fan or natural ventilation can store nighttime 'coolth' in high mass interior surfaces, thus reducing or eliminating air conditioning.

16. Humidify hot dry air before it enters the building from enclosed outdoor spaces with spray-like fountains, misters, wet pavement, or cooling towers.

17. Locate garages or storage areas on the side of the building facing the coldest wind to help insulate.

18. Use plant materials (ivy, bushes and trees), especially on the west, to shade the structure (if summer rains support native plant growth).

19. Heat gain from equipment, lights, and occupants will greatly reduce heating needs so keep home tight and well insulated (use ventilation in summer).

20. Keep the building small (right-sized) because excessive floor area wastes heating and cooling energy.

APPENDIX B

VB.NET SCRIPTS FOR SOLAR INCIDENCE COMPONETS IN GRASSHOPPER

DEFINITION BY TED NGAI

VB.NET SCRIPTS FOR SOLAR INCIDENCE COMPONETS IN GRASSHOPPER DEFINITION BY TED NGAI

The Solar Insolation Grasshopper (GH) definition by Ted nGai includes several VB.NET components that allow crucial calculations for solar profile angles and solar irradiance values. This GH definition with the appropriate modifications was the base ground for the *Solar Control Visual Script* work. In *Figure 1* the tagged numbers correspond to each VB.NET component included in the definition and which scripts are shown below. This work was developed by Ted nGAi in 2009.
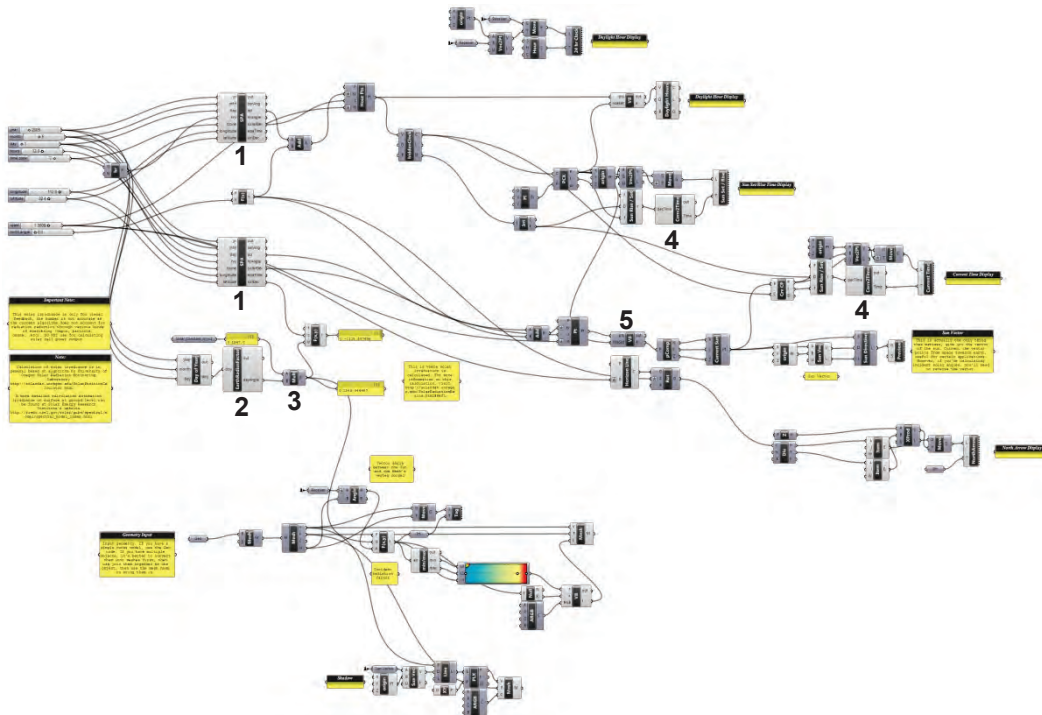

Figure 1. Grasshopper definition for solar insolation.

1. Solar Profile Angle (SPA)

```
Private Sub RunScript(ByVal yr As Double, ByVal mth As Double, ByVal day As Double,
ByVal hrs As Double, ByVal tzone As Double, ByVal longitude As Double, ByVal latitude
As Double, ByRef zenAng As Object, ByRef azi As Object, ByRef hrAngle As Object,
ByRef solarElev As Object, ByRef eqaTime As Object, ByRef solDec As Object)
  ' The Solar Position algorithm is based on National Oceanic and Atmospheric
Administration's Solar Position Calculator
http://www.srrb.noaa.gov/highlights/sunrise/azel.html
  'Code is ported into vb.net and integrated into Grasshopper by Ted Ngai Jan 30, 2009
www.tedngai.net

  Dim hourAngle, haRad, csz, zenith, azDenom As Double
  Dim azRad, azimuth, exoatmElevation, refractionCorrection, te As Double
  Dim solarZen, elevation, coszen As Double

  'timenow is GMT time for calculation
```

```
    Dim timenow As Double = hrs - tzone
    longitude = longitude * -1

    Dim JD As Double = calcJD(yr, mth, day)
    Dim T As Double = calcTimeJulianCent(JD + timenow / 24.0)
    Dim R As Double = calcSunRadVector(T)
    Dim alpha As Double = calcSunRtAscension(T)
    Dim theta As Double = calcSunDeclination(T)
    Dim Etime As Double = calcEquationOfTime(T)
    'Dim theta As Double = calcGeomMeanLongSun(T)

    Dim eqTime As Double = Etime
    Dim solarDec As Double = theta
    Dim earthRadVec As Double = R

    Dim solarTimeFix As Double = eqTime - 4.0 * longitude + 60.0 * -tzone
    Dim trueSolarTime As Double = hrs * 60 + solarTimeFix

    While trueSolarTime > 1440
      trueSolarTime -= 1440
    End While

    hourAngle = trueSolarTime / 4.0 - 180.0
    If hourAngle < -180 Then
      hourAngle = hourAngle + 360
    End If

    haRad = degToRad(hourAngle)

    csz = Math.sin(degToRad(latitude)) * Math.sin(degToRad(solarDec)) +
Math.cos(degToRad(latitude)) * Math.cos(degToRad(solarDec)) * Math.cos(haRad)
    If csz > 1.0 Then
      csz = 1.0
    ElseIf csz < -1.0 Then
      csz = -1
    End If

    zenith = radToDeg(Math.acos(csz))
    azDenom = (Math.cos(degToRad(latitude)) * Math.sin(degToRad(zenith)))

    If Math.abs(azDenom) > 0.001 Then

      azRad = ((Math.sin(degToRad(latitude)) * Math.cos(degToRad(zenith))) -
Math.sin(degToRad(solarDec))) / azDenom
      If Math.abs(azRad) > 1.0 Then
        If azRad < 0 Then
          azRad = -1.0
        Else
          azRad = 1.0
        End If
      End If

      azimuth = 180.0 - radToDeg(Math.acos(azRad))
      If hourAngle > 0.0 Then
        azimuth = -azimuth
```

```vb
      End If
    Else
      If latitude > 0.0 Then
        azimuth = 180.0
      Else
        azimuth = 0.0
      End If
    End If

    If azimuth < 0.0 Then
      azimuth = azimuth + 360
    End If

    exoatmElevation = 90.0 - zenith
    If exoatmElevation > 85.0 Then
      refractionCorrection = 0.0
    Else
      te = Math.tan(degToRad(exoatmElevation))
      If exoatmElevation > 5.0 Then
        refractionCorrection = 58.1 / te - 0.07 / (te * te * te) + 0.000086 / (te * te * te * te * te)
      ElseIf exoatmElevation > -0.575 Then
        refractionCorrection = 1735.0 + exoatmElevation * (-518.2 + exoatmElevation *
(103.4 + exoatmElevation * (-12.79 + exoatmElevation * 0.711)))
      Else
        refractionCorrection = -20.774 / te
      End If
      refractionCorrection = refractionCorrection / 3600.0
    End If

    solarZen = zenith - refractionCorrection
    elevation = (Math.floor(100 * (90.0 - solarZen))) / 100
    If solarZen < 108.0 Then
      azimuth = (Math.floor(100 * azimuth)) / 100

      If solarZen < 90.0 Then
        coszen = (Math.floor(10000.0 * (Math.cos(degToRad(solarZen))))) / 10000.0
      Else
        coszen = 0.0
      End If
    End If

    zenAng = coszen
    azi = degToRad(azimuth)
    hrAngle = hourAngle
    solarElev = degToRad(elevation)
    eqaTime = eqTime
    solDec = solarDec

    ''' </your code>
  End Sub

'<Custom additional code>

'Basic Functions
'-------------------------------------
```

```vbnet
'Convert radian angle to degrees
Function radTodeg(ByVal angleRad)
  radTodeg = (180.0 * angleRad / Math.Pi)
End Function
Function degToRad(ByVal angleDeg)
  degToRad = Math.Pi * angleDeg / 180.0
End Function
'Purpose: Julian day from calendar day
'Arguments:
'year : 4 digit year
'month : January = 1
'day : 1-31
'Return value: The Julian day corresponding to the date
'Note: Number is returned for start of day. Fractional days should be added later.
Function calcJD(ByVal yr, ByVal mth, ByVal day)
  If mth <= 2 Then
    yr = yr - 1
    mth = mth + 12
  End If
  Dim A As Double = Math.Floor(yr / 100)
  Dim B As Double = 2 - A + Math.floor(A / 4)
  Dim JD As Double = Math.floor(365.25 * (yr + 4716)) + Math.floor(30.6001 * (mth + 1))
+ day + B - 1524.5
  calcJD = JD
End Function
'Purpose: convert Julian Day to centuries since J2000.0
'Arguments: jd - the Julian Day to convert
'Return value: the T value corresponding to the Julian Day
Function calcTimeJulianCent(ByVal jd)
  Dim T As Double = (jd - 2451545.0) / 36525.0
  calcTimeJulianCent = T
End Function

'Functions to calculate Rad Vector
'-------------------------------
'Purpose: calculate the Geometric Mean Longitude of the Sun
'Arguments: t - number of Julian centuries since J2000.0
'Return value: the Geometric Mean Longitude of the Sun in degrees
Function calcGeomMeanLongSun(ByVal t)
  Dim LO As Double = 280.46646 + t * (36000.76983 + 0.0003032 * t)
  While LO > 360.0
    LO -= 360.0
  End While
  While LO < 0.0
    LO += 360
  End While
  calcGeomMeanLongSun = LO
End Function
'Purpose: calculate the Geometric Mean Anomaly of the Sun
'Arguments: t - number of Julian centuries since J2000.0
'Return value: the Geometric Mean Anomaly of the Sun in degrees
Function calcGeomMeanAnomalySun(ByVal t)
  Dim M As Double = 357.52911 + t * (35999.05029 - 0.0001537 * t)
  calcGeomMeanAnomalySun = M
End Function
```
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```
'Purpose: calculate the eccentricity of earth's orbit
'Arguments: t - number of Julian centuries since J2000.0
'Return value: the unitless eccentricity
Function calcEccentricityEarthOrbit(ByVal t)
  Dim e As Double = 0.016708634 - t * (0.000042037 + 0.0000001267 * t)
  calcEccentricityEarthOrbit = e
End Function
'Purpose: calculate the equation of center for the sun
'Arguments: t : number of Julian centuries since J2000.0
'Return value: in degrees
Function calcSunEqOfCenter(ByVal t)
  Dim m As Double = calcGeomMeanAnomalySun(t)
  Dim mrad As Double = degToRad(m)
  Dim sinm As Double = Math.Sin(mrad)
  Dim sin2m As Double = Math.Sin(mrad + mrad)
  Dim sin3m As Double = Math.Sin(mrad + mrad + mrad)

  Dim C = sinm * (1.914602 - t * (0.004817 + 0.000014 + t)) + sin2m * (0.019993 -
0.000101 * t) + sin3m * 0.000289
  calcSunEqOfCenter = C
End Function
'Purpose: calculate the true longitude of the sun
'Arguments: t : number of Julian centuries since J2000.0
'Return value: sun's true longitude in degrees
Function calcSunTrueLong(ByVal t)
  Dim lo As Double = calcGeomMeanLongSun(t)
  Dim c As Double = calcSunEqOfCenter(t)
  Dim O As Double = lo + c
  calcSunTrueLong = O
End Function
'Purpose: calculate the true anamoly of the sun
'Arguments: t : number of Julian centuries since J2000.0
'Return value: sun's true anamoly in degrees
Function calcSunTrueAnomaly(ByVal t)
  Dim m As Double = calcGeomMeanAnomalySun(t)
  Dim c As Double = calcSunEqOfCenter(t)
  Dim v As Double = m + c
  calcSunTrueAnomaly = v
End Function
'Purpose: calculate the distance to the sun in AU
'Arguments: t : number of Julian centuries since J2000.0
'Return value: sun radius vector in AUs
Function calcSunRadVector(ByVal t)
  Dim v As Double = calcSunTrueAnomaly(t)
  Dim e As Double = calcEccentricityEarthOrbit(t)
  Dim R As Double = (1.000001018 * (1 - e * e)) / (1 + e * Math.cos(degToRad(v)))
  calcSunRadVector = R
End Function

'Functions to calculate Ascension
'---------------------------------------------
'Purpose: calculate the apparent longitude of the sun
'Arguments: t : number of Julian centuries since J2000.0
'Return value: sun's apparent longitude in degrees
Function calcSunApparentLong(ByVal t)
```

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```vbnet
  Dim o As Double = calcSunTrueLong(t)
  Dim omega As Double = 125.04 - 1934.136 * t
  Dim lambda As Double = o - 0.00569 - 0.00478 * Math.sin(degToRad(omega))
  calcSunApparentLong = lambda
End Function
'Purpose: calculate the mean obliquity of the ecliptic
'Arguments: t : number of Julian centuries since J2000.
'Return value: mean obliquity in degrees
Function calcMeanObliquityOfEcliptic(ByVal t)
  Dim seconds As Double = 21.448 - t * (46.815 + t * (0.00059 - t * (0.001813)))
  Dim eO As Double = 23.0 + (26.0 + (seconds / 60.0)) / 60.0
  calcMeanObliquityOfEcliptic = eO
End Function
'Purpose: calculate the corrected obliquity of the ecliptic
'Arguments: t : number of Julian centuries since J2000.0
'Return value: corrected obliquity in degrees
Function calcObliquityCorrection(ByVal t)
  Dim eO As Double = calcMeanObliquityOfEcliptic(t)
  Dim omega As Double = 125.04 - 1934.136 * t
  Dim e = eO + 0.00256 * Math.cos(degToRad(omega))
  calcObliquityCorrection = e
End Function
'Purpose: calculate the right ascension of the sun
'Arguments: t : number of Julian centuries since J2000.0
'Return value: sun's right ascension in degrees
Function calcSunRtAscension(ByVal t)
  Dim e As Double = calcObliquityCorrection(t)
  Dim lambda As Double = calcSunApparentLong(t)
  Dim tananum As Double = (Math.cos(degToRad(e)) * Math.sin(degToRad(lambda)))
  Dim tanadenom As Double = (Math.cos(degToRad(lambda)))
  Dim alpha As Double = radToDeg(Math.atan2(tananum, tanadenom))
  calcSunRtAscension = alpha
End Function


'--------------------------------------
'Purpose: calculate the declination of the sun
'Arguments: t : number of Julian centuries since J2000.0
'Return value: sun's declination in degrees
Function calcSunDeclination(ByVal t)
  Dim e As Double = calcObliquityCorrection(t)
  Dim lambda As Double = calcSunApparentLong(t)
  Dim sint As Double = Math.sin(degToRad(e)) * Math.sin(degToRad(lambda))
  Dim theta As Double = radToDeg(Math.asin(sint))
  calcSunDeclination = theta
End Function


'--------------------------------
'Calculate the difference between true solar time and mean solar time
'Arguments: t : number of Julian centuries since J2000.0
'Return value: equation of time in minutes of time
Function calcEquationOfTime(ByVal t)
  Dim epsilon As Double = calcObliquityCorrection(t)
  Dim lo As Double = calcGeomMeanLongSun(t)
```

```
    Dim e As Double = calcEccentricityEarthOrbit(t)
    Dim m As Double = calcGeomMeanAnomalySun(t)
    Dim y As Double = Math.tan(degToRad(epsilon) / 2.0)
    y = y * y
    Dim sin2lo As Double = Math.sin(2.0 * degToRad(lo))
    Dim sinm As Double = Math.sin(degToRad(m))
    Dim cos2lo As Double = Math.cos(2.0 * degToRad(lo))
    Dim sin4lo As Double = Math.sin(4.0 * degToRad(lo))
    Dim sin2m As Double = Math.sin(2.0 * degToRad(m))

    Dim Etime As Double = y * sin2lo - 2.0 * e * sinm + 4.0 * e * y * sinm * cos2lo - 0.5 * y
* y * sin4lo - 1.25 * e * e * sin2m
    calcEquationOfTime = radToDeg(Etime) * 4.0
  End Function


  '---------------------------------------
  'Return the hour angle for the given location, decl, and time of day
  Function calcHourAngle(ByVal time, ByVal longitude, ByVal eqtime)
    calcHourAngle = 15.0 * (time - (longitude / 15.0) - (eqtime / 60.0))
  End Function


  '------------------------------
  '</Custom additional code>

End Class
```

2. Day of the year (DOY)

```
  Private Sub RunScript(ByVal year As Integer, ByVal month As Integer, ByVal day As
Integer, ByRef doy As Object)
    '''
    '''
algorithm based on OnlineConversion.com
http://www.onlineconversion.com/day_week_number.htm
    Dim accumulateNY() As Integer = {0, 31, 59, 90,120,151,181,212,243,273,304,334}
    Dim accumulateLY() As Integer = {0, 31, 60, 91,121,152,182,213,244,274,305,335}
    month = month - 1

    If year Mod 4 = 0 And year Mod 100 <> 0 Or year Mod 400 = 0 Then
      doy = day + accumulateLY(month)
    Else
      doy = day + accumulateNY(month)
    End If

    ''' </your code>
  End Sub

  '<Custom additional code>

  '</Custom additional code>

End Class
```

3. Earth Radius Factor

```
Private Sub RunScript(ByVal doy As Double, ByRef dayAngle As Object)
    ''' equation based on algorithm published in National Renewable Energy Laboratory
(NREL)
    ''' http://rredc.nrel.gov/solar/pubs/spectral/model/section2.html

    Dim D As Double = 2 * Math.Pi * (doy - 1 ) / 365
    dayAngle = 1.00011 + (0.034221 * Math.Cos(D)) + (0.00128 * Math.Sin(D)) +
(0.000719 * Math.Cos(2 * D)) + (0.000077 * Math.Sin(2 * D))

    ''' </your code>

  End Sub

  '<Custom additional code>

  '</Custom additional code>

End Class
```

4. Conversion of Time

```
  Private Sub RunScript(ByVal decTime As Double, ByRef Time As Object)
    ''' <your code>
    Dim A, DT, M, S As Double
    Dim H As Integer
    H = Math.Floor(decTime)
    DT = decTime - H
    A = DT * 3600
    M = (A Mod 3600) / 60
    S = (((M - Math.Floor(M)) * 3600) Mod 3600) / 60
    H = Math.Floor(H)
    M = Math.Floor(M)
    S = Math.Floor(S)
    Dim allStr() As String = New String(){H,M,S}
    Time = String.Join(":", allStr)
    ''' </your code>
  End Sub

  '<Custom additional code>

  '</Custom additional code>

End Class
```

5. Sun Vector Start Point

```vb
  Private Sub RunScript(ByVal pts As List(Of On3dPoint), ByVal riseSet As List(Of
On3dPoint), ByRef A As Object)
    ''' <your code>
    Dim i As Integer
    Dim newPtArray As New List(Of On3dPoint)
    Dim tempPtArray As On3dPoint

    newPtArray.Add(riseSet(0))
    For i = 0 To pts.Count - 1
      tempPtArray = pts(i)
      If tempPtArray.IsValid Then
        If tempPtArray.z > 0 Then
          newPtArray.Add(tempPtArray)
        End If
      End If

    Next
    newPtArray.Add(riseSet(1))
    A = newPtArray

    ''' </your code>
  End Sub

  '<Custom additional code>

  '</Custom additional code>

End Class
```

APPENDIX C

TMY3 DATA SET EXCEL PIVOT TABLE FOR HOURLY AVERAGE FOR

TEMPERATURE AND IRRADIANCE VALUES PER MONTH

TMY3 DATA SET

722780 PHOENIX SKY HARBOR INTL AP, AZ   -7   33.45   -111.983

Row Labels	Values Sum of GHI (W/m^2)	Sum of DNI (W/m^2)	Sum of DHI (W/m^2)	Sum of Dry-bulb (C)	Sum of RHum (%)
7/1/1988	873	537	357	40.6	17
2:00:00 PM	873	537	357	40.6	17
7/2/1988	1027	910	155	42.8	12
2:00:00 PM	1027	910	155	42.8	12
7/3/1988	1011	896	150	40.6	14
2:00:00 PM	1011	896	150	40.6	14
7/4/1988	1032	914	154	40.6	12
2:00:00 PM	1032	914	154	40.6	12
7/5/1988	1021	901	156	42.2	15
2:00:00 PM	1021	901	156	42.2	15
7/6/1988	854	561	314	41.7	13
2:00:00 PM	854	561	314	41.7	13
7/7/1988	1036	806	263	40.6	23
2:00:00 PM	1036	806	263	40.6	23
7/8/1988	995	842	188	41.7	19
2:00:00 PM	995	842	188	41.7	19
7/9/1988	1008	873	171	41.7	20
2:00:00 PM	1008	873	171	41.7	20
7/10/1988	1007	884	158	40	22
2:00:00 PM	1007	884	158	40	22
7/11/1988	1000	863	174	36.7	27
2:00:00 PM	1000	863	174	36.7	27
7/12/1988	1045	897	187	41.1	13
2:00:00 PM	1045	897	187	41.1	13
7/13/1988	584	108	481	42.2	8
2:00:00 PM	584	108	481	42.2	8
7/14/1988	1009	886	162	42.8	10
2:00:00 PM	1009	886	162	42.8	10
7/15/1988	986	838	185	43.3	10
2:00:00 PM	986	838	185	43.3	10
7/16/1988	1022	886	175	43.3	10
2:00:00 PM	1022	886	175	43.3	10
7/17/1988	787	308	493	40	23
2:00:00 PM	787	308	493	40	23
7/18/1988	801	170	640	37.2	31
2:00:00 PM	801	170	640	37.2	31
7/19/1988	899	625	303	38.9	30
2:00:00 PM	899	625	303	38.9	30
7/20/1988	975	738	272	39.4	25
2:00:00 PM	975	738	272	39.4	25
7/21/1988	928	731	232	40.6	23
2:00:00 PM	928	731	232	40.6	23
7/22/1988	1004	889	157	42.2	16
2:00:00 PM	1004	889	157	42.2	16
7/23/1988	996	864	173	41.7	21
2:00:00 PM	996	864	173	41.7	21
7/24/1988	1004	866	181	41.1	24

2:00:00 PM	1004	866	181	41.1	24
7/25/1988	**980**	**821**	**199**	**41.1**	**24**
2:00:00 PM	980	821	199	41.1	24
7/26/1988	**996**	**837**	**203**	**40**	**20**
2:00:00 PM	996	837	203	40	20
7/27/1988	**989**	**840**	**192**	**40**	**24**
2:00:00 PM	989	840	192	40	24
7/28/1988	**778**	**578**	**231**	**38.3**	**28**
2:00:00 PM	778	578	231	38.3	28
7/29/1988	**969**	**840**	**173**	**39.4**	**28**
2:00:00 PM	969	840	173	39.4	28
7/30/1988	**853**	**503**	**378**	**34.4**	**39**
2:00:00 PM	853	503	378	34.4	39
7/31/1988	**773**	**266**	**523**	**35**	**40**
2:00:00 PM	773	266	523	35	40
Grand Total	**29242**	**22478**	**7780**	**1251.2**	**641**
Average	**943.29**	**725.10**	**250.97**	**40.36**	**20.68**

72

TMY3 Average Hourly Data

Time	GHI (W/m^2)	DNI (W/m^2)	DHI (W/m^2)	Dry-bulb ©	Dew-point (C)
			JULY		
1:00 AM	0.00	0.00	0.00	32.86	34.77
2:00 AM	0.00	0.00	0.00	32.01	36.65
3:00 AM	0.00	0.00	0.00	31.30	38.23
4:00 AM	0.00	0.00	0.00	30.51	40.58
5:00 AM	0.00	0.00	0.00	30.14	42.26
6:00 AM	10.03	28.19	7.16	29.89	42.48
7:00 AM	100.77	240.19	55.45	30.50	41.10
8:00 AM	271.06	440.42	102.26	31.90	37.45
9:00 AM	451.23	507.26	162.26	33.75	33.35
10:00 AM	651.32	608.58	204.35	35.40	29.94
11:00 AM	816.45	691.77	220.42	36.95	26.71
12:00 PM	940.52	737.10	243.87	38.38	24.19
1:00 PM	962.42	715.68	261.58	39.39	22.45
2:00 PM	943.29	725.10	250.97	40.36	20.68
3:00 PM	851.32	711.55	223.35	41.00	19.48
4:00 PM	729.48	720.45	179.77	41.44	18.97
5:00 PM	508.61	596.58	139.81	41.16	18.90
6:00 PM	269.90	431.77	85.61	39.97	21.39
7:00 PM	99.26	163.45	62.35	38.85	22.29
8:00 PM	10.16	24.19	7.61	37.62	24.26
9:00 PM	0.00	0.00	0.00	35.47	28.87
10:00 PM	0.00	0.00	0.00	35.63	28.00
11:00 PM	0.00	0.00	0.00	34.39	31.65
12:00 AM	0.00	0.00	0.00	33.82	33.65
			AUGUST		
1:00 AM	0.00	0.00	0.00	31.26	35.68
2:00 AM	0.00	0.00	0.00	30.34	37.77
3:00 AM	0.00	0.00	0.00	29.86	39.42
4:00 AM	0.00	0.00	0.00	29.08	42.39
5:00 AM	0.00	0.00	0.00	28.49	44.03
6:00 AM	0.13	0.97	0.06	28.05	45.39
7:00 AM	57.87	209.87	31.84	28.22	45.13
8:00 AM	227.39	466.16	73.94	29.88	41.29
9:00 AM	434.55	593.16	122.90	31.83	36.45
10:00 AM	635.19	659.90	176.68	33.69	32.03
11:00 AM	777.32	665.42	228.48	35.18	29.19
12:00 PM	897.48	738.23	226.35	36.47	26.39
1:00 PM	947.19	746.16	247.26	37.45	24.35
2:00 PM	912.42	736.23	240.94	38.29	23.23
3:00 PM	786.16	693.32	208.35	38.72	22.87
4:00 PM	659.13	691.52	169.23	39.07	21.71
5:00 PM	468.68	642.45	119.16	39.16	21.29
6:00 PM	256.84	502.55	81.68	38.89	21.19
7:00 PM	66.45	201.10	37.84	37.81	22.68
8:00 PM	0.29	1.06	0.19	36.47	23.94
9:00 PM	0.00	0.00	0.00	35.07	26.61
10:00 PM	0.00	0.00	0.00	33.65	29.74
11:00 PM	0.00	0.00	0.00	32.83	31.32
12:00 AM	0.00	0.00	0.00	31.92	33.65

SEPTEMBER

Time					
1:00 AM	0.00	0.00	0.00	27.55	34.73
2:00 AM	0.00	0.00	0.00	26.94	35.57
3:00 AM	0.00	0.00	0.00	26.21	37.50
4:00 AM	0.00	0.00	0.00	25.56	38.80
5:00 AM	0.00	0.00	0.00	24.87	40.97
6:00 AM	0.00	0.00	0.00	24.59	42.03
7:00 AM	40.30	117.10	27.40	24.71	40.97
8:00 AM	192.67	430.73	77.17	26.23	37.00
9:00 AM	403.90	619.33	115.27	28.31	33.33
10:00 AM	598.27	706.80	149.27	30.30	29.87
11:00 AM	746.83	766.37	162.57	32.11	27.03
12:00 PM	837.00	773.97	187.90	33.61	23.70
1:00 PM	884.00	813.07	184.33	34.96	21.23
2:00 PM	826.13	776.47	185.57	35.90	19.30
3:00 PM	726.27	759.63	167.10	36.49	18.37
4:00 PM	562.83	703.10	141.07	36.44	18.27
5:00 PM	345.53	573.13	101.97	35.82	19.07
6:00 PM	150.67	391.13	62.40	35.10	20.27
7:00 PM	25.80	64.27	18.23	33.51	22.17
8:00 PM	0.00	0.00	0.00	32.13	25.27
9:00 PM	0.00	0.00	0.00	30.74	28.57
10:00 PM	0.00	0.00	0.00	29.98	29.97
11:00 PM	0.00	0.00	0.00	29.03	32.10
12:00 AM	0.00	0.00	0.00	28.13	33.57

OCTOBER

Time					
1:00 AM	0.00	0.00	0.00	22.03	40.39
2:00 AM	0.00	0.00	0.00	21.18	42.13
3:00 AM	0.00	0.00	0.00	20.47	44.35
4:00 AM	0.00	0.00	0.00	19.74	45.84
5:00 AM	0.00	0.00	0.00	19.28	46.87
6:00 AM	0.00	0.00	0.00	18.98	46.35
7:00 AM	12.48	69.77	4.48	18.84	47.00
8:00 AM	132.52	436.81	49.39	20.55	42.65
9:00 AM	305.81	615.94	71.71	22.92	37.19
10:00 AM	484.68	691.74	110.74	25.08	32.84
11:00 AM	630.58	725.94	153.65	27.23	28.45
12:00 PM	702.81	741.61	165.26	28.81	25.90
1:00 PM	721.10	756.61	162.00	30.07	24.35
2:00 PM	674.94	741.84	159.03	30.99	22.32
3:00 PM	546.58	663.32	147.94	31.35	21.74
4:00 PM	390.87	481.68	169.61	30.93	23.81
5:00 PM	191.52	449.94	64.90	30.18	24.77
6:00 PM	28.90	138.23	12.65	28.59	26.97
7:00 PM	0.03	0.32	0.03	27.19	30.00
8:00 PM	0.00	0.00	0.00	25.90	32.65
9:00 PM	0.00	0.00	0.00	24.93	34.26
10:00 PM	0.00	0.00	0.00	24.06	36.06
11:00 PM	0.00	0.00	0.00	23.43	37.16
12:00 AM	0.00	0.00	0.00	22.71	38.03

NOVEMBER					
1:00 AM	0.00	0.00	0.00	15.38	44.23
2:00 AM	0.00	0.00	0.00	14.66	46.17
3:00 AM	0.00	0.00	0.00	14.11	47.70
4:00 AM	0.00	0.00	0.00	13.50	48.87
5:00 AM	0.00	0.00	0.00	13.14	50.00
6:00 AM	0.00	0.00	0.00	12.72	52.07
7:00 AM	1.47	4.13	0.70	12.53	52.43
8:00 AM	56.60	246.07	29.70	13.37	49.63
9:00 AM	216.33	561.03	64.10	15.71	42.77
10:00 AM	387.93	677.20	99.43	18.06	37.27
11:00 AM	511.70	729.50	118.00	20.04	32.40
12:00 PM	574.63	732.63	131.33	21.59	28.93
1:00 PM	598.50	740.70	141.30	22.82	26.60
2:00 PM	556.63	737.13	132.23	23.52	25.80
3:00 PM	449.63	693.80	114.70	24.18	24.33
4:00 PM	287.40	580.03	86.87	24.08	23.87
5:00 PM	113.40	377.97	47.50	23.33	25.17
6:00 PM	18.50	61.40	11.37	21.51	28.10
7:00 PM	0.00	0.00	0.00	20.24	31.27
8:00 PM	0.00	0.00	0.00	18.83	34.33
9:00 PM	0.00	0.00	0.00	17.95	37.03
10:00 PM	0.00	0.00	0.00	17.24	39.00
11:00 PM	0.00	0.00	0.00	16.51	40.27
12:00 AM	0.00	0.00	0.00	15.79	42.00
DECEMBER					
1:00 AM	0.00	0.00	0.00	9.58	58.13
2:00 AM	0.00	0.00	0.00	8.99	60.29
3:00 AM	0.00	0.00	0.00	8.64	61.16
4:00 AM	0.00	0.00	0.00	8.06	63.81
5:00 AM	0.00	0.00	0.00	7.62	66.10
6:00 AM	0.00	0.00	0.00	7.41	66.10
7:00 AM	0.00	0.00	0.00	7.09	67.16
8:00 AM	3.26	83.03	1.45	7.40	66.29
9:00 AM	123.61	434.19	41.74	9.18	57.87
10:00 AM	271.97	572.29	75.39	11.02	49.77
11:00 AM	401.19	654.42	99.94	12.85	44.45
12:00 PM	474.58	682.77	111.39	14.27	39.97
1:00 PM	488.16	662.97	121.97	15.50	36.19
2:00 PM	486.13	689.48	127.00	16.42	34.10
3:00 PM	386.71	627.84	110.97	17.02	32.00
4:00 PM	282.00	575.52	102.00	17.20	31.52
5:00 PM	152.42	464.74	81.97	16.63	33.06
6:00 PM	0.00	0.00	0.00	15.29	37.94
7:00 PM	0.00	0.00	0.00	13.99	44.13
8:00 PM	0.00	0.00	0.00	12.78	49.00
9:00 PM	0.00	0.00	0.00	12.20	50.35
10:00 PM	0.00	0.00	0.00	11.37	51.35
11:00 PM	0.00	0.00	0.00	10.67	53.74
12:00 AM	0.00	0.00	0.00	9.98	57.42

APPENDIX D

SOLAR CONTROL VISUAL DEFINITION (GRASSHOPPER)
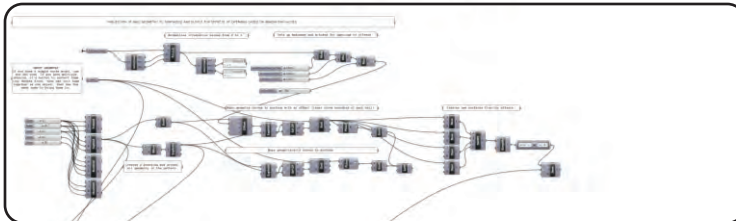
SOLAR CONTROL VS
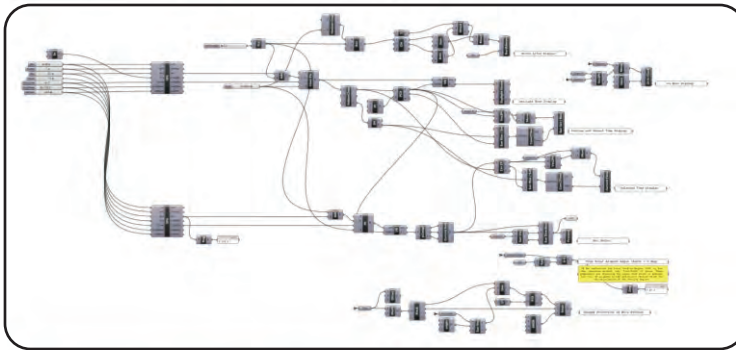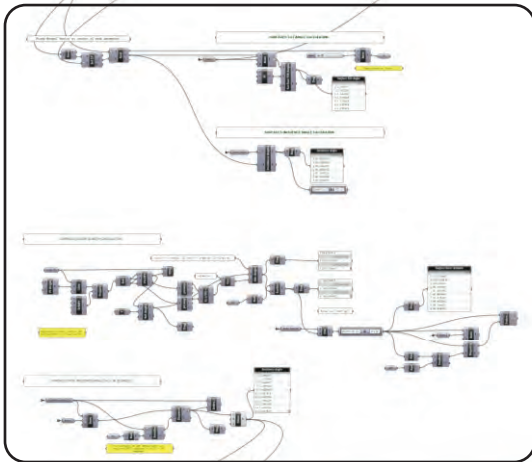
Solar Path and Sun Vector

1
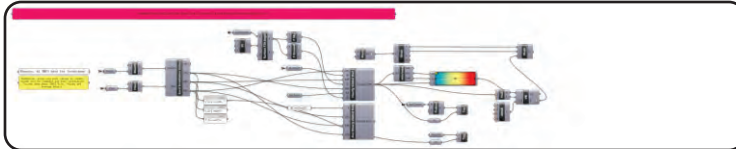
Solar Irradiance / TMY3
Excel Data

2

Surface Geometry
Analysis / Grid Pattern
Selection

3

Solar Profile Angles
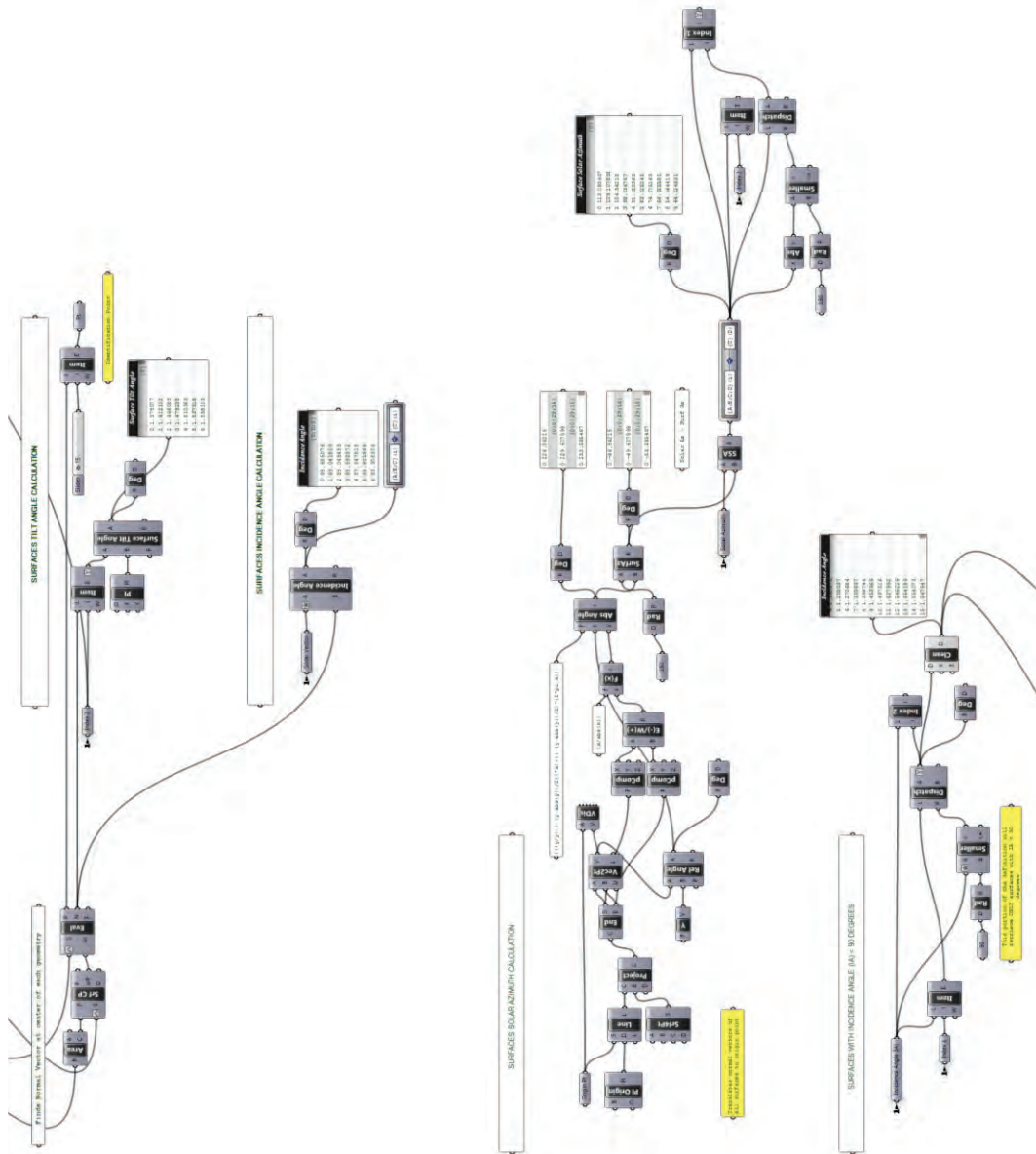
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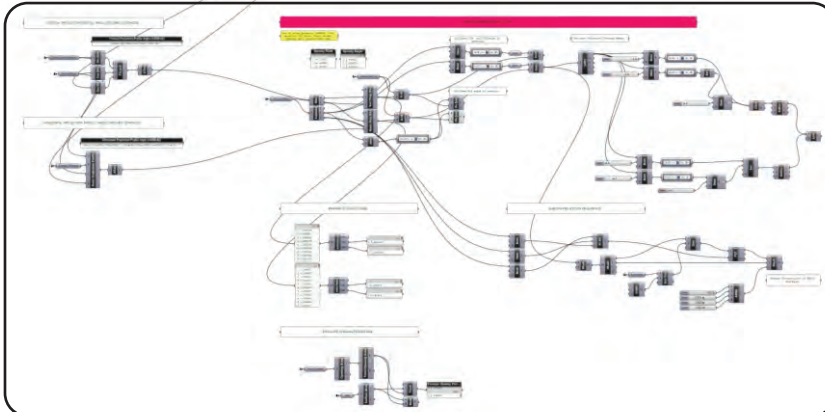
Shading Geometry
Profile Angles

5

SOLAR CONTROL VS

SOLAR PATH AND VECTOR DEFINITION

APPENDIX E

BURTON BARR CENTRAL LIBRARY

BURTON BARR CENTRAL LIBRARY

Owner: City of Phoenix

Gross square footage: 280,000 sq. ft.

Cost: $18.1 million

Completion date: May 1995

Architect: Will Bruder and DWL Architects
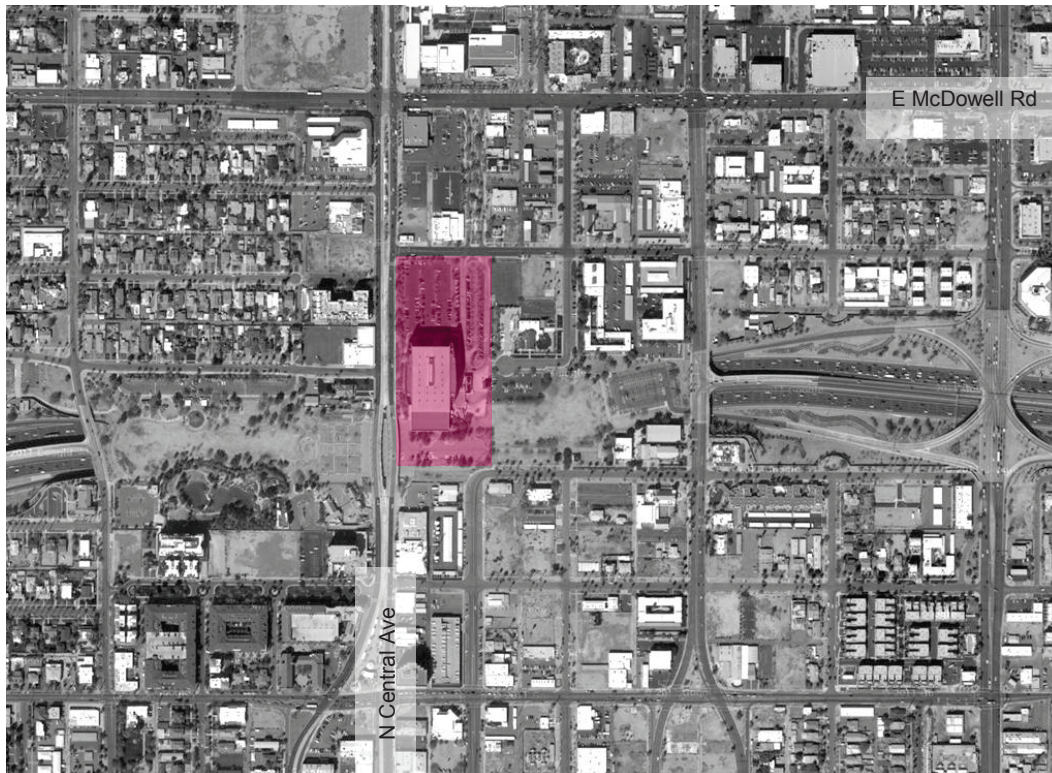
Figure1. Burton Barr Central Library Site Location (Google Maps).

Project Description. Located at 1221 N. Central Avenue, this building was designed to replace the old library building from 1956. The design for the library was inspired by the forms of Monument Valley. The programming and master planning for the project took approximately 5 months, the project's design and documentation about 3 years and its construction 2 years. This five-story building was conceptualized in two main container geometries: the central box, functioning as the warehouse of books and public spaces, and the saddlebags, which house all the service modules for offices, meeting rooms, restrooms and mechanical equipment. The saddlebags are steel framed

structures clad with perforated copper sheeting, except at access points, where stainless steel sheeting is used to emphasize wayfinding. The central box is fitted between the saddlebags, glazed façades face north and south, and 12 inch precast panels face east and west. The great reading room, the largest reading room in the United States, is located on the fifth floor of this box; all the floors are connected by the Cristal Canyon, an open lobby with a water feature and glass-and-steel elevator and precast concrete stair. The reading room culminates in a roof supported by a tensegrity structure and candlestick columns, the tips of which are designed to light during the summer solstice through a series of skylights sitting above each of the columns.

Exterior Shading Devices. Shading devices for sun control and glare are located on the north and south façades of the library building. *Figure 2* illustrates the building's north façade, on which the fixed array system of external vertical fins made of Teflon coated acrylic sail fabric aim to eliminate direct sun penetration and control solar heat gain during the period between spring and autumn equinox days, and early and late hours of the summer months.

The south glazed façade illustrated in *Figure 3* has a computer controlled horizontal perforated aluminum louver system. The design goal for this system was to improve solar control – heat and glare – during winter months.

Findings. On the north façade, because of the 32 foot extensions of the saddlebag geometries over the central box, only a small portion of the north wall is exposed to direct heat gain. The translucency of the sail fabric helps to diffuse any direct and reflected illuminance; thus, it helps to decrease glare in the interior spaces.
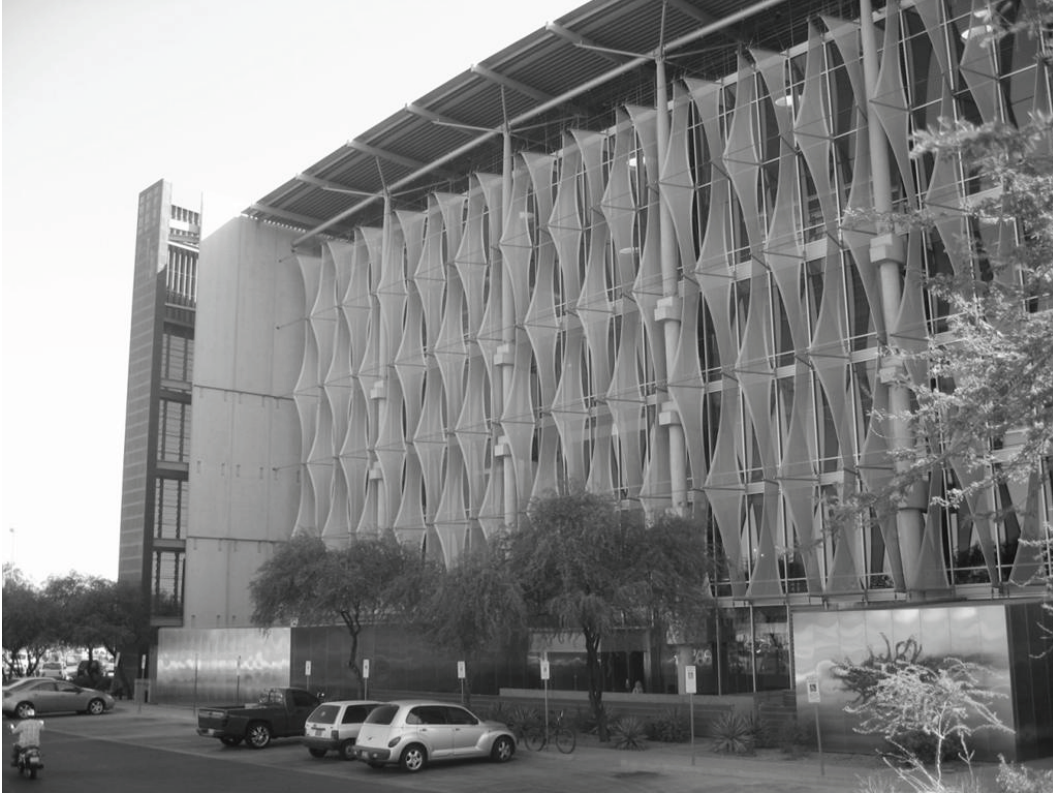
Figure 2. Burton Barr Central Library. North Façade.

One of the goals in a research study by the University of California at Berkeley was to determine how much energy savings were related to the use of the computer controlled louvers on the south façade of the building; due to improper functioning, however, the system was disconnected soon after the building was opened to the public. The research study highlighted the maintenance that the system requires and by being down, also it is down its efficiency. Systems such as the fixed vertical fins on the north elevation can be less challenging and more effective.
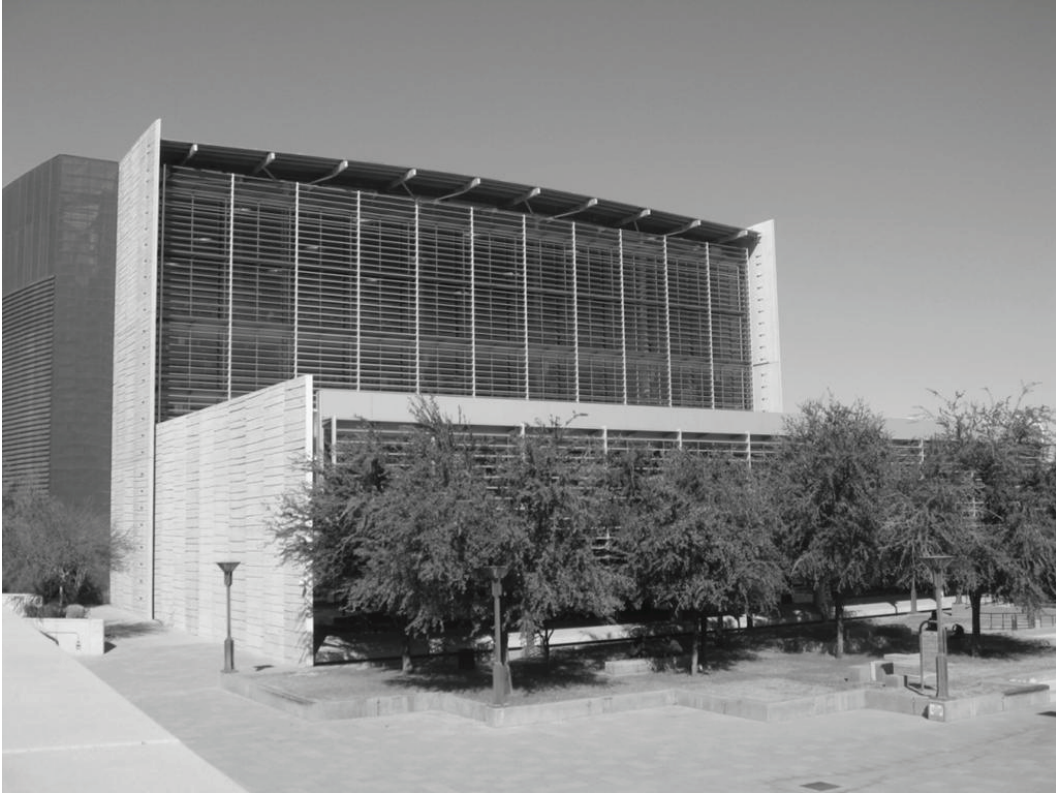
Figure 3. Burton Barr Central Library. South Façade.

APPENDIX F

TEMPE TRANSPORTATION CENTER

TEMPE TRANSPORTATION CENTER

Owner: City of Tempe

Gross square footage: 40,300 sq. ft.

Cost: $18.1 million

Completion date: December 2008

Architect: Architekton and Otak

      Project Description. The Tempe Transportation Center is located at 200 E. Fifth Street at the base of A-Mountain in Tempe, AZ. The facility has an exterior shaded courtyard and a transit plaza serving the METRO light rail and local and regional bus patrons. The building is placed on a site approximately 22.92° clockwise from north, *Figure 1* shows the project aerial view.

Figure 1. Site Aerial View (Google Maps).

      The Tempe Transportation Center is a 3-story building. It is programmatically organized in two bars and one wing: A translucent bar that houses most office spaces, an

opaque bar accommodating private offices, conference areas, services and restrooms, and an elevated wing for a community room. The building's ground floor includes retail, a transit store, security office, and bicycle cellar (with bike repair and accessories). The second floor includes the city of Tempe Transportation Office and a Community Room (the elevated wing). The third floor houses the Transit Operations Center and leasing space. The team design and client's objective was to achieve Leadership in Energy and Environmental Design (LEED) Platinum Certification for this building.

Figure 2. Transportation Center Building, Southeast view.

Exterior Shading Devices. The Tempe Transportation Center was designed to implement a mechanical Solar Veil Shading system for sun control. Several months after the building was occupied, the system stopped working properly. In January 2012 a replacement system was implemented with fully retractable aluminum horizontal louver modules that are controlled manually from the interior of the building.

Figure 3. Transportation Center Building, Retractable. Exterior Louver System.

During the Design Development phase, Solarc Architecture and Engineering, Inc., the energy consultant for the project, tested a total of nine (9) shading type analyses for the east façade, three of which prevailed for the final detailed analysis:

- Solar Veil with South Overhangs. The veil was modeled with 47% visible transmittance.

- Focused Shading. Vertical Louvers. The options analyzed were louvers being perpendicular (2 ft of depth and 1 ft of spacing) and 30 degrees north, the second one was deemed to be more efficient.

- Eggcrate Shading.

The shading analysis evaluated performance on the 21st day of each month. The modeling program used for analysis was DOE2, in which the disaggregated loads for the cooling load on the model results show that window conduction represents 15% of the total cooling load, while glazing solar gain represents 4%.

From the energy analysis performed for the building, the vertical focused shading control device was the top recommended option; the egg-crate system was the second

recommendation. Both systems demonstrated good performance, providing 60% to 100% shading conditions between 8 a.m. and 1 p.m. *Figure 4* displays the three shading type analysis studied.
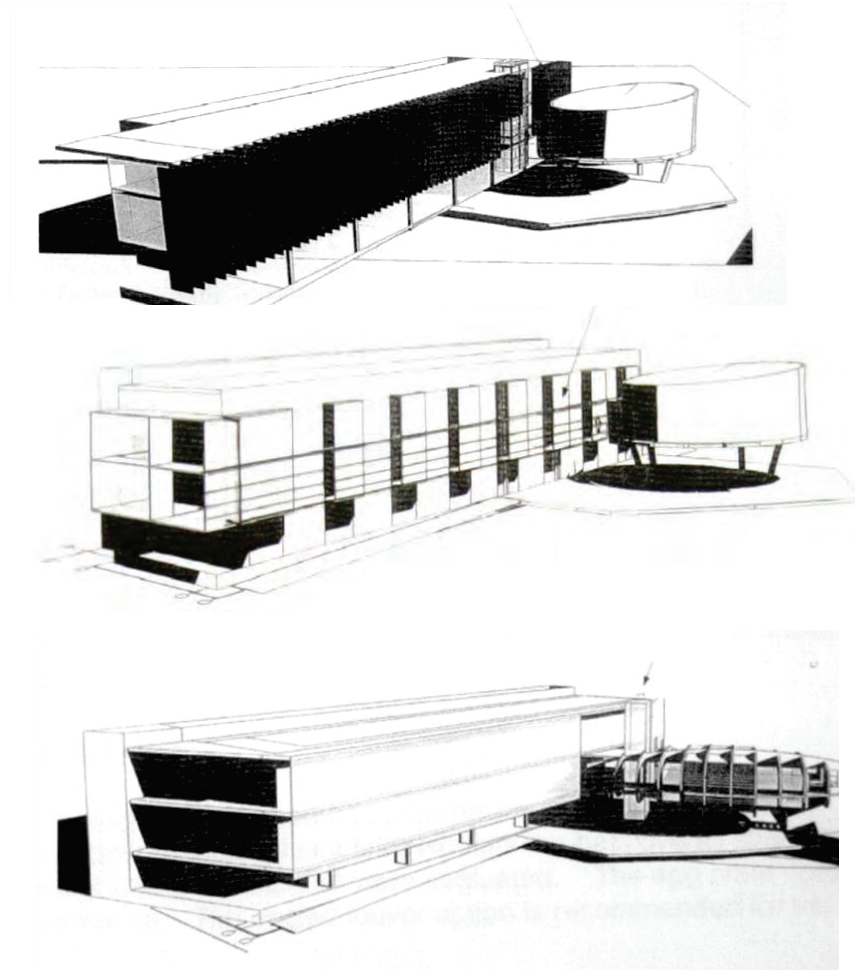
Figure 4. Shading options analyzed for Tempe Transportation Center (Architekton and Solarc Architecture and Engineering, Inc., 2008).

By adding up all of the energy efficiency strategies implemented (refer to Appendix F) the project is expected to have a 52% reduction of cooling loads, with the target of being 60% lower than ASHRAE standards. On the energy model, the lighting and cooling energy use add up to 39.3% (ASHREA 90.1 baseline) versus 14% for applying efficiency measures.

The Solar Veil system was selected by consensus by the client and design team. The client's desire for an open view and free visual connectivity with the Transportation Center area on the east was predominant.

Findings. On this second project, the mechanism for the shading veil system failed as well, which made ineffective the efficiency assumed for the mechanically controlled system during the low sun angle position for the early morning hours until recently when the installation of the new exterior louver system replaced the original one.

APPENDIX G

ENERGY EFFICIENCY MEASURES FOR TEMPE TRANSPORTATION BUILDING

Tempe Transportation Center Project Goals [1]

Environmental response
Strategies used to reduce the energy footprint by 52%:
* green vegetated desert roof
* underfloor air distribution system
* solar hot water system
* natural lighting
* energy efficient emergency electrical generation
* double-pane/low-emissive glass
* retractable exterior shade screens
* operable windows for natural ventilation

On-going sustainable practices in the facility:
* public transportation
* regional bike station with secure parking, showers, lockers, services
* green cleaning and maintenance program
* water collection and reuse
* flexible design = 100 year building life
* green Touchscreen interactive educational program
* green leases for tenant spaces

Strategies supporting a healthy and productive work environment:
* low emitting paints, sealants, carpets and agrifiber
* adjustable underfloor air distribution system
* natural lighting and window views from all regularly occupied offices

Reduced impact on natural resources:
* construction waste reduced by 94%
* rapidly renewable materials
* regional materials
* recycled content in carpet, tile, millwork, ceiling finishes
* no/low emitting paints, sealants, carpets and agrifiber
* "Reuse & Recycle" signage program
* innovative stormwater retention and reuse
* drought resistant native landscaping
* low flow/dual flush plumbing fixtures and waterless urinals
* graywater collection and reuse

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[1] www.tempe.gov/greenprograms/transitcenter.htm

APPENDIX H

PAPAGO GATEWAY CENTER

PAPAGO GATEWAY CENTER

Owner: Chestnut Properties, LLC

Gross square footage: 267,000 sq. ft.

Cost: $62 million

Completion date: 2008

Architect: Smith Group JJR

Figure 1. Site Aerial View (Google Maps).

   Project Description. This six-story research and office building is oriented for optimum solar exposure with its long axis from east to west. The new mixed-use development captures scenic views of its namesake, Camelback Mountain and Tempe Town Lake. The floor plates will serve either research or office functions, lending flexibility and longevity for future tenants. Twin elevator entrances allow for better access for multiple tenants at opposite ends of the building (Smith Group, 2009).
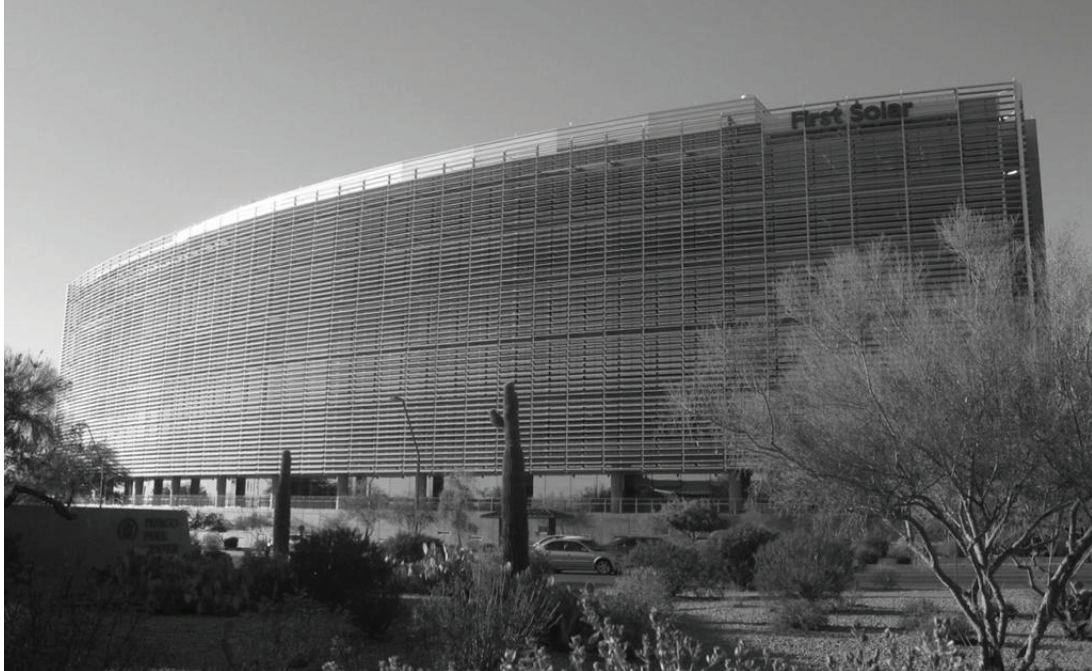
Figure 2. Papago Park Center. South Elevation.

Exterior Shading Devices. A major design feature of the building is the photo-sensitive operable louver system on the east, south and west exposures. The system's goal is to provide substantial motorized solar shades while ventilating and reducing glare on those façades. The devices are perforated aluminum louvers designed with 27% openness; this translates into a solar transmittance of 0.27. There are over 2000 individual louvers, which are organized in 200 banks with 10 louvers each. The louvers' manufacturing company is Colt International, based in Great Britain. The cost of the system was $3 million.

Figure 3. Papago Park Center. Louvers Detail.

Findings. When the energy simulation was performed during the design phase of the building, the percentage of solar heat gains (SHG) expected to be reduced in the building by the use of the mechanical exterior shading was 80%, but this included other efficient envelope items besides the louvers. The shading analysis indicated that the shading system itself can be reduced from 58% to 73% depending on the time of year. Post construction SHG measurements at the southern elevation were not done after the building was completed.

Similar to the other two cases, the designers considered a fix system for exterior shading as an option, prior to choosing the automatic system. However, due to the typology of the building and the client's desire to have a strong statement in regard to sustainability and new technology, a dynamic system prevailed over a fixed system.

The owner saw this system as an experiment to see if this kind of technology could be pushed. He liked the fact that this system was more dynamic and responsive to the sun and climate in lieu of something static. It tells a story about sustainability that the public can understand.