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I, Mark Landis, hereby submit this original work as part of the requirements for the degree of Master of Architecture in Architecture.

It is entitled:

Development of a Parametric Data-Driven Fixed Shading Device Design Workflow

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Development of a Parametric Data-Driven Fixed Shading Device Design Workflow

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By

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Abstract

This thesis presents a new workflow, this thesis calls the Vector Method, to optimize a fixed shading device to reduce heating and cooling energy use so that performance and aesthetic and other design goals can be balanced while exploring various shading forms and typologies during any stage of design. This method is created out of the critique of existing shading device design methods, at times borrowing inspiration from each method's successful attributes. Baseline test studies are conducted to determine this new method's effectiveness in terms of reducing thermal loads against the main existing design methods in use today. Studies looking at the iterative capabilities of this method and user interactions with a tool created based upon this method are also included. This thesis culminates in a design project set just north of Civic Plaza in Albuquerque, New Mexico to explore the potential for the Vector Method to create design solutions that perform and support a design intent for an architectural project in physical context.

This thesis innovates the shading device design process by combining foundational works of Olgyay and parametric analysis abilities of Rhinoceros and Energyplus to inform data driven design decisions. The workflow presented in this paper will demonstrate optimization of fixed shading devices for cooling and heating loads while providing multiple aesthetic options by not limiting the shading device typology in the beginning of the process. This workflow produces iterations that perform similarly in terms of energy savings so that a designer can select a shading device based on other criteria such as aesthetic concerns or constructability issues. The user can move between different shading typologies and add their own creative, artistic interpretations, while not being required to run many simulations after each design change. This paper will present how a tool based process can be agile enough to handle frequent design changes. This paper will demonstrate a process that is more in-line with the building design process and can facilitate more creative, innovative, design solutions based on performance criteria such as reducing heating and cooling loads.

Foundational works by Victor and Adler Olgyay are taken to establish existing shading device design principles. Works such as *Design with Climate* and *Solar Control and Shading Devices*, form the initial effort to design shading devices that respond to the character of the project and also perform quantitatively. The logic behind the process the Olgyay brothers layout is of particular interest. Works such as *SHADERADE: Combining Rhinoceros and EnergyPlus for the Design of Static Exterior Shading Devices* (2011) by Sargent, Niemasz, and Reinhart looks at a variant of a cell based analysis method to create shading devices. Various works by Robert Woodbury are taken into consideration to inform how a useful parametric design structure should be created and implemented.

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Table of Contents

List of Figures

Introduction: Architecture, Building, and Shading

Currently, there exist a host of design methods to create shading devices for the purpose of satisfying performance criteria such as reducing energy loads and increasing thermal comfort. However, many of these methods are either ineffective, or overly complicated to the point they cannot be used effectively in the design process. In a 2012 survey of European architects, 82% stated that they believe designing for solar energy is ‘Important’ while at the same time a majority of respondents rated themselves as ‘poor’ or ‘very poor’ with solar design tools or advanced tools.[1] This indicates designers have a strong desire to design shading devices that perform well, however, they lack the ability to do so due to undisclosed deficiencies in the available tools. Shading device design tools do exist, however, it is possible that these tools embody shading device design methods that do not work well within the normal designer’s design process.

Many researchers working on the topic of optimizing shading devices for pragmatic goals recognize common issues pertaining to thermal loads and energy use, arising due to increased use of glazing. “Office buildings in contemporary architecture usually have a high value of window to wall ratio (WWR) determining transparent façade as the most important part of the building façade to control solar gains, thermal losses and visual comfort”.[2] Windows represent issues for thermal loads through conduction and solar gains, conduction cannot be controlled through shading devices. However, as Victor and Alalar Olgyay provide a study showing the thermal impact of each building element and the largest component is the solar gain through the window.[3] This means that the largest contributor to thermal loads in a building can be controlled through shading devices so that heat gain can be permitted when necessary and blocked when it is harmful. Another article comes to similar conclusions;

> Nowadays office buildings present extensive glazed areas for enhancing daylighting availability but, especially in Mediterranean area, this leads to high cooling loads and increasing problems related to glare. The installation of external shading devices or glazing systems with low solar gain is becoming a natural solution for reducing the aforementioned problems.[4]

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[1] Kanters, Jouri, Miljana Horvat, and Marie-Claude Dubois. "Tools and Methods Used by Architects for Solar Design." 721-31Elsevier B.V., 2014. 724.
[2] Zani, Andrea, Michele Andaloro, Luca Deblasio, Pierpaolo Ruttico, and Andrea G. Mainini. "Computational Design and Parametric Optimization Approach with Genetic Algorithms of an Innovative Concrete Shading Device System." 1473-83Procedia Engineering, 2017. 1473
[3] Olgyay, Aladar, and Victor Olgyay. *Solar control and shading devices*. Princeton: Princeton University Press, 1976. 73.
[4] Manzan, Marco, and Alberto Clarich. "Fast Energy and Daylight Optimization of an Office with Fixed and Movable Shading Devices ", 175-84Building and Environment, 2017. 175

Designing to allow large amounts of daylight and to provide sweeping views does come at a cost in terms of energy consumption and in terms of comfort. At the same time the openness and availability of large pieces of glazing introduce problems related to negative solar gains and glare issues.[5] Olgyay and Olgyay state the problem of increased glazing quite clearly;

> The single window, liberated by the structure, instead of remaining a fenestration becomes a window wall. Man is presented with a psychological sense of freedom, unrestricted views, and a variety of spatial relations. But this transformation has brought saome new problems- or rather old problems in sharply enlarged magnitude of controlling the sun's radiation.[6]

The theme of shading devices has not changed significantly, only the magnitude of importance. Olgyay and Olgyay link the role of the shading device directly to the glazing in a building, "The architectural appearance of the sun control is not an effect in itself-it is the result of several other developments. It is the direct consequence of the glass pane, which in turn was born from structural possibilities."[7] Effectively, the development of larger glazed surfaces combined with the modern drive to condition spaces to be comfortable at all times, in terms of thermal comfort and glare avoidance, create a situation where there are conflicting goals. The existing design culture and user culture expect buildings to be comfortable at all times, or else something is not working correctly, and people are willing to use large amounts of energy to accomplish this.

Aside from energy reduction goals architecture has long understood the shading device to be a part of the function and form of its practice. Marcel Breuer speculates the dynamic the sun played in the development of European cities,

> The warmth of the sun made this kind of life possible and still does to some degree, on the piazzas and streets of Italy, the patios of Spain, on the terraces of the Paris cafes. At the same time, the sun was recognized as a formidable source of discomfort and danger. Streets were laid out and houses were built with strict rules to provide shade to protect against the sun, the great friend and deadly enemy.[8]

Breuer talks about the sun in this instance in the context of urban spaces, however, it can easily be seen how this applies to specific buildings. Victor and Aladar Olgyay mention North American examples of shading devices becoming a part of the architectural vernacular in the past "In Southern California the

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[5] This is not to say anything about the increased U-value of a glazed assembly compared to an opaque wall structure. Of course window to wall ratios matter in energy savings, however, this thesis takes window sizes as given and tries to make the best of the situation through innovative application of shading devices.
[6] *Solar control and shading devices*, 9.
[7] *Solar control and shading devices*, 6.
[8] Breuer, Marcel, and Peter Blake. *Marcel Breuer: Sun and Shadow: The Philosophy of an Architect.* New York: Longmans, Green, 1956. 116.

Indians of the Yokut Tule Lodge not only protected their huts, but in generous, direct manner provided for pleasant living and shaded communal areas."[9]

Figure 1. North Armerican Native Shelters. Source: Solar Control and Shading Devices, 9.

Olgyay and Olgyay go on to mention general shading strategies found in other cultures such as using balconies to shade areas below in Arabian buildings and in India using balconies that stretch much of the length of the streets.[10] All of these examples sought to fulfill a functional role within the context of the physical place as well as the culture of the society that produced them. In fact, some of these typologies such as ancient Greek approaches to architecture were readily adopted by other cultures in part due to the performance of shading devices, "Greek Revival architecture was so successful in the American South because it offered much needed shading, as well as symbolic and aesthetic benefits."[11]

Marcel Breuer calls the shading device the next Doric column, "And because this device is so important a part of our open architecture, it may develop into as characteristic a form as the Doric column." He is saying that the shading device is becoming such a necessary element tied to the function of a building, he likens it to structure that holds a building up, yet has the potential to have architectural styles applied to it and developed around it. Similar to a Doric column a shading device should not become simply ornamentation that is not designed to function. This would be like the structural deceits John Ruskin warns about in the *Seven Lamps of Architecture*,

> nevertheless, that building will generally be the noblest, which an intelligent eye discovers the great secrets of its structure (…) however, the intermediate shell were made of wood instead of stone, and whitewashed to look like the rest, this would, of course, be direct deceit, and altogether unpardonable.[12]

[9] *Solar control and shading devices*, 9.
[10] Ibid.
[11] Norbert Lechner, *Heating, Cooling, Lighting: Sustainable Design Methods for Architects* (Hoboken, NJ: John Wiley & Sons, 2015), 208.
[12] Ruskin, John. *The Seven Lamps of Architecture.* New York: Wiley & Halsted, 1857. 40.

A designer who designs the shading devices all to be the same on every façade orientation or is more interested in creating a façade pattern as opposed to designing shading devices that perform is essentially creating false structure and deceiving designers and users as to what makes this building perform just as a false column would mislead a designer or user to understanding how a building is held up.

The questions surrounding the shading device as a Doric column lead to the conclusion that there must be functional and non-functional considerations. Shading devices are often a very visible component of architecture. Breuer mentions the fact that shading devices are more effective on the exterior of a project,

> The sun, however, has to be reflected before it is trapped and fills the inside with radiant heat (…) The sun control device has to be on the outside of the building, an element of the façade, an element of architecture.[13]

If the sun is not stopped before reaching the interior of the glazing then, in terms of heat gain, the shading device has not performed. This means the shading device is, by nature, a façade element. This does not necessarily make it an architectural element only on the virtue that it must be highly visible, but it does leave open the strong potential for the shading device to become an element of architecture. John Ruskin's delineation between building and architecture is very useful; "Building does not become architecture merely by the stability of what it erects"[14] Just because something functions, stands up, does not make it architecture. Ruskin's definition of architecture is as follows; "Architecture is the art which disposes and adorns the edifices raised by man for whatsoever uses, that the sight or them contributes to his mental health, power and pleasure"[15] This would mean that ornamentation, psychological impacts/effects, and adherence to a local or regional style all can elevate a normal element of a building to become an architectural element.

Building and architecture do not exist independently and some designers such as Peter Zumthor believe that the delineation between the two is not consistent with experiences in reality, "Form and construction, appearance and function are no longer separate. They belong together and form a whole."[16] It is not that there is no way to rationally separate these topics for the purpose of discussion, but what he is saying is, in reality, all of these topics will manifest themselves. There is no way to remove construction considerations from architecture, even the act of concealing construction methods is itself a mode of construction that is represented. When shading devices are added to a façade, if there is no

[13] *Marcel Breuer: Sun and Shadow : The Philosophy of an Architect*, 117.
[14] *The Seven Lamps of Architecture*, 15.
[15] Ibid.
[16] Peter Zumthor, Maureen Oberli-Turner, and Catherine Schelbert, *Thinking Architecture* (Basel: Birkh user, 2015), 26.

consideration to appearance and form this may reflect poorly on the architecture. Good architecture that is a bad building is not acceptable in today's contemporary culture, just as a good building that is bad architecture should not be accepted.

This thesis understands that what constitutes 'architecture' can be boiled down to a conversation on aesthetics. This being the case, this thesis is not attempting to promote one mode of architectural or aesthetic expression over another, but is attempted to provide a new design methodology focused on offering flexibly. A sufficiently flexible method should be able to accommodate more designers' interpretation of what makes a building into architecture.

Due to advances in technological capacities in the realm of construction means and materials, the role of shading devices in architecture has become more difficult to ignore. Everything from increased use of glazing to increased expectations of comfort at more efficient levels necessitates further exploration into shading device design methodology. A contemporary shading device design method needs to respond to the needs and mindset of contemporary designers. The method must be user-friendly and quick while not sacrificing the quality of the outcome. Shading device design methods need to respond to pragmatic concerns to ensure that the resultant design will reduce thermal loads and increase comfort in a space as reliably as possible. At the same time one cannot forget, shading devices are often highly visible components of a building and have the potential to contribute greatly to the architectural character of a space. A holistic shading device design method attempts to incorporate a user friendly workflow with building performance goals while allowing for architectural exploration. This thesis examines and critiques the main existing shading device design methods being used today in order to propose a new workflow approaching a holistic shading device design method.

0.1 Design Metrics

Thermal loads and daylighting concerns are often privileged above other metrics, "Office buildings in contemporary architecture usually have a high value of window to wall ratio (WWR) determining transparent façade as the most important part of the building façade to control solar gains, thermal losses and visual comfort".[17] Thermal conditions and visual conditions are important. Additionally, a third metric could be cost. Thermal loads, aside from thermal comfort, coupled with the cost of fabricating and installing the shading devices is often very important to any designer seeking to value engineer a project on behalf of a client.

[17] *Computational Design and Parametric Optimization Approach With Genetic Algorithms of an Innovative Concrete Shading Device System*, 1473

Within Thermal conditions there are both heating and cooling loads that need to be accounted for. Existing design methods often add heating and cooling loads together (cooling loads minus decrease in heating loads) and create a gradient so that a user can set their own binary boundary as to where to shade and where not to shade.[18] There is then the distinction between thermal comfort and money spent on conditioning the space. These two concepts are closely linked, but not necessarily the same. In the case of designing for thermal comfort the goal would be to reduce peak loads so that the HVAC system can respond easily to changes in demand and no change is too sharp for the system to compensate. This is in contrast with cost centric view where any meaningful reduction in energy use, no matter what time of day, is desirable. The main difference between these two views would come in where the designer sets the threshold to determine when shading begins and ends based on the baseline energy simulation.

Many sources suggest shading devices can be economically feasible if designed right. Studies have been able to show almost a twenty percent reduction in cooling loads that resulted in a payback period of 3.4 years, which is very cost effective in most cases.[19] Victor and Aladar Olgyay provide a number of charts to highlight the economic feasibility of shading devices.

[18] Sarget A, Jon, Jeffrey Niemasz, and Christoph Reinhart F. "Shaderade: Combining Rhinoceros and Energyplus for the Design of Static Exterior Shading Devices." 310-17. Sydney, Australia: 12th Conference of IBPSA, 2011.
[19] Cho, Jinkyun, Changwoo Yoo, and Yundeok Kim. "Viability of Exterior Shading Devices for High-Rise Residential Buildings: Case Study for Cooling Energy Saving and Economic Feasibility Analysis." 771-85Energy and Buildings, 2014. 774

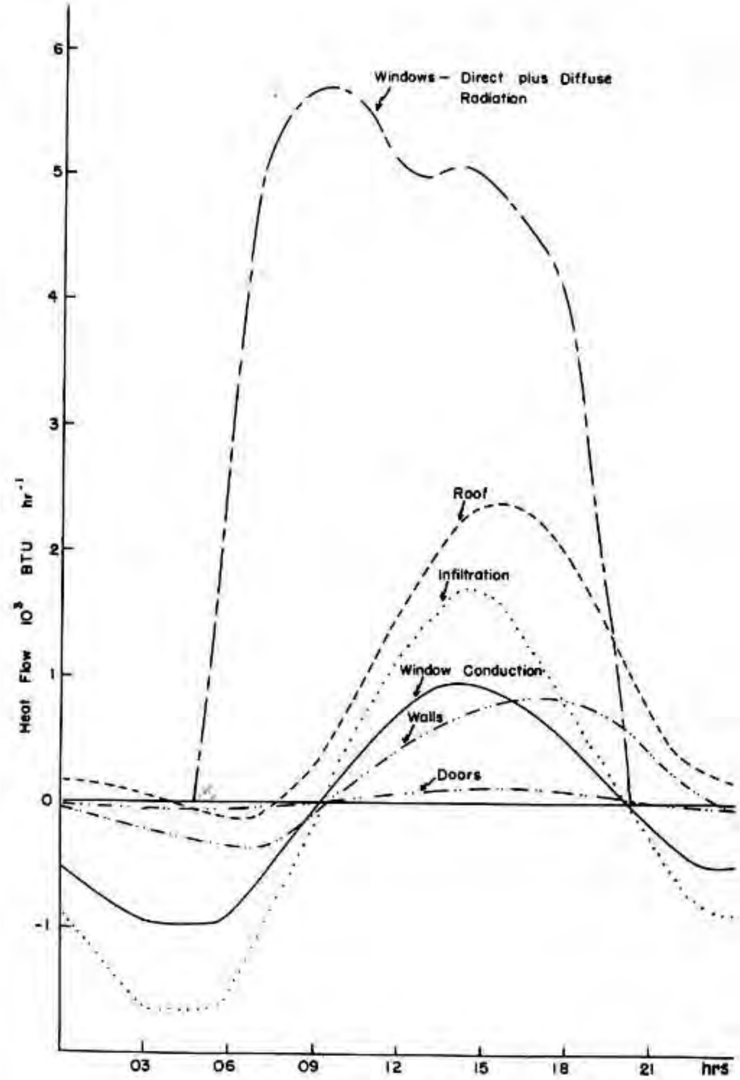

Figure 2. Thermal Movement through Building Elements. Source: Solar Control and Shading Devices, 73.

This image represents the heat flow through different building elements for a test case in the New York-New Jersey area.[20] This shows that windows can be the largest point of heat gain or loss in a building. Shading devices do not have an impact on the conduction of a window, however, they do have a large impact on the direct solar gain of window, which is the most significant source of heat flow according to this chart. These series of charts show the difference in heat flow for windows on different façade orientations, shaded as the dashed lines and unshaded as solid lines.[21]

[20] *Solar control and shading devices*, 73.
[21] Ibid. 72

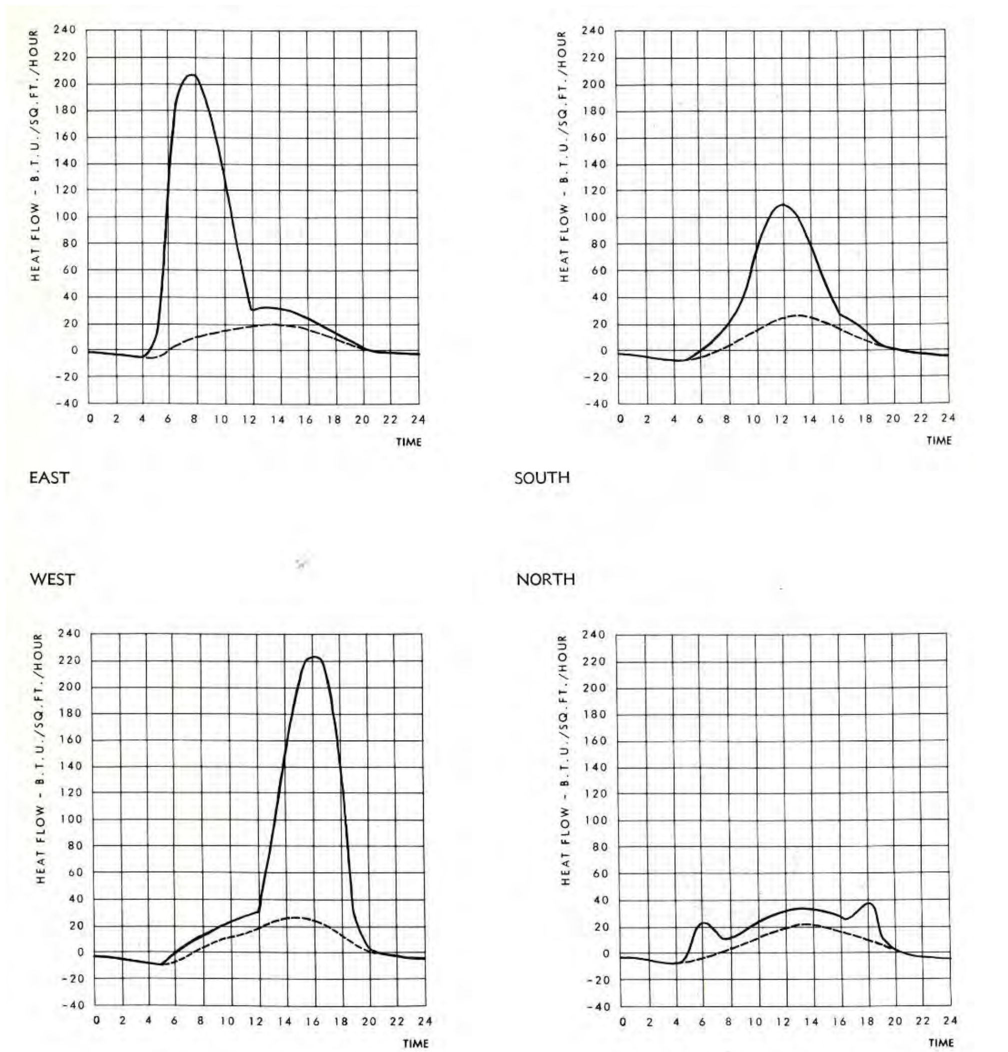

Figure 3. Solar Gain by Orientation. Source: Solar Control and Shading Devices, 72.

Diffuse sunlight does not make up much of the resulting heat flow and therefore does not need to be taken as seriously as direct solar gain. One can see from these four charts exactly at which point direct solar gain begins on the east and west facades by looking for the point in which the heat flow spikes. Diffuse daylight would be very difficult to design for as it reflects off of many surfaces and comes from unpredictable angles. Direct sunlight is much more manageable as the position of the sun can be calculated given a time and location. By just looking at direct solar gain in overheated times, given a cutoff point, shading devices could have a large impact on thermal comfort and consequently energy costs for heating and cooling.

Daylighting is similarly multifaceted topic where there are multiple metrics. In the study by Jinho and Lee a metric of average illumination level is introduced with an ideal target level illumination.[22] It is possible to set illumination goals according to standard such as those by IES per space use type.[23] IES is setting goals for electric light applications, however, if daylighting is being used to replace electric light use, these standards could be used as a starting point for design. From Jinho and Lee's study they mention that appropriate levels of daylighting can reduce artificial lighting power costs from 50 to 80%.[24] Another study found an annual lighting power reduction of 37.8%, "After the shading and lighting controls are adopted, lighting was dimmed linearly when outdoor illuminance was sufficient, reducing the annual lighting energy demand by 37.8%".[25] Both of these studies represent particularly significant proportion of energy use in lighting, however, shading devices reduce light entering into a space. It could be important for a shade to permit a certain level of illumination into a space for the benefits of natural light as well as for cost savings in reduced need for electric illumination.

In a recent study, the authors mention that most people just expect quality daylighting out of a design, "People nowadays expect good natural lighting in workplaces especially as glazed facades have become more popular. However, among all components of the building envelope, these surfaces demonstrate the weakest thermal performance".[26] These expectations mirror quite well the assertion of Marcel Breuer where he comments, "Some may say: let's give up the glass. No- we intend to guard this new and great achievement of an open architecture. How otherwise could we could we enjoy the sun in the winter- and all the changes in weather, clearly visible from a protected inside (…)?".[27] Occupants expect quantity and quality of daylight in their spaces. Quality is usually assessed in terms of glare. EnergyPlus includes metric for glare calculations, "Since the impact of shading device on visual comfort is crucial, the glare was quantified by calculating the Daylight Glare Index (DGI) on EnergyPlus".[28] Daylight Glare Index combines a number of factors including position of a person in relation to the window, a field of view, and the use of the space to determine if the DGI is acceptable.[29] Other metrics might include DGP, daylight glare probability, which might have a higher correlation between predicting

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[22] Park, Jinho, and Woo-Hyoung Lee. "A Study on Optimizing Shading Device Configuration for Glass Curtain Wall Buildings." 5-8Advanced Science and Technology Letters, 2015.
[23] IES Foot Candle Recomendations. Accessed October 21, 2018. http://www.bristolite.com/Interfaces/media/Footcandle Recommendations by IES.pdf.
[24] *A Study on Optimizing Shading Device Configuration for Glass Curtain Wall Buildings*, 1844
[25] Al Touma, Albert, and Djamel Ouahrani. "Shading and Day-Lighting Controls Energy Savings in Offices with Fully-Glazed Facades in Hot Climates." 263-74Energy and Buildings, 2017. 273
[26] Ibid. 263
[27] *Marcel Breuer: Sun and Shadow : The Philosophy of an Architect*, 117.
[28] *Shading and Day-Lighting Controls Energy Savings in Offices with Fully-Glazed Facades in Hot Climates*, 272.
[29] LLC, Big Ladder Software. "Group – Daylighting[LINK]." Input Output Reference — EnergyPlus 8.0. Accessed October 21, 2018. https://bigladdersoftware.com/epx/docs/8-0/input-output-reference/page-016.html.

levels of glare and whether people actually report discomfort due to glare.[30] These metrics can be used to evaluate one scene or one point in a day, but they might not be as easily studied for every hour of daylight in a year.

An additional metric might include the quality of a view from a window. Windows are often designed to permit not only light but to permit a view to or from a space. It is important that the design of a shading device does not defeat the design intent of the window. Richard Neutra was an architect during the time of Olgay and Olgyay who was very interested in designing for climate and the sun in particular, “Finally, try to understand the character and peculiarities of your site. Heighten and intensify what it may offer, never work against its inner grain and fiber. You will pay dearly for any such offense, though you may never clearly note what wasting leak your happiness has sprung”.[31] Opportunities might include views from the site or from the surrounding area into the building. Creating shading devices can hinder views if the wrong typology is designed or if a typology is incorrectly implemented. Office workers might want to see neighboring buildings, or maybe a view of the sky would be enough. Connections to nature and activity are acknowledged benefits to a project. The description of the LEED (Leadership in Energy and Environmental Design) Quality View credit has this in mind, awarding points for design situations that permit quality views of nature and activity.[32]

Architectural principals are not overridden by quantitative metrics, instead the qualitative and quantitative need to be incorporated together. David Leather Barrow has this to say about the design work of Olgyay and Olgyay,

> Does this mean the building’s design was based on programmatic and environmental functionalism? In part, yes, but that is not all; for the Olgyays also saw the building as revealing new forms of expression: ‘a pulsating lively rhythm born from the architecture itself’, a ‘constructive rhythm’, in which ‘new expressions’ made evident the ‘creative power of architecture.’ The stylistic aspects of the facade place it among buildings in the heroic period of Modernism: unadorned surfaces, prismatic rectangular volumes, white walls, a roof terrace, and an external sun screen.[33]

Olgyay and Olgyay might have been very concerned with quantifying aspects of shading device design, however, they never forgot the goals of architecture in general. Many designs by the Olgyay brothers

[30] Wienold, Jan. "Daylight Glare Analysis and Metrics." Radiance-online.org. Accessed October 21, 2018. https://www.radiance-online.org/community/workshops/2014-london/presentations/day1/Wienold_glare_rad.pdf.
[31] Ibid.
[32] "LEED BD C: New Construction V4 - LEED V4 Quality Views." LEED Credit Library. Accessed October 21, 2018. https://www.usgbc.org/node/2614128?return=/credits/new-construction/v4/indoor-environmental-quality.
[33] Leatherbarrow, David, and Richard Wesley. "Performance and Style in the Work of Olgyay and Olgyay ", 167-76Cambridge University Press, 2014. 169

might seem regimented an uninteresting by today's standards, however, in their time the shading devices, however plain, were the ornamentation on a striped down modernist architecture. While pragmatism was a major driver of many decisions in the modern movement, Leather Barrow is clear that Olgyay and Olgyay were not only thinking pragmatically,

> Do shading devices on buildings perform similarly? By negating what exists according to nature (or by necessity) can they both conceal and reveal? The answer for the Olgyays was clear: solving problems of glare and solar gain was necessary in the type of construction that allowed window walls, but was not sufficient – 'the practical and direct expression of rational necessities no longer gives complete satisfaction'. Even though 'the battle for functional solutions had been won' in the heroic period of Modernism, the fight on behalf of the shading device had to continue into Modernism's second critical period, for there was still the struggle for 'the lyrical heart and its emotional needs.' A formalist approach was the farthest thing from their minds, for it was only after 'the more abstract ground work' had been completed that the 'luxury of emotional variation [could] flourish'. Shading devices are expressive because they 'invite a rich play of light and shadow', and to their 'plastic appearance they add rhythm, light, color, and texture'. 'Patterns might be geometrical or use the fluid play of the *claire-obscure* [sic] of the light.[34]

This play on shadow and light sounds a great deal like the aspiration John Ruskin challenges young architects to rise to, "And among the first habits that a young architect should learn, is that of thinking in shadow, not looking at a design in its miserable liny skeleton; but conceiving it as it will be when the dawn lights it, and dusk leaves it".[35]

The pragmatic metrics that could help to drive a shading device's design could incorporate a wide number of topics. A shading device could be used to reduce overall thermal loads, reducing cooling loads more than it increases heating loads in a space. This could be done for the purpose of increasing the amount of time thermal comfort is achieved without mechanical systems or to save an owner money from reduced utility costs. A shading device could help to regulate natural daylight, allowing the right light level to enter the space while reducing high glare situations. Lastly, a shade could be judged on the metric of visibility from and to a space. If a window was incorporated to visually connect a person to a scene, it is important that the shade is designed to not hinder this intent.

[34] Ibid. 173-4
[35] *The Seven Lamps of Architecture*, 84.

0.2 Study Methods

Having established the goal of creating a shading device design method that produces solutions that perform and have the potential to become architectural elements, the existing shading device design methods are critically evaluated in terms of meeting performance goals and flexibility in design. Existing methods are compared in a baseline simulation study where the climate design method, the iterate method, and the cell method are tasked with creating a simple overhang shading device with the goal of reducing overall thermal loads. Holding all other variables equal, aside from the each design method (to be explained in subsequent chapters), will help gage the effectiveness in terms of reducing heating and cooling loads for each method for this test case. While at the same time this thesis is looking at other possible outcomes in terms of design to evaluate each method's ability to offer design alternatives, flexibility in form, and relative ease design changes can occur.[36]

The critique of existing design methods feeds the creation of a new shading device design method this thesis calls the 'Vector Method'. Lessons learned from other methods allow this method to extract concepts that lead to more flexible designs that also adhere to performance goals. This method is embodied in a tool created by this thesis which takes the form of a grasshopper script replying on native grasshopper components as well as components from the plugins Honeybee and Ladybug, which are an interface for EnergyPlus and Radiance.[37]

This new method is compared in terms of meeting performance goals by being used in the baseline study to create a simple overhang, as the other existing methods were used in the baseline simulation. This is to show that the new method performs as well if not better than existing available methods of shading device design in terms of reducing total thermal loads.

Next this new method is explored as a function of its ability to find and alter new forms based on parameters set by the user and by the environment impacting; performance metrics, user defined shading device rules (typologies, design decisions), window geometry, and changes to the energy model.[38] This is to set forward the idea that solutions generated by the vector method are tailored to each specific condition and yet maintain a high degree of flexibility in design through user defined goals and parameters.

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[36] This is more of a theoretical discussion and less of a scientific exploration since this topic of flexibility in design crosses into subjective territory. This thesis acknowledges that some might only ever design simple rectangular overhangs in practice, in which case, flexibility in design might not have as much weight. However, this thesis asserts that maximizing flexibility offers the designer the maximum freedom to explore architectural solutions.

[37] There are more programs incorporated into Honeybee and Ladybug, but these are the most relevant.

[38] Each of these explorations could evolve into separate papers. The point of exposing these topics in thesis is not to diverge on different points of study, but to prove that the vector method is taking all of these variables into account when generating solutions.

Then the vector method will be applied to a design project that is sited just north of Civic Plaza in Albuquerque, New Mexico and incorporates a number of programs into a mixed use office building. The design is based on a number of design precedence while taking into account the immediate context it exists within to establish that this could be a design that occurs in practice and constitutes a realistic test case to apply the vector method. Design that creates complex situations, forms, and goals that other methods find difficult to account for are favored to allow this design project to become a playground for the vector method to exemplify its strengths. The design of the shading devices is not a simple application to the preconceived building but the vector method is used in conjunction with the architecture to enhance and inform the outcome. Similarly design precedence surrounding shading device motifs and forms are important to get an indication as to what the industry gravitates towards and which forms this method should be able to optimize. Design iterations are included in the application to a design project to show that this new method does not lock the user into predefined solutions, but helps guide creativity to find solutions that perform.

Finally the evaluation of the design project occurs where the performance of the building before and after shading devices is evaluated in terms of performance criteria, namely reducing heating and cooling loads, but also in flexibility in design. How easily the tool was applied to varying conditions and dealt with design changes throughout the process is vital. The subjective matter of whether the shading devices contribute to the architecture as architectural elements is also addressed to an extent.

Following the applications in design, the tool is tested by graduate students in the Master of Architecture program at the University of Cincinnati, DAAP, and feedback is collected and analyzed. This aims to evaluate the success of the Vector Method in making shading design more accessible to designers within the design process they are already comfortable with.

This culminates in a number of future studies and uniquely different applications of this method, not explored in this thesis, which are named and discussed briefly to provide a path for future work to be done on this topic. Limitations of the vector method and the process by which the tool is applied will also be addressed in detail.

Chapter 1.0 Existing Methods

Each method is evaluated in terms of performance and design potential. A baseline study is conducted with each method where a simple horizontal shading device is designed and evaluated. Identifying aspects of each process that ensure performance results while not restricting design options is important for the formation of a new hybrid method meant to advance shading device design along these holistic goals.

1.1 Climate Design Method

The climate design method was pioneered by Victor and Aldar Olgyay through the publication of a series of books, most important, *Solar Control and Shading Devices*.[39] In this book, and others, the Olgyay brothers argue for a detailed process whereby the climate is analyzed in conjunction with the building to first determine when a building must be shaded and then design what will shade it. The first step is then to evaluate the building in the context of the climate. The Olgyay bothers suggest to compute the balance point temperature, the outside temperature at which a building does not use energy to heat or cool the space, and compare this to the outdoor temperature to determine which times to shade the window and which times to avoid shading. They suggest using a balance point of 70 degrees Fahrenheit if the specifics of a building cannot be determined, however, now with EnergyPlus and Honeybee to allow a user to more easily navigate EnergyPlus a balance point can easily be calculated.[40] The balance point represents an interaction between climate and the specific building modeled in EnergyPlus. If the assemblies/properties of the building changed this would change the balance point temperature and if the location was changed, not only does that affect the energy model which leads to the balance point but it also impacts the selection of hours to be shaded.

The next step is to combine outdoor air temperature, evaluated with the balance point temperature, with the sun path diagram specific for the location for the project, in this case Albuquerque. The Olgyay brothers show how this can be accomplished using a graphical method.[41]

[39] *Solar control and shading devices*
[40] Ibid. 23
[41] Ibid. 87

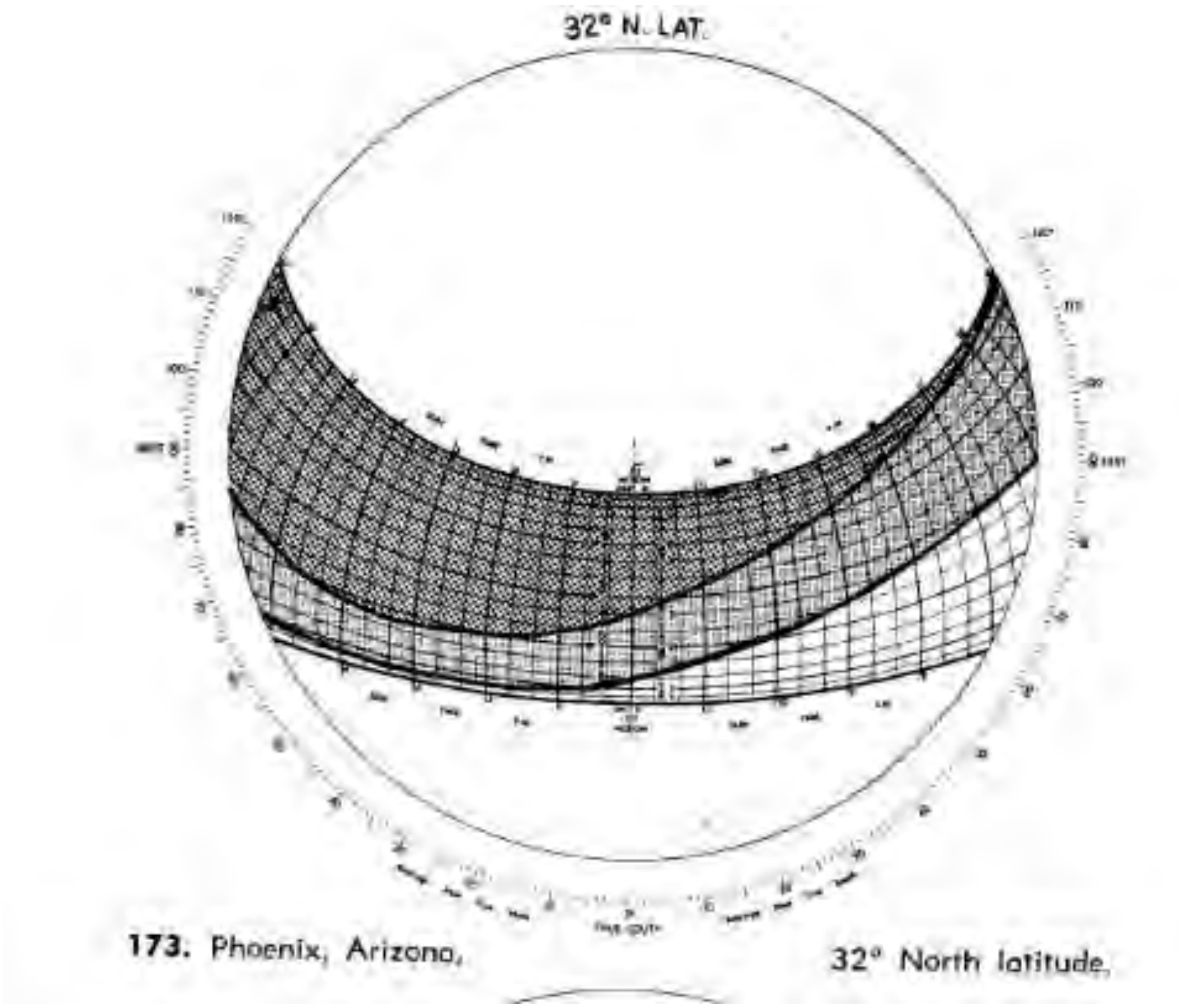

Figure 4. Sun Path for Phoenix, Arizona. Source: Solar Control and Shading Devices, 43.

In this image Olgay and Olgyay have a sun path for Phoenix Arizona and have represented the overheated periods with a dark grey shade. The lines represent the path of the sun, each coordinate represents the azimuth and altitude of the sun. The path overlaid with climate data can help determine the lowest altitude of the sun that needs to be shaded along with the most extreme azimuth angles to the east and west. The darkest grey represents when a shade should be designed to cover 100% of the window in question and the lighter grey represents a 50% shade design where there a more hours where partial coverage might be advantageous. In the case of the modern capabilities of EnergyPlus through Honeybee and Ladybug (another grasshopper plugin) this same data for the baseline model can be visualized in a color gradient. This links each hour of the year with its corresponding outdoor air temperature and plots each hour on the sun chart. Once the sun path has been colored to determine when shading is needed, an appropriate shading mask needs to be selected. At this point Olgaya and Olgyay have highlighted many options to choose from.[42] A designer can select a typology shown in the figures below that has a similar shading mask to the sun path with climate data overlaid. The goal is to cover the points during the year where shading is deemed necessary by sizing a typology of the designer's choosing. To size one of the typologies one only needs to find the lowest altitude angle and azimuth angles to shade and utilize plan and section drawings through the window to size the selected typology. For example a simple overhang's depth would be reliant on the lowest altitude angle and azimuth angles would help to size the side overhangs. Some typologies, such as vertical options, would not adequately cover a south facing window with a sun path diagram like the one in Figure 4. This shading device design method allows the designer to understand beforehand which forms are more likely to work compared to others.

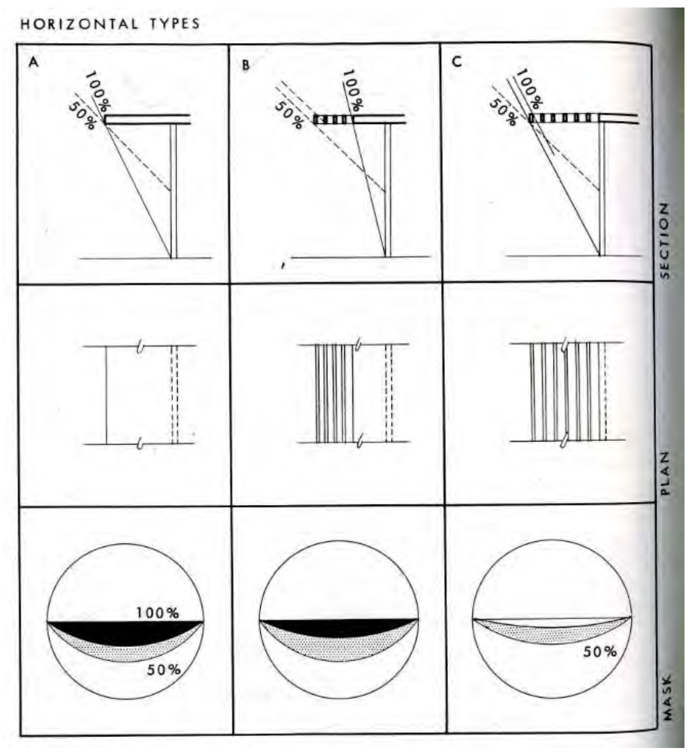

Figure 5. Shading Options. Source: Solar Control and Shading Devices, 88.

[42] Ibid. 88-92

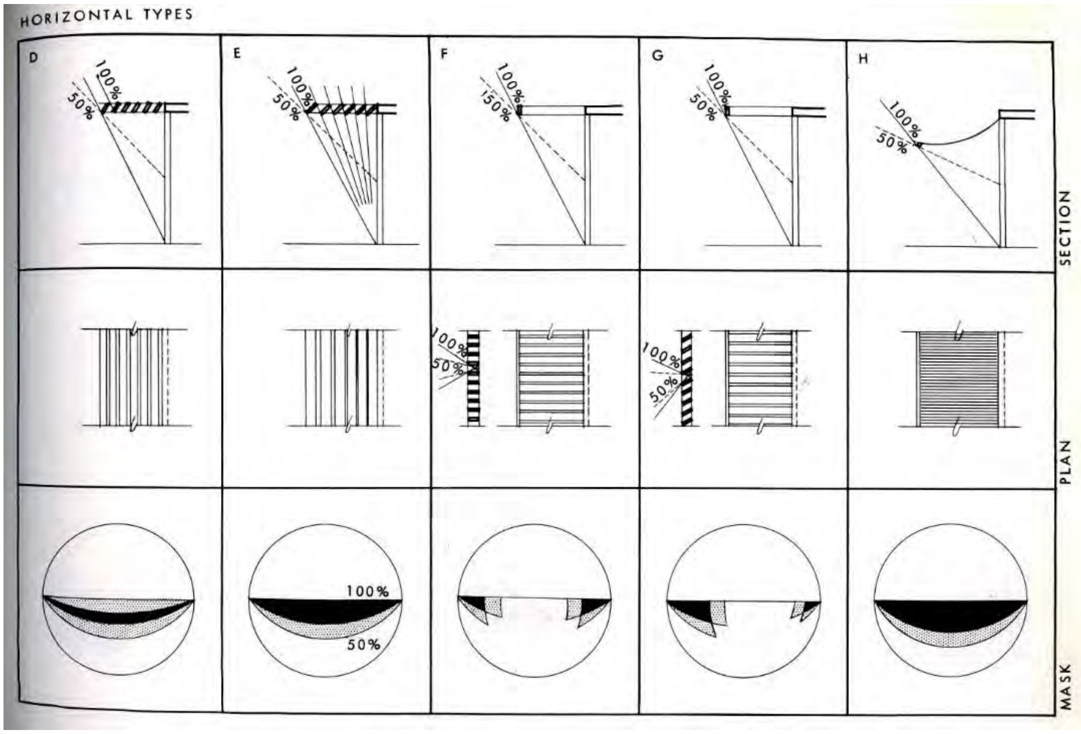

Figure 6. Shading Options. Source: Solar Control and Shading Devices, 89.

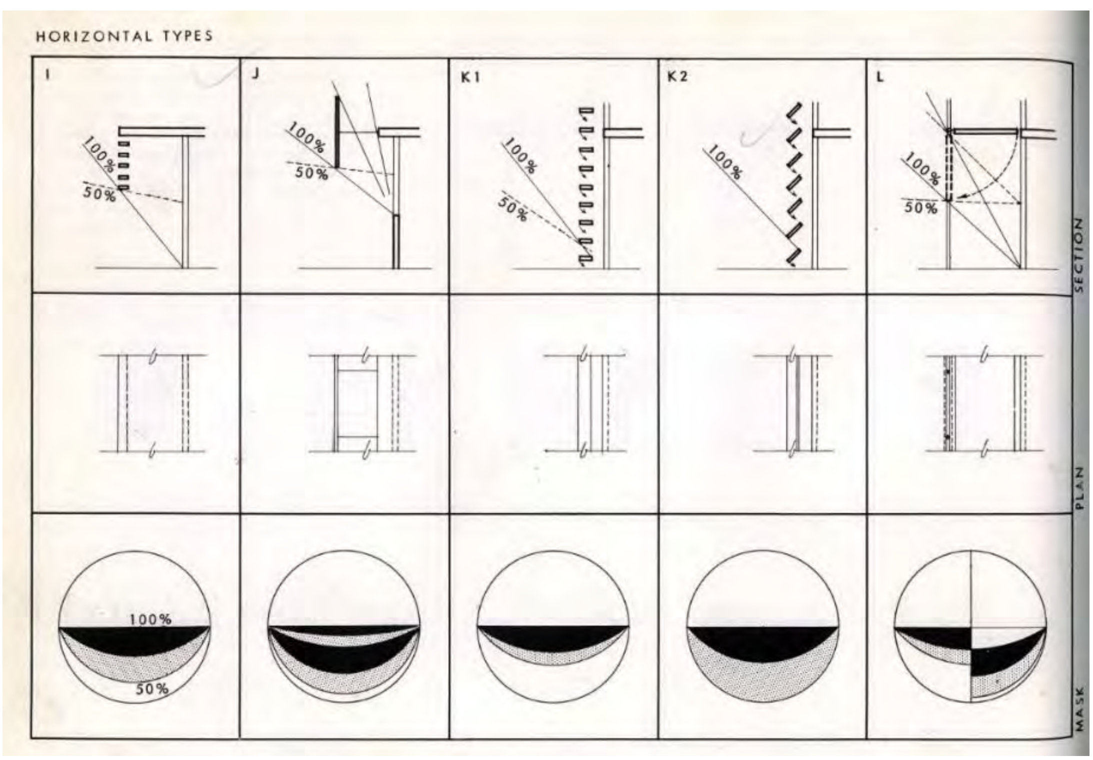

Figure 7. Shading Options. Source: Solar Control and Shading Devices, 90.

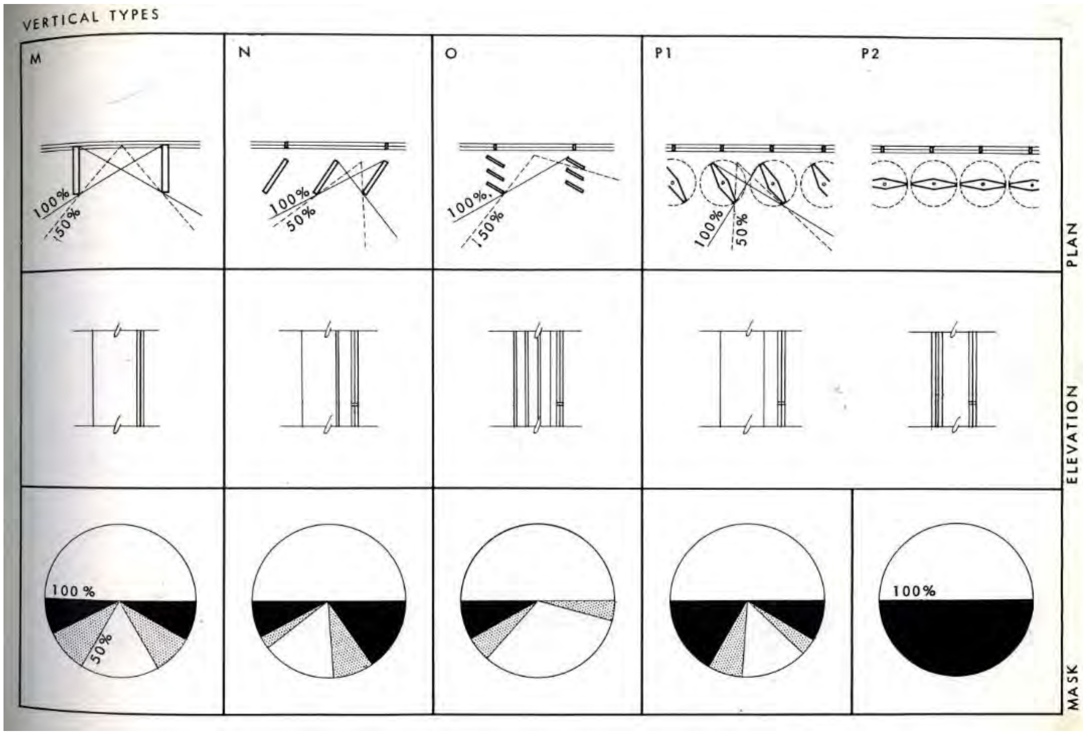

Figure 8. Shading Options. Source: Solar Control and Shading Devices, 91.

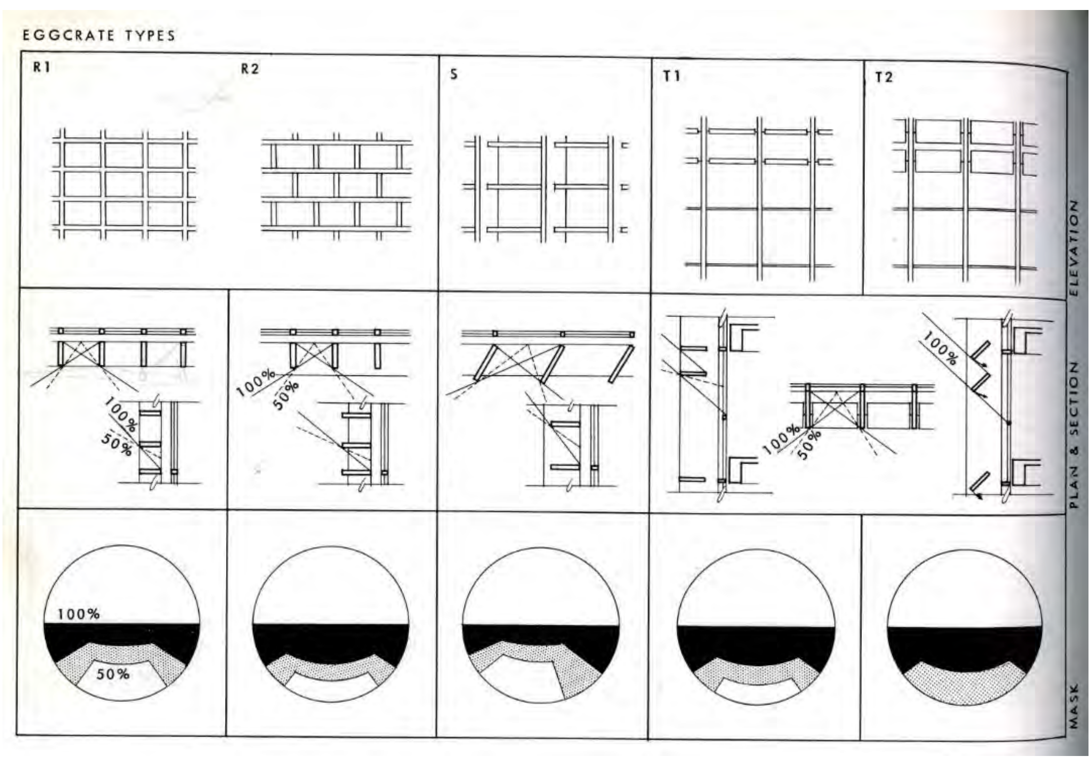

Figure 9. Shading Options. Source: Solar Control and Shading Devices, 92.

This design method allows the designer to do analysis in the beginning to inform design later in the process. If priorities change and a new aesthetic is desired the designer still has the original shading mask to refer to and design a new solution that works better in the context of aesthetic expectations.

There is a limitation in design of this method, namely that while one can freely move between typologies, allowing some designer input in creating architectural expression, the ability to size and shape these typologies is determined based on only a few angles (altitude perpendicular to the window to determine depth and altitude parallel to the window to determine side overhang). This lends itself to producing rectilinear forms effectively, but does not easily support more complex, less typical forms. This could be useful for designs that use off-the-shelf solutions but does not support the types of high profile designs that occur in this time. In the time that the Olgyay brothers were writing many examples of shading devices being implanted were fairly normalized rectilinear devices such as louvers, overhangs, and egg crate typologies.

Figure 10. Design by Oscar Niemeyer. Source: Solar Control and Shading Devices, 155.

This example by Oscar Niemeyer a day nursery in Brazil incorporates vertical shading devices angled for the building's orientation.[43] This creates a rhythm that adds to the aesthetic experience of the building, however, design and analysis through this method only permits rectilinear solutions as shown.

Figure 11. Design by Richard Neutra. Source: Solar Control and Shading Devices, 156.

Richard Neutra's Desert House would not have the same character and level of human comfort and sensibilities without the thought he put into the shading devices.[44] Again the form the shading devices take tend to gravitate towards simple rectilinear forms that fall within the typologies Olgyay and Olgyay list. The rhythm that the vertical louvers establish agaist the horizontal form of the home in the highly landscaped context becomes a poetic solution with pragmatic implications. The shading devices solve a measurable problem in the Desert House making it a good building, but also transcent mere building and move the shading devices into the realm of architectural elements.

[43] Ibid. 155
[44] Ibid. 156

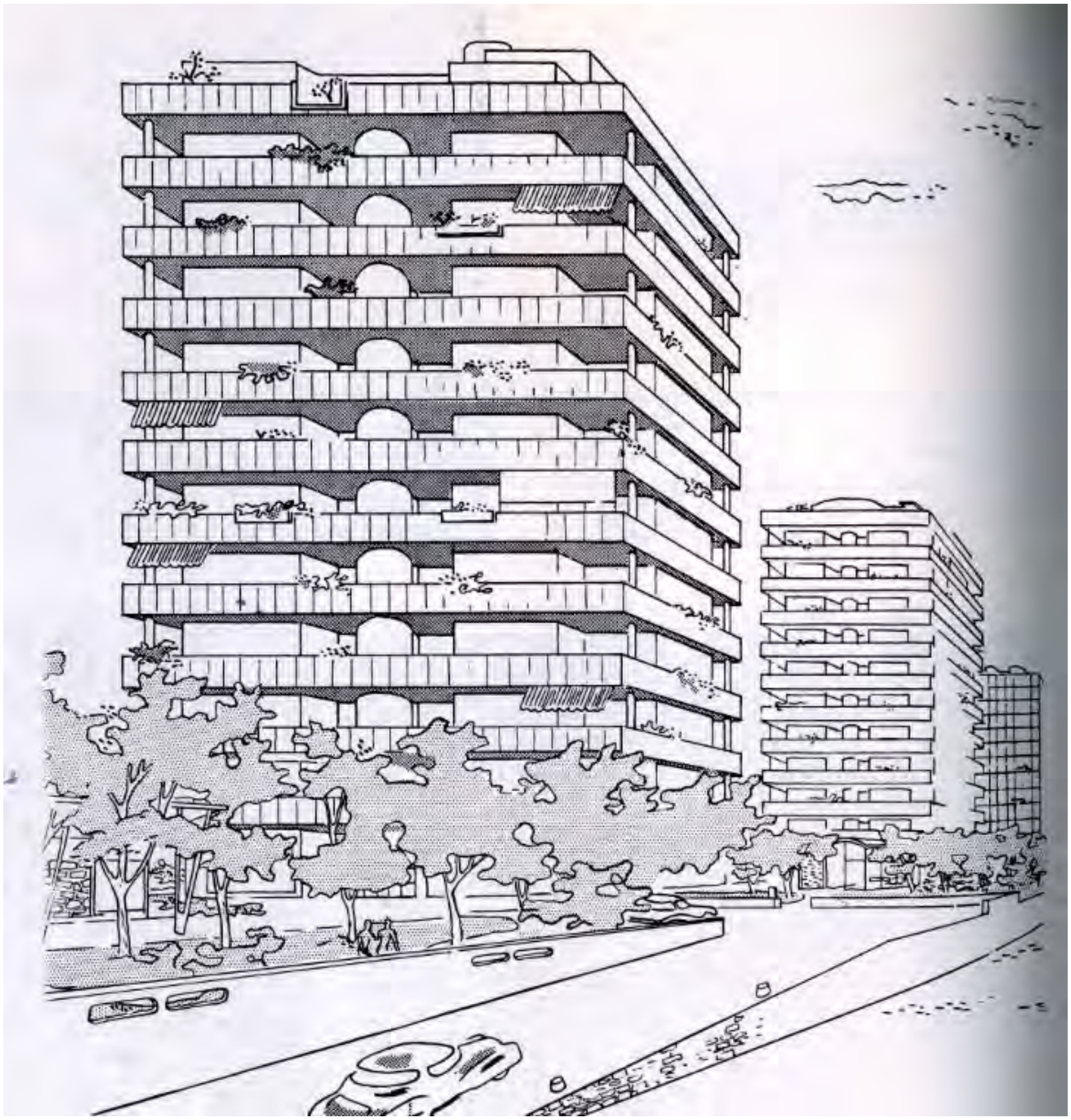

Figure 12. Design by Olgyay and Olgyay. Source: Solar Control and Shading Devices, 108.

This apartment concept by Olgyay and Olgyay shows how the form of a balcony could be designed to shade the apartments below.[45] This is a clever way of integrating form and function to create a functional shading device. This embodies the ideal set up for holistic design earlier, however, the moment the design begins to incorporate more complex angles and forms this method cannot compensate very well.

This method is good for leading a designer to a solution that will perform, while still keeping options open to change as the design evolves. The concept of a shading mask is a very powerful tool,

[45] Ibid. 108

however, the reliance of a selection of typologies and transforming the mask into only a few design angles generalizes the complex data so that the form while always come out to be rectilinear/normalized. This may be helpful in terms of accounting for budget and constructability goals, but it does not seek to find the absolute best performing form/shape and prejudges the designers intensions, that budget and constructability control over performance and aesthetic concerns. With innovations in construction techniques and technologies in prefabrication, much more is possible than what was readily available during the time of Olgyay and Olgyay. This system of generalizing data to fit rectangular solutions does not reflect the times designers operate in now and in this way inhibit the pursuit of holistic architecture.

1.2 Iteration and Genetic Optimization Method

The iteration method is simply a process by which a design scheme is iterated, changing one or more variables slightly and methodically with each iteration, all iterations are evaluated and the best performing iteration becomes the design solution. Genetic optimization can be employed to reduce the number of iterations needed by allowing the software to learn and establish trends that impact the next generation of iterations to be simulated. Trends that lead in an undesirable direction do not need to be continued as a simple iterative process would.

This method has become the most mainstream of all performance driven shading device design methods, due to the ease of use and integration with building energy simulations. This method requires a designer to specify in the beginning what shading device typology or form they will be working with, which variables matter when designing this typology, and finally by what criteria success will be judged. This could be used on normal typologies such as rectangular overhangs as in this test study, or much more complex forms. Because each iteration is subjected to a full building/zone simulation the impact on shading over the baseline takes into account every detail of the building and its interaction with the environment. This method could be used for everyday projects or very complex problems.

The design firm Payette engages in an in depth study of a past project along these lines.[46] In this case horizontal louvers were selected to be the typology that is optimized.[47]

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[46] Korah, Ranjit, and Michael Hinchcliffe. "ABX: The Good, the Bad and the Shady – Payette." Milken Institute School of Public Health – Payette. Accessed September 11, 2018. https://www.payette.com/conferences/abx-the-good-the-bad-and-the-shady/.

[47] Ibid. 31

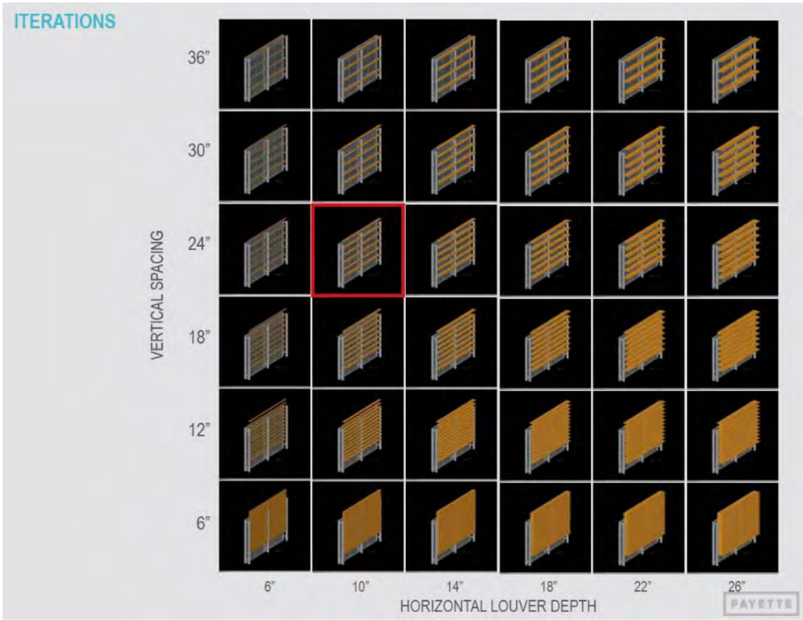

Figure 13. Louver Iterations. Source: The Good, the Bad and the Shady, 31.

The variables that they chose to use to define the iterations included vertical spacing and the horizontal louver depth. This creates a matrix of 36 design options. Other variables such as material reflectance, offset from the window, and others could have been explored as well if that became a priority for the design team. It is important to note that design decisions about general form need to be made upfront in the design process, without knowing anything about the performance of this typology.

Each of these iterations was evaluated on a combination of three criteria starting with solar heat gain reduction during the summer.[48]

[48] Ibid. 35

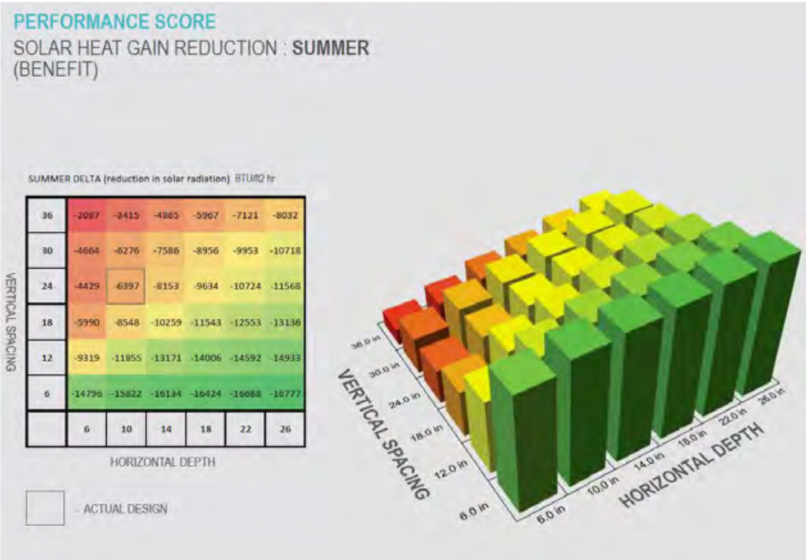

Figure 14. Louver Iterations Evaluated for Heat Gain Reduction in Summer. Source: The Good, the Bad and the Shady, 35.

Figure 14 shows the impact on heat gain during the summer time for each iteration. Green represents the largest benefit (reduction in heat gain) while red represents very little benefit. Figure 15 shows the heat gain reduction during the winter time. Red represents a large amount of positive heat gain that is being blocked by the shading device while green represents very little heat gain being blocked in the winter time.

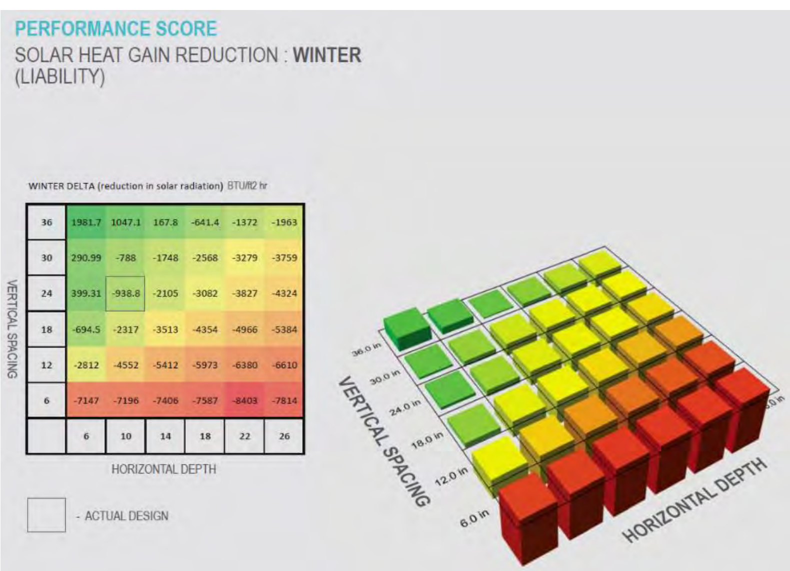

Figure 15. Louver Iterations Evaluated for Heat Gain Reduction in Winter. Source: The Good, the Bad and the Shady, 36.

This is combined with a third metric which evaluates useful daylight permitted to enter the space.[49] Figure 16 shows the level of daylight during a test case day for each design iterations. Payette could have chosen additional metrics as well, dealing with glare, EUI (energy use intensity), or costs in terms of dollars if it made sense to do so. Because building simulations produce a wide variety of outputs there are many ways to tailor the analysis to optimize based on the criteria that is important to each specific project.

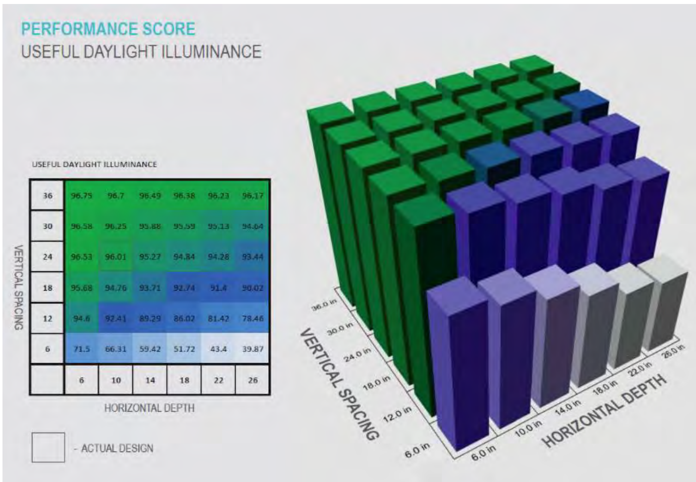

Figure 16. Louver Iterations Evaluated Daylighting. Source: The Good, the Bad and the Shady, 38.

Payette then takes all of these metrics evaluated for all 36 iterations and weights each one to create a final metric which can be directly applied to select the best performing iteration.[50]

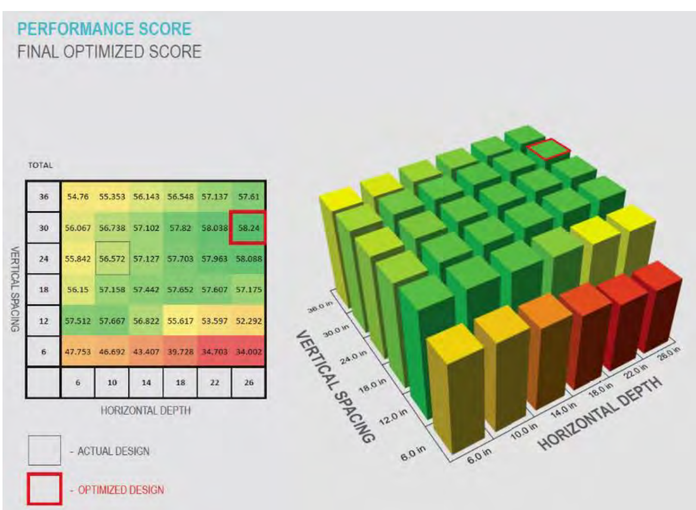

Figure 17. Louver Iterations Weighted Evaluation. Source: The Good, the Bad and the Shady, 39.

[49] Ibid. 38
[50] Ibid. 39

Being able to weight priorities allows designers to evaluate a mix of metrics that do not have similar units and allows designers to determine how important each metric is in selecting the final outcome. Since each project is built by different people for different people it would make sense that the priorities of the people involved would also impact the end design. If energy use was privileged more than access to daylight the results of this same study could have come out very differently.

A very prominent design tool Sefaira uses this method on very simple typologies, such as rectangular overhangs and vertical shades, creating 1 to 10 iterations that are simulated and the results can be read across many metrics a designer might be interested in.

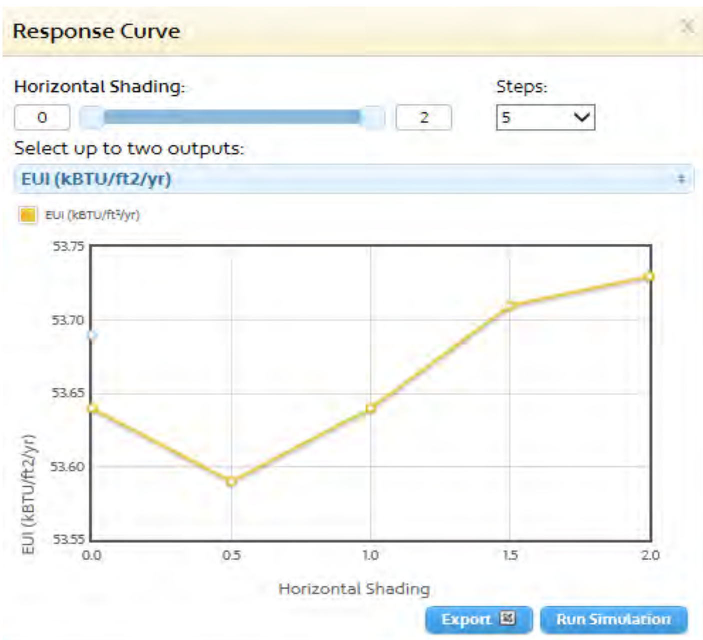

Figure 18. Response Curve. Source: Sefaira

This is a response curve for a rectangular form with a south facing window and a horizontal shading device similar to the baseline test case that is being carried across each design method. In this curve, EUI is the deciding metric and 5 iterations are created between 0 and 2 meter deep. According to this curve a horizontal shading device that is 0.5 meters deep on the south façade should produce the best results in terms of energy use intensity. However, if the number of steps between 0 and 2 meters is increased the results change.

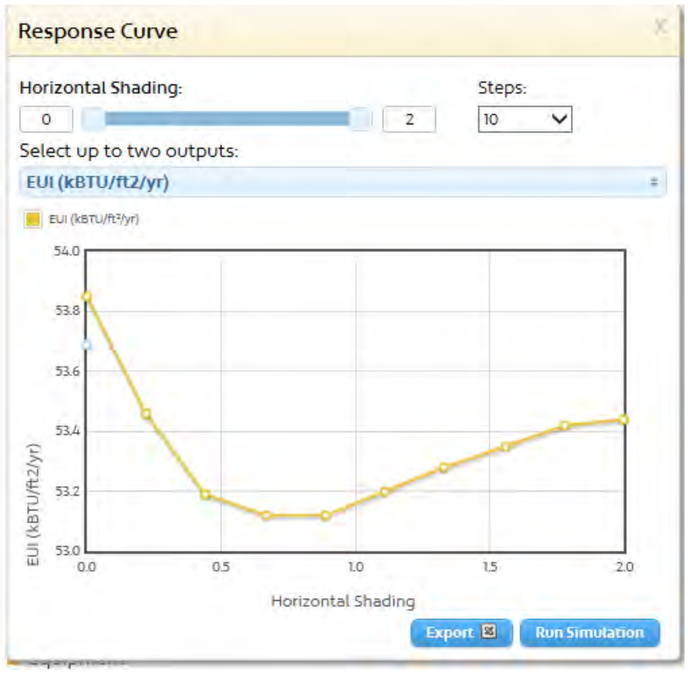

Figure 19. Response Curve. Source: Sefaira

Now it would appear that the best performing shading device would be between 0.6 and 0.8 meters deep. One can assume the more steps, the closer a design will get to being optimized. This would indicate that this method merely approximates optimized design, and is meant to find the best solution out of a predefined group. It is possible that a designer select a typology or form to optimize that could not hope to perform well, such as a vertical shade on a south facing façade.

A study on Optimizing Shading Device Configuration for Glass Curtain Wall Buildings, by Jinho Park and Woo-Hyoung Lee, among other things, actually tries to address the issue of which typology to utilize on a façade. "Our optimization formulation considers how many shading devices are established (…) where the shading devices include vertical fins(fins), shallow overhang(ov1), deep overhang(ov2), and deep overhang with fins(ov2f)".[51] What this study suggests is a designer could perform the same method with normalized typologies being the iterations to determine the most effective type before moving towards a detailed design of a singular typology. This adds an additional step to the process and does remove some creative freedom from the designer, as the selection of typology and design of the form would ultimately be determined based on building simulation results.

This study also seeks to blend pragmatic concerns with aesthetic considerations, "The proposed algorithm is to develop a data-driven design to provide energy-saving potential as well as increased

[51] *A Study on Optimizing Shading Device Configuration for Glass Curtain Wall Buildings*, 7.

aesthetics with optimized shading devices configuration".[52] This study is coming from an engineering perspective, so the focus is more on optimizing for energy savings, however, the ethos is there to say energy savings can drive form selection and therefore have aesthetic implications. Allowing aesthetics be influenced by pragmatic concerns and allowing aesthetics be determined by pragmatic concerns are two separate things, this tends towards the latter. Unlike the Olgyay brother's shading masks results from this study fixes the designer into a solution, not inspire a solution. This study concludes for their test case, deep overhangs with fins performs the best on all façade orientations with a depth of 1.5 meters.[53] It is stated in definable terms that this is the form to use if the best results are to be achieved. There is no room to alter dimensions or experiment with other forms without further study, even then, further study would only serve to restrict design even further. Utilizing a shading mask presents a graphic representation of a pattern that needs to be shaded and allows a designer to select a wide variety of typologies/ forms.[54] The shading mask approach does not aim to present the one ultimate design, but only provide a basis for design that will accomplish the goals set by the designer and provide some freedom in design.

In interesting aspect of these studies tends to be in the parameters that generate the design, not as much in the resultant form. Park and Lee in addition to simulating typologies in order to find the best results for each façade, focus heavily on determining where shading devices need to be placed,

> However, installing shading devices on the curtain wall facade is still considered relatively expensive even considering maintenance costs in long period so that architects and owners are still reluctant to utilize them. Therefore, the needs for more economical and efficient ways by optimizing installed areas and configuration in utilizing shade devices have been raised.[55]

In this study, shading devices are limited and they run daylight studies over different periods of the year in order to determine the best place to use shading devices. This assumes a client/owner would not want to pay to shade a whole building and that there are urban conditions that will provide some free shading, so the problem becomes; which areas contain shading opportunities that make the largest impact on energy use?

[52] Ibid. 5
[53] Ibid. 7
[54] *Solar control and shading devices,* 88-92
[55] *A Study on Optimizing Shading Device Configuration for Glass Curtain Wall Buildings*, 5.

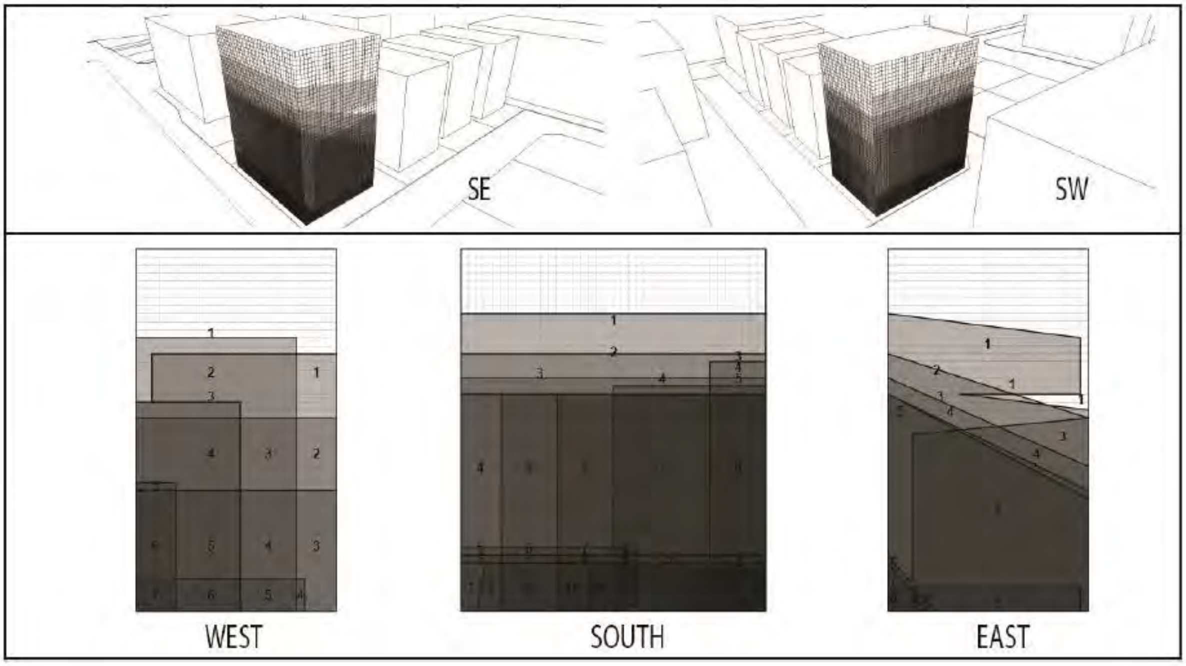

Figure 20. Facade Shade Studies. Source: Park and Lee, 7.

This image shows the mapping on daylight studies on to the exposed facades of a typical building block in an urban condition.[56] The question of which windows to shade is a very unique question with architectural implications. Designing a whole façade system is much different than the prospect of a partial façade system. Sefaira, for example will optimize per façade, but will not consider sections of the façade, all of the southern oriented sections of façade will be treated the same as any other section, even though not every window contributes equally. Sefaira runs whole building simulations and is looking for a best case equilibrium point where each device is the same and perform is optimized. The idea of localizing shading device only where they are need is actually a very novel idea.

Similar results could presumably be achieved if instead of a whole building simulation, a designer moves towards a zone by zone analysis. This would, in fact, vastly increase the number of simulations that need to be run. The Payette study incorporated 36 iterations that involved 36 energy simulations and 36 daylight simulations, if this was done with 10 floors and 8 zones per floor now 2,880 energy simulations and 2,880 daylight simulations are required. In the Study, *FAST Energy and Daylight Optimization of an Office with Fixed and Moveable Shading Devices*, the authors astutely recognize the restrictive nature of large numbers of simulations, "The time required by numerical simulation, in particular using raytracing techniques, is the main difficulty a researcher faces in dealing with

[56] Ibid. 7

optimization and daylighting".[57] They go further to directly state, what they see as the major hurdle in this design process,

> The most robust algorithms can be considered the ones belonging to the category of evolutionary (or stochastic) algorithms, and in particular the ones based on Genetic Algorithms. One limitation of these algorithms when applied to real practice underlies on the large number of simulations that might be required, since they generally grow linearly with the number of input parameters and objectives considered.[58]

Even if a design team is not required to run each simulation manually and they could be run simultaneously or sequentially this method would require dedicated computers or servers to not disrupt office work flows, and still take days, at a minimum to accomplish. If this would be a onetime exploration this would not be so difficult, in fact Sefaira actually utilizes a server to process simulations that users run, however, if a designer wants to incorporate a new variable, or new formal move into the design the process needs to be reset.

> Optimization techniques are widespread in industrial design and are attracting further interest in building design. The main goal of an optimization tool is to explore different configurations during the early design phase process allowing the designers to investigate innovative solutions. The main characteristics of an optimization techniques are the robustness, intended as the capability to explore designs without been stuck in local minima or maxima, the possibility of dealing with multiple optimization objectives and the time required by the process.[59]

This is a very good description of what optimization should aim for, presenting design options that perform well.

Another study, *Genetic Optimization of External Shading Devices*, offers a different perspective and critiques the method used in the Payette study;

> Optimization algorithms can be divided into classical and evolutionary. Classical techniques are not able to deal with multi-objective optimizations, instead they use the so-called utility functions. Namely, with the use of some criteria (weighting operations) in order to combine the objectives, a unique functional is created and optimized as a single objective. On the other hand, evolutionary (probabilistic) algorithms allow maximizing a function without any restriction imposed by functional constraints, as gradient-based algorithms do. Moreover, they can perform truly multiobjective optimizations.[60]

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[57] *Fast Energy and Daylight Optimization of an Office with Fixed and Movable Shading Devices*, 176.
[58] Ibid.
[59] Ibid.
[60] Manzan, Marco, and Francesco Pinto. "Genetic Optimization of External Shading Devices." 180-87IBPSA, 2009. 183.

When the authors mention optimization algorithms, they are referring to the way in which metrics are evaluated. The Payette study created a method for weighting the three criteria, heating loads during the summer, cooling loads during the winter, and useable daylight level.[61] Daylight and heating/cooling loads do not directly share units, so it makes sense that one would need an external unrelated system to collapse all of the metrics into one value that represents the overall performance. The authors claim probabilistic optimization algorithms can solve this issue by reducing multiple criteria to probabilities of occurrence, such as the probability the lights are turned on or off.[62]

In addition to a new take on genetic algorithms, this particular study also incorporates new parameters into the exploration, "A genetic optimization approach has been used for the design of an external shading device in an office with a window and different glass characteristics".[63] It is interesting to see an exploration where glazing properties are altered. This would indicate that not just variables that influence the form and location of a shading device are important, but almost any variable that alters the energy profile of a building or zone could determine how a shading device needs to perform. A building with more insulation will have different under heated and over heat periods to a building with none, the intensity of these periods will be different, thermal mass might play a role, glazing properties as suggested, as well as many other factors.

Other studies focus on optimizing for certain locations and building programs such as a school in Taiwan as is the case in *Optimal Sun-Shading Design for Enhanced Daylight Illumination Of Subtropical Classrooms*.[64] This study simulated lighting conditions for over twenty iterations of shading device configurations looking at simple rectangular overhangs and light shelves at different heights on the window.[65] This is very similar to the Payette study in the way that both were interested in daylight and simulated many iterations in order to find the best design. The authors of this study were not as concerned with the quality of the daylight as much as the potential to use daylight to reduce electric light use. In the beginning of the study they mention a target reduction in electric light usage, "Bodart and De Herde estimated that the implementation of appropriate daylight access devices can reduce artificial lighting power costs from 50 to 80%".[66] In the conclusion to the study 70% reduction in lighting energy is said to be achievable in this case,

> Hence, this optimal sun-shading design not only improves the illuminance conditions within the classroom, but also achieves an energy saving of 70% approximately in this

[61] *ABX: The Good, the Bad and the Shady – Payette*, 35-8
[62] *Genetic Optimization of External Shading Devices*, 183
[63] Ibid. 180
[64] Ho, Ming-Chin, Che-Ming Chiang, Po-Cheng Chou, Kuei-Feng Chang, and Chia-Yen Lee. "Optimal Sun-Shading Design for Enhanced Daylight Illumination Of Subtropical Classrooms." 1844-55Energy and Buildings, 2008. 1844
[65] Ibid. 1850-3
[66] Ibid. 1844

> case study from the results calculated in the date of Winter Solstice and Summer Solstice. However, more accurate calculation of the whole-year power savings needs a large amount of instances over different times of the day and over several days and, of course, the practical operations during the lessons in Taiwan.[67]

This summary brings to light a number of good points. First to be more accurate in this study one needs to look at the whole year instead of just the Summer and Winter Solstice. This is true, but would add many more simulations that might not be practical for a normal firm to undertake for a single design. Second, the times in which school operates in Taiwan should be the focus of the study. It could be assumed, under proper building management, that the lights are not all turned on after the school closes. Therefore, to reduce lighting usage the times classrooms are in use have to be the focus of the study.

In fact other studies do look at heating and cooling load reduction as a function of money and not just comfort, “Proper use of building shading devices can [not] only improve the thermal comfort in indoor environment, but also reduce cooling energy consumption effectively”.[68] This study by Jinkyun, Yoo, and Kim seeks to make an economic case for shading devices. This is an interesting approach as many builders and designers have a view of sustainable methods and technologies that they add too much cost to projects and are often quickly cut from the budget. In a study titled *How Much do Green Buildings Cost? The Perception VS. The Reality in Emerging Markets*, the author had this to say:

> As a result, most developers make simple assumptions, often based on hearsay, such as that the green building design and construction process increases development costs by 5 to 10%, or more. Since this process is obscured by many uncertainties and complexities for the decision makers, even at these rent premiums, most green building ideas are dropped by developers at an early stage, as they do not want to take additional risks associated with what they see as an unknown and obscure course of action.[69]

If a designer does not understand the impact in dollars that shading devices have on their particular project, the devices will be seen as primarily aesthetic decisions and can be easily removed if the budget is under tight constraints. Kagan mentions that building sustainably never was meant to be an expensive exercise, but primarily a process of value engineering,

> Green buildings are not just about elaborate sustainable design solutions and construction practices but also about economical feasibility. In the same way that value engineering is typically performed in every design aspect of a construction project, value engineering for sustainability and green certification criteria is equally essential.[70]

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[67] Ibid. 1855
[68] *Viability of Exterior Shading Devices for High-Rise Residential Buildings: Case Study for Cooling Energy Saving and Economic Feasibility Analysis*, 771.
[69] Ceylan, Kagan. "How Much Do Green Buildings Cost? The Perception Vs. The Reality in Emerging Markets." 26-32Journal of Sustainable Building Technologies, 2015. 1
[70] Ibid. 9

A project attempts to do as much as it can under budget constraints, if one sustainable measure cost too much it is removed and if another adds value and the costs are reasonable it is included. Shading devices have the potential to save the client money on an annual basis in terms of reduced cooling costs in exchange for higher up-front costs in construction. The study by Jinkyun, Yoo, and Kim took a familiar design, iterate, analyze, select method to optimize for cost, as seen in table 2 from their article.[71]

Table 2
Selection and classification of alternatives depending on exterior shading types.

External shading types		Configuration
Baseline model	Baseline	No shading (none)
Type A: horizontal single overhang	A02	Overhang depth (200 mm)
	A04	Overhang depth (400 mm)
	A06	Overhang depth (600 mm)
Type B: horizontal multiple overhangs	B06	Overhang depth (200 mm) and spacing (600 mm)
	B08	Overhang depth (200 mm) and spacing (800 mm)
	B10	Overhang depth (200 mm) and spacing (1000 mm)
Type C: vertical fins	C02	Fins depth (200 mm)
	C04	Fins depth (400 mm)
	C06	Fins depth (600 mm)
Type D: vertical multiple fins	D04	Fins depth (200 mm) and spacing (400 mm)
	D06	Fins depth (200 mm) and spacing (600 mm)
	D08	Fins depth (200 mm) and spacing (800 mm)
Type E: vertical panel	E02	Panel height (200 mm)
	E04	Panel height (400 mm)
	E06	Panel height (600 mm)

Figure 21. Shading Typology Study. Source: Jinkyun, Yoo, and Kim, 774.

Five different types with three iterations per type are explored in this study. The authors mention that this study might not be as complete as they might want, "Finding the optimal shading device installation angle by each orientation would be very important; but since it is also important here to find the general type that can be applied to residential buildings, the installation angle was fixed".[72] They are correct that the angle of the shades will also have an impact on how they perform and should be included in the study. This would have meant a large increase in simulations that the authors might not have been prepared to do. The comment about finding the type that can be applied to residential buildings in general is not correct in that they are optimizing for their baseline, if the project is moved, rotated, altered in any way the energy model changes invalidating the results of this study. They are optimizing for a baseline not residential buildings in general. Through these iterations they were about to find a load reduction for multiple shading types, "The annual cooling load reduction shows a maximum of 19.7% for the

[71] Viability of Exterior Shading Devices for High-Rise Residential Buildings: Case Study for Cooling Energy Saving and Economic Feasibility Analysis. 774.
[72] Ibid. 777

horizontal overhang, and 17.3% for the vertical panel".[73] This size load reduction could lead to sizeable savings enough to justify the shading device's installation along purely economic grounds. The study did find favorable simple payback periods, "Economic feasibility analysis taking installation cost into account showed a simple payback period of about 3.4 years for the horizontal overhang, and 8.7 years for the vertical panel".[74] This is very encouraging to support the argument that the design of shading devices is necessary for some building typologies on economic grounds. The article goes on to point out that the design of shading devices may allow a design to value engineer other areas of the project, "Also, the application of exterior shading devices is expected to replace the use of expensive, high-performance glass".[75] If shading devices can perform well enough glazing, which is also expensive, can be downgraded to become more affordable. This could also work its way into a more in-depth study on the economic impact of shading devices. Another Article, Static Shading Devices in the Architecture of Buildings, brings forward similar concerns about cost; "The planned use of static shading devices initially requires significant investments, which are from the long-term savings viewpoint negligible".[76] This particular study looked at daylight factor as a simple overhang and other typical typologies are extruded at different lengths from a wall hosting a window.[77]

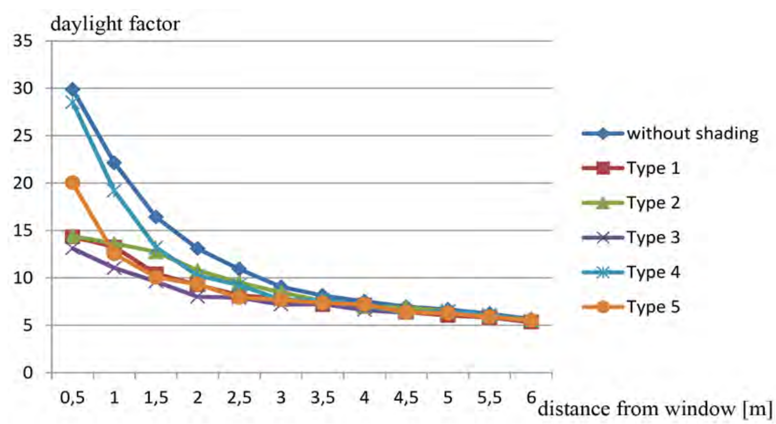

Figure 22. Daylight Factor Study. Source: Static Shading Devices in the Architecture of Buildings, 127.

"The south-oriented facade and effectiveness of five characteristic cases of horizontal static shading devices are analyzed in this section".[78]

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[73] Ibid. 780
[74] Ibid. 785
[75] Ibid.
[76] Komatina, D., S. Paunovic Zaric, E. Alihodzic Jasarevic, N.D Sokolovskiy, and S.A. Riabuhina. "Static Shading Devices in the Architecture of Buildings." 122-34Construction of Unique Buildings and Structures, 2015. 130
[77] Ibid. 127
[78] Ibid.

Up to this point solutions generated by this method have had a wide range of goals and metrics by which to judge the results. However, it is also possible to use the same method to generate more interesting aesthetic shading devices that also perform. In an article titled, *Computational Design and Parametric Optimization Approach with Genetic Algorithms of an Innovative Concrete Shading Device System,* the question of optimizing new forms with new techniques and materials is addressed, "With new concrete materials and innovative digital fabrication process is possible to rediscover concrete for high performance façade/shading solutions".[79]

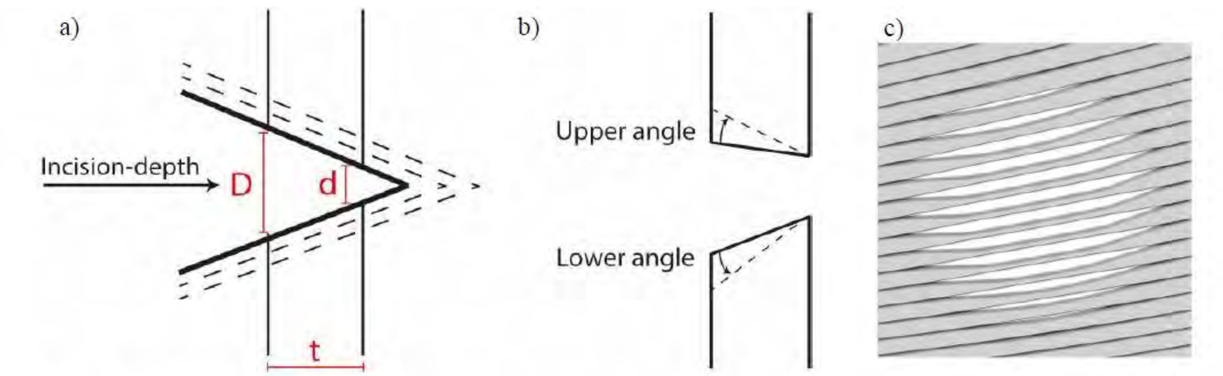

Fig. 4. Main variation parameters in geometry definition (a) Incision depth, d/D factor; (b) Upper and lower angle rotation (from 0° to 25°); (c) Concrete shading system selected for simulation phase.

Figure 23. Concrete Screen Study. Source Computational Design and Parametric Optimization Approach with Genetic Algorithms of an Innovative Concrete Shading Device Sysyem, 1478.

This study is thinking of the problem from the perspective of not just performance with the goal of creating an aesthetic solution, but also from a material property perspective, "As described in figure 2 the first sets of input inserted in the workflow are the material properties, structural and fabrication constrains which affect the maximum dimensions and the minimum thickness of the panel".[80] In the design, iterate, analyze, select method any number of variables on any subject can be taken into account to create iterations or to create metrics by which to judge the result. The inclusion of more variables does mean the process will take much longer. In this case thousands of simulations are run, "After three thousand iterations and preliminary daylighting simulation performed on a set of solutions, an optimized solution has been selected".[81] Three thousand simulations is not acceptable for a normal design work flow. Again, if anything about the energy model changes all three thousand simulations become invalidated. If the R-value of the exterior walls changes, the glazing size, type, shape, or orientation changes, or even the

[79] *Computational Design and Parametric Optimization Approach with Genetic Algorithms of an Innovative Concrete Shading Device System*, 1473.
[80] Ibid. 1475
[81] Ibid. 1481

program of the space behind the shade then another three thousand simulations need to be run to reach an optimized design. Ultimately the authors were able to produce a design that performed better than a simple over hang design,

> Analyzing the results, stated in Table 5, is possible to notice a slightly decrease in total energy demand from 65.3 kWh/m2y, for overhang design solution, to 58.9 kWh/m2y for the optimized system. Whereas, the most important improvements have been obtained in terms of daylighting performance.[82]

Energy savings and improved daylight quality is certainly important, but more importantly they were able to create an architectural solution that solved pragmatic problems. It is worth noting that the comparison to the overhang in the study may not be entirely fair as only one solution was optimized by any system. It could be entirely possible that a simple overhang solution exists that performs as well, however, this study was not looking for that form.

Overall the Iterate Method has strengths and some weaknesses. It is able to allow the designer absolute freedom in expression, and offers a wide range of criteria to judge the final result. However, it does not help to guide the user to design effectively from the beginning. Nothing is in place to stop a user from iterating and optimizing a form that will not work well for their design context. Also, the more iterations that are created the closer one gets to an optimized design. This would indicate the method is only approaching optimized but never truly reaches an optimized design. The number of simulations needed to provide good results may be too high for people in practice to implement. Additionally the results of such a study can be invalidated by simple, common design changes such as insulation levels in the exterior walls, orientation decisions, glazing property changes, alterations to the building's use/program, changes in mechanical systems, and many more. While this method provides freedom in design and has the potential to ensure good performance along many criteria, it is not flexible enough to be adapted to the design process in practice.

1.3 Cell Method

The final design method, the Cell Method, is much more experimental and less mainstream than the other methods discussed in this thesis. This method does attempt to address the same problems as the other methods from a very different perspective that is worth taking into account.

SHADERADE is the most current version of this method, with some earlier work done in 2003 by Marsh and in 2001 by Kaftan.[83] The authors of this method describe it as follows; "The approach is

[82] Ibid. 1482
[83] *Shaderade: Combining Rhinoceros and Energyplus for the Design of Static Exterior Shading Devices*, 310.

implemented as an eponymous tool based on Rhinoceros and EnergyPlus and offers flexible, novel techniques for assessing the thermal desirability of solar transmittance through any potential shading volume or surface".[84]

> SHADERADE traces back individual rays from different parts of a window along different solar angles in order to quantify their competing effects over a 3-dimensional 'shading volume.' The approach resembles the 'cellular method' described by Kaftan and March, but uses a vector-based volumetric analysis, and a fractional rather than binary evaluation of beam desirability for each time segment.[85]

SHADERADE is evaluating for each voxel (3D pixel) how much, by not blocking that space it is contributing to the cooling load and detracting from the heating load and representing this as a gradient between heating or cooling dominated. Past works only represented each cell as a binary, shade or do not shade SHADERADE looks at each cell as on a gradient and allows the user to define the threshold to determine which cells are shaded and which are not. As an evaluative tool this is very effective, as a design tool the decision to shade or not to shade is very often a binary choice for each point in space. There could be translucent shading options, however, in practice one would need to clean the shades frequently or else the amount of light passing through would not remain at the design values. The figure below shows this tool working.[86]

[84] Ibid.
[85] Ibid. 313
[86] Ibid. 314

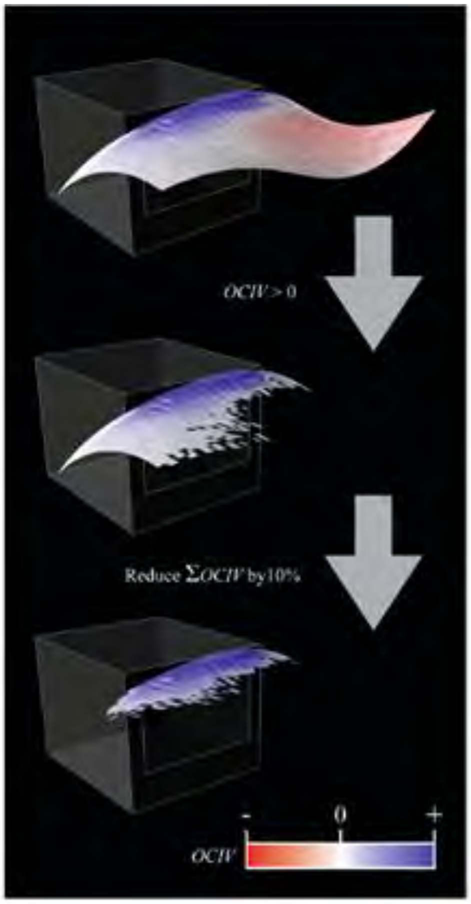

Figure 24. SHADERADE Applied. Source: Shaderade: Combining Rhinoceros and Energyplus for the Design of Static Exterior Shading Devices, 314.

Because one cannot properly visualize the effect of a shading form before it happens, one must design a shade first before evaluating which parts contribute and which do not. This method does calculated the impact of the voxels in a volume and this can be visualized, however, until a shade is designed this method cannot predict beforehand the effect that shade might have on surrounding voxels. This method does not help a designer know if their solution will work before running the simulation, however, it does provide feedback once a design and simulation have been complete.

Their study included running three baseline cases located in Boston, Phoenix, and Anchorage.[87] The methods tested included looking at degree days, thermal selection, and design for the equinox, over different time periods including just noon for the days to shade, 10AM to 2PM, and 9AM to 3PM.[88] Against existing design methods, SHADERADE better than the other test designs, “The SHADERADE

[87] Ibid. 310
[88] Ibid. 315

group produced the largest average savings across the three climates, with a mean load reduction of 26% (…) the method was also the most consistent, with the three SHADERADE solutions always being within 3% of the best performing shading devices for all climates".[89] This would indicate that the Cell Method can produce, if not the best, nearly the best solution consistently compared to a version of the Climate Method. This study does not look at genetic optimization or the Iterate Method in general.

SHADERADE is also very focused on heating and cooling loads. Questions about daylighting cannot be addressed in this method at the moment. This method is relatively free in terms of design constraints, however, it is constantly revising your designs as opposed to generating them. If a designer creates a form that everyone in the project is happy with, SHADERADE can tell the design team which sections work and which do not. This forces the designers to make a choice to change the design, by cutting out sections, or live with a certain measured degree of inefficiency. The act of subtracting from an existing design would not work in many cases where stock shading options exist, however, in cases where form finding/ more creative solutions are being sought this could provide performance based inspiration.

Similar to the Climate Method, thousands of simulations do not need to be run to find an optimized design. However, one of the benefits of the Climate Method was its ability to suggest typologies and then provide the frame work to size them, albeit size only orthogonal versions of these typologies. The Cell Method has a more guess-and-check feel, where a designer creates and architectural solution to shading and then is told by the program which parts function and which do not and the designer must go back and reevaluate the design from what was learned. It is possible that a design just approximates the form the program derives. A rectangle could be fit over the more organic shape if using regular forms is a priority, there is nothing to say the solution must be odd looking.

There is an additional issue pertaining to self-shading that makes it impossible to effectively design some topologies. For example. A set of louvers will shade the ones below and will constitute multiple shading surfaces. The system cannot handle more than one surface at a time at the moment which means primarily overhangs and 'hoods' are the design solutions that can be evaluated/altered within the Cell Method.

[89] Ibid.

Chapter 2.0 Vector Method

This method runs on a combination of Grasshopper, Honeybee, Ladybug, and Rhinoceros as platforms to model building geometry, run simulations through EnergyPlus, analyze and filter data, and bring that information back into the 3D modeling space to allow design to occur. The method is called the Vector Design Method, because it focuses on design and outputting sun vectors that should or should not be shaded according to different quantifiable design metrics. This is not meant to be an evaluative tool like SHADERADE, but more of a generative springboard for design like the shading masks in the Climate Design Method.

The goal is to create a method that becomes a design tool solving many of the issues relating to usability and flexibly in design that occur in the other existing methods, previously discussed.

First the Vector Method will be explained, detailing the process. Then the different variables that impact the form solutions take in the Vector Method are explored. This is taken both as an exploration of the breadth of considerations the Vector Method accounts for in design, but also as a type of form finding to understand conceptually how a shade can be impacted by certain conditions. Next the Vector Method will be compared against the other three existing methods (climate, iterate, and cell) to see how well each performs in a controlled baseline scenario where the same energy model is used with the same goal to create a simple overhang shading device to reduce thermal loads by as much as possible. Next the Vector Method will test its ability to create similar performing iterations, to allow true flexibly in design. The same baseline model is used, however, this time multiple design iterations that all use the Vector Method are simulated and compared to determine if design decisions based on other architectural factors aside from energy performance can be considered without compromising thermal performance.

2.1 Process

This workflow begins with an unshaded energy model of the zone, step 1 in Figure 25. This model is used to create a 3D shading volume to guide design exploration. The Vector Method takes inspiration from the Cell Method's specificity and instead of evaluating every cell, evaluates every sun vector and matches the direct solar radiation passing through the window with the cooling load during the same hour. If there is no cooling load or direct radiation then an hour is culled from the list. A user-defined threshold is introduced to allow a designer to determine how sensitive a design needs to be towards cooling loads. If the threshold is set very low or not set at all, then most or all hours with cooling loads and direct radiation will be included in the shading mask, if the threshold is set higher only the hours with the highest cooling loads will be included. Often there exist hours with more extreme sun angles that do not contribute much to the increased cooling load in a zone and would create a larger mask without providing many benefits. Reducing the data to the highest set of cooling hours reduces the size of the volume and allows more direct sunlight to enter during times when the heating load is dominant. Determining which hours to shade occurs in step 2 in Figure 25.

Once each hour where shading is needed is identified, the position of the sun can be determined according to solar calculations through Honeybee using RADIANCE using the project's location to determine for all daylight hours where the sun is relative to a single point on the ground. The Sun's altitude and azimuth angles at each designated hour can become points (X,Y) and a designated Z height above a prospective window. These (X,Y,Z) points are the same as vectors originating at (0,0,0), step 3 in Figure 25. By taking the profile of this set of vectors a flat shape a Z height that represents all solar vectors at all times that need to be shaded can be established, step 4 and 5. Extruding the profile of the window or area to be shaded along each vector and joining each extrusion results in a three-dimensional shading mask that can be interacted with in modeling space, as any other architectural element. The mask shown in step 6 takes into account the geometry of the window, orientation, and data filtered from the initial energy model to inform the size, shape, and character of the resultant shading mask.

Once the three-dimensional shading mask is created, the user creates a solution that cuts the whole window off from the sun vectors represented in the volume. This could take the form of anything from a simple plane intersecting the mask above the top of the window, as shown in step 7, or smaller tessellated shapes covering the window, each sized to shade their own portion of the window during the desired time frame. Because this shade volume is in model space that can be integrated within the context of the whole project, it is easier to understand the aesthetic impact each decision makes while ensuring that each iteration performs to a similar degree.

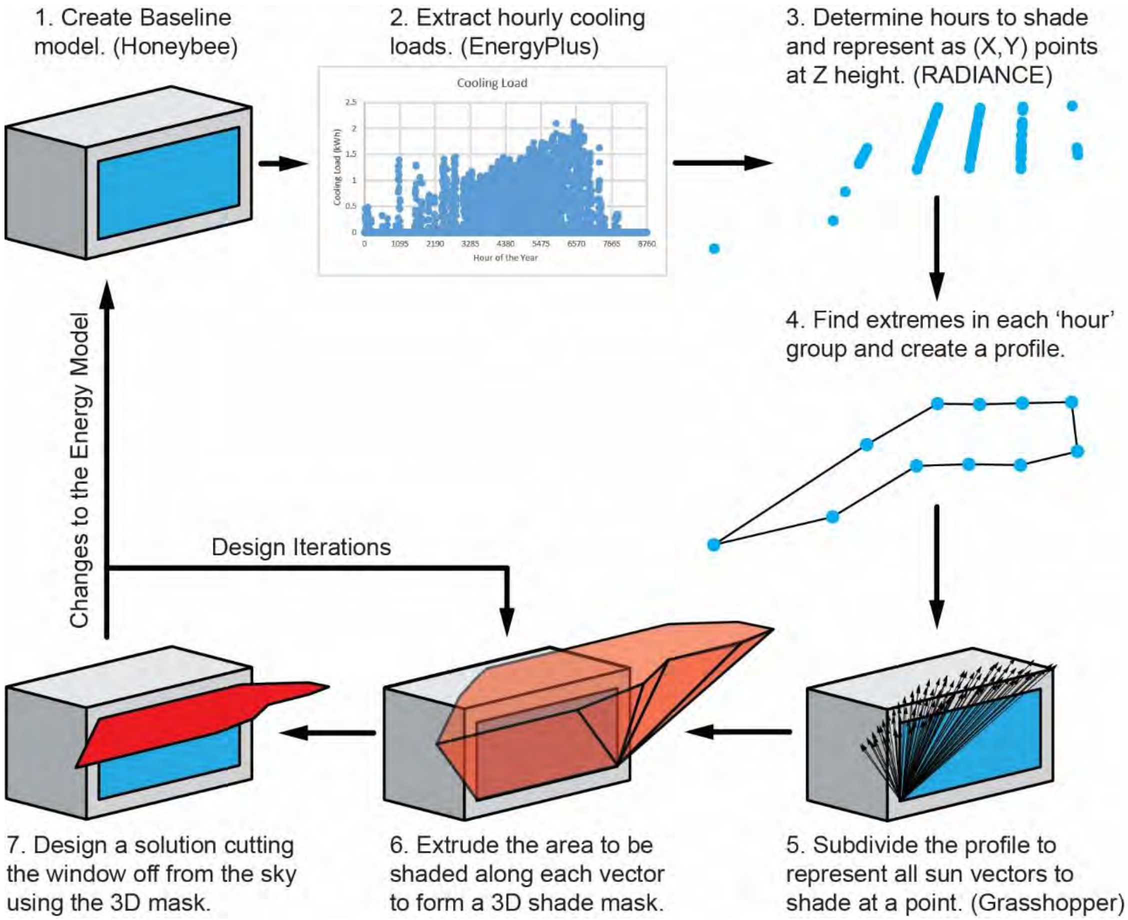

Figure 25. Vector Method Workflow

The incorporation of Grasshopper communicating with a digital interface, highlights that fact that this method is gravitating towards a parametric workflow which could add a needed sense of order to the complex problems faced by shading devices.

Just like the Cell Method searches for new forms a parametric system can find new forms through rigid adherence to a scripted logic,

> Positively, parameterization can enhance search for designs better adapted to context, can facilitate discovery of new forms and kinds of form-making, can reduce the time and effort required for change and reuse, and can yield better understandings of the conceptual structure of the artifact being designed. Negatively, parameterization may require additional effort, may increase complexity of local design decisions and increases the number of items to which attention must be paid in task completion.[90]

[90] Aish, Robert, and Robert Woodbury. "Multi-Level Interaction in Parametric Design." 151-62. Heidelberg Springer-Verlag Berlin, 2005. 151

By relegating the mechanics to the background the user does not need to be concerned with processes that determine vectors and the 3D form generated actually communicates something about the nature of the solution.

A parametric system needs to have a firm repeatable logic, like the generation of the 3D shade mask from an energy simulation of a zone in a building. It is understood that changes will occur in design and a parametric system needs to account for these changes. Edits to the energy model need to relate graphically to the 3D shade mask. As edits occur changes need to become apparent relatively quickly,

> The implication is that commercially-available CAD systems should strongly consider incorporating immediate liveness, if not what we term 'extreme liveness,' into their interfaces. When it comes to other features, designers should consider preview and localization features that build on our study results.[91]

Being able to see changes in real time can help a user connect their actions directly to the impact on shading in the project. Changes to parameters such as window geometry, orientation of the zone, changes in the energy simulation, and others need to reflect directly to the generated form. "The immediate feedback that users received in the model for scripting actions, allowed for quick evaluation of the results, detection of errors on the spot, and fixing them before moving on to the next tasks".[92] Being able to see the impact of design decisions as well as identify problems early on, such as finding out vertical shading alone will not adequately shade a southern facing window in Albuquerque, New Mexico, can help a designer trouble shoot the situation and reevaluate their chosen typology before getting too embedded in the process.

2.2 Design Tool

As a designer and user of the Vector method, one would not be expected to know the technical underpinning each step in the process. A tool based upon this method conceals the inter-workings the user does not need to engage with while bring to the forefront aspects that demand design decisions to be made. This tool represents the workflow that a user would need to engage with, which is unique to the technical workflow represented in Figure 25.

The tool takes the form of an interface generated in Grasshopper for Rhino using the plugin Human UI. Large complex Grasshopper scripts can be extremely overwhelming for users unfamiliar to

[91] Maleki, Maryam M., Robert F. Woodbury, and Carman Neustaedter. "Liveness, Localization and Lookahead: Interaction Elements for Parametric Design", 805-14. Vancouver, BC, Canada: Digital Fabrication Landscapes, 2014.
[92] Ibid. 812

the scripting process. This makes it necessary to have a singular, clean interface as to avoid confusion in the user experience. The interface is laid out so that there are 6 tabs taking the user through 5 steps to create and evaluate shading design solutions and includes a last tab with debugging capabilities if difficulties are encountered at any stage in the process.

In order to use this tool a designer needs to own either Rhinoceros 5 or 6 and have the following free plugins installed; Honeybee, Ladybug, Grasshopper, Human UI, and LunchBox. Honeybee requires Openstudio, Radiance, and Daysim to be installed to run the necessary simulations. If a person does not want to run the simulations through EnergyPlus and would rather use a different simulation software capable of hourly load calculations one can modify the script to read values using another free plugin, Bumblebee, from Microsoft Excel. The only piece of this process that costs the user money is the one time purchase of Rhinoceros. This tool feeds into the open source culture surrounding Grasshopper to enable designers.

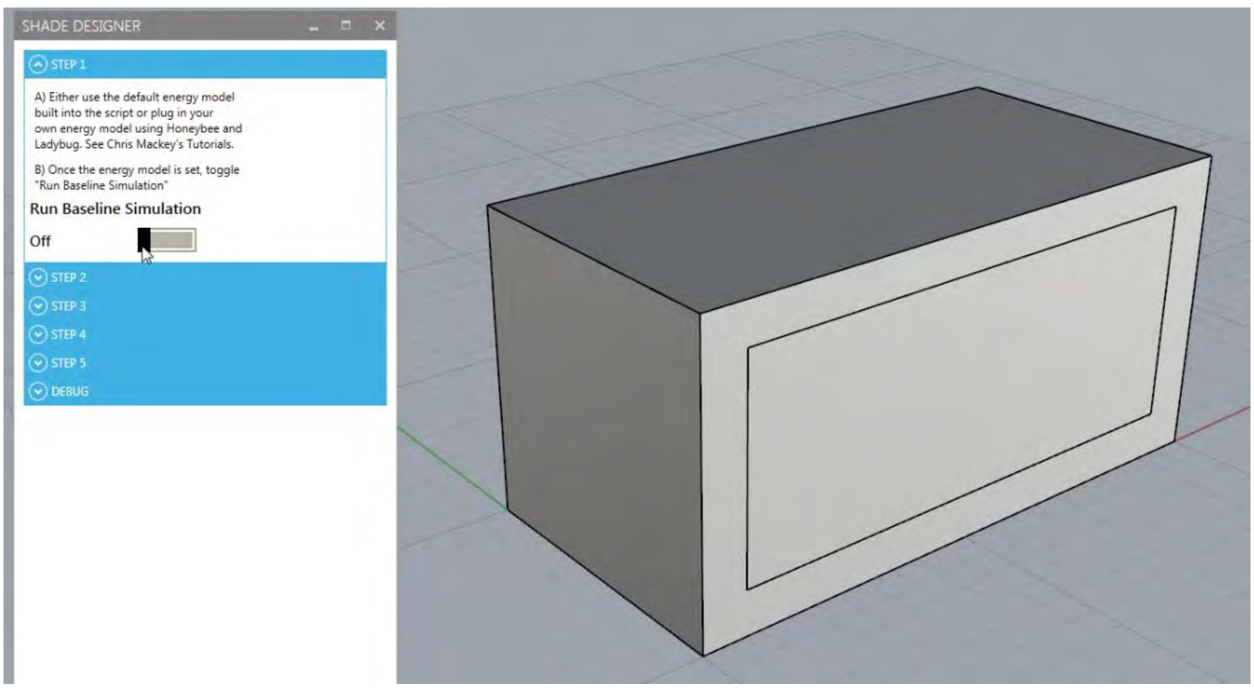

Figure 26. Vector Method Tool Step 1

Step 1 involves setting up and running a baseline model without shading. During this stage the program is actually completing steps 1 through 5 from Figure 25. The background data analytics to determine which hours of the year require shading is completed so that as soon as a profile to shade is selected a 3D shade volume is generated.

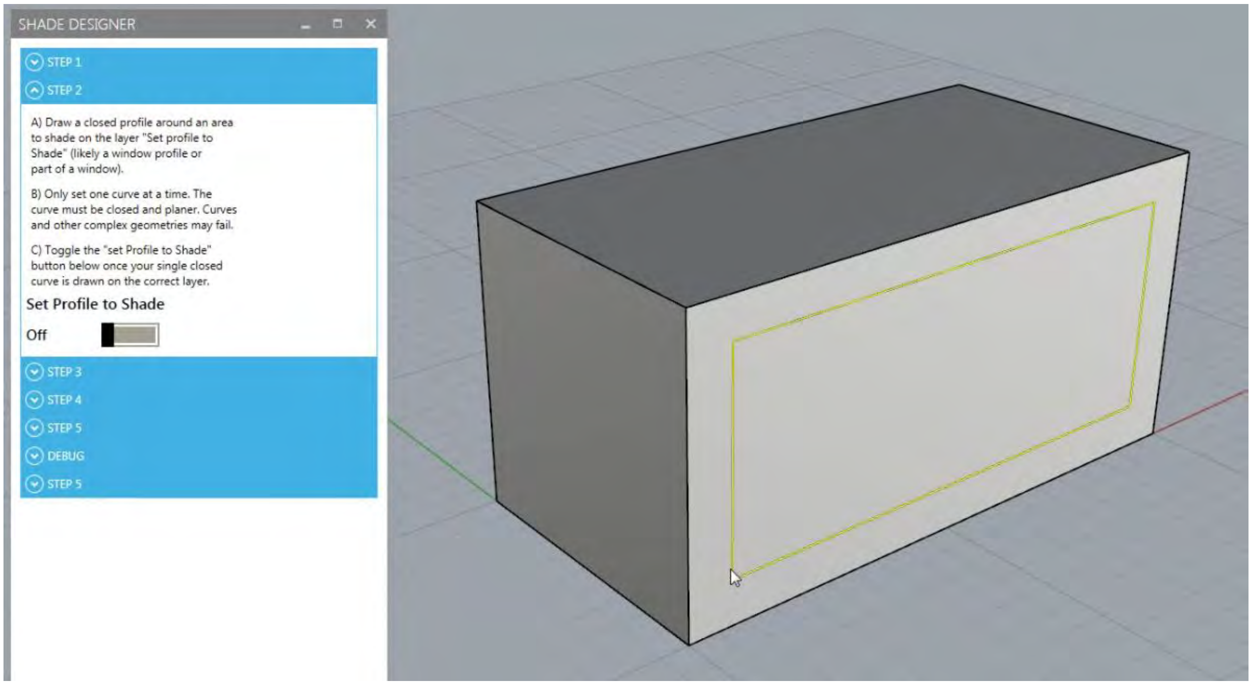

Figure 27. Vector Method Tool Step 2

The second step involves setting a profile to shade. This could be the whole window profile or just a piece of the window to create a tessellating pattern with the goal of creating a screen. The profile must be a closed polyline that is co-planner and does not involve curves. Curves can be incorporated by approximating curves with line segments.

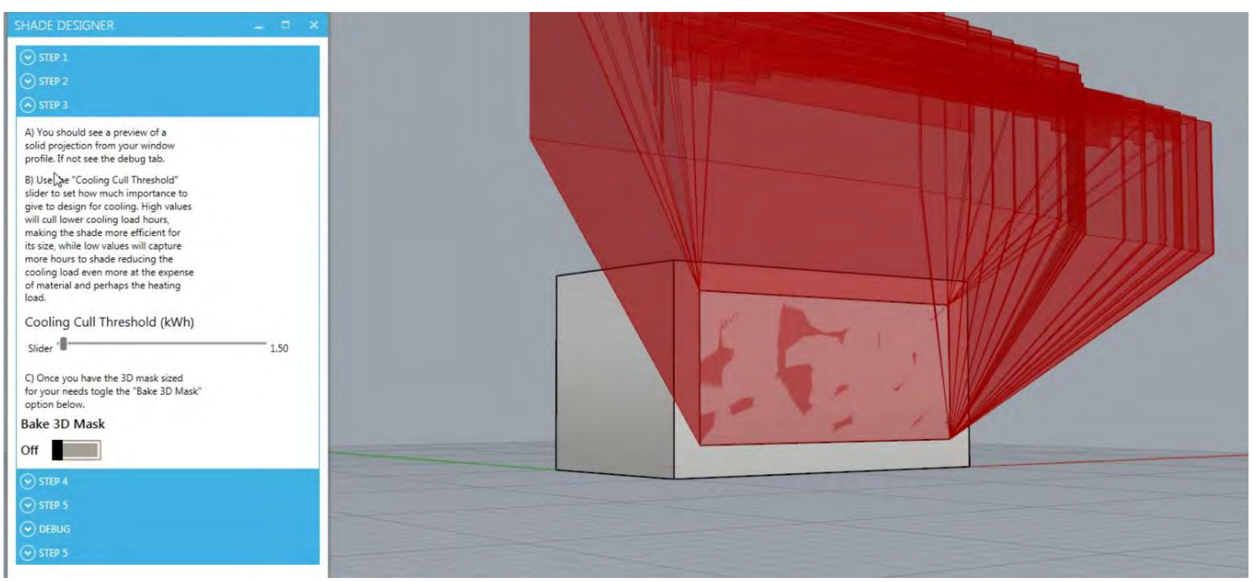

Figure 28. Vector Method Tool Step 3

The third step creates the 3D shade volume and allows the user to easily 'bake' or make solid the form. This allows a designer to more easily interact with the volume to create design solutions in step 4. The generation of the volume is also contingent on a 'culling threshold'. This threshold determines which levels of cooling loads are not worth attempting to shade with 100% coverage. If the threshold is set low, more hours and vectors will be included in the creation of the 3D shading volume. If the threshold is high the volume will become smaller, but will be accounting for times in the year where cooling is a much greater issue. A low threshold will reduce the cooling load at the expense of the heating load and the quantity of material used to build the device. A high threshold will produce designs more efficient for their size and potentially lower heating loads compared to low threshold designs.

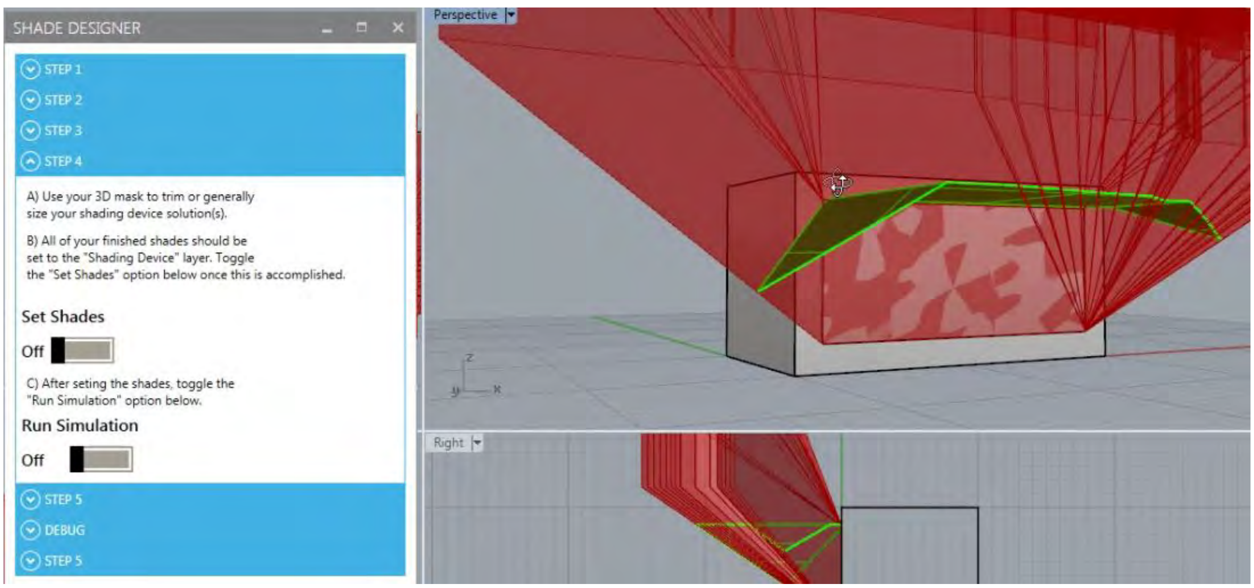

Figure 29. Vector Method Tool Step 4

Step four is to use the 3D shade volume to create design solutions. Anything that blocks the shading volume from the window will produce a functional shading device and each iteration that accomplishes this will perform to a similar degree. The 3D shade volume represents a volume of sunlight that is not to be allowed to enter into the window. The user is free to interpret the constraints literally and use the shade volume to cut a shade generating a unique form based on performance criteria or to use the shade volume as a general guideline to size more conventional forms.

The last step is to run a second simulation with the new shading device design in order to evaluate its effectiveness in reducing thermal loads. This is displayed as cooling load decreased, heating load increased, and the overall impact to the thermal load. A user can then save their design on a new layer and return to step four to create design alternatives. Each design will perform similarly, so the designer is freer to consider other factors surrounding economy, constructability, aesthetics, style, character, visibility, daylighting, and more.

The debugging tab includes sliders to increase or decrease the divisions that create the 3D shading volume. The volume is effectively the Boolean union of many extrusions of the profile to shade along a division of sun vectors to shade. At times these extrusions have difficulty joining consequently not allowing the 3D shade volume to display. This can be solved often by adjusting the divisions up or down by random amounts. Sometimes a form will too closely overlap another and Rhinoceros will not be able to perform the Boolean union function, adjusting the number of divisions will shift the extrusions enough to properly join. The tab also includes tips and reminders for each stage to help the user understand other areas of error previously discussed (such as modeling curves or failing to use co-planner polylines to set profile to shade).

2.3 Design Tool User Studies

The design tool presented in this thesis is the result of feedback gathered based on a user study conducted by the author. 15 graduate students in the Master of Architecture program at the University of Cincinnati were asked a number of background knowledge questions, shown a demonstration on the workflow of the Vector Method Design Tool, asked to design their own solution on the same baseline test model, and asked follow up questions.

Students were asked to rate their general background knowledge on shading device design on a scale of 1 to 10, 10 being very knowledgeable. The average score was 3.6. 20% of participants admitted they had not designed a shading device before on their own and of those that had designed shading devices 58.3% did so intuitively, without design tools or simulations to evaluate their designs. Students were then asked to rate on a scale of 1 to 10 how important various design goals are to them in general.

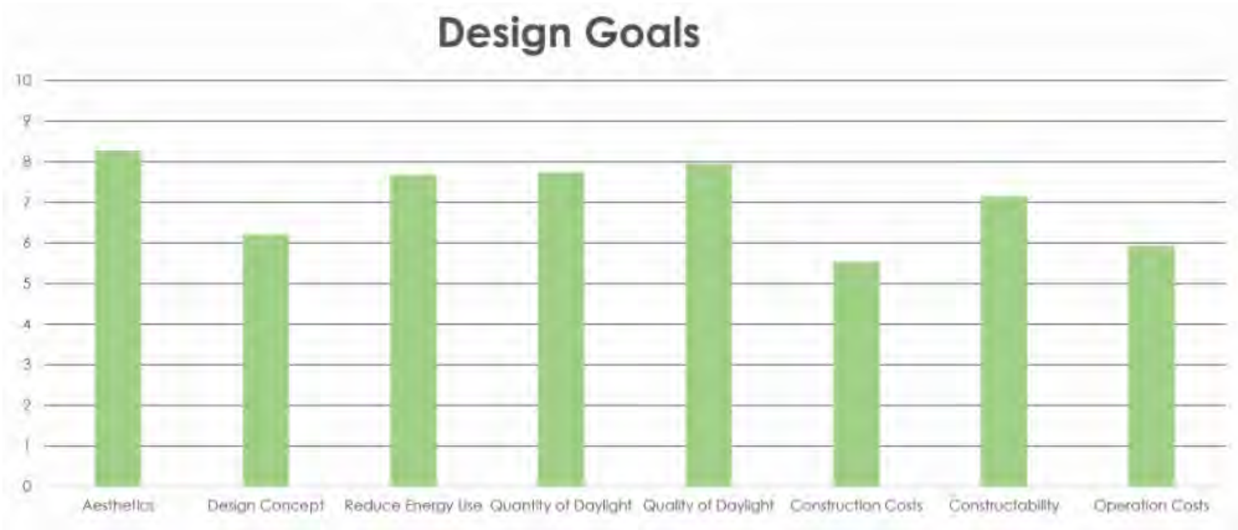

Figure 30. Design Goals Survey

Goals surrounding aesthetics, reducing energy use, and daylighting were higher than others surrounding construction and maintenance costs. However, there was no clear priority common to all 15 participants. It is clear that metrics that can be applied to shading devices are important to these designers even though they rate themselves low in general knowledge about shading device design. This mirrors the 2012 study mentioned at the beginning of this thesis.[93]

[93] *Tools and Methods Used by Architects for Solar Design*, 724.

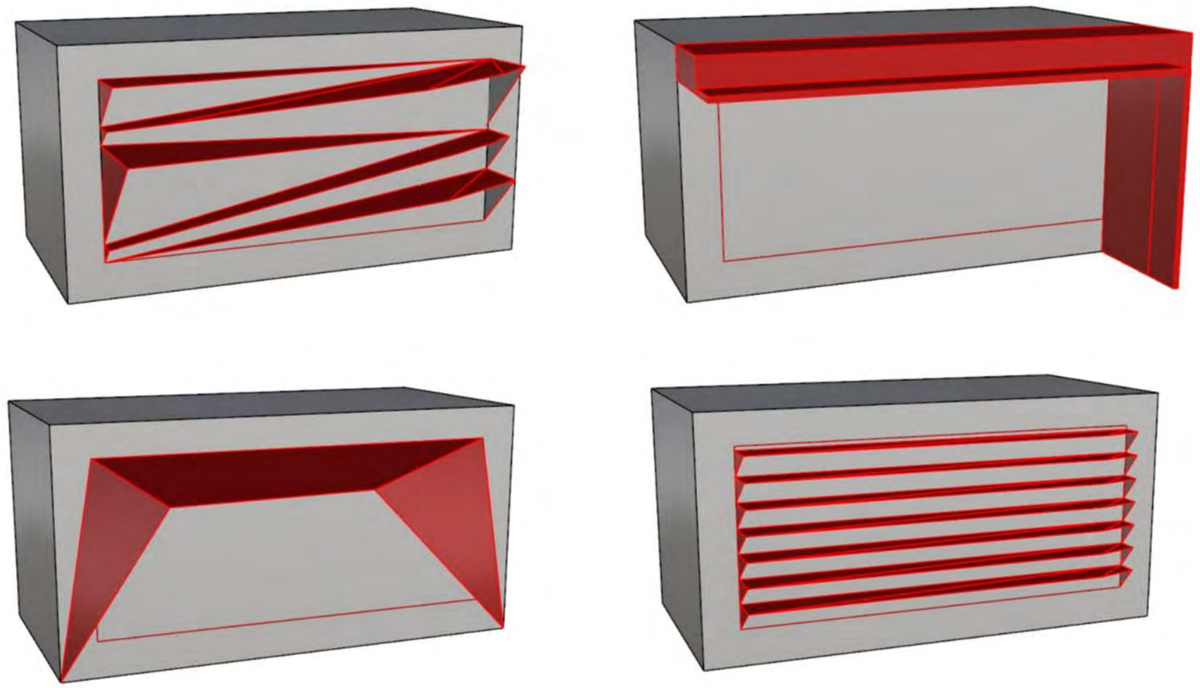

Figure 31. Student Designs

Figure 31 shows a handful of the designs created by participants of the user study. On average students took 12 minutes and 16 seconds to create a design solution, having used the program for the first time. Design solutions reduced the thermal loads for the baseline energy model by 17.23% on average. Designs fell into multiple typological categories including hoods, louvers, overhangs, and screens.

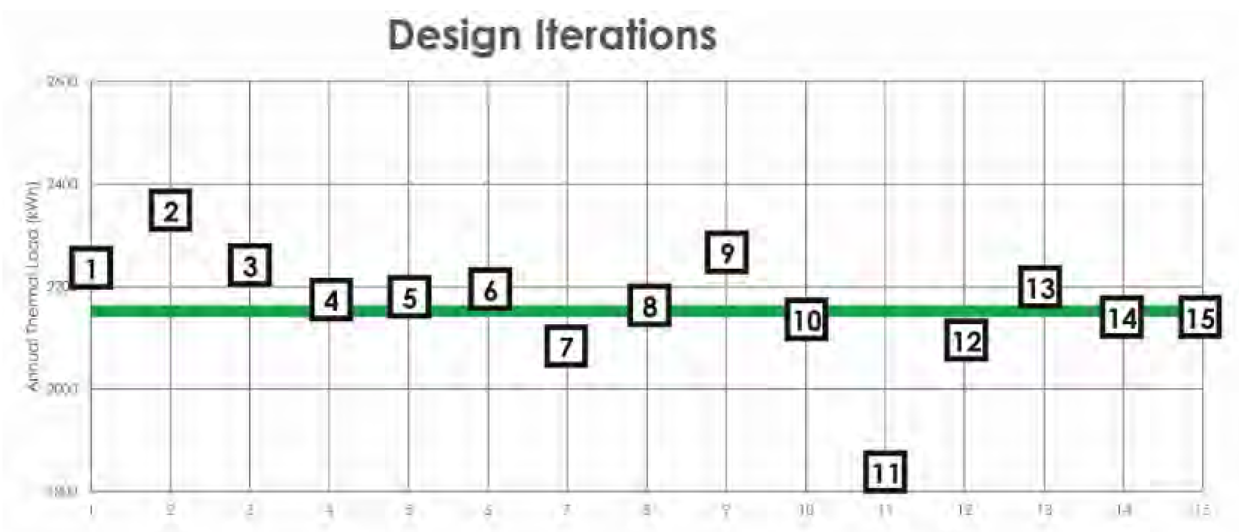

Figure 32. Student Design Performance

Figure 32 shows the performance of all 15 designs created by students, with the green line representing the average performance.

The follow up questions revealed participants were relatively convinced this method is fast compared to shading device design methods they have experience or heard about, while still remaining flexible. Low levels of difficulty were encountered and students were very confident they could repeat this exercise on similar conditions as well as create additional design iterations.

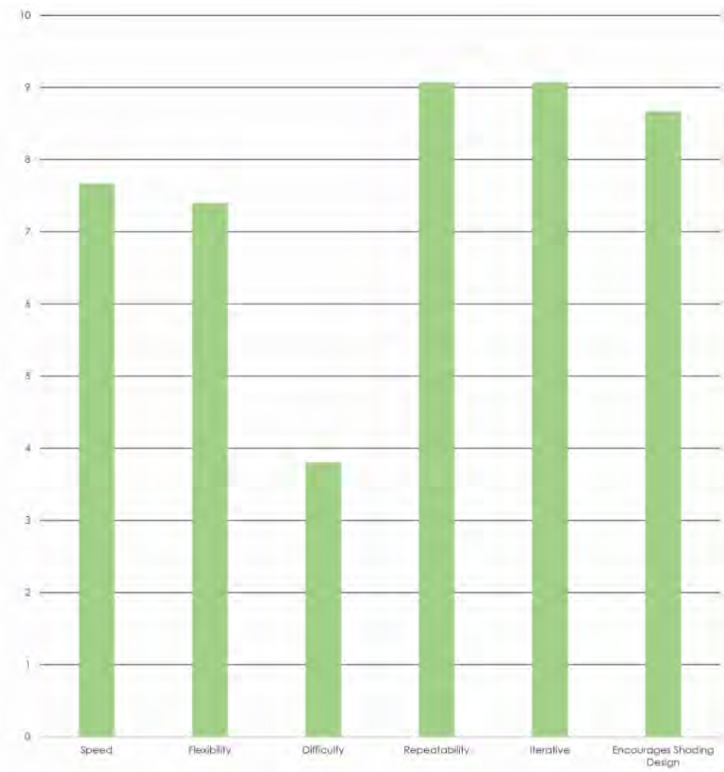

Figure 33. User Reactions to the Tool

This study influenced the current version of the tool, presented in this thesis, to incorporate all aspects into one interface and forgo the need to interact with the Grasshopper script directly. Users also suggested the tool be laid out in the steps needed to get from baseline model simulation to the end design to make it more intuitive and easy to follow. Users liked the fact one can see the model being worked on next to the design interface and updates were relatively instantaneous. Overall many said they would be more likely to design shading into future projects given access to a tool such as this in the future.

Chapter 3.0 Comparative Case Studies

3.1 Performance Study

To determine how the Vector Method performs in pragmatic terms, in its ability to design a shade that reduces overall thermal load, it is tested against each of the other existing design methods. This is accomplished by using Honeybee as an interface to EnergyPlus to run a baseline simulation and then, using the existing and new methods described above, create simple horizontal overhangs to reduce thermal loads as much as possible. The baseline consists of a single zone 3.05m x 6.10m x 3.05m (10’ x 20’ x 10’) with one south facing window 5.18m x 2.13m (17’ x 7’). The baseline uses the default closed office schedule and ASHRAE 189.1 envelope assemblies. The study is run for three separate locations, in different ASHRAE climate zones to ensure the Vector Method performs as well or better in multiple situations. The Climate Method is carried out by using the ‘Honeybee_Balance_Temperature_Calculator’ in conjunction with the Ladybug sun path and shading mask components to determine graphically which parts of the sky need to be shaded and to match a rectangular form to shade this area. The Iterate Method mimics the Sefaira workflow to simulate this method realistically being used in practice. The shade is assumed to be the width of the window and incrementally increased from a .30m (1’) overhang to a 3.05m (10’) overhang. Each result is analyzed through the same settings in Honeybee as the other methods, and the best performing option of the group of ten is selected. The Cell Method uses the ‘Energy_Shade_Benefit_Evaluator’ in Honeybee, which was based directly on the SHADERADE process, provides the cell-by-cell analysis as well as visualizing this data on the surface of the shade using Ladybug. The simple overhang starts as an oversized rectangle and is trimmed based upon the results of the shade evaluator component to create the Cell Method solution. The Vector Method is carried out utilizing a mix of Honeybee, Ladybug, and native Grasshopper components to create a script that creates the three-dimensional shading mask as described earlier. The shading mask is used to trim a surface at the top of the window. The resulting shape is the Vector Method solution. The design solutions for each method for the three locations are shown in Figure 2 below.

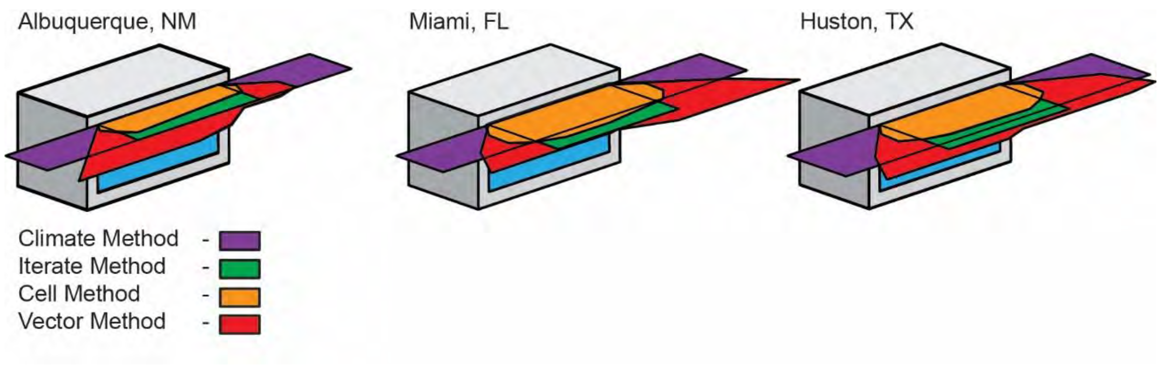

Figure 34. Comparative Method Study Designs

Table 1: Comparative Method Study

	Location		
Design Method	Albuquerque, NM	Miami, FL	Houston, TX
Baseline (Annual kwh)	2,611.3	5,222.5	3,964.3
Climate (Annual kwh) % Improvement	2,084.3 21.18%	3,694.9 29.25%	2,903.9 26.75%
Iterate (Annual kwh) % Improvement	2,073.6 20.59%	3,784.0 27.54%	3,011.1 24.04%
Cell (Annual kwh) % Improvement	2,084.9 20.16%	3,749.1 28.21%	3,045.5 23.18%
Vector (Annual kwh) % Improvement	2,060.3 21.90%	3,676.5 29.60%	2,922.8 26.27%

Table 1 shows the performance results of each design in Figure 2 compared to an unshaded baseline. Annual thermal loads are presented (kwh) and the percent improvement over the baseline.

The Vector Method performed the best in two of the three cases against existing methods and followed closely behind the Climate Method in the third case. Overall, each method was able to achieve a design that performed in a similar manner for the three test locations, however, the form that each design took was unique. The Climate Method was restricted to rectilinear forms with wide side overhangs, the Iterate Method was confined to predefined rules in the beginning of the process, and the Cell and Vector Methods created more unique geometries. Even though the typology of simple overhangs was utilized the form each solution takes is unique due to the effect of each method on the end product. This indicates that there are multiple design solutions that function to a high degree and multiple paths to achieve these designs. This shifts the focus back to how much time is required to generate a solution and how much effort is required to create design iterations based on aesthetic criteria.

The Climate, Cell, and Vector methods all rely on setting a threshold, whether it is a quantifiable number or interpreting a graphics display, to design a solution. For this reason, user error could easily be to blame for one method overtaking the other, and it would not be right to say that the Vector Method is the 'best performing' method. However, this study does show that the Vector Method has the potential to work as well or better than existing methods in designing shades that reduce thermal loads.

3.2 Iteration Study

To study the aesthetic potential of the Vector Method, the Albuquerque baseline model is used, and twelve different design options are created and evaluated using only the Vector Method, as shown in Figure 3. It is impossible to create an aesthetic that could be agreed upon by all to be objectively better than another. In that light, demonstrating that the Vector Method can quickly produce unique design iterations leaves the potential for each designer to decide for themselves what is aesthetically pleasing for their project. Overhangs, hoods, louvers, and screens are iterated and simulated.

Table 2: Vector Method Iteration Study

Iteration	Thermal Load (Annual kwh)	% Improvement Over Baseline
Baseline	2,611.3	-
Overhang 1	2,060.3	21.10%
Overhang 2	2,029.9	22.26%
Overhang 3	2,092.7	19.86%
Hood 1	2,087.6	20.06%
Hood 2	2,070.7	20.70%
Hood 3	2,114.8	19.01%
Louvers 1	2,061.5	21.06%
Louvers 2	2,074.6	20.55%
Louvers 3	2,047.0	21.61%
Screen 1	2,128.8	18.48%
Screen 2	2,100.0	19.58%
Screen 3	2,107.8	19.28%

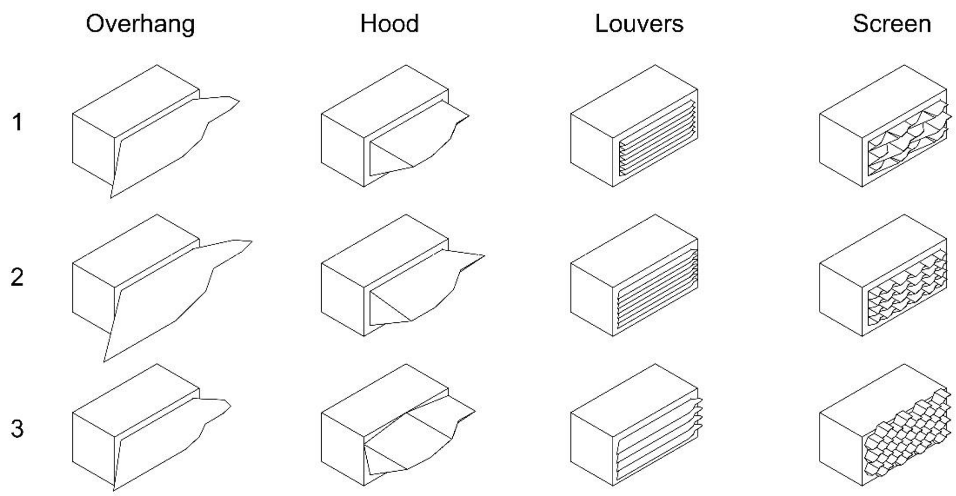

Figure 35. Design Iterations Using the Vector Method.

Table 2 includes the annual simulation results for all of the iterations generated by the Vector Method shown in Figure 3. Annual thermal loads are given (kwh) and the percent improvement over the baseline is provided.

All iterations from Table 2 show between an 18.48% and 22.26% reduction in thermal loads. Variation in iterations is likely due to how the Vector Method is only addressing direct sunlight and is attempting to create a binary list of shade hours. Each hour is either assessed to be 100% shaded or not, which means different typologies and forms might create different hours with partial shade. Despite these shortcomings, shades were able to be altered at the designer's discretion without significant sacrifices in performance. The Climate Method can move freely between most typologies, but cannot account for irregular forms such as screens and complex geometry such as non-rectilinear forms. The Iterate Method requires too many simulations to adequately explore this many typologies and variables to be feasible in practice. The Cell Method can help to evaluate many options (aside from self-shading typologies) but can only evaluate what the designer creates, meaning each iteration is not guaranteed to perform similarly if changes between iterations are drastic enough.

Iterations through the Vector Method likely vary for a number of reasons. First, this method is primarily concerned with direct solar radiation. Indirect solar radiation is going to interact differently with each iteration and the Vector Method tool is not designed to respond to this type of light. The tool is only concerned with designing for 100% shading coverage of a window for a specified period of time. Direct solar radiation has a much greater impact on heating and cooling than does indirect, resulting in similar performance but not identical across iterations. Additionally, this method does not attempt to address thermal mass/lag. It is known that the sun will heat materials during the day and the materials will store that energy and begin radiating that energy later in the day. Therefore, it is appropriate to begin shading before an actual cooling load might appear in the energy simulation to avoid overheating due to this effect. This would require a user to input material properties from the start and for the tool to account for many more calculations than it currently does. To keep the inputs more simple and understandable on the user side and to keep the tool running quickly behind the scenes sacrifices are made that could improve performance slightly.

Overall, due to the relative small variation observed in this study between unique shading device iterations, one can conclude that this method keeps a designer accountable to performance goals while allowing for freedom in design.

Chapter 4.0 Design Application

In reality designers deal with complex problems that transcend the context of a baseline model. Factors including, constructability, cost, client input, cultural context, physical context, zoning regulations, building code restrictions, and more create a unique blend of obstacles and opportunities adding character to the project. It is then necessary to take a project in a real location with a hypothetical program and apply the Vector Method to determine what a finished design might look like and how it might perform. The design project is used as a ‘playground’ to explore different types of shading devices, different design strategies, and different ways to integrate shading devices with the architectural expression and creation of space.

The baseline models have primarily used Albuquerque, New Mexico (due to the large amount of solar radiation available and the presence of seasons where sun is needed for parts of the year and not needed in others to make the design more challenging for any design method to accommodate), as a location to pull weather data. In this design case, the parking lot just north of Civic Plaza in downtown Albuquerque is utilized as the staging ground for this ‘playground’ building. The program consists of ground level retail and restaurant space with open office space above.

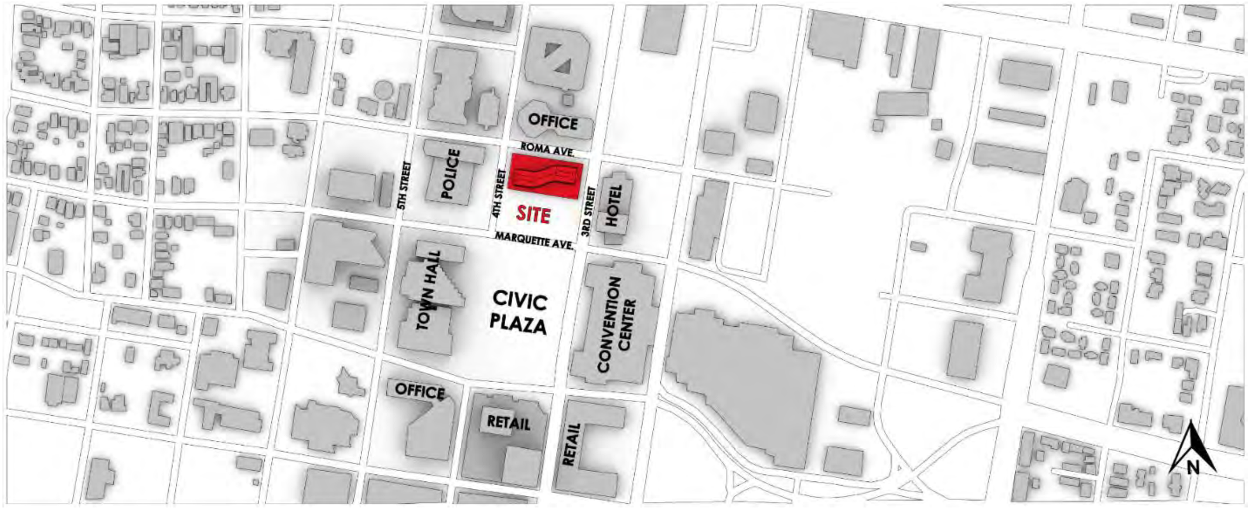

Figure 36. Site Plan of Downtown Albuquerque, NM

Figure 37 shows the general functions and streets in the area surrounding Civic Plaza and the site for the design project.

The project is used as an opportunity to explore four unique shading opportunities in the building as a whole. This helps to explore the range of possible situations that can be solved using the Vector Method. Additionally, multiple iterations of one design problem are explored to explore the aesthetic range that can emerge using the Vector Method. Each design solution is evaluated in terms of thermal load reduction to ensure performance criteria are being met as in the baseline cases. This study goes further than the baseline studies and attempts to place the designs in the context of the building and the context of the city to give a sense of the architectural impact of shading on the project.

4.1 Design Process

The design of this project attempts to mimic much of architectural practice, using common formal typologies and making simple, yet recognizable moves to give the architecture character. This project is not meant to be overly complicated as to distract from the shading solutions. The way the Vector Method reacts to the unique context is of particular interest.

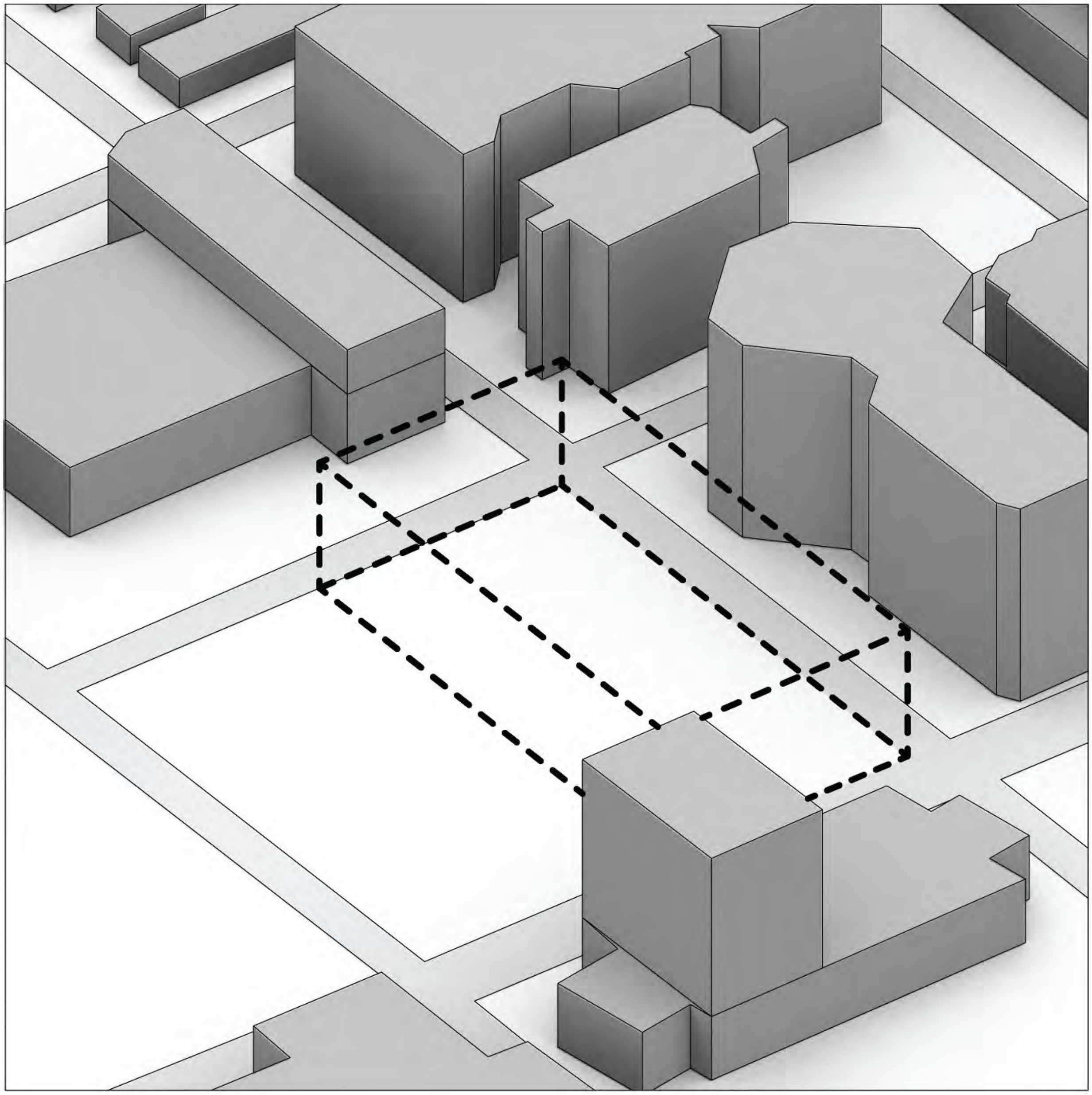

Figure 37. Build on the North Side of the Site.

The first move in this design project is to site the building on the north side of the site. Civic Plaza is to the south and often hosts public events involving thousands of pedestrians. By building to the north and opening up the south, the site can contribute to these public events while retaining great views of the activity.

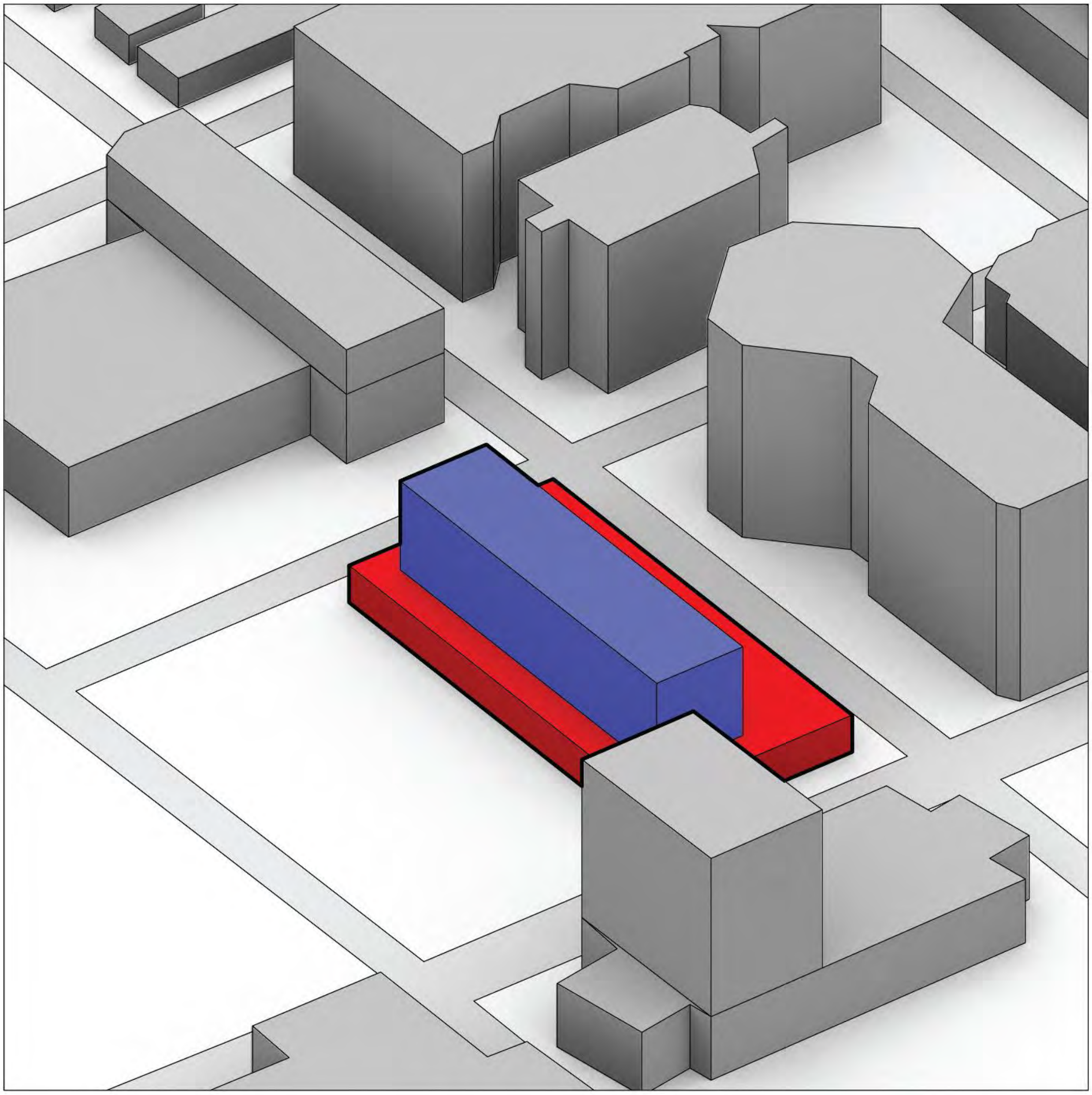

Figure 38. Commercial Base, Office Above.

The formal typology of a base that acts as a plinth with a bar or tower above is a very common design solution in urban contexts. This also presents additional opportunities, to be explored in latter steps, for shading device development. The programmatic typology of commercial on the ground and work above is also common and presents the project with diverse opportunities for the Vector Method to respond to different occupancies schedules, as in the baseline cases in past chapters.

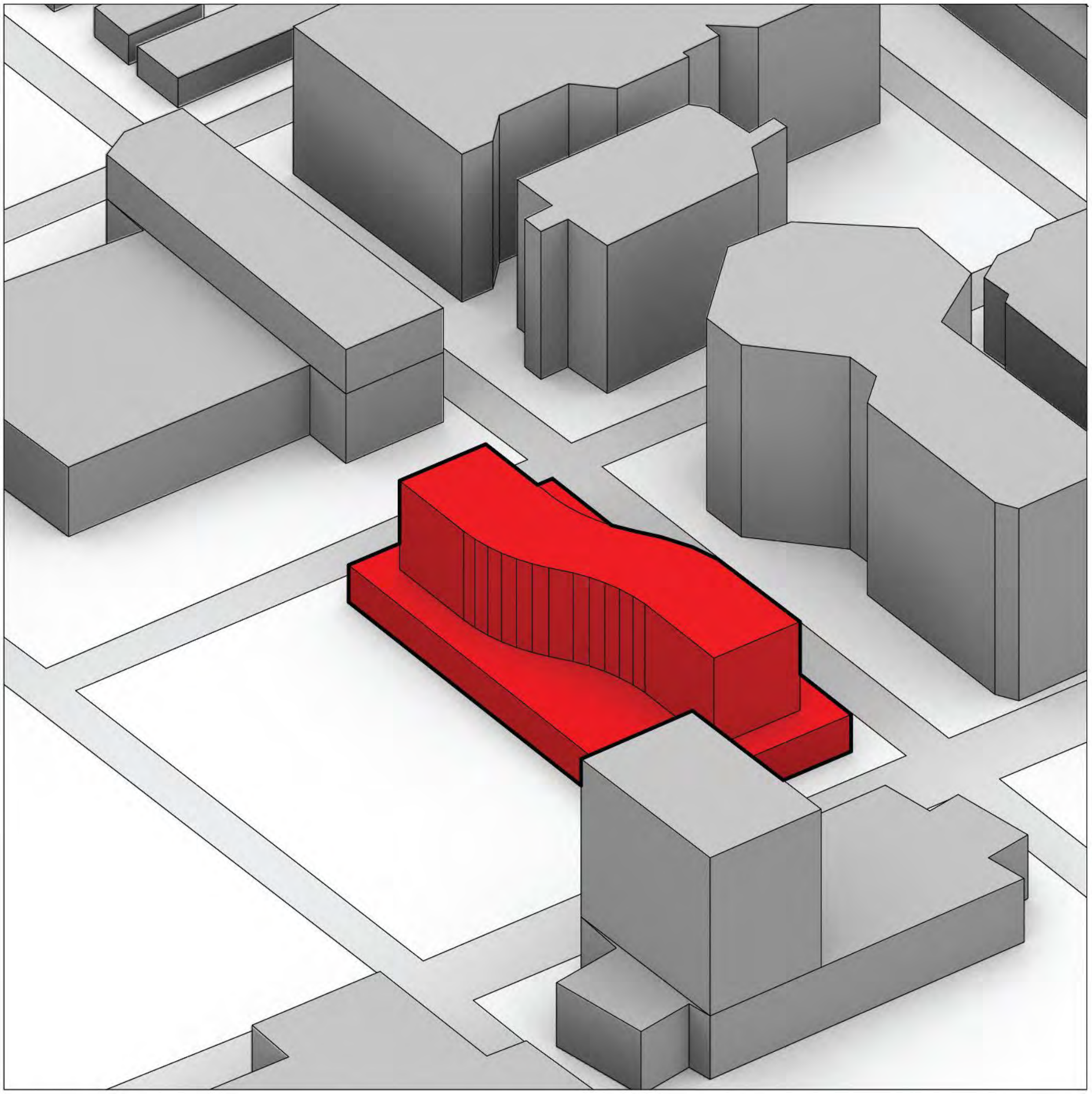

Figure 39. Curve the Office Block

By curving the office block above the ground level plinth, the building gains a defining architectural move that common people can reference as a method of wayfinding. It is the only building in the area with a curved office bar. The curve also makes shading solutions much more difficult which allows the Vector Method to overcome additional problems and engage in some level of form finding.

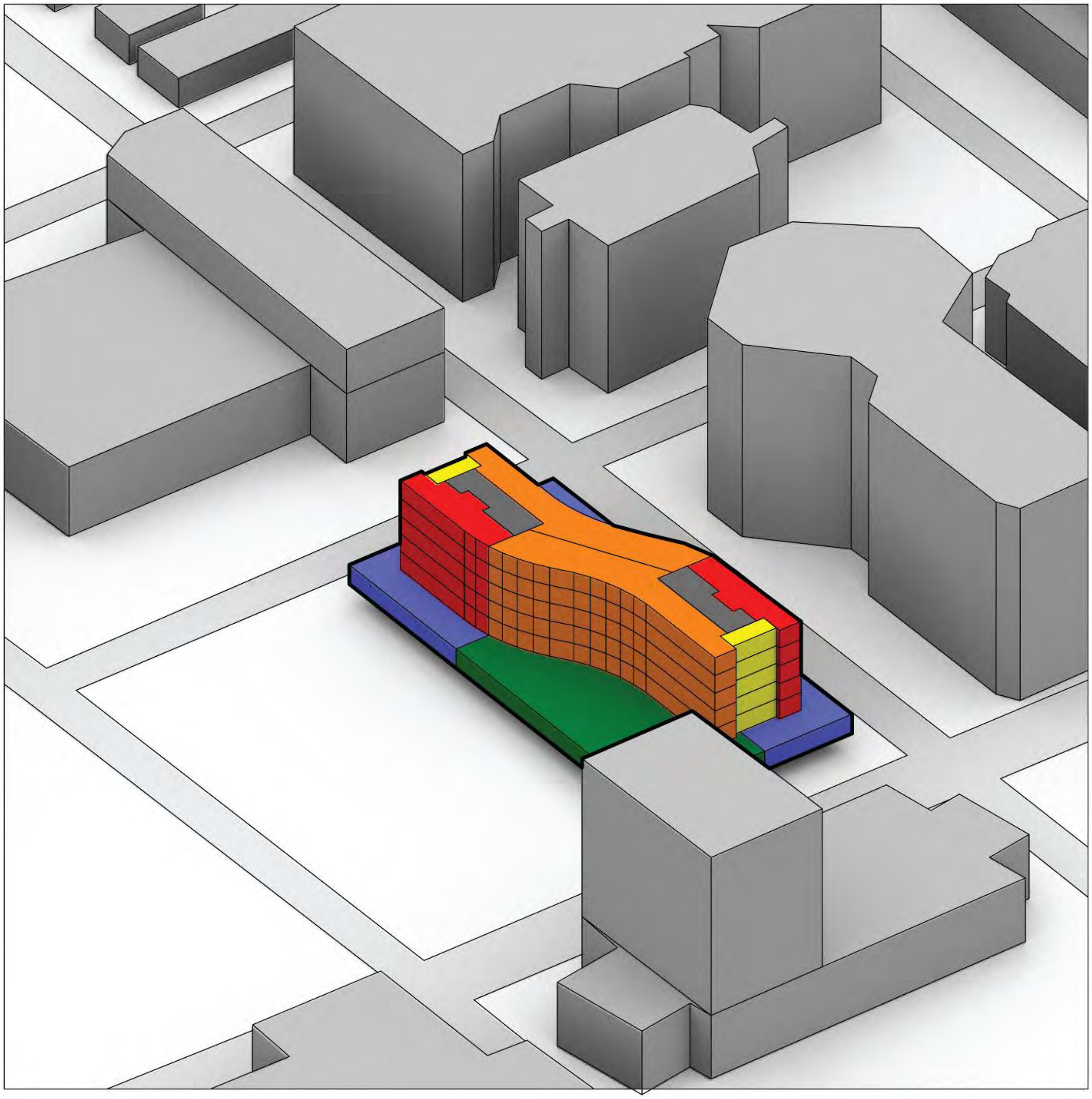

Figure 40. Programing and Zoning.

Dividing space by program and zones is important from an architectural perspective as well as from a shading device design point of view. Orange represents open office, yellow conference rooms, red lobbies, blue retail, green restaurants, and grey are the building's core. Each zone carries with it a unique energy profile and unique architectural requirements.

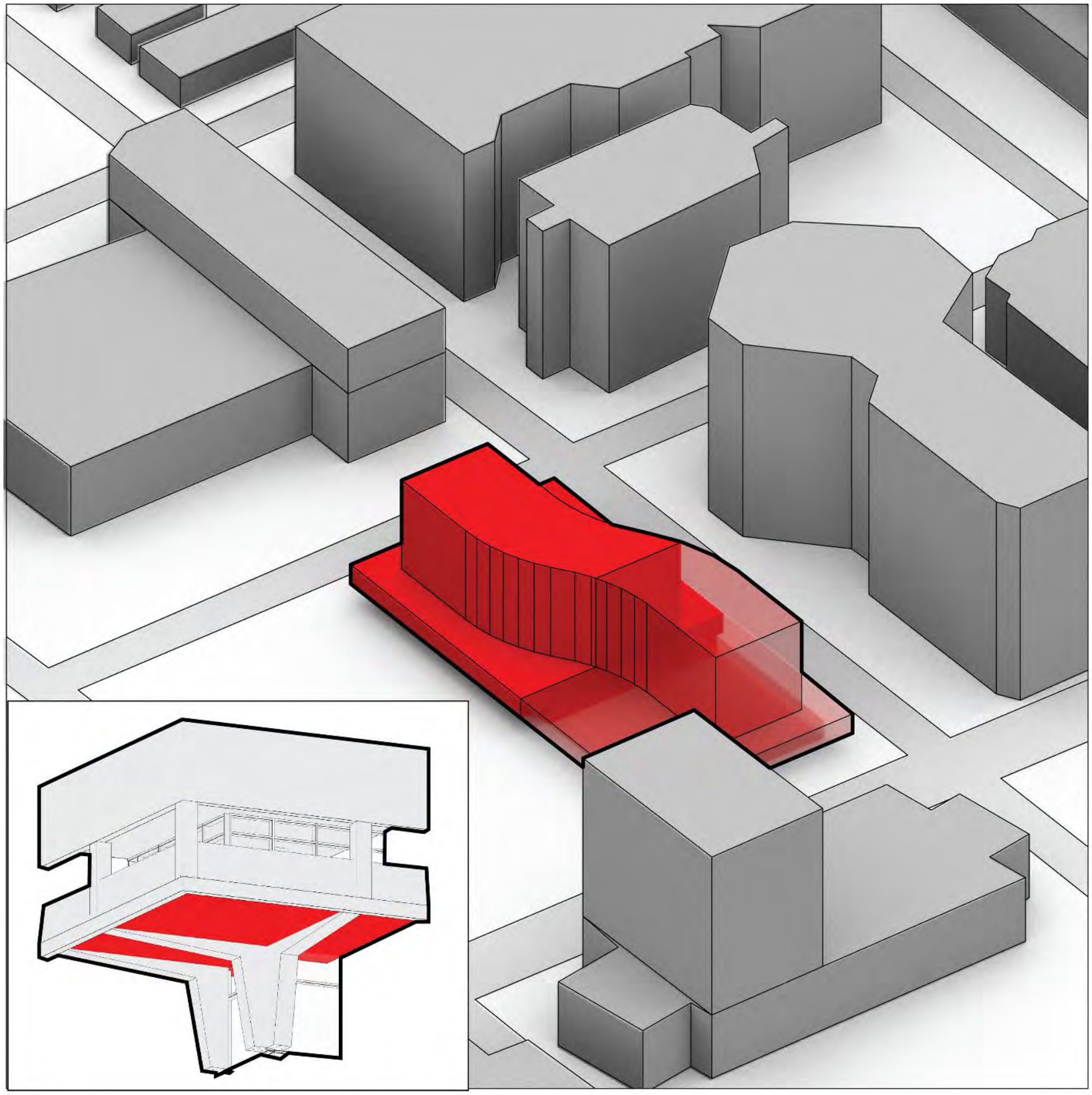

Figure 41. Overhang Building's Base.

The first implementation of shading devices/strategies in this project comes in the form of a ground level overhang. The Vector Method can be used to generalize rectilinear overhangs, as any method can, to create a space that engages the public with the retail and restaurant spaces.

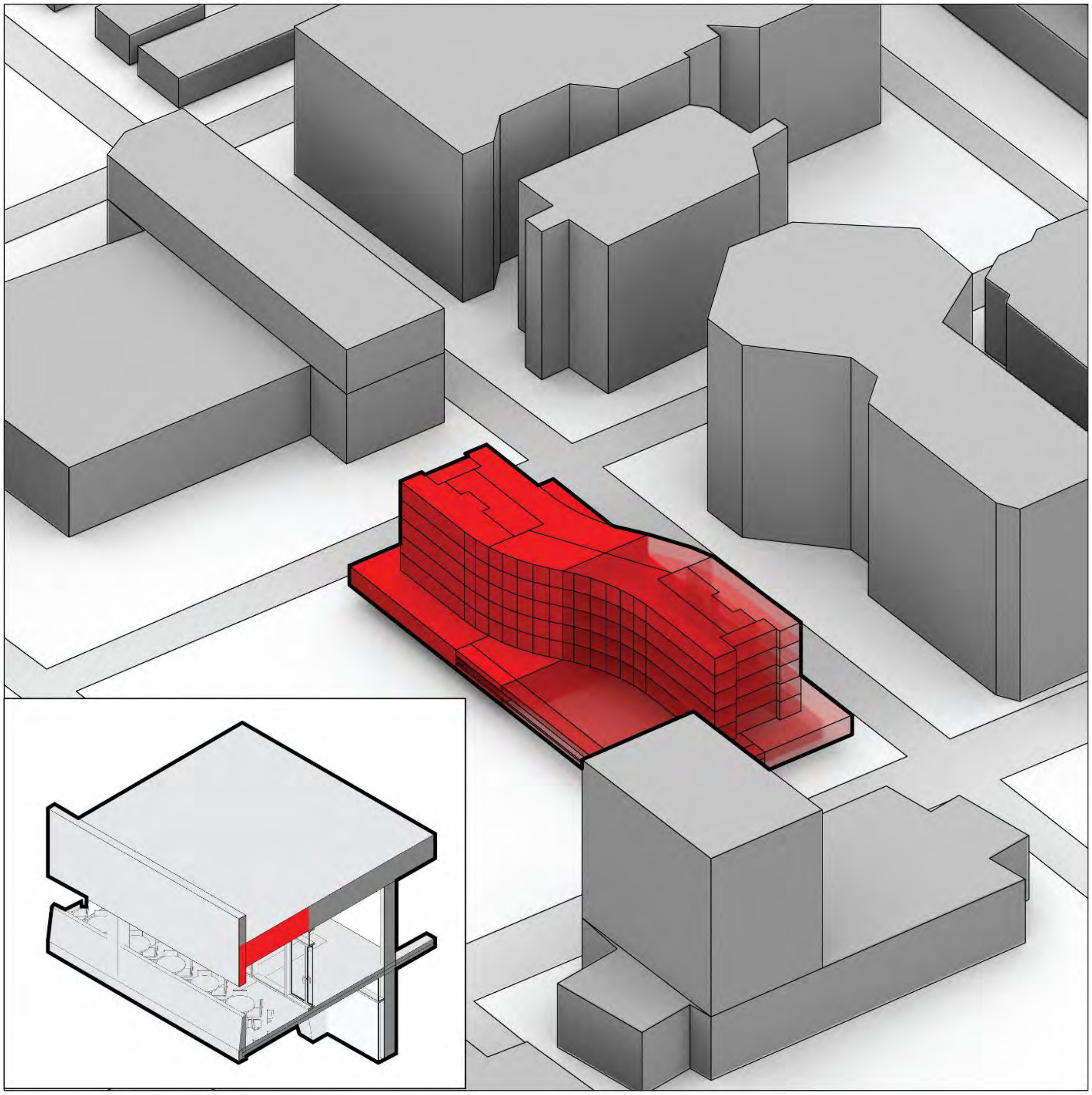

Figure 42. Recess Restaurant Space.

The next design opportunity in the restaurant spaces lofted above the ground floor functions. By using the Vector Method to size another rectilinear overhang, outdoor seating with a view of Civic Plaza is created. The solution saves energy in the building, but also creates pleasant spaces and meaningful experiences as well as adding to the depth and variation in the façade.

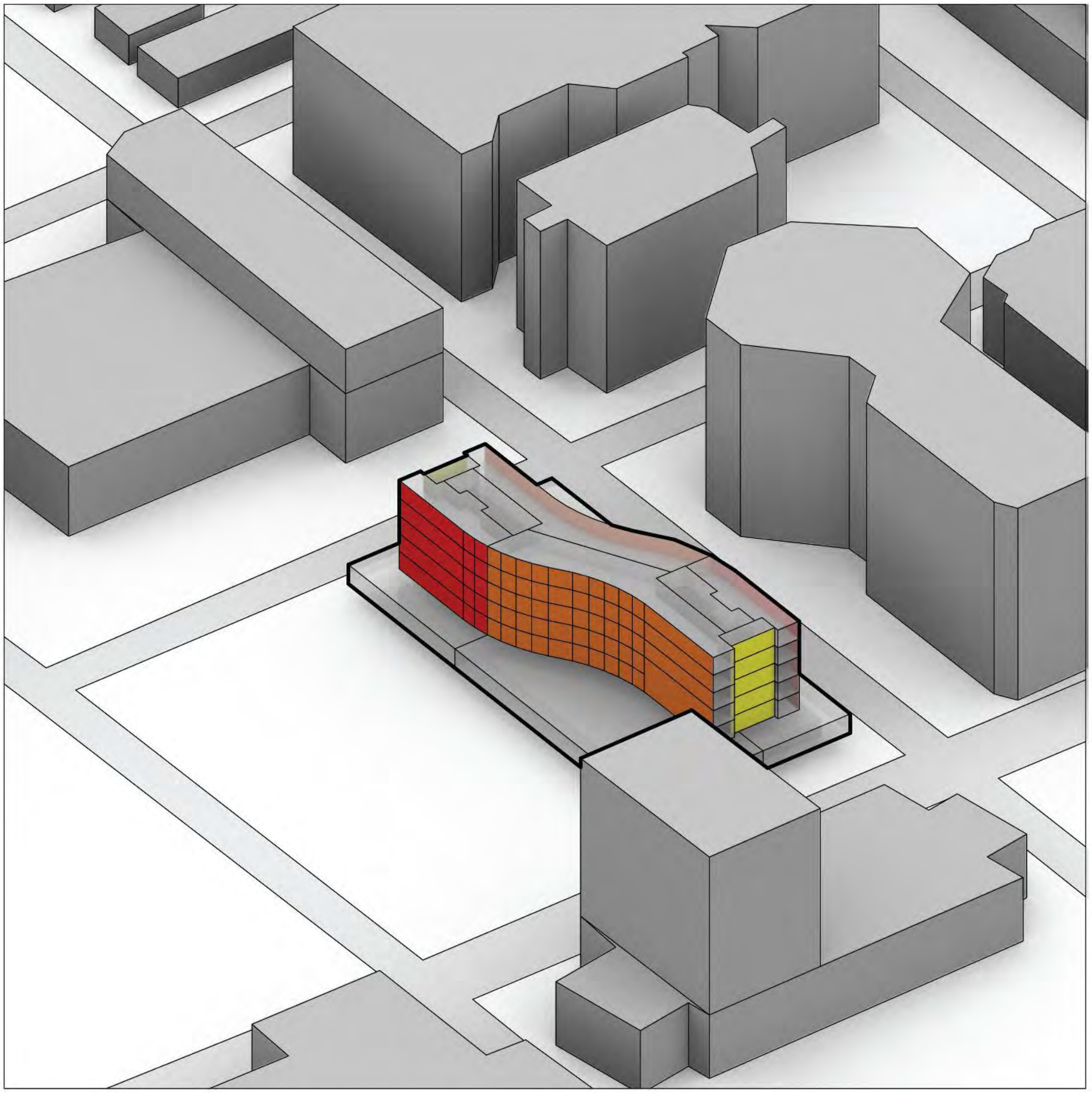

Figure 43. Zoning the Office Skin

The office block above actually consists of three unique program sections in different orientations. There is the curved orange open office zones facing north and south, the yellow conference spaces facing east and west, and the red lobby zones facing north and south. The red and orange zones could be designed in a similar manner, however, the yellow end caps might require different treatment.

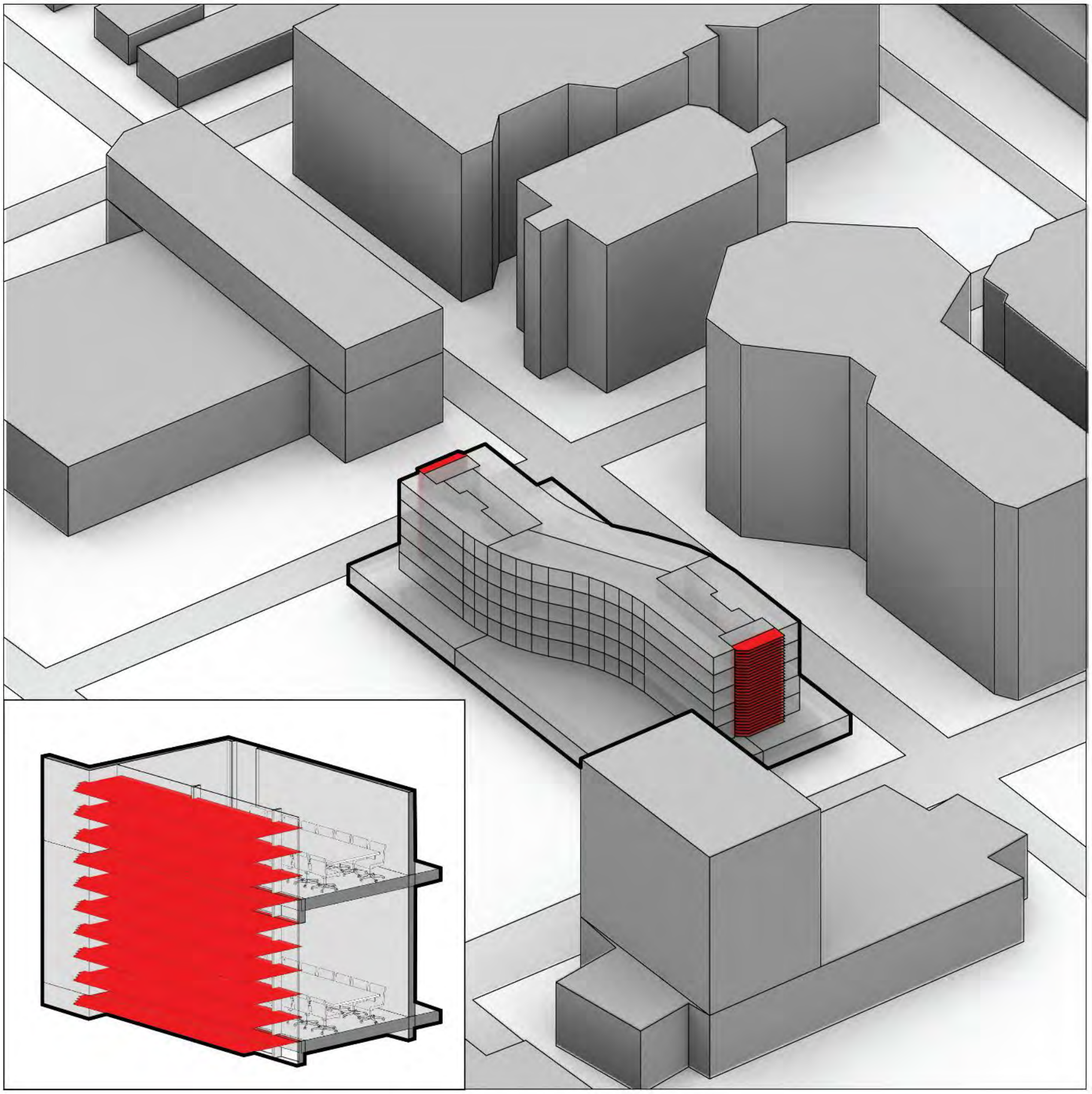

Figure 44. Louvers on the East and West

On the east and west ends louvers were designed to shade the conference rooms. The east and west do not provide pleasant views to the exterior, therefore it is not a priority to ensure the shading devices perform and allow unobstructed views. The louvers create a dense pattern that visually contains the design's two ends.

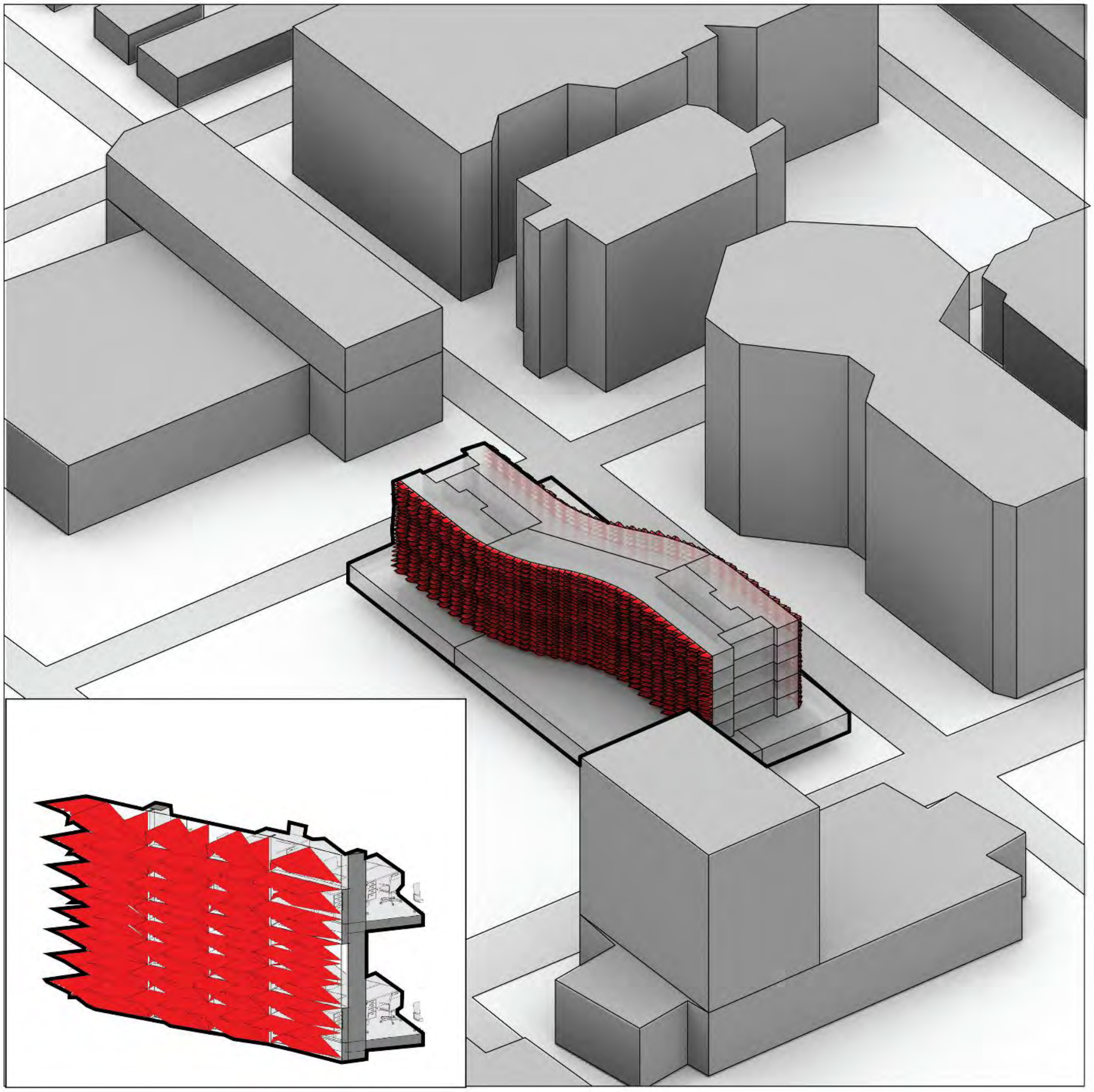

Figure 45. Triangulated Screen

A triangulated screen is used of the office and lobby spaces. By varying the height of the triangles in the screen the Vector Method is able to adapt to the different shaded areas and to the unique orientations along the curve of the building to create hundreds of uniquely sized shades to create a screen born out of performance based form-finding. The screen adds a visual texture to the exterior of the building while being large enough to allow views of Civic Plaza from the building.

The idea of creating a screen as an architectural element is not a new concept and has been done successfully in the past. The Esplanade in Singapore by DP Architects and Michael Wilford and Partners utilizes a screen of aluminum triangles over the glazed panels making up the skin of the project.

Figure 46. The Esplanade in Singapore, Photo by SengKang

In an interview Vikas, a director of DP Architects, had this to say about the creation and inspiration of the screen;

> We worked with an engineering firm called Atelier One in designing the cladding system. The distribution of the sunshades we designed follow slowly changing pattern. To design the exterior sunshade screen, we drew inspiration from things the properties of the structural geometry itself as well as elements from nature such as sunflowers, fish scales, the patterns of a bird's feathers etc. Such elements in nature also feature geometry that appears repetitive but changes slowly over the subject. Traditional Asian buildings also

inspired us, ranging from "jali" screens in medieval South Asian architecture to the woven mat walls in Southeast Asian buildings.[94]

The screen solved a problem where it helped to avoid a greenhouse effect in the large glazed interior, but it also drew on inspiration from nature and South Asian culture to connect it to the region. The screen is more than a technical solution, it is a visual experience that could be seen as a cultural experience with multiple layers of information built in taking a building into the realm of architecture.

The Broad Museum by Diller Scofido + Renfro in Los Angeles, California the idea of a screen or veil is used as a visual effect. The planar surface penetrated by angled openings creates a unique texture and a unique play on light when the building backlights the screen at night.

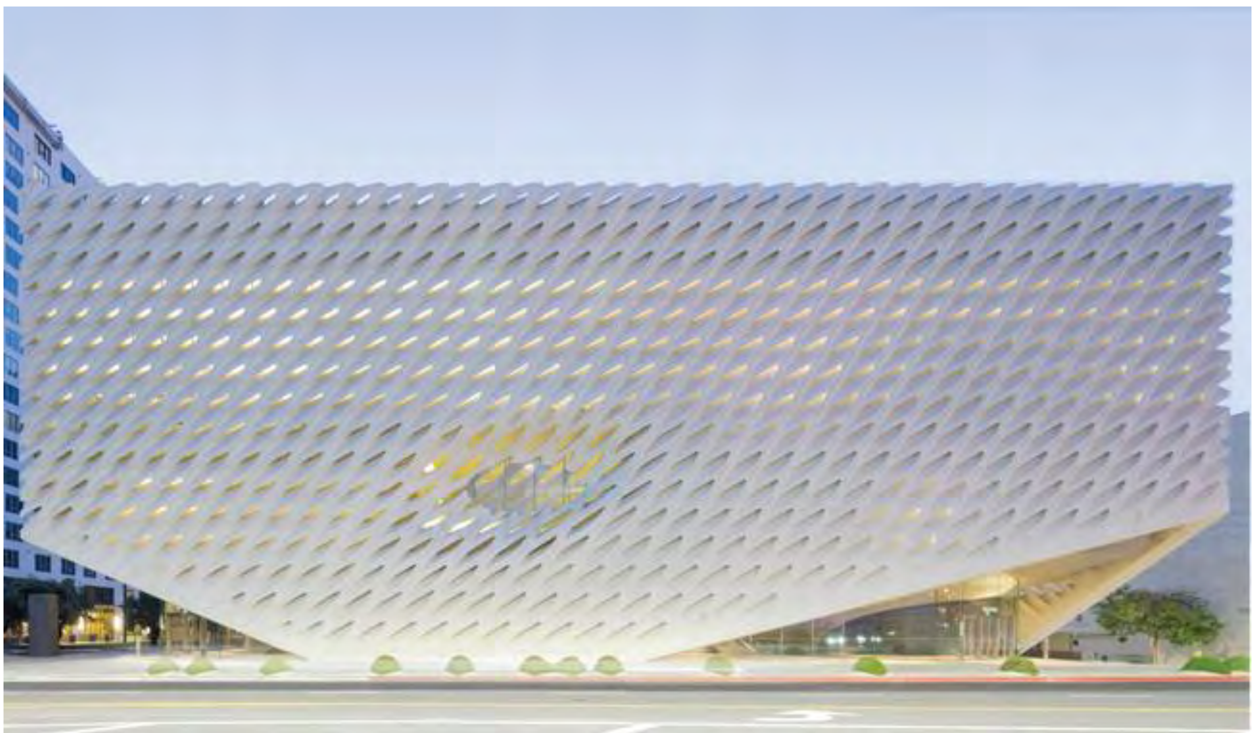

Figure 47. The Broad Museum, Photo by Iwan Bann

This screen has more to do with geometric plays on solid, porous, and open surfaces and is not designed to reduce thermal loads. This is an example of an architectural move that does not necessarily contribute to creating a functional building. The Vector Method could help orient and size the openings in the screen

[94] "Esplanade Integrates Modern and Asian Elements." Accessed March 21, 2019. https://www.webcitation.org/query?url=http://www.geocities.com/shinyeesiek/vikas.htm&date=2009-10-26 02:31:38.

based upon thermal loads in the spaces behind to attempt to achieve good building performance and good architectural moves at the same time.

The Phoenix Public Library by William Bruder and DWL Architects is another project that utilizes solar screens to make an architectural statement. The North entry façade incorporates translucent vertical fabric pieces to block east and west light during extreme points in the day during the summer.

Figure 48. Pheonix Public Library, Photo by Ellen Forsyth

The screens create a visual effect that is unique to this project adding a sense of place and identity to the Library. This makes it memorable to those who use it through its treatment of sun shading.

The design project in this thesis utilizes a screen for many of these reasons. It uses uniquely sized and angled planes as in the Esplanade to create a unique texture informed by pragmatic concerns in its particular place and environment. It also aims to create a unique form that modifies the curved bar behind it similar to how the screen in the Broad Museum changes the character of the overall space. And this screen is also meant to help identify this building from others in the area by creating a shading solution that does not match the exact strategies of other similar buildings in Albuquerque.

4.2 Design Results and Analysis

Up until now this thesis has discussed the reasoning behind the formal moves that drove this exploration design project. Now it is necessary to evaluate the design in terms of performance and aesthetics. Performance is evaluated in terms of thermal load reduction, looking at the building performance before shading devices were implemented to after the shading devices were designed and deployed. Aesthetics is explored through rendering in the context of the site and city of Albuquerque. How the building looks, feels, and functions from the street, from the vantage point of neighboring buildings, and from the interior of the project are all important in determining if the Vector Method has produced a design outcome that could be elevated to the realm of architecture. It goes without saying that aesthetics is a very subjective area of study. It is very possible that a reader may not be drawn in at the least by the aesthetic moves by this project. However, the question is not whether this method can produce a design that all people agree is universally agreeable, because this is impossible. Instead the goal is to allow the reader to see how they, themselves, might be able to use this method to add their own touch to their own projects. This thesis is not arguing for a particular style or putting forward a design treatise, but offering flexibility in design.

The performance evaluation section is broken down floor by floor as well as by façade orientation and then finally by giving the overall reduction in thermal load.

Figure 49. Ground Level Plan

Figure 47 shows a color coded detailed plan of the ground level. Green is restaurant space, red is lobby, and blue is retail. The lobbies represent entries to the office zones above, while the retail and restaurant spaces respond to the streets and plazas nearby. The restaurants are situated to respond to public events in Civic Plaza and the retail spaces are arranged along the streets to attract the attention of passing vehicular and pedestrian traffic. All of the grey areas represent zones without access to daylight and are excluded from the study. The grey zones mainly consist of core and service spaces that would not usually be occupied during all hours of the day. For the ground floor cooling loads were reduced by 25.41% while heating loads increased by 9.91%. Heating loads always increase in these scenarios due to the fact that an unshaded baseline will be able to maximize solar gain to reduce heating energy far more effectively than any shaded window where some light is blocked. The aim is to reduce solar gains in the right times so that cooling saving outweigh, by a significant margin, heating load increases. Overall, the ground floor was able to achieve this and reduce the total thermal load by 10.91%.

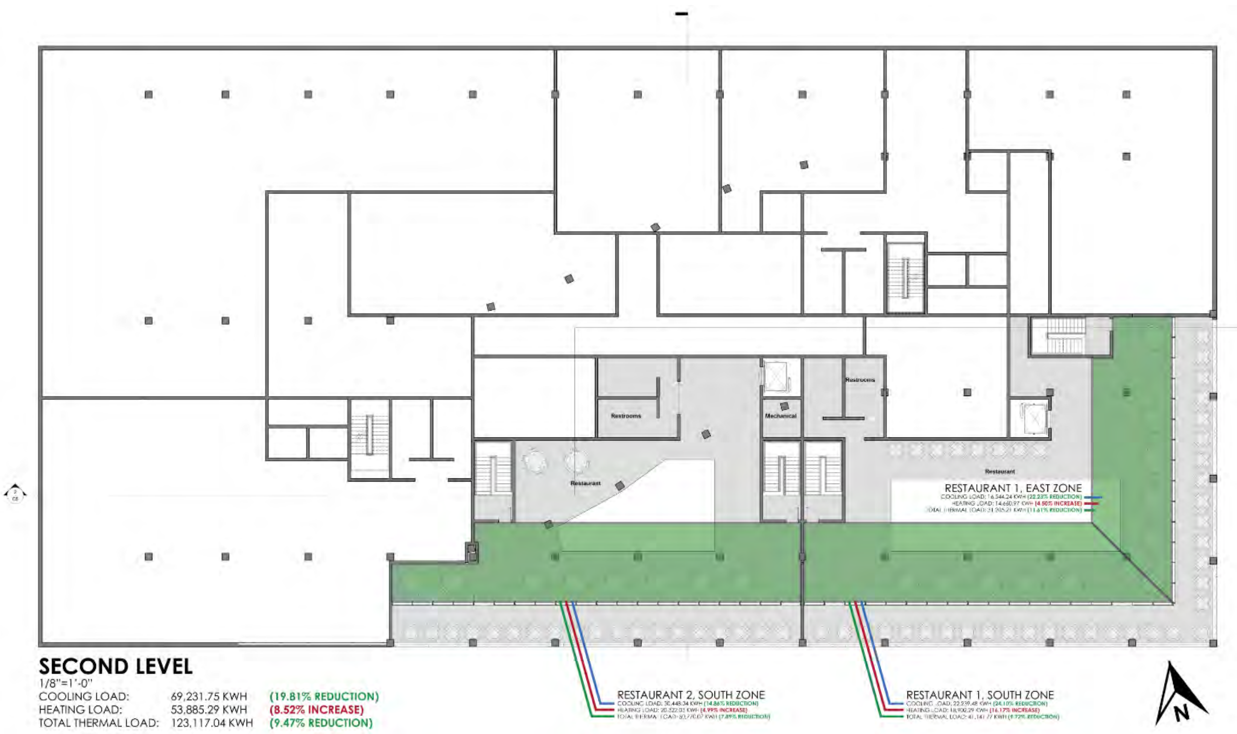

Figure 50. Second Level Plan

The second level is much simpler with only upper level restraint areas highlighted in green. These spaces primarily overlook Civic Plaza. They also include covered outdoor seating, as previously mentioned, to act as a shading device and create pleasant dinning spaces with good views. Cooling loads were reduced by 19.81%, heating loads were increased by 8.52% and overall thermal loads fell by 9.47%. These figures differ from the ground level like because the ground level included a mix of functions with different occupancy schedules. Remember that most of the baseline cases discussed in previous chapters used an open office schedule for the energy model. Now that this thesis is getting into more realist program mixes, more schedules are used and each program type carries with it different potentials to save energy.

Figure 51. Typical Office Level Plan

There are five office levels consisting of conference rooms in yellow, lobbies in red, and open office in orange. Each floor is laid out the same, however, because of the triangulated screen producing slightly different patterns on each level, each floor's zones were simulated and averaged to create the statistics seen in Figure 49. In plan one can notice how the shading devices generated on the south and north differ from each other as well as how the forms change as they curve along the building. This effect is more important to note in the rendering views, however, it can also be seen here. Overall, each typical office from reduced the cooling load by 28.16%, increased the heating load by 19.06%, and reduced the whole thermal load by 10.92%.

When each orientation is explored a different perspective is uncovered. Each orientation is broken down by percent energy savings as well as nominal energy spaces and energy saved per square foot. These additional metrics will help to determine the effectiveness of each façade's shading strategies.

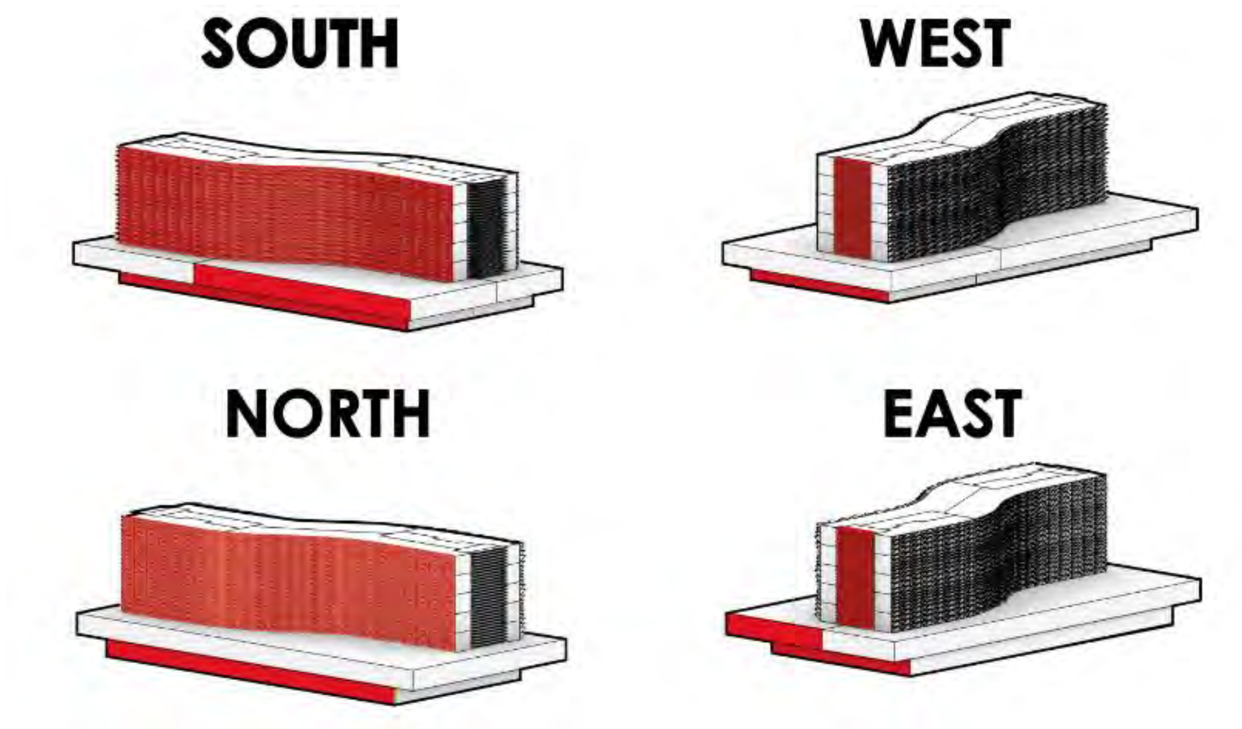

Figure 52. Project with each Orientation Highlighted.

Table 3: Façade Orientation Study

Orientation	Thermal Load Saved (Annual kwh)	% Improvement Over Baseline	kwh/SF/Year Saved
South	49,569	12.87%	1.41
West	13,428	19.57%	3.01
North	9,776	4.37%	.31
East	11,621	10.35%	2.52

Table 3 shows the performance data for each orientation as visualized in Figure 50. The south façade provides the highest nominal reduction of thermal load. This makes sense as the building is primarily oriented towards the south with no obstructions from the surrounding context. The west and east achieved high thermal load reductions over relatively small areas, represented by the high kwh/SF/Year values. The east and west design solutions likely produce the largest effect for minimal effort, while the south has the most potential to reduce energy costs overall. The north façade is the lowest performing of all of the facades due to the lack of potential to reduce harmful solar gain. This project is in the northern hemisphere, meaning the north side of a building will not get very much direct sunlight. This is reflected in how the Vector Method responded to the place to create a more minimal triangulated shading screen for the north as compared to the south where direct light is more prevalent. The designer responds to the design in sizing the openings and determining their orientation and the software responds to these conditions to size the resultant shade.

The low performing nature of north facades in general brings to light the question of what the shading screen is actually doing for and in the project. In this particular design case would the office bar be as unified aesthetically if only the south had a screen and north did not? There is value in aesthetic unity to some projects and to some clients and designers, so it might be realistic to assume certain areas might be shaded in order to maintain an overall appearance that is important to the project. If this is the case, the Vector Method has shown it can design for situations at all orientations and is able to size these conditions as well, optimizing form.

The overall building reduced thermal loads by 10.69% which translates to 84,394 kwh per year. This can also be expressed as saving 1.12 kwh/SF/Year. The average electricity costs in Albuquerque, New Mexico for commercial customers in 10.2 cents per kwh.[95] These are thermal load reductions, which does not account for the actual heating and cooling systems in the project. No system is 100% efficient meaning it is conservative to say that energy cost savings would be a least $8,608.19 per year just through shading. These types of savings could help a designer justify their designs of architectural skins and shading devices on the basis of operating cost, depending on the costs of fabrication, installation, and desired payback period. As seen previously the Vector Method will highlight areas with low energy savings potential such as the north façade. This offers value engineering opportunities very early on in the design process.

To determine whether or not the shading device designs can be considered architectural elements and contribute to the whole experience, this thesis now presents a number of renderings from the perspective of people at different vantage points that are likely to be common in the day-to-day life of the project.

[95] "Albuquerque, NM Electricity Rates." Electricity Local. Accessed January 28, 2019. https://www.electricitylocal.com/states/new-mexico/albuquerque/.

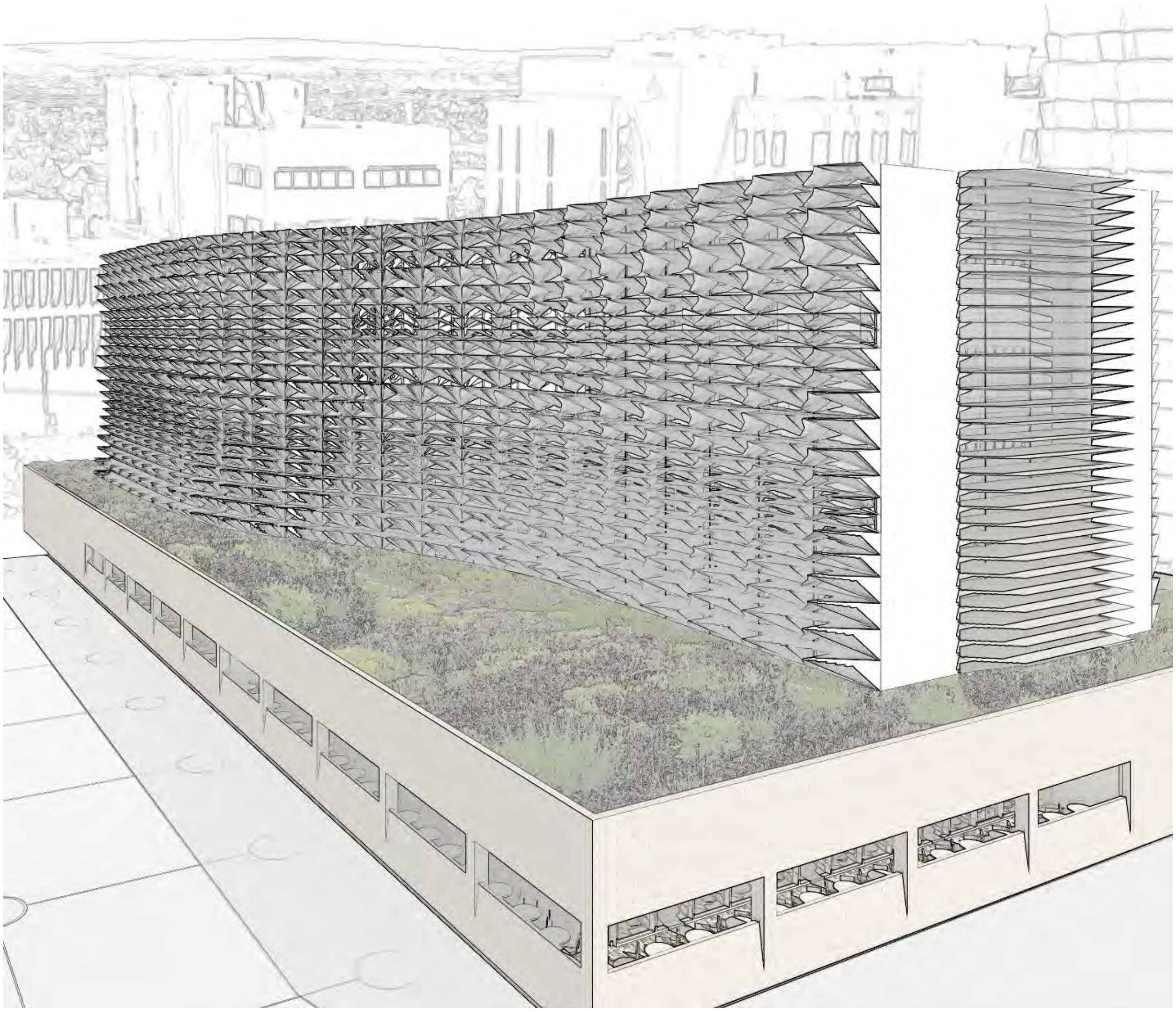

Figure 53. View from Hotel.

First, the views from the neighboring hotel are explored. The hotel has a view of the restaurant outdoor seating, exposing public activity and suggesting things for visitors to engage with later. The way the user defined triangular openings are oriented in landscape create a horizontal emphasis to lead the eye across the curved form, reinforcing and responding to the decision to curve the office block. By varying the heights of the triangular openings methodically and allowing the Vector Method tool to size the shades accordingly one can perceive a gentle wave that also helps to reinforce the horizontality of the office form. The deep overhangs on the east and west help to cap the ends allowing the design to be defined on either end.

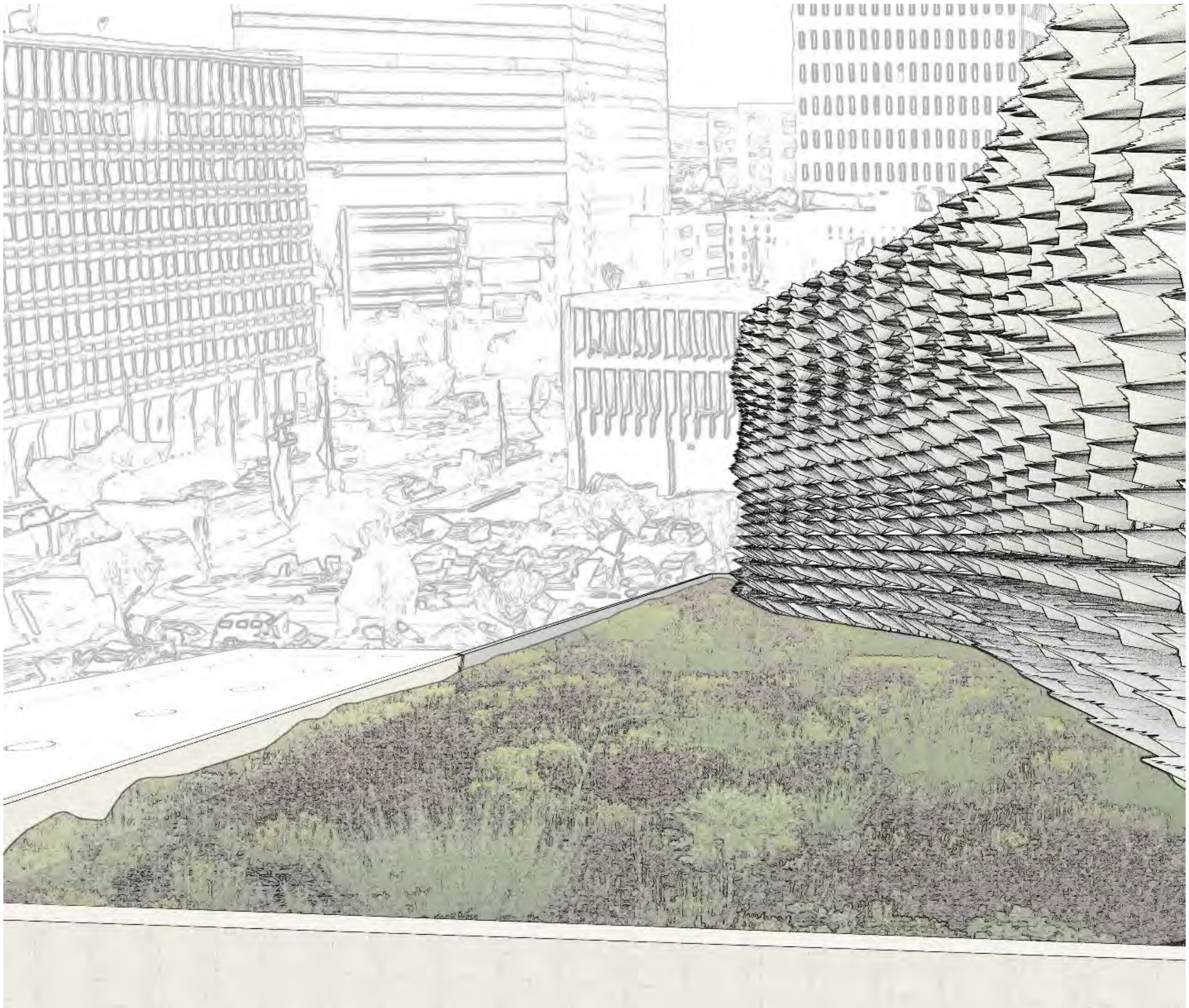

Figure 54. View from Hotel.

The triangulated screen along the south façade produces a textured pattern with a gentle wave as the size of the units change vertically. The screen blocks oblique views into the office from the hotel, preserving the privacy of the office workers. The screen becomes a skin with a unique texture created out of form optimization through the Vector Method. Each orientation and each unique profile results in a slightly different design responding to the same design goals. This façade includes hundreds of unique solutions all generated quickly through the design tool and each contributes to the same overall aesthetic goal without competing. Each part is integrated into a shading system.

Figure 55. View from Office Space.

The screen on the south and north sides of the office bar create a unique pattern from the inside of the building as well. The screen creates visual effects which still permitting views of the surrounding area. Each point in the screen is designed and sized for the specific situation in which it exists. The optimized form makes the visual effect all the more interesting. As the different sized openings move up and down the façade this means different floors have slightly different sized openings adding a subtle sense of uniqueness to each floor. While the shading devices on each floor may be slightly different they are sized using the same methods and perform very similarly. The only real distinction is aesthetic, which can be read floor by floor on the interior or as a whole from outside.

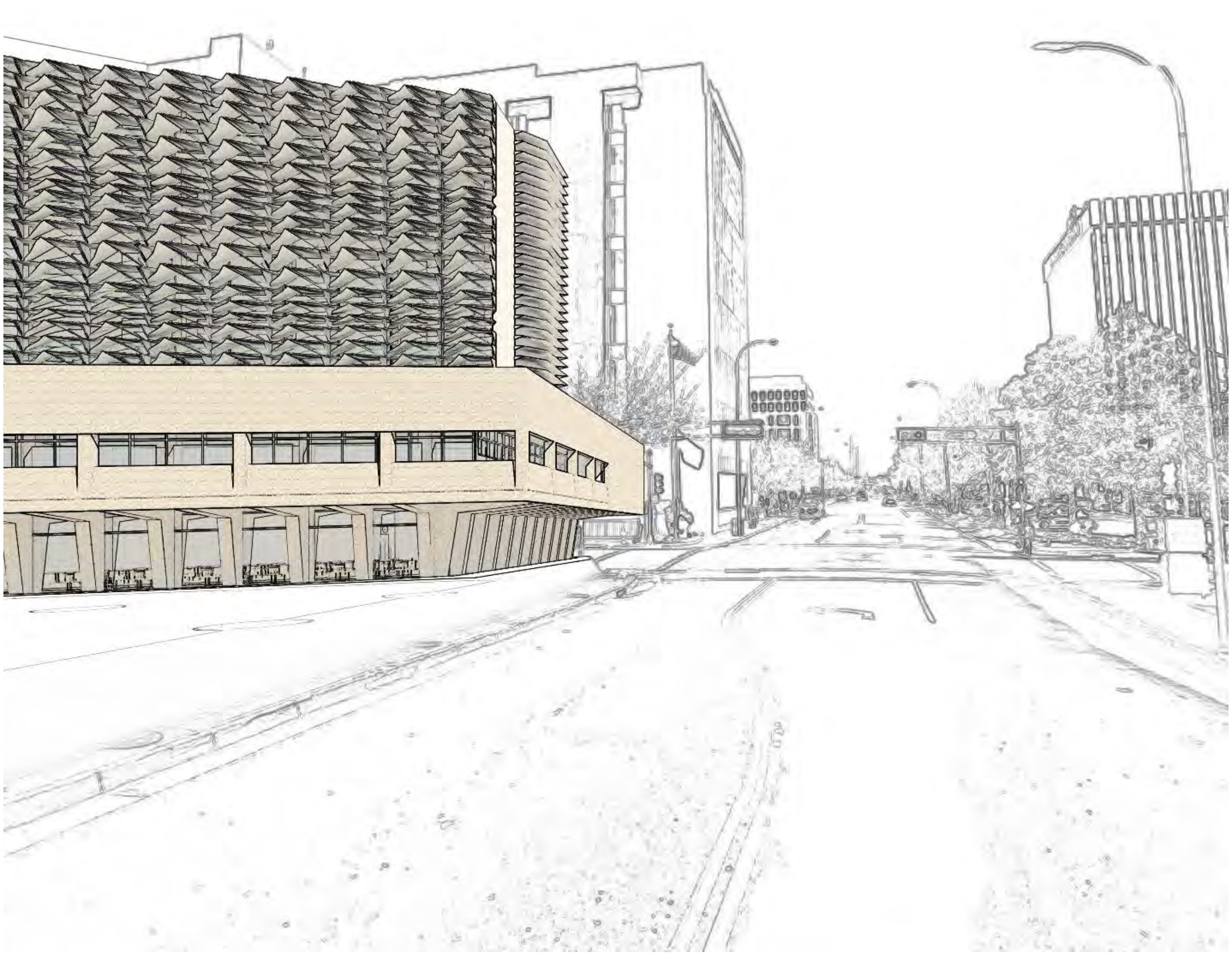

Figure 56. View from 3rd Street.

From 3rd street, this project stands out from the immediate context, not due to the form as much as the shading devices that create the unique texture. The differing size of the shading devices in the screen can be read from the street. The outdoor dining above can be seen adding to the public sense of activity down town. The ground level overhang adds to the pedestrian zone and invites people to walk within the sphere of influence of this project to get into the shade for a short while.

Figure 57. View from Roma Avenue.

From Roma Avenue The rhythm that the supports the ground level overhang and the screen curving around the north side add a sense of movement along the street. As discussed previously, the performance potential on the northern façade is not substantial compared to other orientations. If the north façade had no ground level overhang the building would lack a sense of depth that the other façade orientations express. If there was no screen on the northern side of the offices the experience on Roma Avenue would be much less interesting than it is from 3rd street and the building would lack a sense of cohesion.

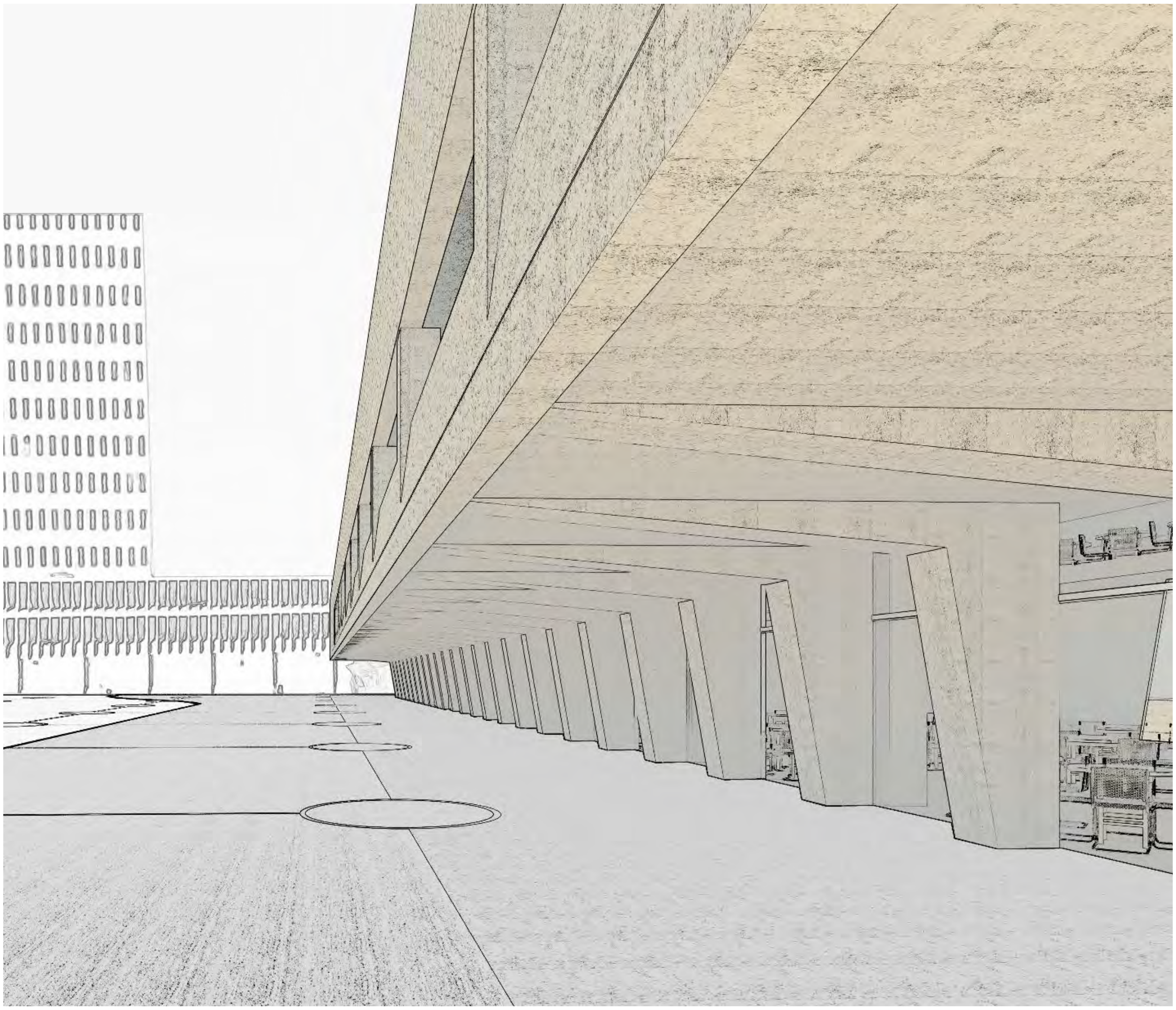

Figure 58. View from Plaza.

The last vantage point revolves around the plaza created on this site, connecting to Civic Plaza to the south. The ground level overhang, sized by the Vector Method, allows the plaza to better engage with the building allowing it to come under the overhang and extend activity into the building.

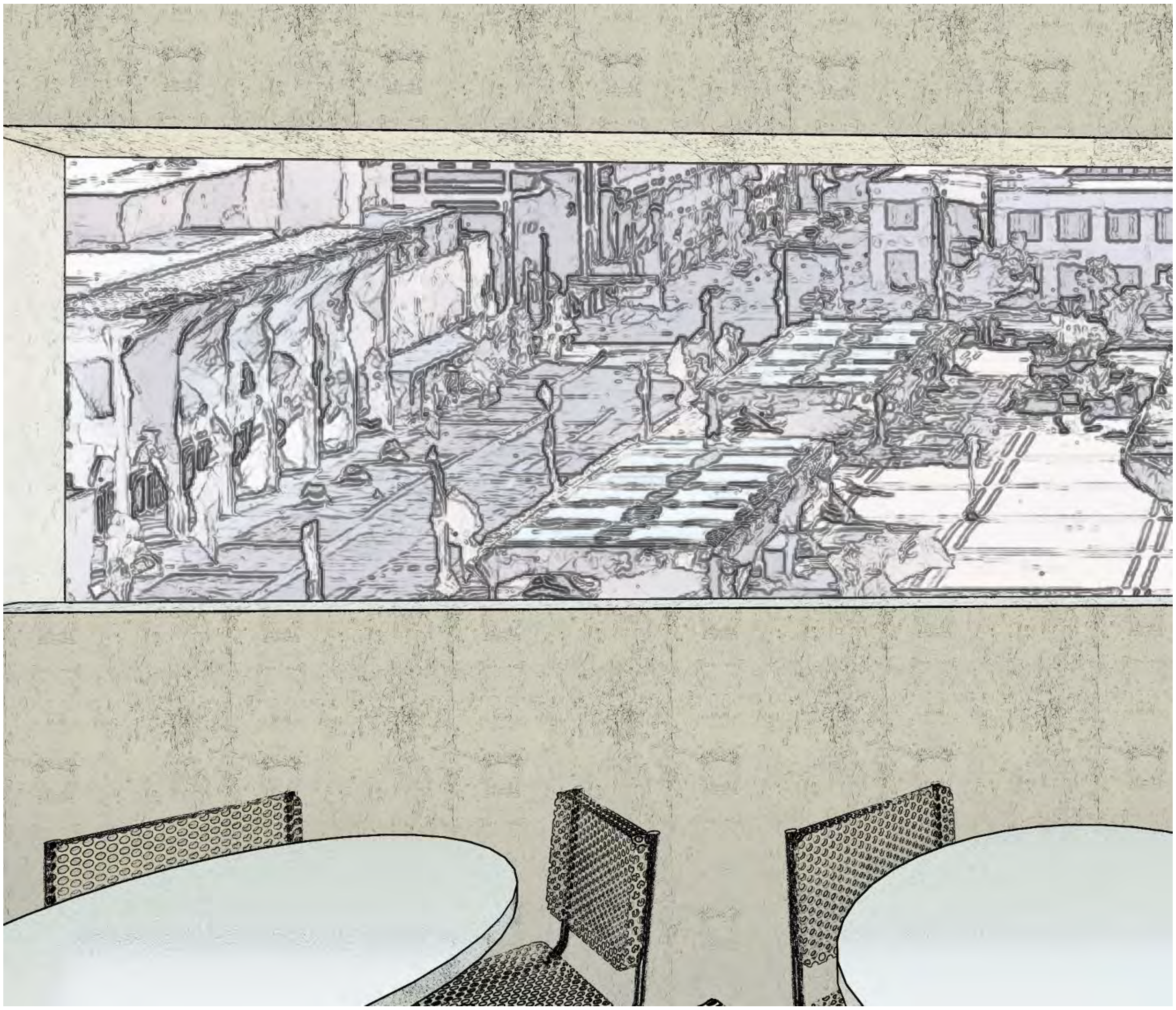

Figure 59. View from Restaurant.

From the outdoor seating area above Civic Plaza is plainly visible. This further reinforces the idea that this inhabitable space created out of necessity for thermal performance can add to the architectural experience of the users.

In each rendering the four shading device schemes express qualities that go beyond the quantitative. The shading devices might provide energy savings that could translate to a meaningful amount of savings in terms of operational funds, but this alone does not justify such outwardly visible fixtures to the building. As this thesis has asserted from the beginning merely functioning in the classical sense creates a good building. The experiences, effects, and qualities seen in these renderings take the project into the realm of architectural experience. The shading devices effect many different quantitative and qualitative aspects of the project the blending of each allows a design to be successful.

4.3 Iterations through Design

Each design represents one singular point. Additional iterations are created to make a case that the Vector Method can create design iterations that influence the architectural expression of the building. Previously, iterations were created to show that each performed in a similar manner on a baseline case. This was to highlight the possibility of different design styles to exist while still designing shading devices that perform. Now different iterations are presented to highlight the flexibility the Vector Method offers in an architectural context. Each design iteration will be expressed in terms of thermal load reduction as well as in renderings, just as the whole building design study. The south office façade is the focus of this exploration.

The Vector Method allows a designer to design for performance and frees the designer to respond to other architectural aspects. This study focuses more on formal moves and the psychological and aesthetic impact of these moves. A designer could easily decide to focus on material choice, constructability concerns, daylighting, historical concerns, local culture, or many other areas of study in which architecture overlaps. The variety in formal moves in this study can help potential users see the flexibility in design available to aid in accomplishing their own design goals.

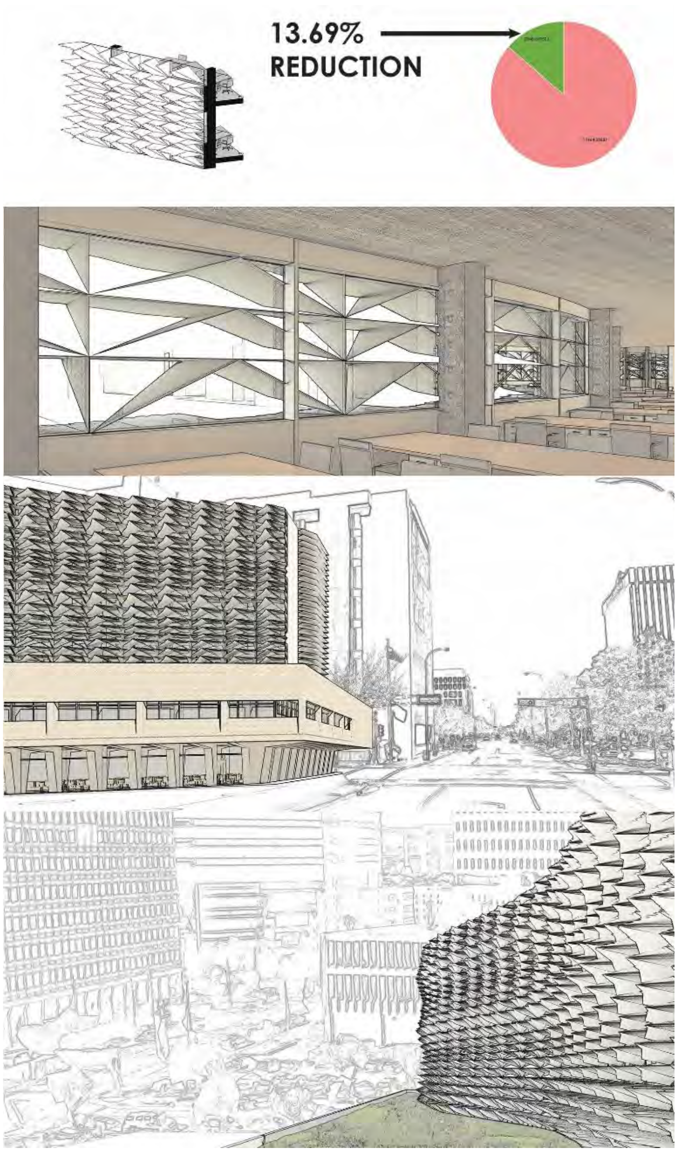

Figure 60. Original South Facade

The original south façade resulted in a 13.69% reduction in thermal loads in the office zones above. The triangular screen with varying size openings created a horizontal emphasis that led the eye across the façade while creating an interesting visual texture. From inside the office space, the screen contains large enough openings to allow for views of Civic Plaza and nearby buildings. If a designer or client valued views of the surroundings while creating a unique aesthetic different from any building in the area this could be a viable solution.

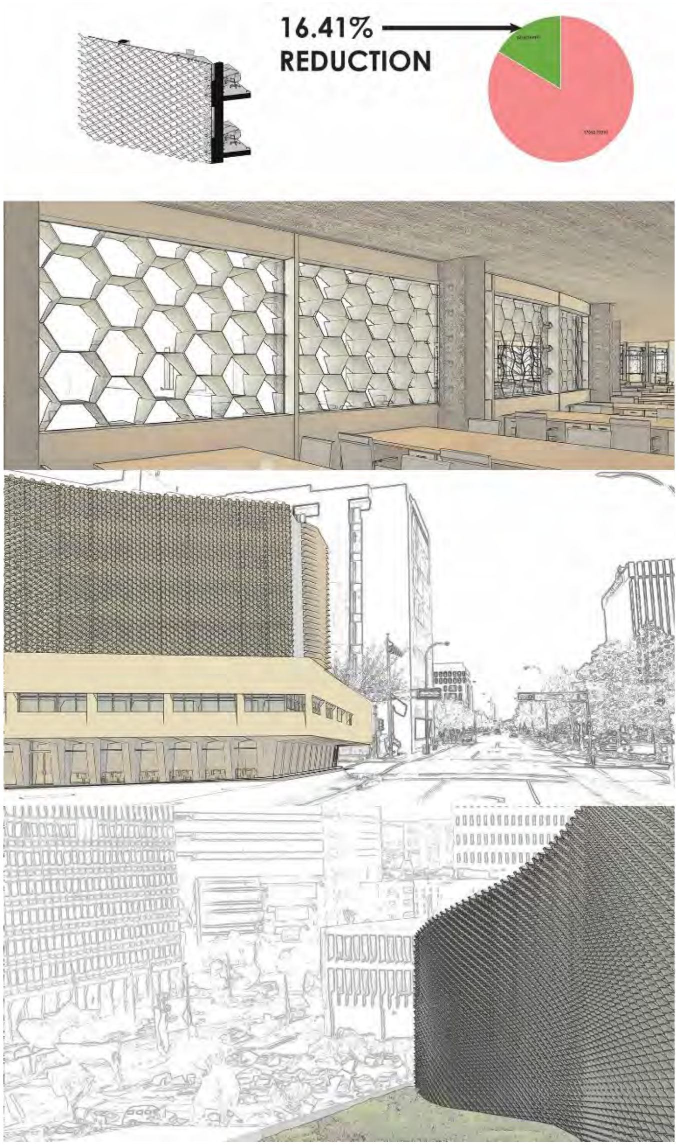

Figure 61. Second Iteration of South Facade

The screen could be more uniform and made of smaller modules. This iteration includes a uniform field of small hexagon units. The hexagons produce a completely different aesthetic from the exterior. Because they are small the visual texture is not so apparent allowing the original curved block form to read more clearly. The smaller openings make it less easy to view the surrounding buildings and Civic Plaza from the office. If this client valued privacy and uniformity in appearance this solution could become viable. This iteration lead to a 16.41% reduction in thermal loads for the south office zones. This is greater than the original design, however, the decision to pick one over the other is not only about performance. Shading screens are a highly visible part of architecture and have many qualities.

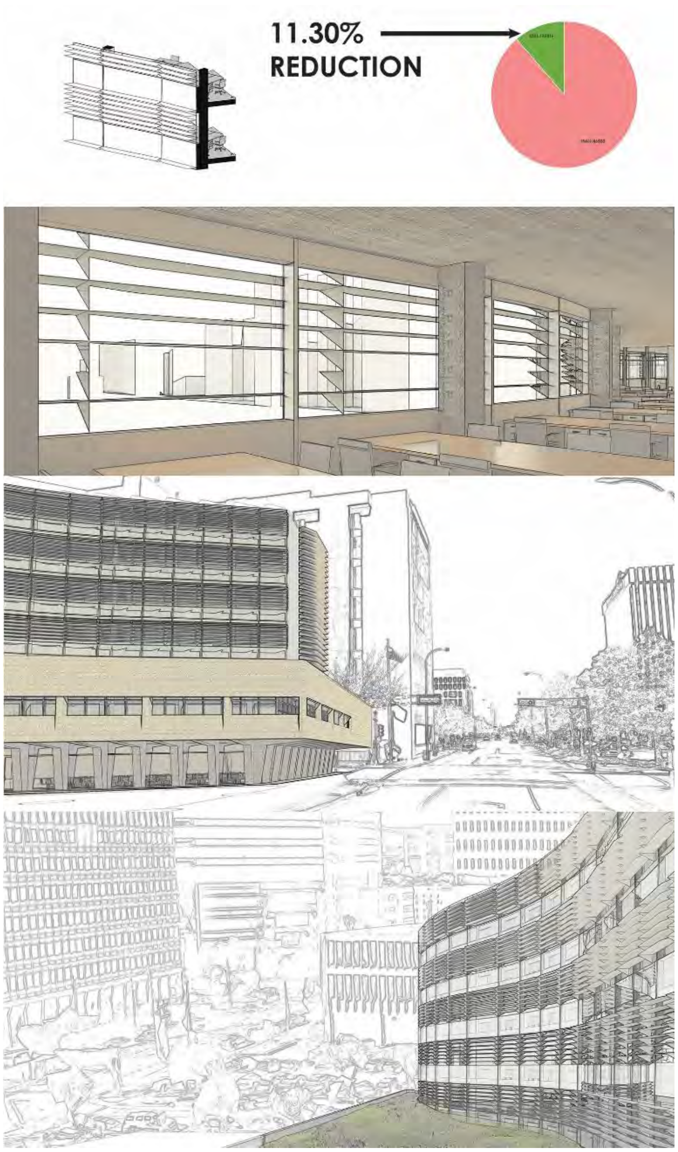

Figure 62. Third Iteration of South Façade

This design incorporates a system of louvers spaced one foot vertically and placed only where window openings actually occur to minimize material use. All of the louvers are mostly rectilinear and have a reasonable depth to height ratio. They would be easy to produce, install, and maintain over the life of the building. They allow the spandrel panels to be read along with the glazing responding to the highly glazed contemporary open architecture. This system is a very minimalist approach reinforcing a horizontal emphasis without competing with the simple building form. From the interior views are accessible without the shades becoming too distracting due to the horizontal nature of the design. This system reduced thermal loads in the office by 11.30%. This is less than other versions, however, this iteration would likely make this difference up in upfront costs. If a client is focused on the total costs with minimal impacts this solution could be the best fit.

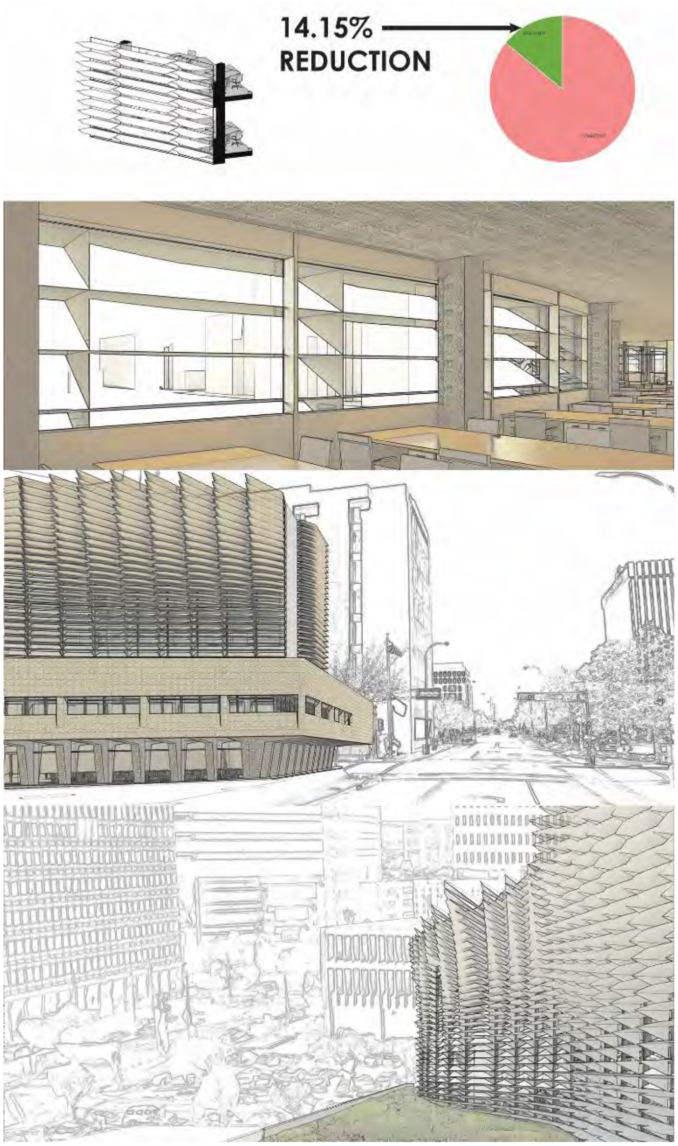

Figure 63. Fourth Iteration of South Facade

This iteration involves a system of louvers that are angled along a gradient to produce the flaring effect towards the top. As a shade is angled more and more towards the sky it must extend further to shade the same area. The curved block is only curving in plan, however, this shade system produces an effect to make it appear as if it is curved in multiple dimensions. The calculation and form generation techniques in the Vector Method become the driver in architectural form finding allowing the building to move past mere function and become more playful. From inside, users experience views in a relatively unhindered manner until one reaches higher floors where the shades flare up at greater angles. This solution lead to a 14.15% reduction of thermal loads in the office. This is very similar to the original design concept's performance. A client or designer that is seeking to create an unusual landmark form that has important reasons for taking that exact form might be drawn to this solution.

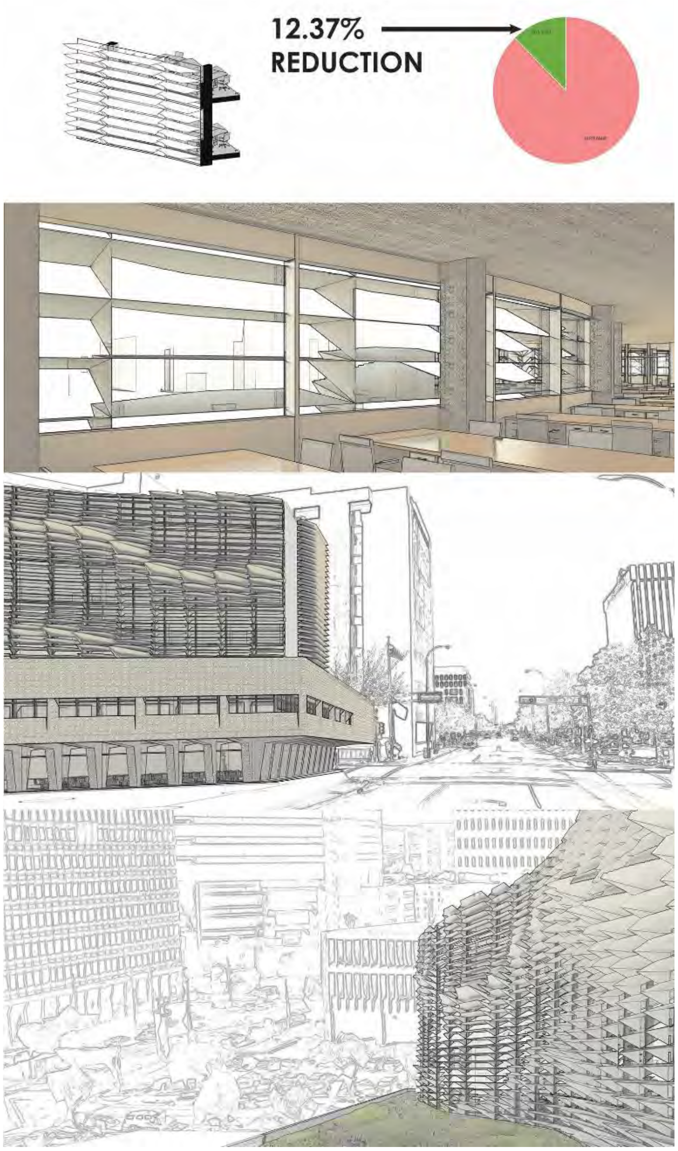

Figure 64. Fifth Iteration of South Facade

This iteration moves past the simplistic idea of horizontal and vertical emphasis to express the possibility of nonlinear movement across a surface. Solutions from the previous design iteration are reorganized to create a wave effect across the façade. The last iteration has view issues for occupants on the higher floors where the shades angle up the most, this iteration has isolated pockets on each floor with this issue but there are no floors that do not have a view. The wave could be intended as a sharp formal contrast with the regular orthogonal base the office sits upon. This solution reduced thermal loads in the office by 12.37%. This is not different enough to exclude this design making the decision about other factors. A client who is interesting in strong formal moves while still valuing the user experience and views from the work space might select this version.

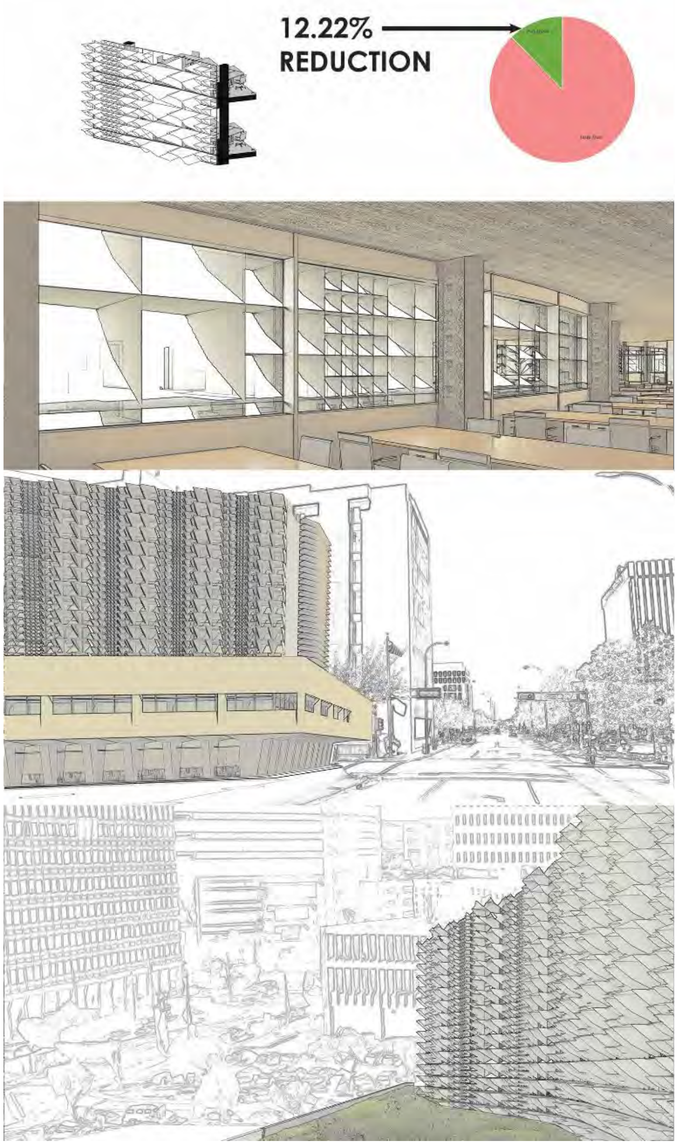

Figure 65. Sixth Iteration of South Facade

This last design iterations takes a different direction and chooses to implement a vertical visual emphasis. By allowing the Vector Method to size hoods from different size rectangular modules, visually more and less dense vertical bands. Other designs had horizontal motifs to bring down the visual height of the design. It could be that a client or designer would like to express the height of a design and not suppress it. Within the Vector Method this is accomplishable. From the interior views are unobstructed from the less dense portions in the screen and more restricted in the more dense areas. This could create more private zones for those who prefer less distractions while they work. This design reduces thermal loads in the office by 12.22%. Again, this is within the range of the other design solutions, meaning performance is not necessarily a concern in the selection process. A client or designer who would want a building that expresses its height and provides a gradient of more and less private work spaces might appreciate this design scheme.

Looking at the possible design solutions for just the south façade on one test case design highlights the potential of the Vector Method to support a wide range of not only physical forms but design intentions. By shifting the concern from which design reduces the thermal load the most to which design is in line with the design's goals architecturally, experientially, or aesthetically a design team can create solutions that function well and become architectural features. Even within just the six iterations presented one can see how aspects such as view from and to a space, visual textures, formal moves, visual movement, material costs, and other factors can move a design in one direction or another. The Vector Method is flexible enough to move with these intensions while ensuring performance is not left behind. This supports the goal of creating good buildings that can become good architecture.

Conclusion

Many aspects of modern life and construction have made the role of shading devices in architecture more difficult to ignore. Larger expanses of glazing, expectations of thermal comfort at more efficient levels, and an expectation of a certain quality in architectural design drive the need for additional thought into shading device design. This thesis puts forward the Vector Method as a solution that responds to the needs of contemporary designers seeking a holistic approach that incorporates performance with architectural qualities.

Existing shading device design methods present obstacles to architectural design for performance goals. The Climate Method produces mostly rectilinear forms and has great difficulty designing anything organic or complex such as a screen system. The Iterate Method consumes too much time to generate one solution and does not help to guide early design. The Cell Method cannot design self-shading devices such as screens and louver systems. Additionally, it does not help to generate a solution, only edits an existing design.

The Vector Method uses a 3D shading volume to indicate the physical space a solution needs to occupy, meaning any form from rectilinear to organic is possible. This takes inspiration from the Climate Method's 2D shading masks that allow a designer to move between shading typologies and improves it to allow more freedom in design. Only one simulation is required before designing in the Vector Method, cutting down significantly on the time required to produce a solution. This takes inspiration from the Climate and Cell methods that also take additional steps to limit simulation times. The Vector Method generates the 3D shading volume to help guide the initial design like the Climate Method does, solving the issue in the Iterate and Cell Methods. The Vector Method recognizes that iterations are important to the design process, however, they should be design iterations, not slight variations on the same design for selecting the best performance solution. Design iterations help a team identify options to support the design intent as explored in the design project portion of this thesis.

The method is user-friendly and quick, as evidenced by limited user trials where graduate students were able to navigate the Vector Method Tool interface easily and create design solutions in an average of 12 minutes and 16 seconds. The Vector Method does not sacrifice the quality of the outcome in terms of thermal load reduction, as shown by the iteration study in section 3.2 showing relatively similar performance levels across many different design solutions.

Shading devices are often highly visible components of a building and have the potential to contribute greatly to the architectural character of a space. As a holistic design method, the Vector Method, as able to respond to different design intentions in the design of a mixed use office building in Albuquerque, New Mexico. The design tool supported the design of simple overhangs for the retail and restaurant areas as well as various iterations of the screen on the office block above. Each space carries different design intents and requirements drawing on the function and performance of each space as well as the potential user experiences. The Vector Method is able to respond to each building program, each orientation along the curved office block, and still accommodate separate visions for the direction of the design.

The Vector Method is not without its limitations. There do exist a number of technical errors with the design tool where the 3D shade volume is not always formed. This is often due to a problem with the Boolean Union command in Rhinoceros and can be solved by changing the division numbers in the Debug tab. Curved geometry must be approximated by polyline segments due to limitations in EnergyPlus' ability to read organic forms. Additionally, this method, as all of the others discussed in this thesis, require the user to know how to create an energy model for their project. This can be a significant barrier to entry that this thesis does not offer a solution to. Also, the tool based on this method is limited to Rhinoceros as a platform. This could make full scale implementation difficult into workflows that rely more heavily on other software such as Revit.

Future work could include a number of unique directions. First, making a shading device design system that is specifically tailored towards users that do not understand energy modeling to promote the most accessible shading device design system using the Vector Method. Work on the interface, sequence of steps, and user inputs could all use additional work and study to become a fully accessible method. Second, this method has significant form finding potential which could lead to studies on the shading forms produced. This could lead to studies comparing regional approaches to shading based on the formal outcome of the Vector Method, comparing shading needs in different climate zones through formal exploration using the Vector Method, studies on the material efficiency of different shading typologies generated through the Vector Method, and many others. Lastly, additional work could focus on integrating additional performance criteria such as daylighting, glare, material use, overall cost, and any other measurable metric. The system is in place for hourly data interpretation of cooling and heating loads. The design of a system to track and interpret even more variables and allow the user to weight priorities between metrics could be extremely useful to a community of designers that recognize each project is unique and does not necessarily have the same goals.

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