High-performance façades for commercial buildings

How can modern, transparent façade systems for commercial buildings fulfill the contemporary demands of sustainable building in regard to their thermal and functional performance, as well as high aesthetic characteristics?

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by
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Professional Report

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Abstract:

Due to the fact that construction, maintenance and operation of buildings consume almost 50% of the energy today, architects play a major role in the reduction of energy consumption. The building’s envelope (façades and roof) can have a significant and measurable impact. With regard to overheating and the potential lost of internal heat, transparent parts of the building envelope have a large effect on the building’s energy consumption. Modern, transparent façade systems can fulfill contemporary demands, such as energy conservation, energy production or the degree of visual contact, of sustainable buildings in order to reduce internal heating, cooling, and electrical loads.

An analysis of existing shading devices and façade design leads to a comparative analysis of conventional shading devices like horizontal and vertical blinds as well as eggcrate and honeycomb shading structures in a hot-humid climate like Austin, Texas. This study helped evaluating strengths and weaknesses of each device resulting in an optimization process of conventional shading devices. Ultimately, an optimized shading structure has been developed.

This project aimed to develop an advanced transparent façade system for a south-oriented commercial façade in Austin, Texas, which fulfills high standards with regard to low energy use, by limiting cooling loads and demands for artificial lighting while avoiding glare and heat losses during the cold season. The optimization has been achieved in providing full shading for a specified period of time throughout the year while providing maximized solar exposure. The shading structure consists out of an array of fixed shading components varying in size and proportion to fulfill criteria like specific views, transparency and aesthetics. The shading structure has been compared to conventional shading devices and analyzed with regard to the reduction of annual solar radiation. The improvement in design and energy consumption contributes to the variety of shading structures for building skins. It is anticipated that the solutions will help to widen the options for aesthetically pleasing, high-performance façades for commercial buildings.
High performance façades for commercial buildings

Fig. 2  Mock-up of optimized honeycomb shading structure
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Chapter I

Fig. 4 Theater, Singapore
I. Introduction

1. Objectives: Design and mock-up of innovative shading structure

2. Energy consumption and building envelopes
1. Objectives: Design and mock-up of innovative shading structure

The goal of this study was to design and develop an innovative shading structure for a hot climate. Preliminary research has been conducted on the typology of existing façade solutions as well as on the diverse options for shading structures. These studies were used to define the basic design criteria for designing shading structures. A parametric analysis of orientation, wall and glass types and window to wall area ratios has been conducted in order to understand the influences of the building physics on the overall energy consumption of a building. This information was useful in attaining an understanding of the influence of shading structures on the energy consumption of a building. Based on this study, the design criteria for an innovative shading structure have been determined.

For the purpose of this study, the shading structure was designed for Austin, Texas. Austin is located in a hot climate, in the northern hemisphere. For such a climate, it is very important in the summer to protect the interior environment from receiving direct solar radiation. The exterior temperature is higher than the comfort level. Thus, solar radiation leads to overheating as soon as direct sunlight penetrates the façade. In contrast, in the winter, direct sunlight is actually desired in order to reduce heating loads and electric consumption caused by artificial lighting. Thus, a fixed shading structure had to be designed which is able to provide full shading in the summer while allowing solar exposure on the window in the winter.

In order to meet those design criteria, it was necessary to gain further knowledge in 3-dimensional modeling tools as well as in algorithmic modeling tools [scripting]. This knowledge was essential since a preliminary study on the optimization of horizontal blinds [see chapter ‘2. Appendix B - Optimized shading blinds’] demonstrated that this procedure is very time-consuming and allows results only for one specific location at a time. This initial study was conducted manually. Another location would have required a reiteration of the whole process of constructing and drafting labor. Nevertheless, this study has been very helpful with regard to the basic understanding of the solar-path and the requirements of a shading structure, which has a holistic approach to the solar challenges in Austin, Texas. From this study, the idea evolved to design a structure, which fulfills exactly the requirements as described before using algorithmic modeling tools, which allow for a quick changing of the parameters. Full shading and maximum solar exposure for specified times throughout the year. Looking at the optimized blinds for a south oriented building, it seemed that the blinds describe a semi-circular path throughout the day by overlaying of the blinds of each hour throughout the day of a south-oriented building. This is not surprising since the sun-path itself describes a semi-circle throughout the day. In order to be able to create a continuous grid, a honeycomb structure has been chosen.

The algorithmic modeling tool 'Grasshopper®' [GH], a plug-in for the 3-dimensional modeling tool 'Rhinoceros™' [Rhin], enabled the design process to become flexible. With these tools, it was possible to instantly change not only the location and orientation of the building but also different specified times throughout the year to
see how the optimized shading structure would change with a different set of variables. The initial study about shading blinds (see chapter ‘2. Appendix B - Optimized shading blinds’), could be transferred into GH and be animated. The optimization of the shading structure has been achieved in orienting the surfaces towards the sun. Therefore, the sun would always see the maximum possible surface of the shading structure, assuring maximum shading respectively. It gets more challenging to achieve an optimization for this mechanism since the attachment points of the blinds change every hour. This is not the case for the conventional optimized horizontal and vertical blinds. These structures can always be attached to the façade at defined points.

The optimized shading structure has been compared to conventional shadings such as horizontal louvers and vertical louvers as well as eggcrate and honeycomb shading structures. To compare these devices, ‘Autodesk Ecotect Analysis’ (Ecotect) has been used to compare their performance with regard to shading to each other. Another goal of this study was to compare annual heat gains of an interior environment for different shading devices against each other. This idea evolved out of an existing research facility of the University of Texas at Austin - School of Architecture (UTSoA), called ‘Thermal Lab’ (see chapter ‘V. Research facility: Thermal Lab’). It would have been possible to compare accurate measured data from the Thermal Lab to calculated data from energy simulation tools such as eQuest (the QUick Energy Simulation Tool), e+ (EnergyPlus), Ecotect (Autodesk Ecotect Analysis) or EcoDesigner (ArchiCAD). Unfortunately, the program that would have been needed to be developed for this comparison has not been finished in time. Being able to validate real measurements with results from a program, written for a specific building, can tell how close the program delivers results to measured values. Conventional energy simulation tools can then be compared to this specific program, resulting in a certain percentage of accuracy which leads back to real measured data. Since this wasn’t possible for this study, a comparative analysis was conducted in Ecotect with regard to annual solar radiation on a vertical surface. Furthermore, a comparative analysis of solar radiation and daylight-levels has been conducted for the optimized shading structure using a mock-up, built for the dimensions of the Thermal Lab.

Based on the results of the designing process in Rhino and GH, it was possible to design a shading component, which is able to provide full shading over a certain period of time. For this study, based on the dry-bulb temperatures in Austin, the time for which the window is completely shaded is from March 21 until September 21. Due to a limitations to an extrude volume, it is not possible for this component to provide full solar exposure for another specified period of time. The component would need to exceed the extruded surface in order to provide full solar exposure. The 3-dimensional structure that has been designed in GH can be processed for construction. A cnc-router has been used to produce the mock-up of the optimized shading structure.

The goal was to develop an alternative shading solution with improved functional, ecological and aesthetic properties to be applied in future developments in central Texas and other regions with similar climatic conditions.
2. Energy consumption and building envelopes

Modern, transparent façade systems can fulfill contemporary demands of sustainable buildings in order to reduce internal heating, cooling, and electrical loads.

The reduction of the emission of CO$_2$ and other greenhouse gases and our dependence on fossil fuels are among the most challenging tasks of the 21st century. This paper addresses a very specific niche in today’s energy crisis. Transparent modern façade systems can have a significant impact on the energy consumption of commercial buildings due to their functional capabilities, such as day lighting and glare control, or operability, and thermal performance. The significance of this aspect and its importance for the overall energy demand of the United States will be discussed below.

Roughly 50% of the energy consumed today is used in the construction and operation of buildings, which account for 81% [or $272$ billion] of the total U.S. electricity expenditures.$^{1,2}$
In the United States, commercial buildings consume 3.9% of primary energy (fig. 6). The total energy consumption by end-use of commercial buildings represent 18% of this overall energy consumption (fig. 7) and 55% of the electricity demand (fig. 8). The commercial sector’s contribution to the overall demand is projected to increase faster than any other sector, and take over the electricity demand of the residential sector by 2014. In commercial buildings, the majority of the electricity demand is related to lighting (almost 20%), and heating and cooling [36% and 8%] (fig. 9). Examining the primary energy consumption, 17% goes into lighting, 21% into space heating and 9% into cooling (fig. 10). Each of these energy demands is closely related to the building envelope, and can be decreased with efficient envelope design (fig. 11).

The envelope is the most important subsystem of the building, serving as the link between all other components of the building system. In figure 11, the overall building system-diagram, the major subsystems of the building are broken down into the structure, envelope (building skin), heating ventilation and air-conditioning [technical
services), and the interior walls of the building (spatial sequence). The envelope is connected to each of the other subsystems in turn.\(^6\)

The structure of the building places constraints on envelope design but may also serve as the base for the most creative and novel façade design. The load on building services (heating, ventilation and air conditioning - "HVAC") is intrinsically linked to the efficiency of the envelope; the better the envelope performs, the less energy is needed for cooling or heating. During warm seasons, shading devices can significantly reduce the cooling demand by protecting the façade from direct insolation. The performance of thermal insulation determines both heating and cooling demand, by limiting the exchange of heat and cold through the envelope. In some instances, the envelope is even more intimately integrated through the inclusion of HVAC functions within the envelope. As an example, the interior walls, ceiling and floor slabs of the building may be used as thermal mass for storing heat or cold depending on an appropriate envelope design.
Existing commercial buildings represent 18% of the total U.S. energy consumption. Of the 15.4 Quadrillion Btu’s that commercial buildings consume each year, windows account for 1.1 Quads, and lighting 3.83 Quads. If it is assumed that 25% of the lighting could be attributed to windows, then lighting in commercial buildings represents 2% of the entire national energy consumption. By targeting renovation of existing buildings in concert with new construction, the potential to make a serious impact is heightened.

The extensive use of glazing on commercial, particularly office-buildings and high-rise façades, makes them a perfect target for new energy-efficient designs. In 2007, there were 536 million square feet of built/integrated glazing in non-residential buildings within the United States. The potential to use commercial buildings as an energy asset rather than energy burden in building construction is essential. It is no longer sufficient to create a building skin that merely provides a view to the external world. The envelope design should support the energy concept of the building and reduce its energy consumption while avoiding overheating during the summer.
warm seasons and reducing heating loads during the cold seasons. Furthermore, functions of the façade design should also include daylighting, glare control and natural ventilation.
2. Energy consumption and building envelopes

Fig. 14  World-wide energy consumption by night
Chapter II

Fig. 15  Horizontal blinds as overhang
II. Preliminary research - qualitative and quantitative

1. Shading systems
   1.1 Importance of shading
   1.2 Shading types
   1.3 Manipulators
   1.4 Special types of shading systems

2. Façade design
   2.1 Approach
   2.2 Methodology
   2.3 Design solution

Fig. 16   Horizontal blinds as overhang
II. Preliminary research - qualitative and quantitative

1. Shading systems

This qualitative research has been conducted in order to gain the necessary knowledge to design an optimized shading system. An optimized shading system represents a structure that provides maximum shading for a specified period throughout the year while allowing maximum solar exposure for another period. To be able to do so, a study of a typology of existing conventional shading systems needed to be conducted. Knowing about existing shading solutions helps to define the needs and requirements of an innovative optimized shading structure. To optimize conventional shading systems, the process of designing such systems had to be analyzed (see ‘2. Façade design’).

1.1 Importance of shading

As already discussed in the first chapter (see chapter ‘1. Introduction’) it is highly important to reduce the energy consumption of buildings. A transparent, east-, south- or west-facing building skin without shading devices is fully exposed to direct insolation. In hot climates, such as Austin, Texas, where temperatures exceed the desired indoor temperature for extended periods of time, the need for shading devices is even more important. There are two reasons why direct sunlight has a much higher impact on windows than on walls. First, exterior walls have a higher capability to store heat due to their thermal inertia. Therefore, one could design these wall systems in such a way, that energy [shortwave and longwave radiation] gets absorbed during the day and can be released at night (e.g. phase change materials - PCM). Second, glass is almost transparent to shortwave radiation. If solar insolation hits the surface of the window, the solar rays radiate through the glass and heat up the surfaces behind. One way to reduce the transmittance is to use reflective glazing. With the use of reflective film or coating, the efficiency of the glazing depends on thermal and visual properties. Very often, visual contact is effected by the color of the reflective film, which darkens the view. Thus, the lower the visual quality for the user. As a result, shading the window area from direct insolation usually yields better results than reflective glazing with regard to the quality of visual contact.

Fig. 17  Hyatt Regency Hotel, Dallas (USA)
1.2 Shading types

There is a high variety of external shading devices existing on the market. Yet, for the most part, they can be divided into two major categories: horizontal fins and vertical fins.

Even if there are ways to reduce solar insolation, direct sunlight as well as diffuse sunlight will always have an impact on the indoor environment. Solar insolation not only heats up the internal space due to penetration through the window but also due to energy flow through the whole envelope - the façade and the roof. As soon as the solar rays hit the surface of the building, the energy gets absorbed by the material. The amount of absorption depends on the thermal properties of the material as well as on color. Entirely glazed buildings that are able to deal with direct sunlight without using additional mechanical equipment are rare. Since direct sunlight for the most part causes overheating, designers try to keep it out of the building. Yet, direct sunlight is important for the indoor environment since it affects the comfort
level of the user in a positive way. Natural daylight is desirable in commercial buildings for occupant well-being and productivity. Furthermore, increased natural light reduces demand for artificial lighting. But, due to overheating, the use of natural daylight may increase the electricity consumption and therefore the heating loads of the building tremendously. See figures 20-35.

Internal glare control
When louvers are used on the inside, the thermal performance is highly affected since the shortwave radiation coming from the sun is turned into longwave radiation as soon as it gets absorbed [fig. 36-37]. Thereby, internal shading devices act like radiators. Glass is opaque to longwave radiation so it is reflected to the inside again, causing not only overheating in between the shading device and the window but is also heating up the interior surfaces and interior air through radiation and convection. As a result, internal shading devices should not be defined as shading devices since shading structures are intended to keep the heat outside. They should rather be categorized as glare control devices.
External shading

External shadings on the other hand are affected by weather and wind conditions, which lead to higher capital and maintenance costs. External shading devices block the sun before it can even heat up the surface or penetrate the windows (fig. 22-25, 40-43, 44-49).

Horizontal shading

The most common shading device is the use of horizontal shading devices in order to reduce light coming from the sun at a high profile angle. There are many ways to take advantage of this kind of shading structure such as venetian blinds (fig. 26-29), overhangs (fig. 30-31) or reflective lamella in the cavity between the glazing of the window (fig. 32-33, 38-39). Due to their operability, horizontal fins are usually very effective. They can almost provide full shading according to the requirements of the occupant or depending on the position of the sun (orientation of the building or time during the day).

Overhangs have their strengths in allowing the user to have almost unobstructed visual contact with the exterior.
They are highly efficient for south-oriented façades and especially when the sun is at high positions. But, as the sun gets lower, the wider the shading device has to be to provide sufficient shading. Some overhangs are designed to reflect direct sunlight into the depth of the room. This helps to reduce artificial lighting while providing natural daylight (fig. 46-47). The same may be true of other horizontal shading devices, if designed properly (48-49).

One way to reduce overheating while still protecting a shading device from wind and weather is to place the shading device in the cavity between the panes of glass (fig. 32-33, 38-39). Even if this system produces overheating due to radiation and convection in the cavity, it is still less than if the shading device would be positioned on the inside of the façade. Nevertheless, if there is shading used in the cavity between the panes of glass or on the inside of the exterior surface of a double-façade, the space should be ventilated in order to discharge the heat to the exterior. This usually happens at the upper part of the system due to thermal reasons.
**Vertical shading**

While horizontal shading is highly effective against direct sunlight from a high angle, vertical shading is very effective for direct sunlight at a low angle, such as during the morning, the afternoon and the evening (fig. 44-45). Vertical fins generally block low solar radiation coming from the side. Thus, they are useful on east and west facing façades. Therefore, even if the outside view is limited due to the vertical shadings, similar to horizontal shadings, most of the window is protected from direct sunlight. Vertical fins are generally not successful on southwest or southeast façades since the solar altitude angle is too high during the hot season. For these orientations a combination of vertical and horizontal fins are most effective at blocking the sun for both, high and low positions.
1.3 Manipulators

Shading devices that can be operated either manually by the occupant or mechanically by an automated control device are called Manipulators. One of the very first manipulators is the shutter. It was originally used to protect the window from natural forces (e.g., wind, water, snow, etc.). One of the advantages of manipulators lies in the possibility to adjust the shading device to the sun’s position. As soon as the shading device doesn’t provide enough protection any more, it can be adjusted to the sun’s position in order to reconstruct the optimized shading. Higher costs and maintenance issues have to be considered (fig. 48-49). Furthermore, the occupant has the chance to adjust his environment according to his desires. The occupant is able to adjust variables such as the degree of visual contact or solar radiation depending on his level of comfort. The more detailed the occupant can change the shading device, the more likely he will be satisfied.
1.4 Special types of shading systems: Screens

A different way of providing shadow has been found in the Islamic art: the ‘musharabia’. This is a special kind of wooden screen, which is placed outside the windows (fig. 52-55), both as shading as well a design element. Today, screens are very often already integrated in the building’s envelope. There are many different methods of production available like scratching, milling, plasma and laser cutting, fluid forming and many more that provide a wide variety of screen types. With advanced technologies it is possible today to build these kinds of structures in an affordable way. A modern version of these ‘musharabia’ can be found in printed glass or on scratched surfaces as shown in figures 58-63. They not only serve as a design element but they also provide shading for the interior. On a micro scale, some sunscreens deliver the similar effects with regard to shading (fig. 64). There is a high transparency from the interior to the exterior while having a limited view from the exterior to the interior. Thus a high degree of visual contact is guaranteed.
As mentioned in the previous chapter, in order to be able to design optimized shading structures, it is important to know how to design conventional shading structures. In the following, the necessary design parameters are discussed as well as a methodology of how to design an optimized shading structure.

2.1 Approach

The design of a shading device depends on a variety of different variables. It is rare that a design specific for one location can be applied to another location. The reason for the need of a specialized design can be explained through the following variables.

Climate

It is of high importance to know about the climatic conditions for which the shading structure has to be designed for. The requirements for hot-humid climates like Austin, Texas, are much different than for a moderate climate like in Munich, Germany. Different climates require different designs (fig. 65-68). Basically, in a climate such as Austin, the interior has to be protected in the summer completely from direct sunlight. The solar radiation would heat up the room when the space actually has to be cooled down due to exterior dry-bulb temperatures above comfort level. On the other hand, in the winter, direct sunlight can actually be used to heat up the room and decrease the amount of energy needed to maintain the desired temperature.

Location

Depending on the location, moisture can be an issue as well. The psychometric chart indicates that the comfort zone not only depends on latent and sensible temperature but also on the humidity. In other words, a higher desert temperature might be more comfortable than a lower temperature in a rainforest, where there is high humidity. Furthermore, latitude and longitude play significant roles in the climate related design for a building. The altitude of a location has no direct relation to the façade, it only influences the sizing of the building’s equipment. Furthermore, if a building is located close to the equator instead of nearby the arctic or antarctic circle, the sun’s
path will change significantly. The closer to the equator, the more perpendicular are the solar rays to the ground. A building closer to the arctic or antarctic circle receives solar rays which are much more perpendicular to a vertical surface.

Solar geometry
The position of the sun not only changes throughout the day but also throughout the whole year. It can be described through several geometrical aspects. Depending on the day of the year and the time during the day, the sun’s azimuth angle changes constantly while the earth is rotating around its axis. Due to the tilt of the earth’s axis and its rotating around the sun, the azimuth angle of the location of the rising and setting sun changes throughout the year. In Austin, the sun rises at an angle of 62° east (fig. 76) in December, whereas in June, the sun rises at an angle of 117° east (fig. 75). Furthermore, the sun rises earlier in the morning in the summer than in the winter - the earliest on June the 21st (summer solstice), the latest on December the 21st (winter solstice). See figures 75-76. These phenomena
Orientation of the building

Due to the solar geometry, the impact of solar radiation is very different depending on the façade’s orientation. In situations where heating of the interior is not desired, buildings should be oriented to the direction where it gets the least amount of direct sunlight. In hot climates that would be the north-south orientation. This means the area of east- and west-facing façades should be smaller than the area of north- and south oriented façades. The amount of solar radiation can be seen in the appendix in chapter ‘1. Appendix A - Solar insolation’.

Contrarily, in cold climates, heating of the interior is a desirable side effect of transparent façades, in addition to the visual comfort provided. Since almost 30% of the energy consumption in a building is used for heating and cooling, the reduction of either is desired. In cold climates, the direct solar insolation would heat up the space and reduce the difference between the room temperature and the target temperature. A way to adjust the balance would be to change the window to wall area ratio of a façade. The optimized ratio depends on the solar insolation and the increased amount of energy due to the sunlight. For some cases, shading devices might still be necessary.
Occupancy
Different uses require different approaches toward the design of the façade. A façade of a commercial building has different needs than a façade of an industrial or residential building. Due to the depth of the working space, commercial buildings might have the need for redirected sunlight into the interior of the building. A higher number of occupants lead to an increased number of air-changes, which could be achieved through manipulators in the façade. High internal loads of office spaces require solutions for the resulting greater cooling loads. Also, internal loads help reducing the heating loads in the winter. In residential buildings, higher comfort requirements and the need for a certain degree of privacy usually lead to a lower window to wall area ratio. Internal loads are generally much lower as well. Thus, the heating and cooling loads can be significantly different. Even within the same building, the functional requirements may change depending on the different requirements of the interior, such that the design of the façade may vary in relation to diverse programmatic zones.

Thus, the requirements of a façade can significantly change with regard to climate, location, orientation, and function.

2.2 Methodology
The following steps should be followed to design an optimized shading device:

1. Determine the times when shading is needed.
At cooler temperatures, the direct sunlight is desired to heat up the space, whereas during warm periods, shading devices are needed to achieve or approach comfort conditions. In the temperate zone, a temperature of 70°F can be used to define the times when shading is needed. If the temperature exceeds 70°F, shading should be provided, while everything below 70°F can be neglected. Temperatures above 70°F are considered to be in the category of overheated periods. This level is based on the conditions of the Temperate Zone in the United States, around 40° N latitude. People living below this latitude are more used to warmer conditions, and thus, every
additional 5° of change of latitude toward south will raise the temperature line by 0.75°F. Therefore, in a climate like Austin, the overheated period should start at 71.5°F instead of 70°F, considering its latitude at 33.3° N (6.7° further south compared to the Temperate Zone at 40°, therefore 70° + 2x0.75°). To define the periods when shading is needed, climate data will be used to define when the temperatures falls within the overheating period [see fig. 149, 154-155, 160].

2. Determine the position of the sun when shading is needed. The ‘sun-path diagram’ or a ‘sun position calculator’ can be used to determine the sun’s position at any time with regard to the buildings location and orientation. The sun-path diagram shows the path traced by the sun across the sky dome, projected on to the horizon plane. The diagram can determine the profile angle, the azimuth angle, as well as the altitude angle of the sun for any time during the year.

3. Determine the type and position of a shading device needed between the sun and the point of observation during the overheated period. Shading devices can be projected the same way on a horizon plane as the sun-path diagram, shown in figure 80. From the center of that diagram, the point of observation is looking toward the sky. The area, which overlaps with the sun-path diagram, is shaded, whereas the area which is not covered on the sun-path diagram, is exposed to solar insolation. Any point of a building will show its own specific diagram, which is called the ‘shading mask’. Horizontal shading devices like overhangs show a segmental character, while vertical shading devices show a radial character. Shading devices, which consist of both horizontal and vertical elements, show a combination of both characters. Overlaying a sun-path-diagram with a shading mask will show immediately the times when the point of observation is exposed and when it is shaded. As shown in the example in figure 80, most of the sun-path diagram is overlaying the shading mask. If the sun-path diagram doesn’t cover any part of the shading mask, there would be no shadow over the whole...
year on this specific point. The more of the sun-path diagram that is covered by shade, the less direct sunlight will hit the surface. To design the optimized shading device, the process can be reversed. While indicating the overheating period on the sun-path diagram, the shading mask should cover as much of that area as possible. Since a shading device should have a reasonable form aesthetically, it might happen that the shading device also provides shading when direct sunlight would actually be helpful to reduce heating demands. The effectiveness of the shading device depends on the maximization of covered overheated period area and uncovered area for temperatures when solar exposure is desired. If 100% of the overheating period area is covered, no direct sunlight will hit the surface when the temperature will be over 71.5°F for the Temperate Zone. If 50% of the area is covered, shading will be provided only half of the time and so on. A rule of thumb indicates that if 50% of the window area is covered during the overheating period the shading device will be effective. A thorough analysis of shading devices with regard to different orientations and locations was conducted and is described in chapter III.

Quantitative simulation research: "To choose between the various technically correct possibilities, or develop new variations is the designer’s task. This is the line where the technical method ends and creative expression takes over." 13

2.3 Design solution
As a preliminary study for the optimized shading system as explained in chapter IV. Optimized shading structure", an array of optimized shading blinds has been created. These blinds change their orientation throughout the day and year according to the position of the sun.

How does a sun-tracking shading device have to be adapted during the day?
The following parameters have been set up to conduct this study. The blinds have a width of 1 foot. They are all parallel to each other and they are all connected to the façade on one side. The blinds do always have to be oriented towards the sun so that their surfaces are perpendicular to the solar rays. Thus, the maximum

Figures 82-89:
Elevation views show the required number of fins, their angle and rotation required to provide all shade for a south west facing façade at their respective hours of the day. See figure 90.
the solar position corresponds to March/September 21st, 3:00 p.m. Lat. = 30.5° N. The solar angles are \( a = 45° \), \( b = 37° \). Given this information, a section view in true profile of the solar position has to be drawn. The true profile will result automatically if the horizon line in elevation is parallel to the solar ray in plan. In true profile, the sun will always rest on the perimeter of the circle. After that, the solar ray and structure in elevation, as well as the fold line as the bisector of the solar ray in elevation and perpendicular to the solar ray in plan can be drawn. Then, each corner of the structure from the respective points in plan and in elevation onto the solar view plan can be projected. The resulting axonometric shows the sun’s view of the object. In this view, the fins are shown in their real dimensions. The fins have a width of 1 ft, are parallel to each other and cover the whole window with a minimized number of fins and total surface area. In this view, the window is not to be seen in order to cover the whole window in shade.

The surface area of the shading devices is facing the sun and protecting the window from direct sunlight. This study has been conducted for different orientations. Figures 82-89 show the design solution in elevation for a southwest oriented building. The complete study is shown in the appendix in chapter ‘2. Appendix B - Optimized shading blinds’. Figures 82-90 represent a design solution, which provides full shading from March 21st until September 21st from 10 a.m. until 5 p.m. The shading devices have been designed for the sun’s position for every full hour of the day from 10 a.m. until 5 p.m. Thus, there are eight different designs for the shading devices throughout the day. The elevations of the shading devices for each hour show that the fins follow the sun, which moves around the earth on a circular path [fig. 82-89]. For a southwest oriented building it can be stated that the lower the altitude angle of the sun, the higher the number of fins necessary to cover the window. This means an increasing surface area of shading devices is needed in order to protect the window from direct solar insulation [compare fig. 84 and 89, where at 12 noon, the altitude angle is at 60° while at 5 p.m. it is at 12°]. Since all the fins have the same width (1 ft), the surface area depends on the sum of the length of all the fins necessary to cover the window at a specific time. At 12 noon, 5 fins with a total length of 55 ft have a surface area of 55 ft². While at 5 p.m., 12 fins with a total length of 104 ft achieve a surface area of 104 ft², which is almost the double the area that is needed at 12 noon. This result was expected, since the sun is at a much lower position at 5 p.m. The altitude angle of the sun is 12° and the azimuth angle closer to 90° W, so that the solar rays hit the surface almost perpendicular. Thus, the fins have to be almost parallel to the surfaces and perpendicular to the rays. This fact increases the amount of necessary fins in order to cover the whole window and respectively the surface area. Figure 90 shows how these shading elements have been designed. Views from the sun’s position can be very useful to visualize an entire scene at one moment in time. First, the plan view with the solar ray along the horizontal has to be drawn. Then, the south and east and west direction have to be marked accordingly with regard to the building’s orientation. With the proper orientation in plan view, the building can be drawn in elevation. The solar position corresponds to March/September 21st, 3:00 p.m. Lat. = 30.5° N. The solar angles are \( a = 45° \), \( b = 37° \). Given this information, a section view in true profile of the solar position has to be drawn. The true profile will result automatically if the horizon line in elevation is parallel to the solar ray in plan. In true profile, the sun will always rest on the perimeter of the circle. After that, the solar ray and structure in elevation, as well as the fold line as the bisector of the solar ray in elevation and perpendicular to the solar ray in plan can be drawn. Then, each corner of the structure from the respective points in plan and in elevation onto the solar view plan can be projected. The resulting axonometric shows the sun’s view of the object. In this view, the fins are shown in their real dimensions. The fins have a width of 1 ft, are parallel to each other and cover the whole window with a minimized number of fins and total surface area. In this view, the window is not to be seen in order to cover the whole window in shade.
2. Façade design

Orientation: south-west
Criteria: provide full shading from Mar 21 - Sep 21 at 3 p.m.
Width: 1'
Azimuth window: 45° W
Azimuth sun: 63° W (red: 18° W)
Altitude angle sun: 37°
Shading device: diagonal shading / fins

Fig. 90 Construction of solar view

Solar rays - sun at 3 p.m.
Altitude of the sun = 37°
Chapter III

Fig. 91: South-west oriented building with vertically oriented honeycomb shading structure with a circumference of 4 feet
III. Quantitative simulation research

1. Solar radiation on vertical planar surfaces
2. Types of conventional shading devices used for this study
3. Performance of conventional shading devices depending on the orientation
4. Influence of material thickness on results and the degree of visual contact
5. Performance of eggcrate shading structures depending on the orientation
6. Performance of shading devices for a specific orientation
7. Solar radiation on east/west and southeast/southwest and the influence on the performance of the shading devices
8. Performance of shading devices in Austin versus Munich
9. Conclusion
III. Quantitative simulation research

Comparison of conventional shading devices

In the following section, different shading devices will be discussed with regard to different orientations as well as different locations. This study has two purposes. First, to find out where the strengths and the weaknesses of each shading device are. And second, to find out which shading device is most effective for each orientation. Three variables play a major role in this decision: provided shading, visual contact and use of daylight. Provided shading due to the reduction of cooling loads. Visual contact to provide a high comfort level and the use of daylight to reduce artificial lighting due to an increased level of diffuse skylight. Autodesk Ecotect Analysis (Ecotect) has been chosen as the analysis tool to conduct the parametric analysis. The advantage of Ecotect over other analysis tools is the possibility to measure solar radiation on a surface which is shaded by a structure which has been created in a 3-dimensional modeling tool such as Rhinoceros® [Rhinol]. In order to be able to compare the shading structures to each other, a coefficient has to be introduced - the shading coefficient ‘sc’. It represents the ratio of the amount of solar radiation between an unobstructed and an obstructed surface. For example a vertical south oriented surface receives 920 kWh/m² of solar radiation. If a surface with a shading device receives only 600 kWh/m², the sc is 0.65. The lower the sc, the more shading is provided. A sc of 0 would not allow any solar radiation at all on the surface. An sc of 1.0 is basically an unobstructed surface, which receives full solar radiation. The results are summarized in figures 111-112 and 125. Numbers used in this chapter refer to these tables.

1. Solar radiation on vertical planar surfaces

In order to be able to compare different shadings structures for different orientations, it is essential to know how the different orientations compare to each other with regard to the respective annual solar radiation on the surface. A vertical surface has been rotated towards different orientations in Austin, Texas, which is located in a hot climate. The global horizontal radiation [GHR] in Austin (30.3° N latitude; -97.7° W longitude) is 1.765 kWh/m². A vertical south oriented surface receives 920 kWh/m² of solar radiation per year in Austin (52.12 %...
of GHR), a southwest oriented surface 877 kWh/m² (49.69% of GHR) and a west oriented surface 735 kWh/m² (41.64% of GHR) (fig. 105). Thus, a south oriented surface has a 2.43% and 10.48% higher solar exposure compared to southwest and west oriented surfaces. The results seem to be reasonable. A south oriented surface receives solar radiation as long as the azimuth angle of the sun is between 90° E and 90° W (180° in sum, see fig. 100). A southwest oriented surface receives only solar radiation from 45° E until the sun sets. The highest amount of solar radiation is on June 21st, which is, according to the NOAA Solar Calculator from the National Oceanic & Atmospheric Administration (NOAA), at 102.19° W. That means for 147.19° in sum (see fig. 101). West only receives solar radiation from noon, which until sunset, which is again the most at 102.19° W, resulting in a maximum sum of 102.19° (see fig. 102). Thus it is logical that there is a decreasing amount of solar radiation from south to southwest to west. Diffuse solar radiation has not been taken into account.

It is assumed that surfaces on east and west as well as southeast and southwest receive a similar amount of solar radiation throughout the day and year. The assumption is made due to the symmetrical path of the sun during the day, having solar noon as the symmetry axis. Disregarding the daylight saving hour, the sun rises and sets at the same time in the morning and respectively at night (i.e. position of the sun at 6 a.m. = analog position of the sun at 6 p.m.). According to NOAA, the sun rises on June 21 at 6:04 a.m. at a solar elevation of -0.38° and a solar azimuth angle of 101.88° E. Respectively, the sun sets at an elevation of -0.58° at an azimuth angle of 102.19°. At solar noon, around 12:30 p.m. the sun reaches its highest point with 69.65° of elevation. The sun performs a similar symmetrical curve from east to south as from south to west. While a south oriented surface has its peak of the monthly solar radiation distribution in the winter, a west oriented surface receives its highest solar radiation in the summer. In the summer the sun rises earlier and sets later during the day. The amount of solar radiation of a southwest oriented surface is almost evenly distributed throughout the year. Yet, it receives a little peak in March and October (see fig. 104).
2. Types of conventional shading devices used for this study

The following types of conventional shading devices were examined and tested on different orientations for Austin (see fig. 92-95):

Type 01:  Horizontal louvers
Type 02:  Vertical louvers
Type 03:  Eggcrate shading structures*
Type 04-07: Honeycomb shading structures**

<table>
<thead>
<tr>
<th>Type</th>
<th>Max. length of edge / circumference</th>
<th>Max. width / height</th>
<th>Distance between louvers [min / max]</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>1' / ---</td>
<td>12' / ---</td>
<td>1'</td>
<td>full width</td>
</tr>
<tr>
<td>02</td>
<td>1' / ---</td>
<td>--- / 9'-6&quot;</td>
<td>1'</td>
<td>full height</td>
</tr>
<tr>
<td>03</td>
<td>1' / 4'</td>
<td>1' / 1'</td>
<td>1'</td>
<td>full window</td>
</tr>
<tr>
<td>04</td>
<td>6 7/8&quot; / 3'-5 1/4&quot;</td>
<td>1'-1 7/8&quot; / 1'</td>
<td>1'-1 7/8&quot;</td>
<td>full window</td>
</tr>
<tr>
<td>05</td>
<td>6 7/8&quot; / 3'-5 1/4&quot;</td>
<td>1'-1 7/8&quot; / 1'-1 7/8&quot;</td>
<td>1'-1 7/8&quot;</td>
<td>full window</td>
</tr>
<tr>
<td>06</td>
<td>8&quot; / 4'</td>
<td>1'-1 7/8&quot; / 1'-4&quot;</td>
<td>1'-1 7/8&quot;</td>
<td>full window</td>
</tr>
<tr>
<td>07</td>
<td>1'-4&quot; / 1'-8 3/4&quot; (min) 7'-2'' (max)</td>
<td>2' / 2'-8 1/4&quot;</td>
<td>6&quot; [min] 2'-8 1/4&quot; [max]</td>
<td>full window</td>
</tr>
</tbody>
</table>

Fig. 104  Monthly solar radiation on vertical surface per orientation (Austin, TX)

Fig. 105  Annual solar radiation on vertical surface per orientation (Austin, TX)

Fig. 106  Dimensions of conventional shading devices
Eggcrate shading structures are tested with a square opening, a horizontally (1:4 - 1/2:2') and a vertically oriented opening (3:1 - 1 1/2:1/2'). If not indicated differently, a square eggcrate shading structure was used for the experiment.

Honeycomb shading structures are tested with horizontally (04) and vertically (05) oriented openings and openings with a circumference of 4' (06), similar to the square eggcrate shading structure. 07 represents the final optimized shading structure discussed in chapter ‘IV. Optimized shading structure’.

3. Performance of conventional shading devices depending on the orientation

** Horizontal louvers (type 01)**
The type of horizontal louvers that is tested in this study consists out of blinds that are perpendicular to the surface. They have a depth and a distance between each blind of 1'. They span over the whole width of the window. See figure 92. It is assumed that horizontal shading
III. Quantitative simulation research

devices perform generally best in south for Austin, Texas. The calculated data proofs this assumption. Yet, it is only a small improvement of 3.24% compared to southwest and even 10.55% to west. Horizontal louvers on southwest allow 7.31% more solar radiation than for a west oriented surface. Horizontal louvers have a minimum shading coefficient (sc) of 0.47 (west). See figures 107-108.

Vertical louvers (type 02)
The design of the vertical blinds has a depth and a distance between each blind of 1’ and covers the whole height of the window. See figure 93. Previous research has proven that vertical blinds, which are perpendicular to the surface, are more efficient for west oriented façades than for other orientations. This has not been proven in this study. Vertical shading devices on west oriented surfaces provide 10.10% less shading than on the south and also 2.85% less than on southwest. Compared to horizontal louvers, vertical blinds can only provide a minimum sc of 0.68 (west), no matter the orientation. See figures 107-108.

Eggcrate shading structure - type square (type 03)
### Comparison of conventional shading devices

<table>
<thead>
<tr>
<th>Shading type</th>
<th>Total length of unrolled shading structure (ft)</th>
<th>Total area of visible shading structure (ft²)</th>
<th>Degree of visual contact (%) A (opening) / A (area of shading structure)</th>
<th>Total area of unrolled shading structure (ft²)</th>
<th>Total volume of unrolled shading structure (ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal blinds</td>
<td>120 ft</td>
<td>1.25 ft</td>
<td>98.90 %</td>
<td>120.00 ft²</td>
<td>1.25 ft</td>
</tr>
<tr>
<td>Vertical blinds</td>
<td>123.5 ft</td>
<td>1.29 ft</td>
<td>98.87 %</td>
<td>123.50 ft²</td>
<td>1.29 ft</td>
</tr>
<tr>
<td>Eggcrate shading structure (type square)</td>
<td>243.5 ft</td>
<td>2.54 ft</td>
<td>97.78 %</td>
<td>243.50 ft²</td>
<td>2.54 ft</td>
</tr>
<tr>
<td>Eggcrate shading structure (horizontal 1:4)</td>
<td>306.5 ft</td>
<td>3.19 ft</td>
<td>97.20 %</td>
<td>306.50 ft²</td>
<td>3.19 ft</td>
</tr>
<tr>
<td>Eggcrate shading structure (vertical 3:1)</td>
<td>333.5 ft</td>
<td>3.47 ft</td>
<td>96.95 %</td>
<td>333.50 ft²</td>
<td>3.47 ft</td>
</tr>
<tr>
<td>Honeycomb shading structure (horizontal oriented)</td>
<td>265.1875 ft</td>
<td>2.76 ft</td>
<td>97.58 %</td>
<td>265.19 ft²</td>
<td>2.76 ft</td>
</tr>
<tr>
<td>Honeycomb shading structure (vertical oriented)</td>
<td>255.83 ft</td>
<td>2.66 ft</td>
<td>97.67 %</td>
<td>255.83 ft²</td>
<td>2.66 ft</td>
</tr>
<tr>
<td>Honeycomb shading structure (vertical - 4' circumference)</td>
<td>216.02 ft</td>
<td>2.25 ft</td>
<td>98.03 %</td>
<td>216.02 ft²</td>
<td>2.25 ft</td>
</tr>
<tr>
<td>Honeycomb shading structure (optimized)</td>
<td>231.0625 ft</td>
<td>2.41 ft</td>
<td>97.89 %</td>
<td>135.52 ft²</td>
<td>1.41 ft</td>
</tr>
</tbody>
</table>

**Fig. 111** Comparison of the degree of visual contact with uniform material thicknesses

<table>
<thead>
<tr>
<th>Shading type (material thickness)</th>
<th>Total length of unrolled shading structure (ft)</th>
<th>Total area of visible shading structure (ft²) with realistic material thicknesses</th>
<th>Degree of visual contact (%) A (opening) / A (area of shading structure)</th>
<th>Total area of unrolled shading structure (ft²)</th>
<th>Total volume of unrolled shading structure (ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal blinds (2&quot;)</td>
<td>120 ft</td>
<td>20.00 ft²</td>
<td>82.46 %</td>
<td>120.00 ft²</td>
<td>20.00 ft²</td>
</tr>
<tr>
<td>Vertical blinds (2&quot;)</td>
<td>123.5 ft</td>
<td>20.58 ft²</td>
<td>81.94 %</td>
<td>123.50 ft²</td>
<td>20.58 ft²</td>
</tr>
<tr>
<td>Eggcrate shading structure (type square) (1&quot;)</td>
<td>243.5 ft</td>
<td>20.29 ft²</td>
<td>82.20 %</td>
<td>243.50 ft²</td>
<td>20.29 ft²</td>
</tr>
<tr>
<td>Eggcrate shading structure (horizontal 1:4) (1&quot;)</td>
<td>306.5 ft</td>
<td>25.54 ft²</td>
<td>77.60 %</td>
<td>306.50 ft²</td>
<td>25.54 ft²</td>
</tr>
<tr>
<td>Eggcrate shading structure (vertical 3:1) (1&quot;)</td>
<td>333.5 ft</td>
<td>27.79 ft²</td>
<td>75.62 %</td>
<td>333.50 ft²</td>
<td>27.79 ft²</td>
</tr>
<tr>
<td>Honeycomb shading structure (horizontal oriented) (1/8&quot;)</td>
<td>265.1875 ft</td>
<td>2.76 ft²</td>
<td>97.58 %</td>
<td>265.19 ft²</td>
<td>2.76 ft²</td>
</tr>
<tr>
<td>Honeycomb shading structure (vertical oriented) (1/8&quot;)</td>
<td>255.83 ft</td>
<td>2.66 ft²</td>
<td>97.46 %</td>
<td>255.83 ft²</td>
<td>2.66 ft²</td>
</tr>
<tr>
<td>Honeycomb shading structure (vertical - 4' circumference) (1/8&quot;)</td>
<td>216.02 ft</td>
<td>2.25 ft²</td>
<td>98.03 %</td>
<td>216.02 ft²</td>
<td>2.25 ft²</td>
</tr>
<tr>
<td>Honeycomb shading structure (optimized) (1/8&quot;)</td>
<td>231.0625 ft</td>
<td>2.41 ft²</td>
<td>97.89 %</td>
<td>135.52 ft²</td>
<td>1.41 ft²</td>
</tr>
</tbody>
</table>

**Fig. 112** Comparison of the degree of visual contact with realistic material thicknesses
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Eggcrate shading structures are a combination of the horizontal and vertical blinds as described before. Thus, they should provide both the advantages and disadvantages of each shading component. The square type is designed with an opening of 1’ width/height and a depth of 1’. Each component is perpendicular to the surface. This assembly covers the whole window. See figure 94. South oriented eggcrate shading structures deliver the best results with regard to shading. With 4.84% more shading in south than southwest and even 11.57% more shading than west, eggcrate shading structures show a minimum shading coefficient (sc) of 0.39 (west) in all orientations. See figures 107-108.

Horizontally oriented honeycomb shading structures (type 04)
The honeycomb structure consists of symmetrical hexagonal components with a depth of 1’. They have a diameter of 1’ and a circumference of 3’-5 1/4”, resulting in 6 7/8” long edges. The maximum component height is 1’-1 7/8”. These honeycombs are wider than tall. They have two horizontal edges. See figure 97. Similar to eggcrate shading structures, this type performs best in
south. It provides 5.12% more shading than southwest and 10.70% more shading than west. With a minimum sc of 0.38 [west] this type of honeycomb has a similar behavior as an eggcrate type. See figures 109-110.

Vertically oriented honeycomb shading structures (type 05)
This structure is similar to a horizontally oriented honeycomb but rotated for 90°. Thus, the components are taller than wide and have two vertical edges. See figure 98. This honeycomb, oriented towards south, performs best of all honeycomb structures in type and orientation. With a sc of 0.27, it is slightly better but performs similar on south as the horizontally oriented type. It performs 4.50% [southwest] and 10.65% [west] better than in the other orientations. The minimum sc is 0.38 [west]. Comparing the percentages of horizontally and vertically oriented honeycomb structures, it can be concluded that a change of its orientation has a slight impact on the shading performance. In general, vertically oriented honeycombs perform better than horizontally oriented types. See figures 109-110.

Vertically oriented honeycomb shading structure with 4'
The third variation of a honeycomb structure has a circumference equal to the sum of the sides of the square openings of the eggcrate structure, which is 4 feet. Thus, this honeycomb structure is actually bigger than type 04 or 05. See figure 99. Similar, but with 3.69% (type 04) and 3.91% (type 05) less provided shading than the other honeycomb types, this type also has its best performance on a south oriented surface. As expected, it performs in every direction slightly worse than the other types. It was assumed that an increasing size of the opening would decrease the provided shading since the surface area, providing shading, decreases. Compared to south, this type provides 5.49% less shading in southwest and 11.64% in west. See figures 109-110.

Disregarding the type of honeycomb structures, the minimum expectable shading coefficient is 0.4218 [west]. This is an interesting fact considering that this type of shading is a derivative of the eggcrate shading structure, which provides a sc of at least 0.4177 [west]. To be able to compare eggcrate with honeycomb shadings, the
Comparison of conventional shading devices

4. Influence of material thickness on results and the degree of visual contact

This study has been conducted to compare the performance of different shading structures for different orientations with regard to the degree of visual contact. In order to have a realistic comparison of shading devices, the degree of visual contact and thus, material thickness have to be taken into account. If a shading structure provides full shading throughout the year, it might fail to provide a high comfort level for the user. A high amount of provided shading might lead to a low degree of visual contact. The ultimate shading device provides maximum amount of shading with a maximum degree of visual contact.

The tests that have been conducted so far treated the
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Fig. 121 Monthly solar radiation - comparison of shading structures per orientation (Munich, Germany)

Fig. 122 Annual solar radiation - comparison of shading structures per orientation (Munich, Germany)

Shading components as simple 2-dimensional surfaces. Horizontal blinds would have much thicker elements than an eggcrate structure due to the span length. These shading structures not only have to be prevented from sagging, but they also have to be protected from the natural elements like wind, water, rain, snow, etc. Figure 111 shows a comparison of the different shading devices with regard to the degree of visual contact. If shading devices are treated as surfaces, clearly, the one with the smallest total length of shading device has the highest degree of visual contact. In our case horizontal and vertical blinds. The vertical oriented honeycombs with a circumference of 4', similar to the eggcrate structure provides the next best degree of visual contact.

Fig. 111 also shows that a honeycomb shading structure with a circumference of 4' actually has a lower sum of length of the edges compared to the square eggcrate shading structure, which was assumed initially. The advantage of using either an eggcrate or honeycomb shading structure lays in the combination of horizontal and vertical elements. These structures offer more
Comparison of conventional shading devices

shading for a changing position of the sun. Taking a look at figure 112, it becomes clear what impact a change of material thicknesses can have on the comparison. As stated before, horizontal and vertical blinds would need to be thicker compared to eggcrate or honeycomb shading structures. Today, a typical horizontal blind is between 34 mm and 60 mm thick. For this study, a thickness of 50.8 mm (2”) for horizontal and vertical blinds has been chosen. Since eggcrate structures are a combination of those two types, but with a significantly smaller span, 1” of material thickness was assumed. Assuming that a honeycomb shading structure can be build out of 1/8” material and eggcrate shading structures out of 1” elements, the order of performance changes significantly. Thus, honeycomb structures perform best. The material thickness of honeycomb structures can be reduced tremendously due to their structural advantages. The component is closer to a circle and therefore very stable.

The degree of visual contact not only depends on the area of visible shading structure in 2D, but also on the total area of the shading structure obstructing the view. Again,
similar to the results for the visible structure in 2D, horizontal and vertical blinds offer the highest degree of visual contact, followed by the honeycomb shading structure with a circumference of 4', which delivers the best results of the more complex shading devices. Taking the material thickness into account, the highest overall unobstructed view is provided by the series of honeycomb structures. The lower the material thickness, the greater the unobstructed view from a non-2-dimensional viewing point.

Horizontal and vertical blinds may provide the highest degree of visual contact for a uniform material thickness, but they don’t perform as well in providing shading. On the other hand, eggcrate structures provide the most shading, but they have a lower degree of visual contact for the same thickness. Honeycomb shading structures perform second best in providing shading and have a higher degree of visual contact than eggcrate shading structures with a similar material thickness.

5. Performance of eggcrate shading structures depending on the orientation

Three different shaped eggcrate shading structures were compared to each other: a square, a horizontally oriented (4:1) and a vertically oriented (1:3) eggcrate shading structure.

All eggcrate shading structures, perform best on south. Yet, the horizontally oriented type provides the highest amount of shading for every orientation. It has a shading coefficient of 0.24 on south. This is 2.83% better than the square type and 8.04% better than the vertically oriented type for south. For southwest, there is a high distribution of the amount of provided shadow by eggcrate shading structures. With a range of sc of 0.26 to 0.37, the horizontally oriented type provides the most shading with a sc of 0.26, 6.05% better than the square and 10.95% better than the vertically oriented type. For west, again, the horizontally oriented type leads the shading performance with 6.80% better than the square and 9.93% better than the vertically oriented type. Generally, the horizontally oriented type performs best, followed by the square type and then followed by the vertically oriented type, which performs worst for every orientation. The fact that the horizontally oriented eggcrate shading structures performs better than the vertical ones is in agreement with the results for horizontal and vertical blinds, where horizontal blinds perform better as well. The horizontally oriented shading structure also performs best compared to all shading structures in type and orientation.

6. Performance of shading devices for a specific orientation

For this study, horizontal and vertical blinds are compared to eggcrate and honeycomb shading structure. From the different eggcrate and honeycomb structures, the type with the highest performance was chosen: the horizontally oriented eggcrate shading structure and the vertically oriented honeycomb shading structure.
South oriented surfaces have their peak of solar radiation on the surface in the winter between December and January, due to the lower sun throughout the day. See figures 113-114. The eggcrate structure provides the highest amount of shading. It allows 2.39% more shading than the honeycomb structure, 11.74% more than the horizontal blinds and even 32.69% more shading than vertical blinds. The eggcrate shading structure performs similar to the honeycomb structure, which is true for the other orientations as well. Thus, eggcrate structures perform best with a sc of 0.24 and vertical blinds perform worst with a sc of 0.58.

Southwest
As well as south oriented surfaces, in the southwest, the peak of solar radiation appears in the winter as well. See figures 115-116. This orientation receives generally more solar radiation in the summer since the surface still captures solar radiation when the azimuth angle of the sun passes 90° W until the sun sets (102.19° W on June 21st). This orientation delivers the same order of shading devices for providing shading as on south. Eggcrate shadings perform best with a sc of 0.26 followed by honeycomb structures with 5.75% less shading, then horizontal blinds with 13.66% and then vertical blinds with even 39.43% less shading.

West
Unlike the south and the southwest, the west has its peak in the summer around July, when the sun is at a position more perpendicular to the surface and at a very high azimuth angle. See figures 117-118. Thus, the sun sets very late in the evening. Again, eggcrate shadings perform best with 5.56% better than honeycomb structures, 14.69% better than horizontal blinds and 36.81% better than vertical blinds.

Yet, it has to be mentioned that even if vertical blinds always perform worst for each orientation, they still have a sc of at least 0.68, which is 31.97% less solar radiation on the surface. Thus, about 30% less energy will be penetrating the façade, which will resolve in a tremendous amount of energy savings.

According to Ecotect (see figures 123-124), there is an uneven distribution of solar radiation for different respective orientations. It was assumed that east performs similar to west, southeast similar to southwest. South would have the highest amount of solar radiation throughout the year. Even if there is a similar behavior from southeast to east and southwest to west, the solar radiation on east is much higher than on west as well as it is much higher on southeast than on southwest. According to the weather data, Austin has a much higher level of cloudiness in the morning than in the afternoon. Thus, Austin should receive more solar radiation in the afternoon. This is not the case. Ecotect has been contacted but not provided any information yet, about how Autodesk Ecotect Analysis is calculating solar radiation. For the purpose of this study, it is assumed that there is a symmetrical distribution of solar radiation throughout the day.

Nevertheless, the results of the comparison of shading devices...
devices for the orientations south, southeast and east have the same tendencies as for south, southwest and west even if the percentages vary slightly.

8. Performance of shading devices in Austin versus Munich

A comparison between Austin and Munich has been conducted in order to see the differing performance of shading devices with regard to a changing location. Austin is located in a hot climate, while Munich is situated 18° further north at a latitude angle of 48.13°N, in a temperate climate. Therefore, the changes in solar radiation and in the performance of the shading devices should be remarkable. Furthermore, the author of this study is originally from Munich and has a genuine interest in the comparison of the results. As expected, solar radiation is much lower in the temperate zone compared to a hot climate (see fig. 119-120). This has to do with a location’s latitude and longitude and thus its exposure to the sun. The closer to the equator, the higher the solar insolation. South oriented façades in Munich receive only 48.80% of the solar insolation that is received on the same orientation in Austin. A southwest oriented façade receives 43.10% and a west oriented façade only 42.86%. Even though Munich has the same tendency to have a higher solar insolation in the south than in southwest and a higher solar insolation in southwest than west. Furthermore, the further west the sun is, the lower the percentage of solar radiation compared to Austin.

With regard to shading structures, similar to the situation in Austin, horizontal blinds perform best in south. See fig. 121-122. The blinds provide 2.60% more shading than for southwest and 7.63% more shading than for west. On the other hand, vertical blinds actually perform worst on southwest. But there is an almost even distribution of provided shadow for each orientation. The difference only varies within 1.20%, which represents the lowest difference of all shading devices disregarding the location. The next closest distribution is for eggcrate shading structures with 6.40%. Even horizontal blinds differ only for 7.36% in Munich. These facts proof that the solar distribution is more even in Munich than in Austin. It resolves in a possibility to use one type of shading device for several orientations in Munich. While in Austin, the difference is usually almost double compared to Munich.

For more detailed information see chapter ‘1. Appendix A - Solar insolation’.

9. Conclusion

Generally, eggcrate shading structures always perform best no matter the location or orientation. Yet, to provide maximum shading might not always be the desired goal since the degree of visual contact from the interior might suffer. The more shade, the more obstruction, the lower the degree of visual contact. Nevertheless, to provide shading already resolves in a minimum reduction of solar radiation of almost 32%. This will result in a reduction of heat gain and thus a reduction of energy consumption, which is the final goal.
### Comparison of conventional shading devices

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<th>Orientation</th>
<th>East</th>
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<th>Southwest</th>
<th>West</th>
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<td><strong>Location</strong></td>
<td></td>
<td>solar radiation on an unobstructed vertical surface in kWh/m² [without shading]</td>
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<td>percentage of total global horizontal solar radiation (1.765 kWh/m²)</td>
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<td></td>
<td>824 kWh/m²</td>
<td>969 kWh/m²</td>
<td>920 kWh/m²</td>
<td>877 kWh/m²</td>
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<td>of 1.765 kWh/m²</td>
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<tr>
<td>in Austin</td>
<td>46.69 %</td>
<td>53.77 %</td>
<td>50.99 %</td>
<td>49.69 %</td>
<td>41.64 %</td>
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<td>in Munich</td>
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<tr>
<td>Shading type</td>
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<td>shading coefficient</td>
<td>solar radiation on vertical surface</td>
<td>sc</td>
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<td>Vertical blinds in Austin (02)</td>
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<td>Eggcrate shading structure (square) in Austin (03)</td>
<td>298 kWh/m²</td>
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<td>Honeycomb shading structure (optimized) in Austin (07)</td>
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| **Fig. 125** Annual solar radiation on vertical surface per orientation, shading device, and location
Chapter IV

Fig. 126 Optimized shading structure in a 3-dimensional rebuilt of the ‘Thermal Lab’ in front of West-Mall Office Building at the UTSoA.
IV. Optimized shading structure

1. Design optimization of conventional shading devices
2. Design of ‘optimized honeycomb shading structure’
3. Building process of the mock-up
4. Comparison of performance of the ‘optimized honeycomb shading structure’ to conventional shading devices
5. Effect of the shading structure on solar radiation in the interior
6. Effect of the shading structure on the distribution of daylight
1. Design optimization of conventional shading devices

The conventional shading devices that were discussed in chapter ‘III. Quantitative simulation research’ are fixed structures. They can only be optimized on a 2-dimensional base. In the following, it will be explained how those shading devices can be optimized in order to follow the sun to provide maximum shading with maximum degree of visual contact with the exterior while minimizing the dimensions of the structure.

a) Horizontal shading devices

The most common shading devices are horizontal shading structures like overhangs or venetian blinds. Their size can be changed in two dimensions: width and depth. The width only has a limited effect on the provided shade (compare fig. 128 and 129). If the sun is at a higher position, around solar noon, horizontal shading elements are very effective. But in case the sun is at a lower position or the solar rays hit the surface from the side instead of frontal, horizontal blinds cannot provide shade effectively. For example, to provide full shading with an overhang for a west oriented window at 1 p.m., the shading device would need to extend on the right side of the opening. In the afternoon, the depth of the shading device becomes more crucial since the sun is moving around the building and lowering its position, resulting in a position being more and more perpendicular to the surface. Already at 3 p.m. the depth of the shading would be longer than the height of the window in order to provide full shading, which is very uneconomical. Thus, a horizontal shading device on a west oriented façade is only efficient in the early afternoon. As soon as the solar rays are getting closer to be perpendicular to the façade’s surface, horizontal shadings are very inefficient, since they are not able to provide sufficient shading. As a result, a change of width and depth can only effect the optimization of shading to solar insolation ratio to a limited amount.

Movable shading devices are very suitable for providing shading throughout the day and they are able to provide optimized shading related to almost every position of the
sun. The amount of shading is then limited to the width of the shading with regard to the width of the opening. As shown in figure 128, a horizontal blind, which has the same width as the opening, is not able to provide shading on the very edge of the shading device, which is adjacent to the wall. This triangle created by the edge of the wall and the shading device will always be open for solar rays if the shading device does not exceed the width of the opening [fig. 129]. In many cases, this might not be an option. A vertical blind at this point would be able to close this gap [fig. 130]. Figure 132 and 133 show an example of an array of horizontal blinds rotated by the profile angle towards the sun to provide full shading.

‘2009 ASHRAE Handbook - Fundamentals’, chapter ‘Shading and fenestration attachments’ delivers the basic calculations on how to receive the angle needed for horizontal devices to be tilted in an ideal angle to provide maximum shading. This angle called the ‘profile angle’ or ‘shadow-line angle’ $\Omega$ can be calculated in relation to the solar altitude angle $\beta$ as well as the solar azimuth angle $\gamma$. See figure 131.
IV. Optimized shading structure

\[ \tan \Omega = \frac{\tan \beta}{\tan \gamma} \]

where \( \Omega \) = profile or shadow-line angle
\( \beta \) = solar altitude angle
\( \gamma \) = solar azimuth angle.

Figure 131 explains how to use the shadow-line angle to tilt the horizontal shading device to provide maximum shading.

\( \chi = \Omega \)

where \( \chi \) = angle for tilting of horizontal shading device to provide maximum shading.

This angle represents maximum shading for a specific position of the sun. To receive maximum shading over a certain duration throughout the day or year, this angle has to be changed respectively. An example has been created for Austin on Mar/Sept. 21:

\[ \text{Animation for movable horizontal shading devices to provide maximum shading} \]

b) Vertical shading devices

Vertical blinds can be optimized in depth and height. If the height is greater than the opening they can only have a very limited effect on the reduction of solar rays on the surface. An overhang at this point would be very efficient [see figure 134 - 136]. On a south oriented façade at solar noon, vertical blinds only provide a small amount of shadow since the azimuth angle of solar rays are parallel to the direction of the shading blinds. In the early morning as well as late afternoon, vertical blinds are very effective since the angle between the azimuth angle of the sun and the normal vector of the opening is very high. Thus the solar rays hit the blinds from the side rather than frontal, which projects a wide shadow by the blinds. The number of blinds then depends on the depth of each blind. The greater the depth, the fewer blinds are necessary to provide full shading. As soon as the sun rises in the morning and the altitude angle of the sun gets higher, the less shading can be provided by vertical blinds. To optimize vertical blinds, they should be operable so that they can be positioned perpendicular to the sun at all time to provide maximum shading. Maximum shading is
provided when the sun sees the maximum surface area of the shading structure. The smaller the visible area, the smaller the amount of provided shading. If the normal vector of a vertical blind has the same direction as the azimuth angle of the sun, vertical blinds provide the most possible shading. Likewise, the vertical blinds need to rotate throughout the day respectively to the azimuth angle $\gamma$ of the sun (see figure 137-138).

$$\omega = \gamma$$

where $\omega$ = angle for rotating of vertical shading device to provide maximum shading
$\gamma$ = solar azimuth angle

This angle represents maximum shading for a specific position of the sun. To receive maximum shading throughout the day or year, this angle has to be changed respectively. An example has been created for Austin on Mar/Sept. 21 from sunrise to sunset (see fig. 139):

-> Animation for movable vertical shading devices to provide maximum shading
c) Eggcrate shading structures

Eggcrate structures are a combination of horizontal and vertical blinds (see fig. 140). A modification for a non-movable structure can only be made in its direction perpendicular to the opening and the proportion of width and height of the opening. Since eggcrate structures are a combination of the two basic shading structures as described before, an increase of depth is very effective. Yet, the deeper the structure, the lower the degree of visual contact. A change of proportion delivers different results for different orientations. For this study, three different types of eggcrate shading structures were examined. Eggcrate structures with a square, a horizontally and vertically oriented opening. Generally, if the width is greater than the height, eggcrate shading structures are most effective as shown in chapter ‘III. Quantitative simulation research’. This reflects the results of the comparison of horizontal and vertical shading structures. Eggcrate shading structures provide the most shading for south, and the least shading for west. See results in figure 125. Either part of the eggcrate structure - horizontal or vertical component - could be tilted or rotated in a certain direction in order to provide optimized shading (see fig. 141 - 142). Ideally, both components of the eggcrate structure, the horizontal as well as the vertical, should be movable in order to provide maximum shading with a minimum structure. Yet, due to high technical challenges for building a structure which is movable in both direction, as shown in fig. 143, this case will be disregarded for this study. An optimization would be to tilt or rotate either component to a certain position which is optimized for providing shading for a certain time of the day or year. For the purpose of this study only one component at a time will be movable. Analog to the examples of movable horizontal and vertical shading devices, here are two examples for Austin on Mar/Sept. 21 from sunrise to sunset (see fig. 144 - 145):
-> Animation for movable horizontal component of eggcrate shading devices to provide maximum shading
-> Animation for movable vertical component of eggcrate shading devices to provide maximum shading
1. Design optimization of conventional shading devices

Fig. 144 Rotation of horizontal part of an eggcrate structure at 10 a.m. on March 21

Fig. 145 Rotation of vertical part of an eggcrate structure at 10 a.m. on March 21
IV. Optimized shading structure

2. Design of ‘optimized honeycomb shading structure’

In the previous chapter, the optimization process of maximizing shading by rotating conventional shading devices was discussed, which took place on a 2-dimensional base. However, it gets more complicated as soon as an optimization is tried to be achieved for a 3-dimensional structure. It is fairly easy to develop a device, which provides full shading year round. This could be achieved by providing a conventional shading device in a size big enough to provide full shading. The challenge is to minimize the shading structure. This has two major reasons. First, the more diffuse daylight that can access the interior, the less artificial lighting is needed to light up the interior space. Diffuse skylight represents about 20% of the whole solar insolation and is very helpful to reduce artificial lighting. Second, the more a structure is obstructing the opening, the lower the degree of visual contact one has from the interior. Furthermore besides the beauty of natural daylight, it is proven that natural light increases productivity of the occupant. There are certain design criteria that should be taken into account when designing an optimized shading structure.

a) Location and orientation

The shading structure has been designed for the research facility on the campus of the University of Texas at Austin - School of Architecture [UTSoA]. The research facility as described in chapter ‘V. Research facility: Thermal Lab’ is a test room, which allows for the testing of different glazing or shading devices in real conditions. The developed structure was tested with regard to solar insolation and daylight levels. Austin is located on the northern hemisphere, in a hot-humid climate. The annual solar radiation is extremely high and the outdoor temperatures are above comfort level for more than half a year (see fig. 149, 154-155 and 160). Thus, protecting the building skin becomes an important task to the designer. The TL is located at the south side of the West Mall Office Building, and is slightly oriented towards southwest: of about 5° off south. A change of orientation can have a significant impact on the design of the shading structure. Figures 146-148 show the design of an optimized shading structure for the orientations south (0°), southwest (45°), and southwest-west (135°).
2. Design of ‘optimized honeycomb shading structure’

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| Max Hour  | 16    | 16   | 16   | 16   | 15   | 15   | 15   | 15   | 15   | 15   | 15   | 15   |
| Min Hour  | 7     | 6    | 7    | 6    | 6    | 6    | 6    | 6    | 7    | 7    | 7    | 7    |

Fig. 149: Weather data Austin, TX U.S.A. – hourly average temperature distribution from January 1 until December 31 – highlighted cells represent critical temperatures.
IV. Optimized shading structure

b) Definition of shading criteria and base structure

The most important decision to make is how much of the window needs to be shaded and during which time of the day and year. Ideally, a full shading of the window happens as soon as the interior temperature rise above comfort level. The green band in figure 155 indicates the temperatures for Austin in which exterior temperatures are above comfort (thermal neutrality) level. For sure, a shading device can be designed in a way, to provide full shading year round. Yet, this is not desirable for Austin, since temperatures from November until March are actually below comfort level. In the winter, direct solar radiation can be used to reduce heating loads. Since solar radiation, and thus diffuse solar radiation is much lower in the winter, natural daylight is useful to reduce artificial lighting. The challenge in the summer is to protect the window from direct solar radiation while allowing as much indirect solar radiation as possible. The more daylight received in the interior, the lower the electricity consumption for artificial lighting. Furthermore, natural daylight satisfies the user since natural daylight is proven to increase the productivity of the occupant.

W) and southwest-west (60°). In this case, the scenario for the west oriented building is only rotated for 60° W to show the tendency. A completely west oriented building would need to be completely covered resulting in an endlessly long shading structure using this design. The width and the height of the component are reduced to the boundaries of the surface that needs to be shaded. The depth of the component will be limited by factors like the solar path and the orientation of the building.

For this design, the further the building is orientated towards the west, the larger the shading protrudes. This series of shading structures according to the orientation indicates the importance of the specific design of a shading structure with regard to its orientation. In this case it seems the further west the building is oriented, the less this specific shading structure seems to fit. Even though it would provide the same shading and solar exposure as the other shading structures for the respective orientation.
2. Design of ‘optimized honeycomb shading structure’

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Fig. 154 Weather data Austin, TX U.S.A. - monthly maximum, minimum and daily average temperatures

Fig. 155 Weather data Austin, TX U.S.A. - hourly temperature distribution from January 1st until December 31st
IV. Optimized shading structure

Therefore, the challenge and the goal is to design a shading structure which maximizes the amount of provided shading for a specified period of time throughout the year while allowing maximum solar exposure for another specified period of time. In a climate like Austin, full shading should be provided from April until October and full solar exposure should be provided from November until March. Since the sun-paths for February and October are identical, full shading is not only provided for October, but also for February. As figure 154 indicates, high temperatures can also occur during winter months. Thus, completely unprotected exposure can be unpleasant in the winter as well. Therefore, an additional sun-screen or similar can help protecting the interior from overheating for the time when no shading or only partially shading is provided. Taking a look at the sun-path, full shading should be provided for south from 9 a.m.-5 p.m. For southwest from 11 a.m. until 5 p.m. And for west from 1 p.m. until 5 p.m. Since each orientation has different shading requirements, a differentiation of the shape of the structure has to be made between each orientation as explained before (see fig. 146-148).

A honeycomb structure has been chosen as the main structure. There are three reasons for having chosen a honeycomb structure over a conventional eggcrate structure. First, a hexagon provides structurally a higher rigidity than a rectangle. An example can be found in nature where honey bees use a hexagon to create their honeycombs to make use of its structural advantages (see fig. 150). Second, a hexagon tiles the plane with minimal surface area. Thus a hexagonal structure uses the least material to create a lattice of cells within a given volume. This has also been proven in this study as shown in figure 111. The honeycomb structure needs 11.42% less unrolled length than an eggcrate structure to cover the same opening. Furthermore, a honeycomb structure is built in a way that two opposing honeycomb layers nest into each other, with each facet of the closed ends being shared by opposing cells. And third, there was also the interest to explore new interesting structures with high performance.
2. Design of ‘optimized honeycomb shading structure’
IV. Optimized shading structure

In this hexagonal grid, each cell will house one component. Therefore, each component cannot exceed the boundaries of a volume, extruded from its cell. Otherwise, the components would interfere with each other. Due to its spatial limitation, the structure is not minimal and therefore, the components will provide full shading at the expense of the degree of visual contact and solar exposure in the winter, as explained before. To maximize the degree of visual contact and solar exposure, the structure would need to exceed the boundaries to allow direct solar radiation to the respective solar azimuth and solar elevation angle as shown in figure 151. The advantage of having boundaries of an extruded volume is the possibility to place one component next to another without interfering each other.

c) Visibility and purpose of shading structure

Especially in a commercial building, a window has different requirements for the user. The window can be divided into three zones:
1. Bottom zone (floor to desk height)
2. Center zone (desk height to eye level)
3. Upper zone (eye level to ceiling)

As figure 152 indicates, a window has an upper zone, a center zone, and a bottom zone. Today, most commercial buildings changed from a window-façade to a fully glazed post and rail façade resulting in high cooling loads in the summer due to solar radiation. The center zone is mostly used for a high degree of visual contact and daylight. It needs to be highly protected from direct solar radiation and glare. The use of reflective elements in that area is very unlikely unless it is assured not to cause glare to the users. In an office, if the upper zone is used at all, it has structural and thermal purposes. Contrariwise to the center zone, in the upper zone, the use of reflective elements is very helpful, since the direct sunlight can be redirected into the rear part of the room and reflected onto the ceiling surface, which helps lightening up the space without producing glare to the occupants. The bottom zone seems to be unfitting for this purpose unless an illumination of the floor is desired. The bottom zone is
IV. Optimized shading structure

Fig. 165  150 elements - homogenous grid

Fig. 166  150 elements - grid changed with control points

usually just used for structure and thermal protection. It should be protected from direct solar radiation to minimize cooling loads. Figure 166 shows such a differentiation. The openings in the middle are bigger than the opening on top and at the bottom. Thus, the degree of visual contact is higher. An extreme example for emphasizing the degree of visual contact is shown in figure 153.

The shading structure of this study has been designed for commercial buildings, office spaces in particular. With a change of function comes a change of shading criteria. An office generally needs a high level of daylight while avoiding glare on the computer screens. Even though, one could argue that an employee does not need to have an outside view to accomplish his tasks, modern architecture tries to improve the visual connection between inside and outside. An increased degree of visual contact should always be a goal in the design process for commercial buildings. Since the production of the occupant in an office space is improved by creating a nice environment for the occupant, one purpose of
this study was to design a shading component, which is able to have an increased degree of visual contact. This can happen for different heights. First, the occupant should be able to work at his desk and still be able to look outside. And second, the visual contact can be in the height of the eye level to get an instant connection to the outside by entering the room. See figure 156. For this study, the view was focused on the center of the room. The opposing building is 'Sutton Hall', a building of UTSoA. Since there is no other significant focus possible in this scenario, the center components of the shading structure are maximized while the edge components get smaller. See figure 157.

Theoretically, the components can get endlessly small while still providing the same shading proportionally. Therefore, a component can be scaled and multiplied to have repetitive elements without loosing its shading performance. Due to the geometry of solar rays, which we assume are all parallel, by changing the size of one component, the number of components to provide the same shading will have to be adjusted. Thus, the grid
of the shading structure can be changed accordingly, without losing its shading qualities. This is a great advantage with regard to structural challenges. If one component is supposed to provide shading for a window, the component has to be much bigger than if 10 components are supposed to provide the shade respectively (see fig. 158-159). If the component does not necessarily have to be as big as the opening itself, it can be scaled down for structural or visual purposes. In the case of this study, a shading structure with a width of 12' and a height of 9' will result in a shading structure that is built within the boundaries of a cuboid of the size of 12' of width, 9' of height and 5'-2 7/8" of depth. Thus, the shading device would be very big and difficult to produce. It would also cause structural challenges due to large spans of the material. Due to the parallel solar rays, a shadow projected by a shading device is always proportional to the shading device itself. Reducing the height from 9' to 5'-4 3/4", the depth is reduced to 3'-2 1/4". This results in a difference of depth of less than 1%. We assume that the depth changes proportional to the width. Scaling down the component would not reduce the proportion of provided shading. It would only reduce the shaded area since the shading device itself became smaller. Reducing the size of the component would reduce the depth tremendously and it would ease the feasibility of construction. A multiple number of smaller components can add up to the same shadow. Yet, increasing the number of components will increase the volume of the shading components, resulting in a lower degree of visual contact. Figures 161-168 show different versions of a hexagonal grid structure providing the same protection from direct solar radiation. As mentioned before, a change of the grid doesn’t affect the design of the shading structure. Each component has the same shading requirements, which are to fully protect the window from direct solar radiation from March 21 until September 21. For the rest of the year, it will only provide partial shading to allow direct sunlight penetrating the window to heat up the space.

d) Materiality and feasibility

The choice of material is very crucial. It seems to be obvious that some materials are preferable for certain structures than others. Material properties such as rigidity, flexibility, heat storage, degree of reflectance, weather resistance, color, sustainability, and so on, all play a role in the decision process for the right material. Some materials are much more rigid with a lower thickness or weight. Thus, resulting in a lighter overall structure. A high degree of reflectivity can help reducing artificial lighting through the use of sunlight, which is redirected from the surface of the structure into the rear part of the room. Thus, the shading device has a double use: producing shading to minimize cooling loads and redirecting sunlight in order to minimize artificial lighting while avoiding glare. A material with a low heat storage helps reducing cooling loads since less energy is stored within the shading system.

For the purpose of developing the mock-up for this shading study, the choice of material was crucial with regard to feasibility and costs. Since the mock-up needed
2. Design of ‘optimized honeycomb shading structure’

to be produced with either a laser-cutter or a cnc-router (Computer Numerical Controlled router), commonly known as a milling machine, the choices of material were limited. Due to the size of the unrolled shading components, the material had to be available in a size of at least 6’ length and 2’ width. Ideally even larger to facilitate the production process. Therefore, the choice of a laser-cutter was eliminated and the cnc-router was chosen to produce the mock-up. A cnc-router is able to cut wood, plastic or even metal. Metal was eliminated from the beginning due to higher costs. Another option has been plywood. Plywood is very rigid due to its several layers that assure stability. Unfortunately, plywood can’t be folded though.

Each component ideally has to be made out of one piece in order to simplify the building process. An unrolled component and its assembly is shown in figures 169-172. A component had to be folded along the edges to create the form of a honeycomb. This needed to happen without bursting. Therefore, the material needed to be flexible and highly resistant to fatigue. Contrarily, the material also need to be rigid in order not to sag along the longer edges. At this point, polypropylene seemed to be the right choice of material, fulfilling all of the purposes mentioned above. Polypropylene is a thermoplastic polymer, which is tough and flexible and has a good resistance to fatigue.³⁷

e) Multi-purpose shading structure
Shading structures do not need to serve only the purpose of protecting the window from direct sunlight, but they can also use the sunlight to produce energy or to store heat. Especially the use of photovoltaic seems to be very reasonable in a climate like Austin. Thus, the shading structure would be turned into an active façade element and might lead to an energy positive building. Active use of solar energy can be incorporated into the upper surface of the component facing the sun. Photovoltaic elements as well as solar collectors could be integrated into unobstructed parts of the component turning the assembly of components into a multifunctional façade. For the purpose of this study, the use of active elements has not been conducted further and might be the topic of future work in this field.
IV. Optimized shading structure

3. Building process of the mock-up

- a) Design 3-dimensional environment in Rhinoceros®
  (i.e. "Thermal Lab" + surrounding buildings)
- b) Define object for application of algorithmic modeling
  (i.e. opening of "Thermal Lab")
- c) Design solar environment in Grasshopper™
  (i.e. Austin, Texas on March/September 21)
- d) Definition of shading structure
  (i.e. modified honeycomb structure)
- e) Define design criteria for shading structure
  (e.g. cut-off angle, limitations)
- f) Variables of design
  (e.g. location, solar environment, grid)
- g) Implementation of design
  (i.e. laser-cutter, cnc-router)
a) Design 3-dimensional environment in Rhinoceros®

For the purpose of this study, Rhinoceros® (Rhino) has been used to build a 3-dimensional environment to put the design of the shading structure into the context of the campus of the University of Texas at Austin and its geographical location in Austin (chapter 'V. Research facility: Thermal Lab', see figure 173-174). This 3-dimensional environment could also be helpful for energy simulation tools, which need to place the 'Thermal Lab' into a 3-dimensional surrounding to calculate shadows and heating and cooling loads. Furthermore, materials can be assigned to calculate the reflection of longwave radiation and diffuse solar radiation from the surrounding buildings onto the Thermal Lab.

b) Define object for application of algorithmic modeling

The design of the shading structure has to be applied on the surface of the opening of the south oriented 'Thermal Lab' (see figure 175). Thus, the dimensions of the adjustable surface are defined by the opening that
IV. Optimized shading structure

needs to be shaded. The opening has a dimension of 12’ width by 9’ height. Since the shading structure will be attached to the window frame, the position of the window posts had to be taken into account as well for structural purposes. The shading components will be attached along the posts of the window frame. Therefore, there are 4 verticals, which will hold the shading structure in place (see fig. 176-179). Grasshopper, a plug-in for Rhino, is an algorithmic modeling program, that uses Rhino as its graphical interface. Geometries designed in Grasshopper can be assigned to elements in Rhino to be able to be manipulated or to built up on geometries built in Rhino. In this case, the shading will be applied on a surface as large as the opening of the Thermal Lab. Due to the surface the structure has to be applied on, the interior surface of the hexagonal grid has to be planar. Yet, it can change its shape on the exterior to allow an optimization to the sun-path. Due to the combination of Rhino and Grasshopper™ (GH) it is possible to relate parametric design to a specific surface with real dimensions.
c) Design solar environment in Grasshopper™
In order to be able to design a shading structure related to a specific sun-path, the surface that needs to be shaded, has to be placed in the solar context. As already discussed in the previous chapter ‘III. Quantitative simulation research’, the sun changes constantly its position, not only throughout the day, but also throughout the year as shown in figure 180. The ‘Thermal Lab’ is located in Austin, Texas at a longitude of -97.7°N and a latitude of 30.3°W. It is slightly oriented toward southwest for about 5°. For the purpose of this study the shading structure will be designed for a south oriented building.

d) Definition of shading structure
A honeycomb structure has been chosen as the main structure as described in the previous chapter ‘2. Design of ‘optimized honeycomb shading structure’’. Figure 181 shows the final interior hexagonal grid that was used to create the optimized honeycomb shading structure.

Thus, a hexagonal grid was defined as the interior structure, which is extruded perpendicular to the base.
IV. Optimized shading structure

The exterior edge of the component will result out of the intersection of the extruded hexagonal interior structure and the sun-path. The structure of the sun-path is very close to a plane (see fig. 183). There is only a small discrepancy of the resulting surface of all solar-rays hitting one specific point throughout one day and a plane through the same point resulting out of one arbitrary solar ray of this specific day. Assuming, the solar rays are all in one plane, this plane cuts through the extruded surfaces of the interior grid. The resulting exterior structure is another hexagonal structure as well (see fig. 184). This structure is not necessarily symmetric like the interior structure. It will rather be asymmetrical since it is adjusted to the sun-path which is only symmetrical in relation to a south oriented building on the equinox (compare fig. 146-148). An equinox occurs twice a year, when the tilt of the Earth’s axis is inclined neither away from nor towards the Sun, the centre of the Sun being in the same plane as the Earth’s equator. The term equinox can also be used in a broader sense, meaning the date when such a passage happens. The name “equinox” is
derived from the Latin aequus (equal) and nox (night), because around the equinox, the night and day are approximately equally long. It may be better understood to mean that latitudes +L and -L north and south of the Equator experience nights of equal length. At an equinox, the Sun is at one of two opposite points on the celestial sphere where the celestial equator (i.e. declination 0) and ecliptic intersect. These points of intersection are called equinoctial points: the vernal point and the autumnal point. By extension, the term equinox may denote an equinoctial point. An equinox happens each year at two specific moments in time (rather than two whole days), when there is a location on the Earth’s equator where the centre of the Sun can be observed to be vertically overhead, occurring around March 20/21 and September 22/23 each year. Generally, March 21 and September 21 are considered to be the days when the equinox occurs (see fig. 185).

The component will then be built out of the interior and exterior structure, resulting in a deformed honeycomb structure (see fig. 186).
IV. Optimized shading structure

e) Define design criteria for shading structure

As mentioned before, there are three design criteria for the shading component. First, the component has to provide full shading for a specified date. For this study, this will be achieved by using the date of March/September 21 as a cut-off angle. While full shading will be provided during the time from March 21 until September 21, there will be partially solar exposure from September 22 until March 20. The reason for choosing these dates becomes clear by looking at the temperature distribution of Austin, Texas (see fig. 149). Shading is desired as soon as the average dry-bulb temperature is higher than the comfort level. In this case 21°C. As you can see in figure 155, the light blue lines show the average temperature distribution throughout the year. As soon as the daily highest temperatures are higher than 24 °C, shading is needed to avoid overheating. In fig. 154, the critical average temperatures are highlighted. This table shows that the highest temperatures in March are only about 22°C. Thus, it would not be necessary to shade the building since it still gets very cold in the morning and at night. For this case, additional solar insolation is actually desired. But since the sun-path for September is similar to the sun-path for March, theses temperatures and solar radiations have to be considered as well. While March is still a rather cooler month, September has still very high temperatures throughout the day. The temperatures rise up to 30°C in average. Therefore, it is necessary to use the solar-path for March/September rather than for April/August. Furthermore, figure 154 shows the monthly maximum and minimum temperatures as well as the monthly average temperatures. Even in January, it appears that the dry-bulb temperature is higher than 24°C. Even though, it can get colder than freezing temperature as well. This shows that the climate in Austin during the winter months oscillates between very low and very high temperatures throughout the month. Since the daily average temperature is below 22°C from October until April, solar radiation is desired to reduce heating loads. Contrarily the situation in the summer. The temperatures don’t drop below 15°C. The daily average temperatures are above 23 °C from May until September. Therefore shading of the window is desired. Nevertheless, desired shading is not only depending on
3. Building process of the mock-up

Fig. 192  Optimized shading for south in January
Fig. 193  Optimized shading for south in February
Fig. 194  Optimized shading for south in March
Fig. 195  Optimized shading for south in April

Fig. 196  Optimized shading for south in May
Fig. 197  Optimized shading for south in June
Fig. 198  Optimized shading for south in July
Fig. 199  Optimized shading for south in August

Fig. 200  Optimized shading for south in September
Fig. 201  Optimized shading for south in October
Fig. 202  Optimized shading for south in November
Fig. 203  Optimized shading for south in December
IV. Optimized shading structure

the exterior dry-bulb temperature. Even if there is a low outside temperature, the interior temperatures can rise significantly due to the greenhouse effect. On a sunny day, direct short-wave solar radiation heats up the interior surfaces and turns into long-wave radiation. This long-wave radiation radiates back to the window. Since long-wave radiation is not able to penetrate glass, it is trapped inside the room and rises the temperature. Therefore, even on cold days with high solar radiation, shading could be necessary. Figure 192-203 show the development of an optimized honeycomb shading component from January to December. As one can see, the definition of the time when full shading is desired is crucial with regard to the final form of the assembly. The smallest components would be achieved by providing full shading only for June. The more shading that has to be provided in the year, the larger the structure. Figure 187 shows the assembly of an optimized shading structure which provides full shading from March 21 until September 21. A similar development for a southwest and south-southwest oriented surface can be seen in the appendix in chapter "3. Appendix C - Optimized honeycomb
shading structure’. The second criteria is not to exceed the boundaries of the extruded hexagonal structure in order to be able to place components next to each other without spatial interference due to extending structures. See previous chapter ‘2. Design of ‘optimized honeycomb shading structure’: b) Definition of shading criteria and base structure’. If the shape of the shading structure is limited to the extruded base polygon, the component can not be optimized to receive direct sunlight in specified periods of time. This will also even cause unnecessary shadow in the summer. This fact represents the most limiting criteria since one of the major reasons for this design is to provide full shading while allowing maximum diffuse skylight. If there wouldn’t be the limitation by the second criteria, there could even be a defined time frame in which there would be a full exposure to direct sunlight. However, this would result in a larger structure, exceeding the extruded volume of the base surface, which is not discussed in this study. Reasons to achieve such a structure could be for reducing heating loads and artificial lighting in the winter.
IV. Optimized shading structure

The third criteria is only secondarily related to the sun-path. The goal is to have a higher degree of visual contact in the center zone. This will be achieved by increasing the size of the components in the center. To maintain a continuous transition in the size of the components, they will not only increase in the center but also decrease towards the edges (see fig. 156-157). As a result of this transition, the components not only change in width and height, but also in depth. This change of depth makes the surface seem to warp (see fig. 161-162). Since the components increase in width and height in the center, they will also increase in depth. Whilst, along the edge, the components are smaller and thus also shallower. See figure 204. For reasons of symmetry, this transition will be designed in a way to achieve symmetry along the width as well as the height of the shading structure. That way, there is an increased degree of visual contact in the center while maintaining maximum shading. One optimized shading device has been developed for the orientations south, southwest and southwest-west (see fig. 146-148. The final mock-up of this optimized shading structure was developed for a south oriented building.

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Fig. 208 Component received through the ‘baking’ command in Grasshopper

Fig. 209 Unrolled component received through the ‘unrolled’ command in Rhino
3. Building process of the mock-up

f) Variables of Design

There is only a limited number of variables. Starting with the possibility of changing the building’s location. One of the reasons this component was designed in Grasshopper, was the opportunity to use the design at any location in the world. With a change of location, there comes also a change of shading criteria. For example, for a building in a rather colder climate, like Munich for example, there’s a lower need for shading in the summer but a higher need for solar exposure in the winter. This is due to different temperatures throughout the year. For this study, the focus was on the location in Austin, as described before. The change of location for the purpose of this study is possible since a global solar environment has been designed in Grasshopper. With a change of the needs of shading and exposure criteria simply comes a change of the cut-off angles which is defined by this very global solar environment. Figure 205 - 207 show a comparison of the optimized shading structure for Austin, installed at a location in New York and Munich.
IV. Optimized shading structure

Also, the grid can be changed in the number of cells and the size of components. Having components in the same size leads to a homogeneous shading structure as shown in figure 163. The grid decides on focuses of visual contact, the thickness of the shading structure as well as its appearance. General goal is always to keep the shading criteria - to providing full shading through a defined period of time.

g) Implementation of design and final product
In the end, Rhino was used to process the data for visualization and construction purposes. The 3-dimensional data produced in Grasshopper is imported into Rhino to be able to process it further. Grasshopper uses Rhino only as its graphical interface. Using the ‘bake’ command in Grasshopper turns the virtual 3-dimensional constructions into vector based geometries that can be edited and processed further in Rhino [see fig. 208]. In order to manufacture the components with the laser-cutter or the cnc-router, the information has to be transformed from 3-dimensional to 2-dimensional information. In order to do so, Rhino
has to ‘unroll’ each component so that it lays flat on the ground (see fig. 209). This line based cad drawing can then be sent to the manufacturing machine. Each vector or point represents a path for milling or cutting. Before the component is sent to the cnc-router, it has to be edited further. Figure 215 shows the final stage of the component before it is sent for manufacturing. In this study, the full length of the unrolled geometry of the largest components gets up to 6'. Thus, the option of using the laser-cutter was not been given anymore [max. 18” x 32’]. Instead, the cnc-router (60’ x 96”) was used to produce the mock-up (see fig. 211-212). Figure 212 shows a layout of one board that was milled on the cnc-router. To minimize the waste of material, the components had to be rotated and placed next to each other.

As explained before, the base component was designed in Grasshopper to test its shading performance and geometry. In order to build test components and discover upcoming errors or challenges in the building process a laser-cutter was used. The laser-cutter is much faster to use and good to test ideas. In order to
IV. Optimized shading structure

be able to use the laser-cutter, the components had to be scaled down since the available laser-cutter is only able to laser-cut boards of 18” x 32”. As a result of the tests, it became clear that an attachment system for the components to the façade as well as for the components themselves, needed to be designed in order to be able to mount the shading structure to the window. The test models showed, that the components themselves would need to be connected with each other by an adjacent extruded flange from the hexagonal grid to the interior. One inch seemed to be sufficient. Figures 213 show this attachment peace. Attachment pieces were designed along on certain components to hang the components onto the window frame (see fig. 214). From every folding line, in a distance of 1 inch, holes were drilled with the cnc-router to have accurate connections, which serve to stabilize the structure. See figure 215. The system that is used to connect the shading structure to the window frame is an aluminum ‘U’-profile, which has been attached to the window posts. Bolts with a diameter of 1/4” have been attached to these profiles to carry the shading structure (see fig. 217). Figure 218 shows the
attached element that rests on these metal bolts. The structure can easily be hung onto the façade, facilitating the mounting. In order to protect the shading structure from getting blown off by a strong wind, the shading structure could be held in place by replacing this ‘hanger’ with a simple hole. The shading structure would be held in place and fastened with the bolts. Like that, the shading structure would sit tight on the façade. Along the edge of the opening, a tolerance of 1 1/2” was given to allow the structure to expand. Since the whole structure was built with zero tolerance between each component, the structure should not be moving towards the edges since the structure should keep itself in place. The width of the aluminum ‘U’-profiles is 2 1/2”. Therefore, the shading structure would be able to move along these 2 1/2” as well. Having designed the whole structure with zero tolerance made it quite challenging to put it together. Every connection is under a lot of tension. For the future, a tolerance of at least 1/16” should be taken into account. The components were assembled row by row in order to facilitate the assembly process. It turned out that it is easiest to start hanging the first row (upper
IV. Optimized shading structure

row) and then hang the following rows below. This keeps the structure in place due to its dead weight (see fig. 219).

4. Comparison of performance of the ‘optimized honeycomb shading structure’ to conventional shading devices

The data used for this chapter is documented in chapter 'III. Quantitative simulation research'. Figures 111,112 and 125 show the summarized results. As already mentioned before, a shading coefficient (sc) has been introduced in order to be able to compare the shading structures to each other. It represents the ratio of the amount of solar radiation between an unobstructed and an obstructed surface. For example, a vertical south oriented surface receives 920 kWh/m² of solar radiation. If a surface with a shading device receives only 600 kWh/m², the sc is 0.65 (sc = 600/920). The lower the sc, the more shading is provided. For the different orientations, the shading structure, optimized for a south orientation has simply been rotated towards southwest and west. Ideally, a separate optimized shading structure would have been developed for each orientation.

a) Performance of the optimized honeycomb shading structure depending on the orientation

As figure 125 indicates, the optimized shading structure for south does not provide the most shading compared to the other shading structures. The south oriented optimized shading structure provides a sc of 0.38. Considering that diffuse solar radiation can be as high as 20% of the total global radiation, it is assumed that the reason for the results of the optimized shading structure is due to the increased amount of diffuse radiation. Since the optimized shading structure provides full protection from direct radiation the increased value of sc must be caused by the increased amount of diffuse radiation. This is an interesting fact since an increased amount of diffuse radiation increases the degree of visual contact as well. Therefore, the optimized shading structure performs exactly the way it was supposed to perform. It provides maximum shading with a maximum degree of visual contact. The optimized shading structure provides a sc of 0.26 for southwest and 0.29 for west. Thus, it provides the most shading in southwest, 10.35% better than west and even 31.58% better than south. Furthermore, due to the low solar heat gain coefficient of the glazing, in this case 0.37, there is no risk for overheating of the room due to an increased degree of visual contact. A solar heat gain coefficient of 0.37 means that only 37% of the solar radiation will pass through the glass.

\[ \text{SHG} \times \text{SHGC} = Q_{\text{tot}} \]

where \( \text{shg} \) = solar heat gain  
\( \text{shgc} \) = solar heat gain coefficient  
\( Q_{\text{tot}} \) = total radiation getting into the space

b) Comparison of the optimized honeycomb shading structure to conventional shading devices

For this study, the optimized honeycomb shading structure is compared to horizontal and vertical blinds, an eggcrate and a conventional honeycomb shading structure. From the different eggcrate and honeycomb structures, the type with the highest performance was chosen: the horizontally oriented eggcrate shading...
4. Comparison of performance of the 'optimized honeycomb shading structure' to conventional shading devices

Fig. 220  Final assembly of components installed on Thermal Lab
IV. Optimized shading structure

structure and the vertically oriented honeycomb shading structure. Out of these shading structures, the eggcrate shading structure performs best with a sc 0.24. Surprisingly, the south oriented optimized honeycomb shading structure only performs better than the vertical blinds. All other shading structure provide more shading than the south oriented optimized shading structure. However, the optimized shading structure performs best in southwest and west compared to almost every other shading structure. Only the eggcrate shading structure performs slightly better in southwest with only 2.2% [5 kWh/m²]. For west oriented façades, no other shading structure provides more shading than the optimized shading structure.

c) Comparison of the optimized honeycomb shading structure with conventional honeycomb structures

Similar to the comparison in the paragraph before, the optimized honeycomb shading structure provides the lowest sc for south, but performs best for southwest and west. For south, the lowest sc is provided by the vertically oriented honeycomb structure. With a sc of 0.27 this structure provides almost 43% more shading than the optimized honeycomb structure. On southwest, the optimized honeycomb structure provides 15% more shading than the vertically oriented honeycomb structure, which provides the second best sc. Similar results for west, where the optimized honeycomb shading structure provides a sc of 0.29 which is 21.2% better than the second best shading structure, again the vertically oriented honeycomb shading structure. But again, the results could also show that the optimized structure only provides more diffuse solar radiation than the others and thus, it simply allows a higher degree of visual comfort with full shading from March until September, the critical months with regard to high temperatures.

d) Influence of material thickness on results and the degree of visual contact

One of the great advantages of the optimized shading structure is the small amount of material that is necessary for this structure. Even if the total unrolled length of the optimized shading structure is only second after the honeycomb structure with a circumference of 4 feet, it needs 37.3% less of total area of material per ft². At the same time, it only needs 8.9% more area than vertical blinds and 11.5% more area of material than horizontal blinds. Considering the increased material thickness horizontal and vertical blinds will have due to the span length, the optimized shading structure performs much better. With a material thickness of 1/8” and a total volume of 1.41 ft³, the optimized honeycomb shading structure uses the least amount of material providing a highly competitive sc.

e) Conclusion

Due to the minimized use of material, the optimized honeycomb shading structure is highly competitive to the other shading devices. In the end, it even performs third on area of unrolled shading structure and it performs best on the total volume of shading structure. Even if it has a slightly larger area of visible shading structure than the honeycomb shading structure with a circumference of 4 feet, it provides a high degree of visual contact due to the enlarged openings in defined places, which provide the same sc as smaller components.
4. Comparison of performance of the 'optimized honeycomb shading structure' to conventional shading devices

Fig. 221 Final assembly of components installed on Thermal Lab
IV. Optimized shading structure

5. Effect of the shading structure on solar radiation in the interior

The purpose of this study is to test the performance of the optimized honeycomb shading structure. The tests will show the impact of the optimized honeycomb shading structure on the level of solar radiation in the interior of the Thermal Lab.

Solar radiation measurements are compared between the window without shading with the window with the optimized honeycomb shading structure. The level of solar radiation is measured at two locations simultaneously. The first sensor has been placed on the exterior, directly in front of the Thermal Lab at the south facing façade in order to be able to measure the amount of solar radiation, the south facing window receives. A second sensor has been placed in the interior at various locations (see fig. 222). This sensor measures how much of the solar radiation that is received by the window penetrates the glazing and/or the shading. The difference between those two measurements represents...
the transmittance of solar radiation of the glazing and/or the shading. The glass that is installed in the window of the Thermal Lab has a visible light factor of 70%. Since this is a very high factor, the performance of the window without shading will already reduce the solar radiation tremendously.

In the interior, the solar radiation sensor has been placed at three rows - center, left and right - at distances of 1’, 2’, 3’, 4’, 6’ and 8’ from the window [see fig. 224]. The internal solar radiation sensor measured the level of vertical solar radiation at a height of 35” from the ground. This represents almost the working height of a desk. The advantage of measuring vertical solar radiation is that the reflection of solar radiation from the surfaces behind the solar sensor is cut off [see fig. 223]. Therefore, only the solar radiation that passed through the window is measured. The further back the solar sensor is placed in the room (8’ the furthest), the more solar radiation will be measured that has been reflected from the interior surfaces such as the walls, the roof and the floor.

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**Fig. 224** Various locations of measurements
In order to be able to compare two different test set-ups, solar radiation measurements were recorded for two sequential days. It is important to take the measurements not only at the exact same time of the precedent day in order to receive solar radiation from the sun at similar positions but also to have similar weather conditions. For this study, solar radiation measurements have been taken on May 4 and May 5, starting at 2:00 p.m. Each location for the interior measurements was recorded for 5 minutes, with an interval of 1 second per measurement. The solar radiation was measured at different locations inside the room in order to analyze the impact of the shading structure on the solar radiation level in different depths of the room. It was assumed that the amount of solar radiation is higher the closer the measurement is taken at the window. The further back in the room, the lower the solar radiation. The measurements for the case of no shading structure proof this assumption. The column ‘Vertical solar radiation after glazing (day 01)’ shows a reduction of solar radiation the further back the measurements have been taken in the room. It diminishes from having been placed right in front of the window at a distance of 1’ from 48.1 W/m², to the back of the room, at a distance of 8’ from the window, to 6.2 W/m². For the case with the honeycomb shading structure in front of the window, it is reduced from 16.2 W/m² to 7.2 W/m². Since the optimized honeycomb shading structure is providing full shading at the month of May, only diffuse sunlight is entering the room. Therefore, 16.2 W/m² are representing the amount of diffuse sunlight passing through the shading structure. At a distance of 8’, the solar radiation measurements with no shading and with shading converge to be almost the same value [6.2 W/m² versus 7.2 W/m²]. This is due to the fact that there is no direct sunlight in the rear part of the room. This also shows that there is actually an increased amount of diffuse solar radiation for the case with shading. The reason for this can be the higher amount of direct and diffuse sunlight reflected by the surface of the shading structure.

The solar radiation measurements taken on the left side and the right side of the room represent similar tendencies with regard to a reduction of solar radiation the further the sensor has been moved to the back of the room.

Disregarding the location of the interior solar sensor, the shading structure allows 1.77 % less solar radiation in the room in average. The locations 1’ at the center of the room and 1’ at the left part of the room were taken as direct solar radiation was still able to hit the solar sensor. For these cases, a higher amount of reduction of solar radiation was measured. Since all the other measurements were taken when no direct sunlight was able to hit the solar sensor, only the level of diffuse sunlight was measured by the interior solar sensor. As a result, the reduction between shading and no shading vary in between 0.22% and 2.25%. On the other side, as soon as direct sunlight was measured, the reduction increased to about 8.09% in average. Since the sun is already at a very high position in the month of May, only a small amount of direct solar radiation is actually penetrating the window. Therefore, it can be assumed that the reduction of solar radiation is even higher, for lower sun-angles, as in March. For March, the shading should have its best performance since it provides full shading, while the sun is at a lower position and penetrating the window without shading even more.

With regard to the measurements when no direct sunlight was hitting the solar sensor, the shading structure allows almost as much diffuse solar radiation to penetrate the window as the case of the window without shading. This is actually desired since it lightens up the space and reduces the need for artificial lighting.

The small amount of difference in performance between shading and no shading can also be explained with the fact the glazing was used with a visible light factor of 70%, which is very high. If the quality of glazing is lower, the difference in performance would be even higher. Therefore, the worse the glazing with regard to the factor of visible light, the greater the reduction of solar radiation between shading and no shading.
### Location of measurement

<table>
<thead>
<tr>
<th>Location of measurement</th>
<th>Distance to window glass</th>
<th>Time</th>
<th>Total vertical solar radiation on exterior (day 01/ day 02)</th>
<th>Vertical solar radiation behind glazing [day 01]</th>
<th>Reduction of solar radiation due to glazing [%]</th>
<th>Vertical solar radiation behind shading structure and glazing [day 02]</th>
<th>Solar radiation after shading structure and glazing</th>
<th>Reduction of solar radiation due to shading structure and glazing [%]</th>
<th>Reduction of solar radiation of shading structure compared to no shading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of room</td>
<td></td>
<td>14:00 p.m.</td>
<td>387.1 W/m²</td>
<td>48.1 W/m²</td>
<td>87.6 %</td>
<td>377.8 W/m²</td>
<td>16.4 W/m²</td>
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<td>8.08 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2'</td>
<td>14:05 p.m.</td>
<td>385.1 W/m²</td>
<td>94.4 %</td>
<td>378.1 W/m²</td>
<td>12.6 W/m²</td>
<td>96.7 %</td>
<td>2.25 %</td>
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<tr>
<td>Left part of room</td>
<td></td>
<td>14:10 p.m.</td>
<td>385.2 W/m²</td>
<td>17.3 W/m²</td>
<td>95.6 %</td>
<td>376.7 W/m²</td>
<td>11.1 W/m²</td>
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<td>1.56 %</td>
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<tr>
<td>Right part of room</td>
<td></td>
<td>14:15 p.m.</td>
<td>384.0 W/m²</td>
<td>14.8 W/m²</td>
<td>96.1 %</td>
<td>375.3 W/m²</td>
<td>10.3 W/m²</td>
<td>97.3 %</td>
<td>1.13 %</td>
</tr>
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<td></td>
<td>14:20 p.m.</td>
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<td>10.9 W/m²</td>
<td>97.2 %</td>
<td>373.5 W/m²</td>
<td>8.7 W/m²</td>
<td>97.7 %</td>
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</tr>
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<td></td>
<td></td>
<td>14:25 p.m.</td>
<td>379.2 W/m²</td>
<td>6.2 W/m²</td>
<td>98.4 %</td>
<td>371.5 W/m²</td>
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<td>98.1 %</td>
<td>-0.30 %</td>
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<td></td>
<td></td>
<td>14:30 p.m.</td>
<td>377.2 W/m²</td>
<td>46.9 W/m²</td>
<td>87.6 %</td>
<td>370.0 W/m²</td>
<td>16.0 W/m²</td>
<td>95.7 %</td>
<td>8.10 %</td>
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<td></td>
<td>14:35 p.m.</td>
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<td>19.6 W/m²</td>
<td>94.8 %</td>
<td>365.5 W/m²</td>
<td>8.2 W/m²</td>
<td>96.4 %</td>
<td>1.67 %</td>
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<td>14:40 p.m.</td>
<td>370.2 W/m²</td>
<td>16.2 W/m²</td>
<td>95.6 %</td>
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<td>96.9 %</td>
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<td>12.8 W/m²</td>
<td>96.5 %</td>
<td>359.6 W/m²</td>
<td>10.8 W/m²</td>
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<td>8.9 W/m²</td>
<td>97.5 %</td>
<td>353.9 W/m²</td>
<td>7.9 W/m²</td>
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<td></td>
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<td>6.0 W/m²</td>
<td>98.3 %</td>
<td>348.2 W/m²</td>
<td>7.1 W/m²</td>
<td>98.0 %</td>
<td>-0.36 %</td>
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<td></td>
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<td>343.9 W/m²</td>
<td>13.3 W/m²</td>
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<td>15:05 p.m.</td>
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<td>19.8 W/m²</td>
<td>94.3 %</td>
<td>339.2 W/m²</td>
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<td>15.2 W/m²</td>
<td>95.5 %</td>
<td>333.7 W/m²</td>
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<td></td>
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<td>12.9 W/m²</td>
<td>96.1 %</td>
<td>328.6 W/m²</td>
<td>10.1 W/m²</td>
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<td>0.79 %</td>
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<td></td>
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<td>10.1 W/m²</td>
<td>97.0 %</td>
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<td>7.0 W/m²</td>
<td>97.9 %</td>
<td>316.8 W/m²</td>
<td>5.9 W/m²</td>
<td>98.1 %</td>
<td>0.28 %</td>
</tr>
<tr>
<td>Total average</td>
<td></td>
<td>90 minutes</td>
<td>362.8 W/m²</td>
<td>17.5 W/m²</td>
<td>95.2 %</td>
<td>355.5 W/m²</td>
<td>10.7 W/m²</td>
<td>97.0 %</td>
<td>1.77 %</td>
</tr>
</tbody>
</table>

Fig. 225: Results of solar radiation measurements in the interior of the Thermal Lab with shading and no shading.
6. Effect of the shading structure on the distribution of daylight

The purpose of this study is to test the intensity and distribution of daylight within the test room of the Thermal Lab.

The daylight sensors used for these test-runs had a measurement range from 0-20,000 lux. They are accurate up to 5%.

Daylight level measurements are compared between the window with and without the optimized honeycomb shading structure. The level of daylight is measured at two locations simultaneously. One sensor has been placed on the exterior, directly in front of the south facing façade, to measure the level of daylight outside the lab. Since the daylight sensors were not able to give any readings, they had to be placed in a shaded area. Three other sensors have been placed in the interior at various locations (see fig. 228). These sensors measure how much of the daylight penetrates the glazing and/or
the shading. The difference in percentage between those two measurements represents the daylight coefficient of the glazing and/or the shading structure. The daylight coefficient represents the percentage of daylight that is received in the interior behind the window and/or the shading structure in relationship to the exterior daylight level outside the lab. The glass that is installed in the window of the Thermal Lab has a visible light factor of 70%. Since this is a very high factor, the performance of the window without shading will already reduce the daylight level tremendously.

In the interior, the daylight level sensors have been placed at three different locations in front of the window - center, left and right - at the same distance from the window (see fig. 228). The internal daylight level sensors measured the level of daylight at a height of 29” from the ground. This represents the working height of a desk.

In order to be able to compare two different test set-ups, shading and no shading, daylight level measurements were recorded for times equally distant to solar noon.
IV. Optimized shading structure

For example, the test run with shading was recorded from 13-22 minutes before solar noon and the test run without shading was recorded 13-22 minutes after solar noon. Thus, the two different test-runs were recorded during symmetrical positions of the sun. Since the measurements were recorded at a day with constantly changing conditions with regard to the level of cloudiness, it was essential to measure the exterior daylight level simultaneously.

For this study, daylight level measurements have been taken on May 12, starting at 1:05 p.m. until 1:49 p.m. Solar noon was at 1:27 p.m. The location of the three daylight level sensors was changed every minute row by row. For example, the first measurement was taken at 1:05 p.m. for the first row, measurement points 1-3. One minute later, the daylight level was measured for the second row, measurement points 4-6. The third row was recorded again one minute later. The test was repeated twice for each set up, resulting in two measurements for the test-run with shading and two sets of measurements or the test-run without shading.

The daylight level was measured at different locations inside the room in order to analyze the impact of the shading structure on the daylight level in different depths of the room. It was assumed that the amount of daylight is higher the closer the measurement is taken at the window. The further back in the room, the lower the daylight level. The results are in accordance with the solar radiation measurements. Figure 231 represents the second test-run of the case with shading. The graph shows the distribution of daylight levels in the Thermal Lab. Row 1-2-3 has much higher daylight coefficients than row 4-5-6 or row 7-8-9.

Figures 229-230 show the summary of the test-runs. The average daylight coefficient for the case with shading is 26.30%, which is 50% lower than for the case without shading. For the case without shading, the average daylight coefficient is 52.42%. Yet, the average interior daylight level is still 11504 lux, which is very high compared to the minimum required daylight level for working desks, which is 300 lux. The second test-run shows a reduction of almost 55% of the average daylight coefficient between shading and no shading. Therefore, the reduction of the daylight coefficient is 52.5% for the shading structure compared to no shading structure.

The effectiveness of the shading structure is the higher the further away the measurement is taken from the window. For both test-runs, the effectiveness of the first row is 46% in average, for the second row the effectiveness is 56% in average and for the last row, the effectiveness is almost 82%. The result for the third row is significantly higher than the results for the first two rows. Therefore, the lower the exterior daylight level, the higher the daylight level provided in the interior for the case with shading. Thus, the lower the level of exterior daylight, the more daylight is provided for the case with shading compared to no shading.

Figures 232-233 represent the measurements of daylight levels for the two test-runs. Both cases show similar tendencies with regard to the provided daylight level compared to the distance from the window. The further the measurements were recorded from the window, the lower the level of daylight. Since the daylight level on
### Fig. 230 Daylight level measurements - comparison of shading and no shading - test 01

<table>
<thead>
<tr>
<th>Measurement point</th>
<th>Time to solar noon [min]</th>
<th>Daylight level test with shading</th>
<th>Daylight level test without shading</th>
<th>Effectiveness of shading structure [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>First row</td>
<td></td>
<td>11160</td>
<td>3250</td>
<td>29.12%</td>
</tr>
<tr>
<td>1</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>11370</td>
<td>3540</td>
<td>31.13%</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>11370</td>
<td>6070</td>
<td>53.39%</td>
</tr>
<tr>
<td>Second row</td>
<td></td>
<td>11500</td>
<td>2800</td>
<td>24.35%</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>21</td>
<td>11670</td>
<td>3180</td>
<td>27.25%</td>
</tr>
<tr>
<td>6</td>
<td>21</td>
<td>11670</td>
<td>2930</td>
<td>25.11%</td>
</tr>
<tr>
<td>Third row</td>
<td></td>
<td>11600</td>
<td>1580</td>
<td>13.62%</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>11600</td>
<td>1822</td>
<td>15.71%</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>11600</td>
<td>1970</td>
<td>16.98%</td>
</tr>
<tr>
<td>Average</td>
<td>---</td>
<td>11504</td>
<td>3016</td>
<td>26.30%</td>
</tr>
</tbody>
</table>

### Fig. 229 Daylight level measurements - comparison of shading and no shading - test 02

<table>
<thead>
<tr>
<th>Measurement point</th>
<th>Time to solar noon [min]</th>
<th>Daylight level test with shading</th>
<th>Daylight level test without shading</th>
<th>Effectiveness of shading structure [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>First row</td>
<td></td>
<td>12300</td>
<td>9260</td>
<td>75.28%</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>12150</td>
<td>7000</td>
<td>57.61%</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>12580</td>
<td>8310</td>
<td>66.06%</td>
</tr>
<tr>
<td>Second row</td>
<td></td>
<td>12510</td>
<td>3010</td>
<td>24.06%</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>12400</td>
<td>3590</td>
<td>28.95%</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>12350</td>
<td>3360</td>
<td>27.21%</td>
</tr>
<tr>
<td>Third row</td>
<td></td>
<td>12270</td>
<td>1859</td>
<td>15.15%</td>
</tr>
<tr>
<td>7</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>13</td>
<td>12270</td>
<td>2062</td>
<td>16.81%</td>
</tr>
<tr>
<td>9</td>
<td>13</td>
<td>12270</td>
<td>2024</td>
<td>16.50%</td>
</tr>
<tr>
<td>Average</td>
<td>---</td>
<td>12344</td>
<td>4497</td>
<td>36.40%</td>
</tr>
</tbody>
</table>

6. Effect of the shading structure on the distribution of daylight
IV. Optimized shading structure

The exterior has been very stable, it can be concluded that changing the position of the measurement causes the change of the level of daylight. The graph shows the level of daylight depending on the time distance to solar noon. The measurements of figure 232 were recorded from 22 minutes to 20 minutes away from solar noon, while the measurements for figure 233 were taken from 15 minutes to 13 minutes from solar noon. Every minute recorded a full row, meaning three measurement points.

The abnormality of the daylight level at minute 15 in figure 233 is caused by the way the exterior daylight levels were measured. Since the sensors were not able to measure unobstructed daylight, the sensor was placed in the shade. During minute 15, the interior daylight level sensors were exposed to direct sunlight, which caused the very high measurements. There are two reasons why the interior daylight level is higher than the exterior daylight level. First, the exterior sensor recorded the daylight level in the shade. Second, it seems that even if glass reduces the interior daylight level, the daylight level is still higher than the obstructed daylight level.
from the exterior. For the case with shading, the daylight level sensor is not exposed to direct sunlight and thus, the interior daylight levels measurements are below the exterior daylight level measurements for minute 15.

Since the optimized shading structure is supposed to provide full shading from March 21 until September 21, direct sunlight does not play a major role in the performance of the shading structure with regard to daylight level measurements. Quite the contrary, the daylight level measurements should be recorded on a cloudy day, as conducted, in order to have a comparison that represents the difference between shading and no shading. On a cloudy day, even a window without shading structure would then only receive diffuse sunlight. Since full shading is provided by the shading structure, again, only diffuse sunlight passes the interior through the shading structure. Therefore, in both cases, the daylight level caused by diffuse sunlight can be compared.
Chapter V

Fig. 235 Photorealistic rendering of Thermal Lab during construction
V. Research facility: Thermal Lab

1. Construction of Thermal Lab
2. Calibration of Thermal Lab

Fig. 236: Detail of the interior of the Thermal Lab
V. Research facility: Thermal Lab

1. Construction of Thermal Lab

Metal support structure

The platform for the research facility has been set on top of the loading dock of the post office at the back of West-Mall Building (WMB). The platform is accessed from the 4th floor of WMB via a metal staircase.

Dimensions: width: 42'-6” length: 23'-6”
Platform: 20’ elevated from the ground
weight of 60 people allowed on platform
Balustrade: height: 42 1/2”

Chamber ‘Thermal Lab’

The research facility called the ‘Thermal Lab’ is a highly insulated box. The Thermal Lab has one south facing opening and a door, which is located on the east oriented façade. During the first phase of the testing, the south facing opening will be closed for the purpose of base-testings. Later on, the temporary wall will be exchanged with a window. The dimensions of the room represent the measurements of a typical office room.

External dimensions: width: 13’6” height: 11’ depth: 14’6”
Interior dimensions: width: 12’10” height: 10’4” depth: 13’10”
Clearance of opening: width: 12’ height: 9’

Supply plenum

The supply plenum is built similar to a dropped ceiling. It consists out of a metal frame that contains suspended ceiling tiles. The air is supplied through exhaust openings closest to the south wall in order to exhaust hot or cold air in the upper part of the window to reduce heat or cold gains through the glass. An increased number of exhaust openings will assure reduced velocity of the supply air. An even distribution of those openings will assure an even distribution of supply air to the space in front of the window.

Exterior cladding

The chamber has been cladded with hardi-panels in order to assure certain design criteria. The task was to mimic the surrounding buildings with the white sandstone. A metal support structure helped putting the elements in place and to align them properly. This cladding also helps to minimize solar radiation on the exterior surface of the chamber. This solar radiation would interfere with the experiments of the research facility. It also ventilates the exterior surface to keep it as cool as possible.
c) Construction of box (exterior to interior):

**Walls**
1. 1/4" cladding
2. 1" ventilation gap
3. 4" structural insulated panels (SIP)
   4.1 1/32" galvanized steel
   4.2 3 15/16" polyurethane insulation
4. 4 7/16" aged polyisocyanurate insulation (2.5lb) [2 1/16" + 2 3/8"]
5. 2 x 5/8" drywall [mill finish]
6. wall paint white, suitable for repainting

**Floor**
3. 2" x 4" wooden support frame [facilitation of a future displacement, protection of exterior cladding from damage by sitting directly on metal deck]
4. 4" structural insulated panels (SIP)
   4.1 1/32" galvanized steel
   4.2 3 15/16" polyurethane insulation
5. 4 7/16" aged polyisocyanurate insulation (2.5lb) [2 1/16" + 2 3/8"]
6. 2 x 3/4" plywood
7. 1/4" carpet

**Ceiling**
1. 1/4" cladding
2. 1" ventilation gap
3. 4" structural insulated panels (SIP)
   4.1 1/32" galvanized steel
   4.2 3 15/16" polyurethane insulation
4. 4 7/16" aged polyisocyanurate insulation (2.5lb) [2 1/16" + 2 3/8"]
5. 2 x 5/8" drywall [mill finish]
6. wall paint white, suitable for repainting

Fig. 237  Section drawings floor, wall, roof
Weather station

The weather station Vantage Pro 2 Plus is a product by Davis Instruments Corporation. Temperature and humidity sensors are enclosed in a radiation shield. The weather station is solar powered. Electronic components are housed in a weather-resistant shelter. The data is transmitted wireless from the weather station on the exterior to the control panel mounted in the right cabinet inside the box. Connected via USB to the computer enables a graphical display of measured data. It is capable of measuring the following data:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sensor</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global solar radiation</td>
<td>Solar radiation sensor</td>
<td>0 - 1800 W/m²²</td>
<td>± 5 %</td>
</tr>
<tr>
<td>Wind direction</td>
<td>Anemometer</td>
<td>0 - 360°</td>
<td>± 3 °</td>
</tr>
<tr>
<td>Wind velocity</td>
<td>Anemometer</td>
<td>3 - 241 km/h</td>
<td>± 5 %</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Rain collector</td>
<td>0.2 mm per tip of the bucket</td>
<td>± 3 %</td>
</tr>
<tr>
<td>Humidity</td>
<td>Humidity sensor</td>
<td>0 - 100%</td>
<td>± 3 -4 %</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>Barometer</td>
<td>540 - 1100 hPa/mb</td>
<td>± 1 hPa/mb</td>
</tr>
<tr>
<td>Dry-bulb temperature</td>
<td>Temperature sensor</td>
<td>-40 - +65 °C</td>
<td>0.5 - 1.0 °C</td>
</tr>
</tbody>
</table>

Fig. 238 Table of range and accuracy of weather station equipment
Ceiling
10 6" suspended ceiling
11 2’ x 2’ ceiling tiles / metal support structure

Built in furniture
13 wooden cabinets
   - cabinet grade maple plywood/poplar core
   - width: 3’, floor to ceiling height
13.1 purpose cabinet northwest corner:
   a storage space
   b control panel of power meter
   c control panel of flow meter
   d control panel of HVAC system
13.2 purpose cabinet northeast corner:
   a computer
   b display
   c data acquisition equipment
   d control panel weather station

14 return-air plenum
15 fan-coil unit
16 supply-air plenum

Fig. 239 Cross-section Thermal Lab - north-south
Ceiling

10 6'' suspended ceiling

11 2’ x 2’ ceiling tiles / metal support structure

Built in furniture

12 3’ x 6’6” door (SIP, UV resistant gasket)

13 wooden cabinets
- cabinet grade maple plywood/poplar core
- width: 3’, floor to ceiling height
13.1 purpose cabinet northwest corner:
  a  storage space
  b  control panel of power meter
  c  control panel of flow meter
  d  control panel of HVAC system
13.2 purpose cabinet northeast corner:
  a  computer
  b  display
  c  data acquisition equipment
  d  control panel weather station

14 return-air plenum

15 fan-coil unit

16 supply-air plenum

Fig. 240: Longitudinal-section Thermal Lab - east-west
<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Thickness</th>
<th>R-value</th>
<th>U-value</th>
<th>k-factor</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall - main construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cladding</td>
<td>Hardie Reveal panel</td>
<td>7/16&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIP - reinforcement</td>
<td>Galvanized steel</td>
<td>1/32&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIP - insulation [1]</td>
<td>Polyurethane insulation</td>
<td>3 30/32&quot;</td>
<td>28.6</td>
<td>0.035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIP - total</td>
<td></td>
<td>4&quot;</td>
<td>0.14 (75°F)</td>
<td>0.18</td>
<td></td>
<td>2.25 lbs/ft³</td>
</tr>
<tr>
<td>Interior insulation [2]</td>
<td>Aged polyisocyanurate insulation</td>
<td>4 7/16&quot; (2 1/16&quot; + 2 3/8&quot;)</td>
<td>24.5 (5.6/inch)</td>
<td>0.041</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total insulation [1] + [2]</td>
<td></td>
<td>8 7/16&quot;</td>
<td>53.2</td>
<td>0.019</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drywall</td>
<td></td>
<td>1 1/4&quot; (2 x 5/8&quot;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall painting</td>
<td>Glidden Lifemaster No VOC, interior, color: white</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South wall - closed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation [4]</td>
<td>Aged polyisocyanurate insulation</td>
<td>8 9/16&quot; (3 x 2 1/16&quot; + 2 3/8&quot;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total element opening [3] + [4]</td>
<td></td>
<td>9 15/16&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>South wall - open</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window - glass</td>
<td>Double glazing Viracon VE 1-2M (low-e, argon, visible light 70%, SHGC 0.37)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window - frame</td>
<td>Aluminum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation on north wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return plenum</td>
<td>Galvanized steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Built-in closet</td>
<td>Walls: cabinet grade maple plywood/poplar core</td>
<td>1/4&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Back: medium density fiber board (MDF)</td>
<td>1 3/8&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support structure</td>
<td>Plywood</td>
<td>1 1/2&quot; (2 x 3/4&quot;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carpet</td>
<td>Tonal / 2924 platinum, 50 cm x 50 cm tiles</td>
<td>1/4&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceiling / supply plenum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceiling tiles</td>
<td>Fine fissured mineral fiber board</td>
<td>5/8&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 241 Table of range and accuracy of weather station equipment
V. Research facility: Thermal Lab

2. Calibration of Thermal Lab

A calibration of the Thermal Lab needed to be conducted in order to proof initial assumptions such as R-value of the walls, performance of heating, cooling and ventilation system (HVAC) or the monitoring system. In the end, an energy simulation program will be developed that is able to simulate the thermal performance of the Thermal Lab as close as possible. The advantage of having a testing facility such as the Thermal Lab, is to do the comparison between a building in reality and its respective environment and a virtual model in a virtual environment. Common energy simulation tools such as EnergyPlus or eQuest are very general with their assumptions in order to serve as many purposes as possible. The calibrated energy simulation tool for the Thermal Lab, allows the researcher to change parameters of the thermal environment, while being able to trust the results to a certain percentage. Therefore, it would be possible to exchange parts of the south facing wall such as glazing or the window frame without losing accuracy. Features like shading elements can be added to the system and simulate a new solar radiation situation without the need of testing it in reality since a
certain accuracy has already been proven. Furthermore, the Thermal Lab can virtually be placed to any location to simulate different systems. For example, it could be tested, what the difference in performance of triple insulated glass is for different locations. Shading structures could be added to the system to see what kind of impact they have in addition to different glazing for different locations or even orientations.

In case of the Thermal Lab the following three calibrations have been conducted. During these tests, the lab still had a south wall with the same characteristics as the other walls (see fig. 242-245).
- Evaluation of inherent sources of error in the monitoring equipment
- Experimentally determination of the conduction heat transfer coefficient [U-value] of the walls
- Determination of the level of error found in the energy output measurements of the mechanical system for a given flow rate

An extensive report can be found in the appendix.
Chapter VI

Fig. 246. Old operable sun-tracking window shutters in Schwäbisch Hall, Germany
VI. Future prospect

1. Further developments
2. Spatial unlimited optimized fix shading structures
3. Multifunctional optimized shading structure
4. Movable optimized shading structure
5. Aesthetic/visual quality and function
VI. Future prospect

1. Further developments

Throughout the building process of the mock-up of the optimized honeycomb shading structure, several fields for improvement became obvious.

The material that was chosen for the mock-up was polypropylene (PP). A nice feature of this material is its color and low heat storage. Furthermore, this material is tough and flexible and has a good resistance to fatigue. For a mock-up it is important to have a material that can be tweaked and changed easily. Furthermore, a material needed to be chosen that could easily be produced at the University of Texas at Austin - School of Architecture (UTSoA). Accessible knowledge about materials, manufacturing machines and experience of building techniques influenced the decision process and the way of designing. For a transition into reality, instead of PP, a metal could be used since it is much more rigid and very resistant to changing climate conditions such as wind or solar exposure. High wind velocities might loosen, deform or destroy the structure. High temperatures might even change the form of PP constantly.

The mock-up was built with no tolerance in between the components. With a low degree of detailing for the mock-up, it was almost inevitable to have difficulties in assembling the components and attaching it to the window frame. Especially with no experience in the production process of such shading structures. If the final material happens to be metal, the material movement due to changes of temperatures has to be taken into account.

Since the optimized shading structures has been designed to be assembled in single components, a tremendous waste of material was unavoidable. Every adjacent surface of components caused one layer of material thickness of waste. In reality, this should be avoided. Instead, there should be only one layer of material for each ‘wall’ between the components. This would not only lighten the structure since almost half of the weight would be eliminated, but it would also increase the degree of visual contact in 2D. The view in elevation from the interior to the exterior sees every double-wall in the current design. Eliminating the double-wall, results in single layers of material. Since only the edge components have several surfaces facing the exterior instead of another component, this would almost double the degree of visual contact. On the other hand, the doubling of the adjacent ‘walls’ also stiffens the structure. With a single layer-system of a metal structure this might not be a problem due to the material properties of metal.

In order to be able to easily mount the shading structure to the window, aluminum profiles with bolts at specified locations, have been attached to each window post. Ideally, an attachment system of the components would have been designed in accordance to an existing window frame attachment system. In reality, the components would not be designed to be easily removable. Furthermore, having a heavy structure hanging on the window frames would almost ask for a specific design of a post and mullion façade window frame system. Like that, the time of construction could also be reduced to a
minimum. Thinking about a large-scale implementation, long construction time can result out of such a diverse structure. A minimization of construction time and pre-manufacturing is inevitable to be cost-efficient.

2. Spatial unlimited optimized fix shading structures

The research conducted in this study was about a fix shading system that provides full shading for a specified time throughout the year. With the focus on south oriented facades, a shading structure has been developed. Since this shading structure was built in an algorithmic 3-dimensional modelling tool, Grasshopper™, the optimization can not only be used for a south oriented building but also for every other orientation and location. The optimized honeycomb shading structure provides full shading for each of these orientations, but always at a small expense of visual contact. The perfect shading structure would not only provide full shading for a specified time and full solar exposure at another specified time in the year but also with a minimum use of material. For this study, the optimized honeycomb shading structure only provides full shading with a reduced amount of shading structure but does not provide full solar exposure at another specified time, like in the winter for example. In order to do so, the base component would need to be modified. For this study, the form of the component evolves out of an extruded volume that is intersected by the sun-path. The exterior surface of this evolving object represents the shading necessary to provide full shading. March 21 and thus, due to the symmetrical path of the sun, until September 21 has been chosen as specified period of time to provide full shading. In order to provide full solar exposure for December 21 until January 21 to reduce heating loads and electricity consumption due to artificial lighting, the shading structure would need to be adjusted in a way to fulfill that criteria.

Shading devices project a moving shadow for a differing position of the sun. Conventional fixed shading devices can only provide full shading for a specific period throughout the day and year. Every hour, the sun changes its azimuth angle towards the location of about 15°. That
VI. Future prospect

means that there are constantly changing requirements for the shading structure, which cannot be achieved with a 2-dimensional fixed shading structure. The path of the sun changes every day having its extreme sun-paths on June 21st (summer solstice) and December 21st (winter solstice). In the summer the sun rises and sets at a very low solar azimuth angle and is at a very high position at solar noon, opposing to its characteristics in the winter, which results in a sun rising at a later time and setting sooner compared to the summer. Thus, an optimized shading structure only provides full shading for a specific period of time. The only exceptions are corresponding days in the year (i.e. sun-path of March 21 = sun-path of September 21 or sun-path of April 21 = sun-path of October 21st, and so on). Typically, a shading device providing full shading for March 21, and thus also September 21, will provide shading for the summer period in between (March 21 until September 21). The size and shape of an optimized shading device not only depends on the time of the year but also on the orientation of the building. For example, to provide full shading in the summer on a west oriented surface results in a larger shading device than in the winter. This is opposing to a shading structure for a south oriented surface, which tends to be larger in the winter than in the summer. Nevertheless, in a climate like Austin, the temperatures from October until March are below comfort level so that a controlled solar exposure of façade and opening can actually be desired in order to reduce heating loads and electricity consumption of artificial lighting.

Figures 248-251 show a shading device that is able to provide full shading and full solar exposure for a south-oriented window for a specified period during day and year. In this case it provides full shading from March 21 until September 21 and it allows full solar exposure from December 21 until January 21. Thus, for one month, solar insolation is used as an additional heat source. As a follow up study it would be interesting to design such a shading device for different orientations.

In this study, the component is limited by two major criteria. First, it provides full shading from March 21 until September 21. Second, the construction limits of each component do not exceed the boundaries of an extruded volume perpendicular to the surface it has to shade. Thus, the component cannot fulfill another very important daylight criteria: the provision of full solar exposure for a certain period throughout the year, as provided in the shading device. A component, which provides full shading from March until September could also allow full solar exposure for December. In order to do so, the component would actually need to exceed the boundaries of the extruded volume. Since for this study, a series of adjacent components was desired, the components were not supposed to be larger than the extruded volume. If there are no boundaries for the shading device, the component might be larger. Likewise, the shading structure could allow maximum shading and maximum exposure for specified periods throughout the year. It would make an interesting study to design such shading structure and to prove this assumption for different orientations. Furthermore, it should be investigated how such a structure can be applied on a grid, such as the hexagonal grid used for this study.
3. Multifunctional optimized shading structure

As mentioned in the paragraph before, the optimized shading structure that has been designed and built for this study fulfills basically only one criteria: full shading for a specific period throughout the year. A modern transparent façade usually incorporates more than just a shading device. The façade has to fulfill several purposes like climate protection, high degree of visual contact or ventilation. Elements for active use of solar energy like photovoltaic or solar collectors could be integrated in the skin as well. Today, multifunctional façades host more than only the basic functions. They can act like energy producers, transparent climate protectors, air exchangers and especially like sun protectors. Many examples already exist about how such a multifunctional façade could be designed like. In most cases, each function has a different component within the façade. The shading device would either be on the exterior, the interior or in the cavity of the glazing. The air exchanger could be a window or integrated in the support structure of the façade itself. As well as shading devices, energy producers like photovoltaic cells started to be more integrated in different components like shading structures, for example.

The goal is to integrate different components into one base component, which resolves in the ultimate façade component, which fulfills different needs like:

- Full shading for a specific time throughout the year, while providing a maximum degree of visual contact
- Integrated energy positive elements such as photovoltaic or solar collectors (see fig. 252-254)
- Reflective elements to provide natural daylight for the rear part of the room
- Use of phase-change-materials (PCM) (see fig. 255)
VI. Future prospect

4. Movable optimized shading structure

Knowing that the sun’s position constantly changes, it seems to be obvious that a shading device, which would follow the sun would result in a minimized shading structure. Throughout the day and year, this shading device would always be changing its position and shape. An example can be seen in nature where plants and flowers follow the sun in order to maximize photosynthesis. Since this structure would always be perpendicular to the solar rays, its surface would be ideal for placing elements for active use of solar energy to produce energy or heat. Since this structure would only be as large as to protect the window from the sun, a high degree of visual contact would be guaranteed.

A study as shown in ‘2. Appendix B - Optimized shading blinds’ has been conducted about shading blinds that provide full shading throughout the day. The shading blinds have a width of 1 foot and changing lengths according to their position and rotation. The blinds are designed in a way that they are always perpendicular to the position of the sun. Thus, the blinds have a minimized structure needed to provide full shading for a specified time of day and year. One side of the blind is always attached to the building while the other side can rotate and tilt depending on the position of the sun. Assuming the blinds would be able to rotate throughout the day, which is a high structural challenge, they change their position respectively to the position of the sun. Even if this study shows how the shading blinds would need to change position and rotation it is unresolved how to build such a shading structure. The blinds would need to be able not only to tilt towards the sun but they would also need to be able to rotate in the plane of the surface that needs to be shaded. Furthermore, the blinds would need to be able to change their number and length. Instead of a planar construction of blinds, the shading structure could change its form to a 3-dimensional form as well.

The great challenge is how such a movable, shape changing optimized shading structure would look like if it would be able to provide full shading as well as full solar exposure for specified periods throughout the year.
5. Aesthetic/visual quality and function

Without any doubt, measures to protect against solar radiation are important from a design perspective because they have a great impact on the architectural expression of the façade. Therefore, external shading systems should be selected both because of their functionality and because of their potential to visually enrich the façade of a building. Marcel Breuer said: “The sun control has to be on the outside of the building, an element of the façade, an element of architecture. 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.”

A high aesthetic quality should be part of any sustainable design. It should be a design parameter that is as important as proportion or color. Good aesthetics can be defined as something that is functional is beautiful. On the other hand, it not only has to be functional but also beautiful in itself. One quality must be integral to the other. The challenge lies in combining beauty and function seamlessly. Since shading devices and climate related design in a holistic manner are both specific to one place, beauty is also specific to the place. As part of future research, beauty and aesthetics of shading devices could be defined. Several architecture firms that are known for their focus on the aesthetics of sustainable building skins might be focus of the study, such as Behnisch & Partner, Herzog & de Meuron Architekten, Herzog & Partner, Grimshaw Architects, Kohlhoff, Ove Arup & Partners Ltd., and Renzo Piano. The aesthetic appearance of shading devices depends on elements such as the choice of appropriate materials, textures, and colors. The object’s structure, its proportion, the degree of reflectivity, and sensuousness play a major role as well. Therefore, it is important to include shading structures as a highly visibly element of a building into the context of beauty and aesthetics.

Fig. 260  Shading structure by Herzog & de Meuron
Fig. 261  Shading structure by Renzo Piano
Fig. 262  Shading structure by Thomas Phifer
Fig. 263  Shading structure by Ove Arup
Chapter VII

Fig. 264  Optimized honeycomb shading structure
VII. Conclusion

1. Shading systems and façade design
2. Comparison of performance of conventional shading devices
3. Optimized honeycomb shading structure
VII. Conclusion

The goal of this study was to design an optimized shading system with the solar path as its major design parameter. The shading structure is supposed to provide full shading for a specified period of time with a minimum structure. Due to the reduction of the material used to the minimum, a maximum degree of visual contact is given. The shading structure was designed for a hot climate like Austin, Texas. Since the shading was developed in an algorithmic modeling tool, the shading structure could be optimized for any desired location. Even if the mock-up was developed for a south oriented façade, such an optimization can take place for any given orientation.

1. Shading systems and façade design
   The development of a typology of existing shading design solutions helped to gain an understanding of the importance of shading structures and their aesthetic influence on buildings. This research helped to build up on existing solutions instead of redeveloping them. This analysis helped to understand the strengths and weaknesses of each type with regard to purpose, location and orientation.

2. Comparison of performance of conventional shading devices
   As a result of the analysis, it became clear that eggcrate shading structures provide the most shading, as they produce the same shading as horizontal and vertical blinds together. Yet, they reduce the degree of visual contact compared to horizontal or vertical blinds. As a result of this, an analysis was done, comparing eggcrate shading structures with honeycomb shading structures. In particular, the comparison of those two types with the same circumference of a single cell. It turns out that even if the honeycomb structure provides 10.4% less shading in average per orientation compared to the eggcrate type, the honeycomb shading structure provides a 12.8% higher degree of visual contact. Even if the honeycomb structure provides 10.4% less shading in average, it still reduces the solar radiation to at least 58% throughout the whole year (in this case for a west oriented façade). A higher degree of visual contact has been achieved by decreasing the surface area of the shading structure. Therefore, it can be concluded that the higher amount of solar radiation of the honeycomb shading structure has been achieved by increasing the amount of diffuse sunlight. The amount of solar radiation that is used throughout this study includes direct and diffuse skylight. Thus, a lower sc with a higher degree of visual contact does not necessarily decrease the quality of the shading structure.

Nevertheless, taking reasonable material thicknesses into account increases the degree of visual contact of honeycomb shading structures even further compared to conventional shading devices, which would have a higher thickness for reasons of stability. A future study taking a differentiation of direct and diffuse skylight into account would be very interesting to clarify this discussion.
Fig. 266: Optimized honeycomb shading structure
3. Optimized honeycomb shading structure
The reason for designing an optimized honeycomb shading system was not only to provide full shading for a specified time, but also to minimize the structure and therefore increasing the degree of visual contact. Furthermore, the desire of the exploration of new interesting structures with high performance was given. The optimized honeycomb shading structure is a structure that is optimized with regard to the sun-path. In this case, an extruded hexagon is intersected by the resulting plane of the sun-path. This sun-path can be chosen with regard to different design variables such as location, orientation, exterior temperatures, monthly solar radiation or the degree of visual contact.

For the purpose of this study, March 21 until September 21 has been chosen as the period of time in which the optimized shading structure is supposed to provide full shading. Due to the symmetrical path of the sun, March 21 and September 21 have the same sun-path. Providing full shading for March 21 results in full shading for the period of time between March 21 and September 21. For the rest of the year, the shading structure will only provide partial shading. This is actually desired since the outside temperatures are below comfort level. Therefore, solar radiation can help reducing the energy consumption by reducing heating loads and artificial lighting due to an increased amount of sunlight inside the room. As a result of this study, studies for different days throughout the year and locations have been conducted to test the shading structure for different situations. As expected, the shading structure provides full shading for March 21 until September 21. A shading study for December 21 showed that the shading structure allows partial direct sunlight inside the room, which was desired and expected. Changing the location for the shading structure to Munich or New York pointed out the strength of this system to individually design shading structures specific for locations and preferred shading times.

The mock-up that has been built to be attached to window of the research facility "Thermal Lab" of the University of Texas at Austin - School of Architecture. Ideally, the optimized honeycomb shading structure will provide full shading between March 21 and September 21.

With regard to the comparison of performance of the optimized honeycomb shading structure to conventional shading devices, the optimized shading structure actually allows more annual solar radiation for a south oriented façade than eggcrate or honeycomb shading structures. Knowing that the optimized shading structure does not allow any direct sunlight at all between March 21 and September 21 proofs the assumption that it allows a higher degree of visual contact and therefore an increased amount of diffusesolar radiation from September 21 until March 21 and an increased amount of diffuse radiation year round. The comparison of the degree of visual contact shows that the optimized shading structure actually provides 44% higher degree of visual contact compared to eggcrate shading structures and still 37% more than the conventional honeycomb shading structure. As a result, not only the degree of visual contact was increased, but also the volume of used material was decreased. The comparison of the degree of visual contact is based on the comparison of total...
volume of material for the same material thicknesses. A comparison of realistic material thicknesses, in which case the conventional shading devices would have an increased thickness due stability reasons, leads to even better results for the optimized honeycomb shading structure. In this case, the eggcrate shading structure would need to be much thicker compared to the honeycomb shading structure, which can have a reduced thickness due to the structural stability of a hexagonal grid.

In order to even increase the amount of direct solar radiation in the winter, a further optimization can be achieved to allow full solar exposure for a specified period of time, when direct solar radiation is actually desired. Nevertheless, direct solar radiation can also cause overheating even if the exterior dry-bulb temperatures are below comfort level. This fact has to be taken into account when designing and applying an optimized shading system that not only provides full shading but also full solar exposure for specified periods of time throughout the year. The mock-up of this shading structure enabled further questions of how to apply this shading structure in large scale in reality. Besides the manufacturing process, the choice of material and the degree of tolerance play a major role in the success of the shading structure for the ease of production and installation. For the implementation of the structure, an attachment system of the structure to the window/wall has to be developed.

Furthermore, this shading structure has a high potential to be further developed to a multifunctional structure, which could incorporate energy positive elements such as photovoltaic cells or solar collectors or reflective elements to reduce artificial lighting.

From an architectural standpoint the developed optimized shading structure represents an intriguing project. With a high degree of visual contact, considerable energy savings due to reduced cooling and heating loads and reduced need for artificial lighting, this structure has demonstrated a high potential for further development on an industrial scale.
Chapter VIII

Fig. 267 University library Cottbus (DE)
VIII. Bibliography

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Glass façades:

Shading devices:

Research laboratories:
Appendix

Fig. 01  Perspective from Sutton Hall - Rendering 52 x 42
IX. Appendix

1. Appendix A - Solar insolation
2. Appendix B - Optimized shading blinds
3. Appendix C - Optimized honeycomb shading structure
4. Appendix D - Research facility: Thermal Lab

Fig. 02: Detail shading '52 x 42'
Appendix A

Fig. 03  Conventional vertically oriented honeycomb shading structure
1. Appendix A - Solar insolation

a. Solar insolation for conventional shading devices oriented towards S, SW and W
b. Solar insolation for conventional shading devices oriented towards S, SE and E
c. Solar insolation for conventional shading devices in Munich vs. Austin oriented towards S, SW and W
d. Solar insolation for eggcrate shading devices oriented towards S, SW and W
IX. Appendix

1. Appendix A - Solar insolation

a. Solar insolation for conventional shading devices oriented towards S, SW and W

Fig. 05 - Fig. 39 show screen-shots of the various shading structures and orientations used for this study. The object is located in Austin, Texas. The graphs that are shown in this section were created with the output of Ecotect data. Solar radiation on a vertical surface oriented toward south, southwest and west had been measured in Austin for the following cases:

Fig. 40 - Fig. 41: Solar radiation measured on an unobstructed surface
Fig. 42 - Fig. 43: Solar radiation measured on a surface shaded by an eggcrate shading structure oriented toward
Fig. 44 - Fig. 45: Solar radiation measured on a surface shaded by an horizontal shading structure
Fig. 46 - Fig. 47: Solar radiation measured on a surface shaded by a vertical shading structure
Fig. 48 - Fig. 49: Comparison of solar radiation measured on a surface shaded by an eggcrate, horizontal or vertical shading structure
Fig. 50 - Fig. 51: Solar radiation measured on a surface shaded by an vertically oriented honeycomb shading structure
Fig. 52 - Fig. 53: Solar radiation measured on a surface shaded by an horizontally oriented honeycomb shading structure
Fig. 54 - Fig. 55: Solar radiation measured on a surface shaded by an vertically oriented honeycomb shading structure with a circumference of 4’ (same as the eggcrate shading structure)
Fig. 56 - Fig. 57: Comparison of solar radiation measured on a surface shaded by an vertically oriented, horizontally oriented or vertically oriented with a circumference of 4’ (same as the eggcrate shading structure) honeycomb shading structure
Fig. 58 - Fig. 59: Comparison of solar radiation measured on a south oriented surface shaded by the previously discussed shading structures in this chapter
Fig. 60 - Fig. 61: Comparison of solar radiation measured on a southwest oriented surface shaded by the previously discussed shading structures in this chapter
Fig. 62 - Fig. 63: Comparison of solar radiation measured on a west oriented surface shaded by the previously discussed shading structures in this chapter
a. Solar insolation for conventional shading devices oriented towards S, SW and W
IX. Appendix

1. Appendix A - Solar insolation
a. Solar insolation for conventional shading devices oriented towards S, SW and W
IX. Appendix 1. Appendix A - Solar insolation

Fig. 40 Monthly solar radiation on surfaces oriented towards S, SW and W in Austin without shading

Fig. 41 Annual solar radiation on surfaces oriented towards S, SW and W in Austin without shading

Fig. 42 Monthly solar radiation on surfaces oriented towards S, SW and W in Austin with eggcrate shadings

Fig. 43 Annual solar radiation on surfaces oriented towards S, SW and W in Austin with eggcrate shadings
a. Solar insolation for conventional shading devices oriented towards S, SW and W
IX. Appendix 1. Appendix A - Solar insolation

Fig. 48 Comparison of monthly solar radiation on surfaces oriented towards S, SW and W in Austin with conventional shadings

Fig. 49 Comparison of annual solar radiation on surfaces oriented towards S, SW and W in Austin with conventional shadings

Fig. 50 Monthly solar radiation on surfaces oriented towards S, SW and W in Austin with honeycomb-vertical shadings

Fig. 51 Annual solar radiation on surfaces oriented towards S, SW and W in Austin with honeycomb-vertical shadings
a. Solar insolation for conventional shading devices oriented towards S, SW and W
IX. Appendix 1. Appendix A - Solar insolation

Fig. 56 Comparison of monthly solar radiation on surfaces oriented towards S, SW and W in Austin with honeycomb shadings

Fig. 57 Comparison of annual solar radiation on surfaces oriented towards S, SW and W in Austin with honeycomb shadings

Fig. 58 Comparison of monthly solar radiation on south oriented surfaces in Austin with different shadings

Fig. 59 Comparison of annual solar radiation on south oriented surfaces in Austin with different shadings
Fig. 60 Comparison of monthly solar radiation on southwest oriented surfaces in Austin with different shadings.

Fig. 61 Comparison of annual solar radiation on southwest oriented surfaces in Austin with different shadings.

Fig. 62 Comparison of monthly solar radiation on west oriented surfaces in Austin with different shadings.

Fig. 63 Comparison of annual solar radiation on west oriented surfaces in Austin with different shadings.

a. Solar insolation for conventional shading devices oriented towards S, SW and W.
IX. Appendix

1. Appendix A - Solar insolation

b. Solar insolation for conventional shading devices oriented towards S, SE and E

Fig. 64 - Fig. 71 show screen-shots of the various shading structures and orientations used for this study. The object is located in Austin, Texas. The graphs that are shown in this section were created with the output of Ecotect data. Solar radiation on a vertical surface oriented toward east, southeast and south had been measured in Austin for the following cases:

Fig. 73 - Fig. 74: Solar radiation measured on a unobstructed surface oriented toward east, southeast, south, southwest and west
Fig. 75 - Fig. 76: Solar radiation measured on a surface shaded by an eggcrate shading structure oriented toward E, SE, S, SW and W
Fig. 77 - Fig. 78: Solar radiation measured on a surface shaded by an horizontal shading structure oriented toward E, SE, S, SW and W
Fig. 79 - Fig. 80: Solar radiation measured on a surface shaded by a vertical shading structure oriented toward E, SE, S, SW and W
Fig. 81 - Fig. 82: Comparison of solar radiation measured on a surface shaded by an eggcrate, horizontal or vertical shading structure
Fig. 83 - Fig. 84: Solar radiation measured on a surface shaded by an eggcrate shading structure
Fig. 85 - Fig. 86: Solar radiation measured on a surface shaded by an horizontal shading structure
Fig. 87 - Fig. 88: Solar radiation measured on a surface shaded by a vertical shading structure
Fig. 89 - Fig. 90: Comparison of solar radiation measured on a surface shaded by an eggcrate, horizontal or vertical shading structure
Fig. 91 - Fig. 92: Comparison of solar radiation measured on a east oriented surface shaded by the previously discussed shading structures in this chapter
Fig. 93 - Fig. 94: Comparison of solar radiation measured on a southeast oriented surface shaded by the previously discussed shading structures in this chapter
b. Solar insolation for conventional shading devices oriented towards S, SE and E
IX. Appendix 1. Appendix A - Solar insolation

Fig. 73 Monthly solar radiation on surfaces oriented towards E, SE, S, SW and W in Austin without shading

Fig. 74 Annual solar radiation on surfaces oriented towards E, SE, S, SW and W in Austin without shading

Fig. 75 Monthly solar radiation on surfaces oriented towards E, SE, S, SW and W in Austin with eggcrate shadings

Fig. 76 Annual solar radiation on surfaces oriented towards E, SE, S, SW and W in Austin with eggcrate shadings
b. Solar insolation for conventional shading devices oriented towards S, SE and E
IX. Appendix 1. Appendix A - Solar insolation

Fig. 81: Comparison of monthly solar radiation on surfaces oriented towards E, SE, S, SW and W in Austin with conventional shadings.

Fig. 82: Comparison of annual solar radiation on surfaces oriented towards E, SE, S, SW and W in Austin with conventional shadings.

Fig. 83: Monthly solar radiation on surfaces oriented towards E, SE and S in Austin with eggcrate shadings.

Fig. 84: Annual solar radiation on surfaces oriented towards E, SE and S in Austin with eggcrate shadings.
b. Solar insolation for conventional shading devices oriented towards S, SE and E
b. Solar insolation for conventional shading devices oriented towards S, SE and E
IX. Appendix

1. Appendix A - Solar insolation

c. Solar insolation for conventional shading devices in Munich vs. Austin oriented towards S, SW and W

Fig. 95 - Fig. 102 show screen-shots of the various shading structures and orientations used for this study. The object is located in Munich, Germany. The graphs that are shown in this section were created with the output of Ecotect data. Solar radiation on a vertical surface oriented toward south, southwest and west had been measured in Munich for the following cases:

Fig. 104 - Fig. 105: Solar radiation measured on a unobstructed surface
Fig. 106 - Fig. 107: Solar radiation measured on a surface shaded by an eggcrate shading structure
Fig. 108 - Fig. 109: Solar radiation measured on a surface shaded by an horizontal shading structure
Fig. 110 - Fig. 111: Solar radiation measured on a surface shaded by a vertical shading structure
Fig. 112 - Fig. 113: Comparison of solar radiation measured on a surface shaded by an eggcrate, horizontal or vertical shading structure
Fig. 114 - Fig. 115: Comparison of solar radiation measured on a south oriented surface shaded by the previously discussed shading structures in this chapter
Fig. 116 - Fig. 117: Comparison of solar radiation measured on a southwest oriented surface shaded by the previously discussed shading structures in this chapter
Fig. 118 - Fig. 119: Comparison of solar radiation measured on a west oriented surface shaded by the previously discussed shading structures in this chapter
c. Solar insolation for conventional shading devices in Munich vs. Austin oriented towards S, SW and W
IX. Appendix  
1. Appendix A - Solar insolation

Fig. 104 Monthly solar radiation on surfaces oriented towards S, SW and W in Munich without shading

Fig. 105 Annual solar radiation on surfaces oriented towards S, SW and W in Munich without shading

Fig. 106 Monthly solar radiation on surfaces oriented towards S, SW and W in Munich with eggcrate shadings

Fig. 107 Annual solar radiation on surfaces oriented towards S, SW and W in Munich with eggcrate shadings
c. Solar insolation for conventional shading devices in Munich vs. Austin oriented towards S, SW and W

Fig. 108 Monthly solar radiation on surfaces oriented towards S, SW and W in Munich with horizontal shadings

Fig. 109 Annual solar radiation on surfaces oriented towards S, SW and W in Munich with horizontal shadings

Fig. 110 Monthly solar radiation on surfaces oriented towards S, SW and W in Munich with vertical shadings

Fig. 111 Annual solar radiation on surfaces oriented towards S, SW and W in Munich with vertical shadings
IX. Appendix  
1. Appendix A - Solar insolation

Fig. 112 Comparison of monthly solar radiation on surfaces oriented towards S, SW and W in Munich with conventional shadings

Fig. 113 Comparison of annual solar radiation on surfaces oriented towards S, SW and W in Munich with conventional shadings

Fig. 114 Comparison of monthly solar radiation on south oriented surfaces in Munich with different shadings

Fig. 115 Comparison of annual solar radiation on south oriented surfaces in Munich with different shadings
c. Solar insolation for conventional shading devices in Munich vs. Austin oriented towards S, SW and W
IX. Appendix
1. Appendix A - Solar insolation
d. Solar insolation for eggcrate shading devices oriented towards S, SW and W

Fig. 120 - Fig. 127 show screen-shots of the various shading structures and orientations used for this study. The object is located in Austin, Texas. The graphs that are shown in this section were created with the output of Ecotect data. Solar radiation on a vertical surface shaded by an eggcrate shading structure oriented toward south, southwest and west had been measured in Austin for the following cases:

Fig. 129 - Fig. 130: Solar radiation measured on a surface shaded by an horizontally oriented eggcrate shading structure
Fig. 131 - Fig. 132: Solar radiation measured on a surface shaded by a vertically oriented eggcrate shading structure
Fig. 133 - Fig. 134: Comparison of solar radiation measured on a horizontally, vertically oriented and evenly oriented eggcrate shading structure
Fig. 135 - Fig. 136: Comparison of solar radiation measured on a south oriented surface shaded by the previously discussed shading structures in this chapter
Fig. 137 - Fig. 138: Comparison of solar radiation measured on a southwest oriented surface shaded by the previously discussed shading structures in this chapter
Fig. 139 - Fig. 140: Comparison of solar radiation measured on a west oriented surface shaded by the previously discussed shading structures in this chapter
d. Solar insolation for eggcrate shading devices oriented towards S, SW and W
IX. Appendix 1. Appendix A - Solar insolation

**Fig. 129** Monthly solar radiation on surfaces oriented towards S, SW and W in Austin with eggcrate-horizontal shadings

- Eggcrate horizontal S no shading
- Eggcrate horizontal SW no shading
- Eggcrate horizontal W no shading
- Eggcrate horizontal S shading
- Eggcrate horizontal SW shading
- Eggcrate horizontal W shading

**Fig. 130** Annual solar radiation on surfaces oriented towards S, SW and W in Austin with eggcrate-horizontal shadings

- Eggcrate horizontal S shading
- Eggcrate horizontal SW shading
- Eggcrate horizontal W shading

**Fig. 131** Monthly solar radiation on surfaces oriented towards S, SW and W in Austin with eggcrate-vertical shadings

- Eggcrate vertical S no shading
- Eggcrate vertical SW no shading
- Eggcrate vertical W no shading
- Eggcrate vertical S shading
- Eggcrate vertical SW shading
- Eggcrate vertical W shading

**Fig. 132** Annual solar radiation on surfaces oriented towards S, SW and W in Austin with eggcrate-vertical shadings

- Eggcrate vertical S shading
- Eggcrate vertical SW shading
- Eggcrate vertical W shading
d. Solar insolation for eggcrate shading devices oriented towards S, SW and W

Fig. 133 Comparison of monthly solar radiation on surfaces oriented towards S, SW and W in Austin with conventional shadings

Fig. 134 Comparison of annual solar radiation on surfaces oriented towards S, SW and W in Austin with conventional shadings

Fig. 135 Comparison of monthly solar radiation on south oriented surfaces in Austin with different shadings

Fig. 136 Comparison of annual solar radiation on south oriented surfaces in Austin with different shadings
IX. Appendix  
1. Appendix A - Solar insolation

Fig. 137: Comparison of monthly solar radiation on southwest oriented surfaces with different shadings

Fig. 138: Comparison of annual solar radiation on southwest oriented surfaces with different shadings

Fig. 139: Comparison of monthly solar radiation on west oriented surfaces with different shadings

Fig. 140: Comparison of annual solar radiation on west oriented surfaces with different shadings
d. Solar insolation for eggcrate shading devices oriented towards S, SW and W
Appendix B

Fig. 141. Elevation of a southwest oriented building with optimized shading blinds for 5 p.m.
2. Appendix B -
Optimized shading blinds

a. Optimized shading blinds for a south oriented building
b. Optimized shading blinds for a south-southwest oriented building
c. Optimized shading blinds for a southwest oriented building
d. Optimized shading blinds for a southwest-west oriented building
e. Optimized shading blinds for a west oriented building
IX. Appendix

2. Appendix B - Optimized shading blinds

a. Optimized shading blinds for a south oriented building

The following set of drawings shows the hourly sequence of optimized shading blinds for south oriented buildings with differing rotation in two different axis. The rotations of the blinds change respectively with the position of the sun on the solar path. The first rotation happens in the x-z-axis of the surface the blinds are attached to. The angle of rotation of the blinds is equal to the tangent of the sun on the solar path. The second rotation is the tilt of the blinds. The surface normal of the blinds needs to have the same direction as the vectors of the solar rays. Thus, at any time of the day the blinds are rotated towards the sun in a manner that the sun is always able to see the blinds in true size at any time during the day. In Fig. 144 - Fig. 154, you can see the view of the sun to the building on an hourly base. The blinds provide maximum shading if the sun can see the blinds in true size. The blinds change their rotation and tilt respectively to the position of the sun. Fig. 155 - Fig. 165 show an example of such a blind for each hour in front elevation. This sequence is summarized in Fig. 143. In this diagram one can get a feeling for how the blinds change their rotation and tilt throughout the day. The starting and ending hour for this sequence has been chosen based on the time the surface receives solar rays. For example, if a surface receives direct sunlight at 9.45 a.m., the first example shown is for 10 a.m.

The sun-path is has been chosen for Austin, Texas, a location in a hot-humid climate:

- Location: N 30° 17' (lat.), W 97° 44' (lng.)
- Time zone: Central Standard Time [-6.0 hours]
- Solar noon: 12 p.m.
- Solar azimuth: depending on time of the day
- Solar elevation: depending on time of the day

To design a movable shading device for a south oriented building is very challenging since the blinds have to rotate from one extreme to the other - from a vertical orientation to a horizontal orientation back to a vertical orientation. At solar noon the blinds are horizontal to the horizon. The moment the sun sets, the blinds reached a diagonal, almost vertical position. Due to the symmetric solar path for a south oriented building, the rotation of the blinds in the morning is similar to the rotation of the blinds in the afternoon. At solar noon, the tilt of the blinds is equal to the solar elevation.
a. Optimized shading blinds for a south oriented building

Fig. 143  Summary of optimized shading blinds for a south oriented building in elevation
IX. Appendix

2. Appendix B - Optimized shading blinds

Fig. 144 Pers. view from the sun at 7 a.m.

Fig. 145 Pers. view from the sun at 8 a.m.

Fig. 146 Pers. view from the sun at 9 a.m.

Fig. 147 Pers. view from the sun at 10 a.m.

Fig. 148 Pers. view from the sun at 11 a.m.

Fig. 149 Pers. view from the sun at 12 p.m.

Fig. 150 Pers. view from the sun at 1 p.m.

Fig. 151 Pers. view from the sun at 2 p.m.

Fig. 152 Pers. view from the sun at 3 p.m.

Fig. 153 Pers. view from the sun at 4 p.m.

Fig. 154 Pers. view from the sun at 5 p.m.
a. Optimized shading blinds for a south oriented building
IX. Appendix

2. Appendix B - Optimized shading blinds

b. Optimized shading blinds for a south-southwest oriented building

In Fig. 167 - Fig. 175, you can see the view of the sun to the building on an hourly base. Fig. 176 - Fig. 184 show an example of such a blind for each hour in front elevation. This sequence is summarized in Fig. 166.

The sun-path is has been chosen for Austin, Texas, a location in a hot-humid climate:

Location: N 30° 17’ (lat.), W 97° 44’ (lng.)
Time zone: Central Standard Time (-6.0 hours)
Solar noon: 12 p.m.
Solar azimuth: depending on time of the day
Solar elevation: depending on time of the day

To design a movable shading device for a south-southwest oriented surface is a little different than a south-oriented movable shading device since the sun-path is no longer symmetrical. In the morning until the early afternoon, from 10 a.m. until 2 p.m. the solar elevation is very high and the solar azimuth angle is rather perpendicular to the surface. Thus, the blinds are more horizontal than vertical. In contrast to the early morning and late afternoon hours where the solar elevation is lower and the solar azimuth angle relative to the building rather acute. In this case the blinds ought to be vertical. But since solar rays hit the surface at the very latest during the day at a much more perpendicular angle compared to a south oriented building at the same time, the blinds have to be rotated further towards the sun in order to provide full shading. Movable shading blinds for a south-southwest oriented building have to rotate from one extreme to the other as well - from a vertical orientation to a horizontal orientation back to a vertical orientation. Different to the south orientation is the percentage distribution of horizontal and vertical blinds. South-southwest oriented buildings have to accommodate for a sun at an solar elevation angle much lower and much more perpendicular to the surface which results in a shading structure with a lower degree of visual contact than south.
b. Optimized shading blinds for a south-southwest oriented building

Fig. 166: Summary of optimized shading blinds for a south-southwest oriented building in elevation
IX. Appendix

2. Appendix B - Optimized shading blinds

Fig. 167  Perspective view from the sun at 9 a.m.
Fig. 168  Perspective view from the sun at 10 a.m.
Fig. 169  Perspective view from the sun at 11 a.m.
Fig. 170  Perspective view from the sun at 12 p.m.
Fig. 171  Perspective view from the sun at 1 p.m.
Fig. 172  Perspective view from the sun at 2 p.m.
Fig. 173  Perspective view from the sun at 3 p.m.
Fig. 174  Perspective view from the sun at 4 p.m.
Fig. 175  Perspective view from the sun at 5 p.m.
b. Optimized shading blinds for a south-southwest oriented building
IX. Appendix

2. Appendix B - Optimized shading blinds

c. Optimized shading blinds for a southwest oriented building

In Fig. 186 - Fig. 193, you can see the view of the sun to the building on an hourly base. Fig. 194 - Fig. 201 show an example of such a blind for each hour in front elevation. This sequence is summarized in Fig. 185.

The sun-path is has been chosen for Austin, Texas, a location in a hot-humid climate:
Location: N 30° 17’ (lat.), W 97° 44’ (lng.)
Time zone: Central Standard Time [-6.0 hours]
Solar noon: 12 p.m.
Solar azimuth: depending on time of the day
Solar elevation: depending on time of the day

To design a movable shading device for a southwest oriented surface might be the most challenging since the blinds have to accommodate for a very high sun at a low solar azimuth angle around solar noon and for a very low sun at a very high azimuth angle in the evening.
c. Optimized shading blinds for a southwest oriented building

Fig. 185  Summary of optimized shading blinds for a southwest oriented building in elevation
Optimized shadings

Orientation:
Criteria:
Width:
Azimuth window:
Azimuth sun:
Altitude angle sun:
Period:
Mar 21 - Sep 21
South-West
45° W

Fig. 186. Perspective view from the sun at 10 a.m.
Fig. 187. Perspective view from the sun at 11 a.m.
Fig. 188. Perspective view from the sun at 12 p.m.
Fig. 189. Perspective view from the sun at 1 p.m.
Fig. 190. Perspective view from the sun at 2 p.m.
Fig. 191. Perspective view from the sun at 3 p.m.
Fig. 192. Perspective view from the sun at 4 p.m.
Fig. 193. Perspective view from the sun at 5 p.m.
c. Optimized shading blinds for a southwest oriented building
This is an example of how to construct the solar view for certain building. This view is needed in order to design the optimized blinds. Optimized blinds need to be perpendicular to the sun-rays in which case the sun can see the blinds in real size. Fig. 202 shows how these blinds have been designed. Solar views can be very useful to visualize an entire scene at one moment in time. First, the plan view with the solar ray along the horizontal has to be drawn. The south and east and west direction have to be marked accordingly with regard to the building’s orientation. With the proper orientation in plan view, the building can be drawn in elevation. The solar position used for this study corresponds to March/September 21st, 3:00 p.m. Latitude = 30.5° N and longitude = -97.7° W. The solar elevation is 37° and the azimuth angle towards the building is 45°. Given this information, a section view in true profile of the solar position has to be drawn. The true profile will result automatically if the horizon line in elevation is parallel to the solar ray in plan. In true profile, the sun will always rest on the perimeter of the circle. After that, the solar ray and structure in elevation, as well as the fold line as the bisector of the solar ray in elevation and perpendicular to the solar ray in plan can be drawn. Then, each corner of the structure from the respective points in plan and in elevation onto the solar view plan can be projected. The resulting axonometric shows the sun’s view of the object. In this view, the fins are shown in their real dimensions. The fins have a width of 1’, are parallel to each other and cover the whole window with a minimized number of fins and total surface area. In this view, the window is not to be seen in order to cover the whole window in shade.
Optimized shadings

Orientation: south-west
Criteria: provide full shading from Mar 21 - Sep 21 at 3 p.m.
Width: 1'
Azimuth window: 45° W
Azimuth sun: 63° W (red: 18° W)
Altitude angle sun: 37°
Shading device: diagonal shading / fins

Solar rays - sun at 3 p.m.
Altitude of the sun = 37°

Fig. 202: Diagram showing how to design optimized shading blinds for a southwest oriented building
**IX. Appendix**

2. Appendix B - Optimized shading blinds

d. Optimized shading blinds for a southwest-west oriented building

In Fig. 204 - Fig. 209, you can see the view of the sun to the building on an hourly base. Fig. 210 - Fig. 215 show an example of such a blind for each hour in front elevation. This sequence is summarized in Fig. 203.

The sun-path is has been chosen for Austin, Texas, a location in a hot-humid climate:

- **Location:** N 30° 17’ (lat.), W 97° 44’ (lng.)
- **Time zone:** Central Standard Time [-6.0 hours]
- **Solar noon:** 12 p.m.
- **Solar azimuth:** depending on time of the day
- **Solar elevation:** depending on time of the day

To design a movable shading device for a southwest oriented surface might be the most challenging since the blinds have to accommodate for a very high sun at a low solar azimuth angle around solar noon and for a very low sun at a very high azimuth angle in the evening.
d. Optimized shading blinds for a southwest-west oriented building

Fig. 203  Summary of optimized shading blinds for a southwest-west oriented building in elevation
Optimized shadings

South-West-West

12 noon

Axonometric view from the sun

Orientation:
Criteria :
Width:
Azimuth window :
Azimuth sun:
Altitude angle sun:

Period :
Mar 21 - Sep 21

South-West-West

Optimized shadings

South-West-West

1 p.m.

Axonometric view from the sun

Orientation:
Criteria :
Width:
Azimuth window :
Azimuth sun:
Altitude angle sun:

Period :
Mar 21 - Sep 21

Optimized shadings

South-West-West

2 p.m.

Axonometric view from the sun

Orientation:
Criteria :
Width:
Azimuth window :
Azimuth sun:
Altitude angle sun:

Period :
Mar 21 - Sep 21

Optimized shadings

South-West-West

3 p.m.

Axonometric view from the sun

Orientation:
Criteria :
Width:
Azimuth window :
Azimuth sun:
Altitude angle sun:

Period :
Mar 21 - Sep 21

IX. Appendix 2. Appendix B - Optimized shading blinds
d. Optimized shading blinds for a southwest-west oriented building

Fig. 210 Elevation of a building oriented SWW at 12 p.m.
Fig. 211 Elevation of a building oriented SWW at 1 p.m.
Fig. 212 Elevation of a building oriented SWW at 2 p.m.
Fig. 213 Elevation of a building oriented SWW at 3 p.m.
Fig. 214 Elevation of a building oriented SWW at 4 p.m.
Fig. 215 Elevation of a building oriented SWW at 5 p.m.
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2. Appendix B - Optimized shading blinds

e. Optimized shading blinds for a west oriented building

In Fig. 217 - Fig. 221, you can see the view of the sun to the building on an hourly base. Fig. 222 - Fig. 226 show an example of such a blind for each hour in front elevation. This sequence is summarized in Fig. 216.

The sun-path is has been chosen for Austin, Texas, a location in a hot-humid climate:
Location: N 30° 17’ (lat.), W 97° 44’ (lng.)
Time zone: Central Standard Time [-6.0 hours]
Solar noon: 12 p.m.
Solar azimuth: depending on time of the day
Solar elevation: depending on time of the day

To design a movable shading device for a west oriented surface might be the least challenging task since the blinds for each hour are all rotated in the same direction. They all are rotated perpendicular to the plane of the sun-path which is for every hour the same on a west oriented surface. The number of blinds as well as their lengths would still need to vary though. Even if the design might not be as challenging as for the other orientations, a west oriented building faces the strong solar radiation of the sun as well as high dry-bulb temperatures. Thus the window needs to be as much shaded as possible which limits the views from the interior at this orientation tremendously. For a great part of the time the façade is exposed to solar radiation, the solar rays are very close to being perpendicular to the surface which requires the blinds to almost close the façade completely and reduce the degree of visual contact to a minimum throughout the time of solar exposure.
e. Optimized shading blinds for a west oriented building

Fig. 216  Summary of optimized shading blinds for a west oriented building in elevation
Fig. 217  Perspective view from the sun at 1 p.m.
Fig. 218  Perspective view from the sun at 2 p.m.
Fig. 219  Perspective view from the sun at 3 p.m.
Fig. 220  Perspective view from the sun at 4 p.m.
Fig. 221  Perspective view from the sun at 5 p.m.
e. Optimized shading blinds for a west oriented building
Appendix C

Fig. 227. Optimized honeycomb shading structure for oriented building on March 21 at 11:00 a.m.
3. Appendix C - Optimized honeycomb shading structure

a. Hourly shading pattern for a south oriented building on March 21 and December 21
b. Monthly shading pattern for a south, southwest and south-southwest oriented building
c. Comparison of shading pattern of optimized honeycomb shading structure in Austin, Munich and New York

Fig. 228  Optimized shading for southwest
a. Hourly shading pattern for a south oriented building on March 21 and December 21
a. Hourly shading pattern for a south oriented building on March 21 and December 21
Fig. 337  South - March - 11:00 a.m. - Assembly of components

b. Monthly shading pattern for a south, southwest and south-southwest oriented building
b. Monthly shading pattern for a south, southwest and south-southwest oriented building
b. Monthly shading pattern for a south, southwest and south-southwest oriented building
c. Comparison of shading pattern of optimized honeycomb shading structure in Austin, Munich and New York
Appendix C

Fig. 376  Photorealistic rendering of Thermal Lab during construction
4. Appendix D - Research facility: Thermal Lab

a. Floor plans
b. Elevations
c. Sections
d. Detail drawings
e. Graduate Research Assistant Hogan Winn: ‘Architecture Thermal Chamber Calibration Test Narrative’
IX. Appendix

4. Appendix D - Research facility: Thermal Lab

Fig. 378: Floor plan
a. Floor plans

Fig. 379: Roof plan
Fig. 380: Elevation south - Test set-up 01: façade w/o window
b. Elevations

Fig. 381: Elevation south - Test set-up 02: façade w/ window w/o shading
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Fig. 382. Elevation south - Test set-up 03: façade w/window w/shading
b. Elevations

Fig. 383: Elevation north
IX. Appendix 4. Appendix D - Research facility: Thermal Lab

Fig. 384: Elevation east
10 6" suspended ceiling
11 2' x 2' ceiling tiles / metal support structure
12 3' x 6.6" door (SIP, UV resistant gasket)
13 wooden cabinets
   - cabinet grade maple plywood/poplar core
   - width: 3', floor to ceiling height
13.1 purpose cabinet northwest corner:
   a storage space
   b control panel of power meter
   c control panel of flow meter
   d control panel of HVAC system
13.2 purpose cabinet northeast corner:
   a computer
   b display
   c data acquisition equipment
   d control panel weather station
14 return-air plenum
15 fan-coil unit
16 supply-air plenum
c. Sections

Fig. 387: Section north-south: through opening
IX. Appendix  
4. Appendix D - Research facility: Thermal Lab

Elevation south façade

Roof/wall detail

Floor/wall detail

Plan view south/west façade/wall

1 1/4" cladding
2 1" ventilation gap
3 2" x 4" wooden support frame (facilitation of a future displacement, protection of exterior cladding from damage by sitting directly on metal deck)
4 4" structural insulated panels (SIP)
  4.1 1/32" galvanized steel
  4.2 3 15/16" polyurethane insulation
5 4 7/16" aged polyisocyanurate insulation (2.5lb) (2 1/16" + 2 3/8")
6 2 x 5/8" drywall (mill finish)
7 wall paint white, suitable for repainting
8 2 x 3/4" plywood
9 1/4" carpet

Fig. 388: Detail drawing: façade w/o window w/o shading
d. Detail drawings

Fig. 389: Detail drawing: façade w/ window w/o shading

Elevation south façade

Roof/wall detail

Floor/wall detail

Plan view south/west façade/wall

- aluminum profile
- aluminum profile angle 1” x 2 1/8”
- aluminum profile angle 2” x 2 1/2”
- thermal insulation
- post 2” x 6”
- thermal insulation
- continuous wooden frame 3/4” x 2 7/8”
- aluminum profile

- post 3/4” x 4”
- post 3/4” x 2 7/8”
- PUR foam
- post (aluminum) 2 1/2”
- window sill

opening width 12’
IX. Appendix  
4. Appendix D - Research facility: Thermal Lab

Elevation south façade

Roof/wall detail

Floor/wall detail

Plan view south/west façade/wall

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Fig. 390: Detail drawing: façade w/ window w/ shading
Calibration Tests Methodology

Calibration testing is required to experimentally determine the thermal monitoring characteristics of the facility. These characteristics in turn experimentally establish a known level error that isolates the thermal performance effects of an interchangeable south façade. The following tests are performed when the south façade has roughly the same heavily insulated thermal characteristics as all other walls.

The first calibration test is to evaluate the mass flow meter, as all other equipment is calibrated by the manufacturer or the third party calibration company. The calibration of the flow meter will help determine more precisely the mass flow rate in the chilled water loop and therefore the mechanical thermal energy output.

The second calibration test is to experimentally determine the conduction heat transfer coefficient, or U-Value, of the walls. There are manufacturer data that list heat transfer coefficient values for materials

![1-D Conduction Schematic](Incropera at al., 2007)

![Schematic of Mechanical System](Mechanical System for Thermal Load Resolution Calibration Test)
and assembles but the due to variability in materials and construction practices these values have inherent sources of deviation. To determine the level of deviation in these values, several steps are taken to bring the facility as close as possible to unchanging, or steady-state, thermal conditions while having measured surface temperatures and constant energy flux. It should be noted that true steady-state conditions are hard to reach when outside temperatures are varying with the changing weather conditions. To account for this difficulty as few parameters and assumptions are needed.

- Colder winter conditions are needed to achieve larger temperature differences between interior and exterior surfaces.
- The facility southern facade wall is required to be a sealed and share similar construction with surrounding insulated walls.
- The final calculations assume this is a one-dimensional problem, as illustrated by Fig. 391, where actual three-dimensional conduction effects are neglected.

1. Interior Surface Temperature Sensors
2. Exterior Surface Temperature Sensors
3. Heat Flux Meter
4. Symmetric Heat Source
The following steps are taken to determine the U-Value of the facility walls.

1) Sufficiently apply a heat load to the lab with the mechanical system heater to allow any material surface inside the facility to reach a sustained uniform surface temperature, and constant material temperature gradient, to indicate steady-state conditions.

2) Once surface temperatures of the interior materials have reached a constant value the heat is turned off, all other sources of heat are identified and measured, and a measurable / symmetric source of heat flux is placed inside the facility. Please refer to Fig. 393.

3) The data used in calculations are when the heat flux meter output, inside surface temperatures, and outside surface temperatures have reached relatively constant values and the aforementioned parameters and assumptions are satisfied.

4) The governing equation to then determine the heat transfer coefficient ‘U’ for the walls is as follows.

\[
U_{\text{wall}} = \frac{Q_{\text{source}}}{A_{\text{surface}}(T_{\text{in}} - T_{\text{out}})} \quad \text{[equation 01]}
\]

where

- \(U_{\text{wall}}\) = Wall heat transfer coefficient \((\text{W/m}^2\text{K})\)
- \(Q_{\text{source}}\) = Interior heat source \((\text{W})\)
- \(A_{\text{surface}}\) = Interior surface area of surrounding walls \((\text{m}^2)\)
- \(T_{\text{in}}\) = Average temperatures of interior wall surfaces \((\text{K})\)
- \(T_{\text{out}}\) = Average temperatures of exterior wall surfaces \((\text{K})\)

A schematic of the U-Value calibration test is illustrated in Fig. 393 below to show the theoretical design set up and Fig. 394 is a picture of the actual experimental set-up.

The third calibration test is to determine the level of error found in the thermal energy measurements of the mechanical system for a given flow rate. As the heating or cooling load decreases for any given flow rate the resolution of measurement for the energy being supplied by the mechanical system becomes less accurate. This relationship is based on the efficiency of the heat exchanger as function of both the mass flow rate and the temperature difference for the inlet and outlet of the heat exchanger. The limits of accuracy for this relationship are determined by having precise measurements of the amount of electrical power that is being used as heat in the facility and comparing this value to the measured amount of thermal cooling power that comes from the mechanical system to compensate. The thermal cooling power of the mechanical system is evaluated by knowing the mass flow rate, the specific heat of the refrigerant,
and the temperature difference of the inlet and outlet of mechanical system heat exchanger. Fig. 392 illustrates the important aspects of the mechanical system needed to determine the mechanical thermal energy resolution.

The following are a few parameters and assumptions to note for this calibration test.

- The set-point temperature was established by approximating a temperature that would have the smallest temperature difference between inside and outside of the facility. From the aforementioned equation for the first calibration test, this will provide the smallest loss of energy due to conduction through the walls.

- It is assumed that mechanical system air flow is high enough that the interior facility material will not store any thermal energy from the heat source.

- The air flow is assumed to be well mixed and provide uniform convection heat transfer effects on walls.

Fig. 394  U-Value Experimental Set-up for West Wall

1  Interior Surface Temperature Sensors
2  Heat Flux Meters on West Wall
3  100W Light Bulb 'Symmetric' Heat Source
- The 20 amp circuit breaker is the limiting factor for the amount of electrical power that could be converted to heat. Therefore the highest theoretical heat load is \( Q_{\text{source}} = 120 \text{ volts} \times 20 \text{ amps} = 2400 \text{ W.} \)

- The temperature dependent fluid properties of the 19% Ethylene Glycol mixture must be identified to achieve accurate mechanical system thermal load measurements.

The following are the governing equations to determine the resolution limits of the mechanical system.

\[
Q_{\text{st}} = Q_{\text{source}} - Q_{\text{mech}} - Q_{\text{cond}} \quad \text{(equation 02)}
\]

where

- \( Q_{\text{mech}} \) = Cooling energy from mechanical system [W]
- \( Q_{\text{cond}} \) = Conduction energy loss through walls assumed = 0 [W]
- \( Q_{\text{st}} \) = Energy stored in chamber materials assumed = 0 [W].

\[
Q_{\text{mech}} = \rho V c_p (T_{\text{out}} - T_{\text{in}}) \quad \text{(equation 03)}
\]

- \( \rho \) = Fluid density [kg/m\(^3\)]
- \( V \) = Volumetric flow rate [m\(^3\)/s]
- \( c_p \) = Specific heat [J/kg·K]
- \( T_{\text{out}} \) = Temperature of chilled water line outlet [K]
- \( T_{\text{in}} \) = Temperature of chilled water line inlet [K]