Design method for adaptive daylight systems for buildings covered by large (span) roofs

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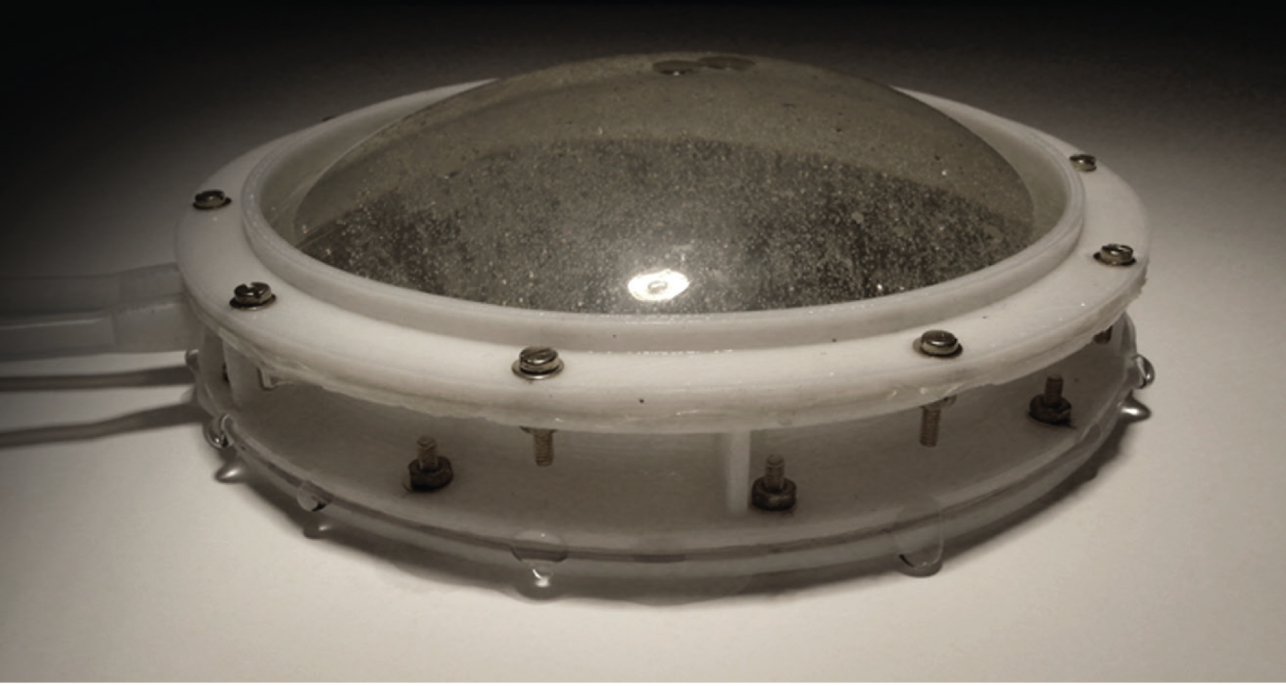

Florian Heinzelmann

/ Department of the Built Environment

bouwstenen 248

Design Method for Adaptive Daylight Systems for buildings covered by large (span) roofs

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Florian Heinzelmann

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Abstract

The rise of digital and more specifically parametric design tools from being developed by avant-garde architectural design practice mostly concerned with form and entering mainstream a couple of years ago lead to a drastic increase in possibilities of managing complexities but also integrating numerous building engineering related disciplines into the digital workflow, be it from early conceptual design stages till manufacturing and building execution.

However, architects and designers dealing with daylighting as an intrinsic part of their practice are sometimes lacking the proper tools or awareness about performative consequences regarding daylighting or solar energy gains at hand. The consequences in terms of energy consumption or wellbeing of inhabitants might not be so dire considering smaller buildings like residential houses but scaling it up to high rises or large roofs is entirely a different matter.

In the design process of the afore mentioned larger scale projects due to budget, profit, importance and complexity a larger team of designers, architects and engineers is employed to solve all the building related questions. In addition, the recent years have seen an increase not only in high rise buildings but also in building types using large roofs like big infrastructural projects in form of train stations, or airports, but also shopping malls and museums, etc. In the Netherlands for example all major train stations are under redesign, or reconstruction, or recently have been finished, like Arnhem Central station by UNStudio with its main hall finished in 2016 and Rotterdam Central station by a cooperative between Benthem Crouwel Architekten, MVSA Meyer & Van Schooten Architects, and West 8 in 2014. The latter won the Velux Daylight Award 2014. Another milestone in terms of daylighting and large span roof for museums is the 2017 finished Louvre in Abu Dhabi by Jean Nouvel, a design where a common roof houses a “museum village” underneath. A further remarkable example in terms of daylighting combined with artificial lighting is the atrium installation at the Philips Lighting Headquarters in Eindhoven designed by LAVA and finished in 2016. The situation in the Asian region with China as powerhouse e.g. stadiums for their Olympic Games but also Japan with the plans for a new stadium in Tokyo and upcoming countries like Indonesia is promising regarding daylight design for large roofs.

Figure 1. Louvre Abu Dhabi, Ateliers Jean Nouvel, image source: Wikiemirati

These types of buildings regarding daylight need to be treated differently in comparison to e.g. High-rise buildings because the part being most exposed towards the sun is the roof. In addition, the issue at hand is that daylight availability inside buildings due to location on the globe, axial rotation of planet earth, its orbit around the sun during one-year, various changing weather conditions, but also usage are not static design parameters but constantly changing and therefore highly dynamic and not only long term but also being responded to in a matter of minutes. Therefore, daylighting and solar energy gain related questions cannot be solved with static building envelopes, or openings but adaptive ones.

The aim of this dissertation is to gain an insight into these design issues and provide designers and architects with a Design Method especially in early design stages where the design team is smaller but most crucial design decisions are taken and to be able to come up with adaptive daylight system in large (span) roofs. For that reason, the dissertation is set up in such a way to clarify different aspects of adaptiveness, daylight performance aspects and revolve around several case studies which are non-adaptive and adaptive, in various geometrical and material configurations to derive from that a design method covering bottom up and top down design elements. Here the main two aspects of this dissertation regarding adaptive daylight systems in large (span) roofs are related to geometry and materiality in both adaptive and static manner. Finally, the design method is fully applied with general applicability in mind as a daylighting device in form of an Adaptive Liquid Lens.

Content

1

Introduction

Vertical façade design is a regular and common design task for any architect or designer in related practices covering the full spectrum of possible building functions. Since windows and frames are fully optimized products in comparison to buildings which themselves can be considered more as prototypes (apart may be from prefabricated houses) they are much more precise in terms of manufacturing tolerances as well as rigorously standardized building elements and in addition are well researched. A designer has the choice of a myriad of products like double, or triple glazing with various low-e coatings, external retractable sun shading also integrating aspects of daylight redirection, etc.

Large (span) roofs in comparison are done by few, potent sometimes specialized architectural firms. This is insofar no wonder since buildings covered by large roofs are often highly prestigious projects, much bigger in scale thus financially, architecturally and engineering wise more challenging and must appeal and cater the needs for a much larger user group than let's say a regular office building. Apart from industrial, storage facilities and may be smaller sports facilities, there is even a lower degree of standardization not only regarding the building itself but also the building envelope and thus the large (span) roof. Here lies a not yet fully explored research potential.

In comparison, vertical facades are often adaptive in terms of shading with respect to louvers, whereas large span roofs are not and if they are adaptive then most of the time kinetically operating in an either/or state, meaning they are either closed and fully shaded or open and let sun- and daylight pass unhindered. In rarer case those roofs do more than shading and improve or alter the lighting situation in the interior with a clear intention.

Therefore, the dissertation is twofold. Firstly, it intends to explore possibilities and designs of adaptive daylight structures in large (span) in form of several case studies (existing and original) and secondly synthesizing the findings in form of a design method to be applied by a wide spectrum of architects and designers.

1.1 Research Motivation and goal

A general motivation behind this research is the interest in design systems consisting equally of material and geometry aspects and their interplay. This stems from several years of design practice where due to time constraints and as a result financial limits, design activities are rarely enabled to be worked out in its fullest details according to rigorous performance assessment. This is not necessarily negative since it forces designers to be more goal oriented and come up with more immediate applicable solutions. However, arguments of design specific decisions can never be fully justified and sometimes are lacking depth. Due to experienced design activities, especially with respect to facades and larger structures, the daylighting aspect became especially intriguing.

Daylight like structural engineering both underlays equally material and geometrical design parameters. However, with daylight it manifests itself differently. In structural engineering, the effect can only be perceived via the structure meaning the materialization and geometry of the built situation itself, but the flow of forces remains hidden within. There are rarer cases where the effect of forces and their influence especially on geometry become visible within adaptive systems like the research work on the Stuttgarter Träger (Sobek, et al., 2006), the University of Stuttgart, ILEK Hydraulic Wooden SmartShell, or static situations of hanging Catenary chains like the model displayed at the basement of the Sagrada Familia.

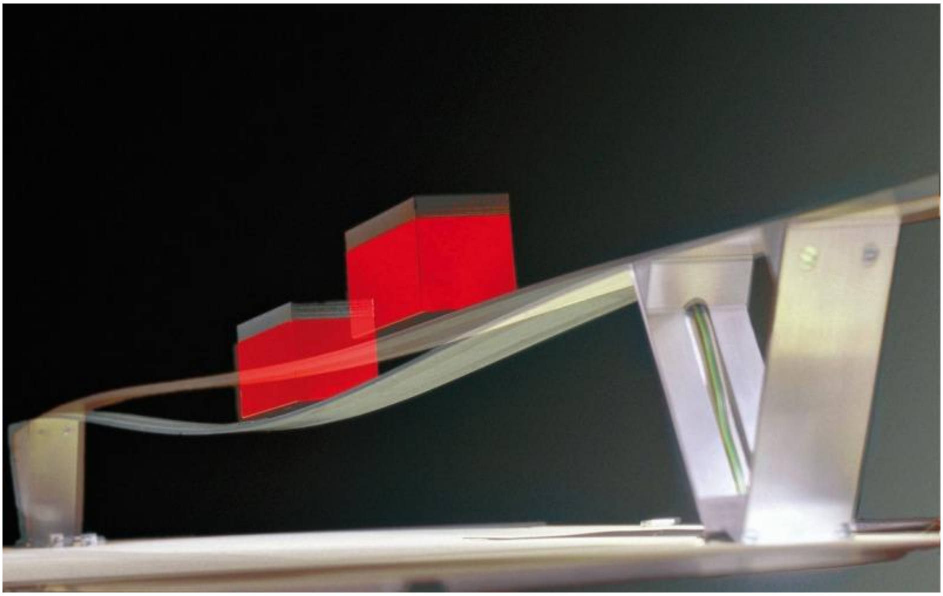


Figure 2. Stuttgarter Träger, Stuttgart, image source: ILEK Stuttgart

Figure 3. Hydraulic Wooden SmartShell, ILEK Stuttgart image source: ILEK Stuttgart

Figure 4. Catenary Chains, image source: Etan J. Tal

However, since the human body does not possess a dedicated organ to perceive external flow of forces this cannot be directly perceived but needs to be interpreted due to visual input of change in geometry. Thus, a certain amount of processing is required. The human eye on the other hand one of human's primary organs exclusively evolved to perceive (visible) light and is one of the organ if not the most important to let us experience our environment. Changes in lighting conditions are immediately registered and the human eye can adapt towards the change of luminance via pupillary response. The human body is therefore prone to react to a change of lighting conditions due to daily and seasonal cycles as the life and activity determining force, especially for thousands of years before high performance artificial light sources in form of electric light found their way into our daily lives. The beauty here lies in the fact that building envelopes or potentially adaptive large roof structure are the interface between human action/interaction and external conditions which have an immediate effect on us. Cause and effect of change in lighting situations are more directly perceptible. Therefore, the explicit understanding of daylight interacting with material and geometry systems are part of the research motivation.

A further motivation lies in the exploration of possibilities of design tools like parametric design, simulation and materialization of prototypes. However, many publications in the field are not very clear how the boundary conditions are defined, how design parameters are translated into geometrical and material systems or how the often-complex results are performing in relation to initially set up design goals. One often encounters the moment of “magic” happens where the reader is confronted with design results and one starts to wonder, how did the designer do that, how did he/she get to that result and how does it perform? Thus, a potential learning effect is reduced to the experience of awe evoked by the design solution. It can be even argued that some publications deliberately set up smoke screens where e.g. students who did not go through a similar regime of design education are not able to reproduce similar results.

Finally, daylight is a dynamic design parameter which is depending on the building’s location, undergoing daily and seasonal cycles and is influenced by changing atmospheric conditions (weather). In addition, the consideration of usability of space and performance is equally necessary. This all leads to the assumption that daylight system in large (span) roofs need to be adaptive to be able to respond to the changing conditions to have an optimal performance.

Thus, the goal of the dissertation is to derive a Design Method which enables designers, students and architects to come up with their own performative design solution for adaptive daylight systems.

1.2 Research questions

How can architects, designers and engineers be supported with the use of a Design Method to be able to design adaptive daylight systems in large roofs under the consideration of daylight performance aspects?

To answer the main question several sub-questions, need to be addressed:
How can this particular Design Method:

- Integrate different time spans e.g. daily and seasonal changes of daylight and availability according to specific locations?
- Take functional aspects like the use of the building, the user and their needs into consideration?
- Make the designer understand the role of large roofs as mediator/interface between user/functional requirements and daylight availability?
- Enable the designer to evaluate the need for either a “static” or “adaptive” design?
- Clarify the role of the overall/global geometry of the roof in terms of design complexity but also potential influence on daylighting performance?
- Make the designer understand implications and outcomes of various materials of roof and openings in terms of daylight performance?
- Give advice about design and evaluation tools available, be it digital or physical and the principle use of them?
- Enable designers to assess their design outcomes and iterate and evaluate them further?

1.3 Research method

As the proposal of a design method for adaptively day-lit large roofs is the main goal of this research, a hypothesis is built supposing a workable three-step design method consisting of an initial assumption/evaluation phase, the design process, and the evaluation and feedback stage. To develop the design method a mixed research approach is conducted consisting of qualitative and quantitative aspects (Creswell, 2008).

Qualitative (exploratory) research aspects

In the dissertation, a selection of case studies is created to develop, test and iterate the design method and adjust it to establish an effective flow of information between the design stages. The nature of the research for establishing the design method is qualitative nature (exploratory research). This is of importance to be able to state the hypothesis (Design Method) itself.

Quantitative (confirmatory scientific method) research aspects

The evaluation of given, external but also self-created case studies is conducted by employing a combination of mostly quantitative and qualitative methods. The quantitative part of the research seeks to quantify the light entering the interior spaces and predict its effect on the users. Either via digital simulations (using e.g. Diva for Rhino) or via physical experimentations (using a lux-meter and Lumination Camera). However, for a complete understanding and definition of the resulting interior lighting conditions a qualitative research is conducted in parallel. With the use of field observations, video material and photographs the light conditions are described and patterns, specific features and problems are interpreted. The combination of research methods allows a more holistic approach to the matter.

The design method with which the case studies are developed, being Top Down, Bottom Up, or a mixture of the two, is also studied in this dissertation. The mix of the two design methods reflects the research method as such since a top-down approach is of more quantitative nature and rather specific, while the bottom up approach is of qualitative nature and more general. The advantages and disadvantages of the two approaches are inquired to highlight the assets of their combination. Components purely developed via a Top Down approach, are often working well within their design specifications but the whole design can fail when different components are assembled together since individual development happened more isolated. Designs emerging from a pure Bottom Up approach start from existing components being assembled together but complexity through combinations can be an issue and result can lack in overall performance. Therefore, a third way of designing is introduced, namely the Bottom Up – Design Exploration replacing the pure Bottom Up approach. Blending the two approaches allows the development of creative solutions in a controllable and realistic way.

1.4 Societal and scientific relevance

Environmental aspects of energy reduction for operating buildings as well as well-being of the inhabitants is of general interest. Here the increased use of natural light can contribute greatly since daylight (diffuse clear sky 150lm/w) has a high luminous efficacy in terms of lumens per watt of heat energy produced in comparison to artificial light (Incandescent light 16-40 lm/w) (natural frequencies). Besides natural light comes for free and is the only light sources covering the full spectrum of visible light (since our eyes evolved in relation to natural light).

Large (span) roofs are insofar relevant since human being spend a great deal of their time indoors, of course in general under large roofs far less than e.g. at home or office. However, buildings with large roofs have generally a high importance within society be it commercial, recreational or infrastructural. Since those are constructed and designed with an increased effort and attention, so should daylighting aspects for those types of buildings be considered with an equal amount of attention.

As earlier mentioned there is a manifold of publications, papers, etc. which explore parametric design, performance driven design, daylighting design and adaptive design. However, integrating those elements into an easy to follow and traceable Design Method is necessary. Therefore, the combination of a well-researched topic and design thinking with the aim to develop a Design Method which is rigorously based on daylighting and adaptive building skins in large (span) roofs can contribute in a novel way.

1.5 Overview of the dissertation

Chapter 2 Performance driven (Daylighting) Design

This chapter explains aspects of Performance Driven Design and specifically Performance Driven Daylighting design and gives an overview of tools at hand ranging from digital to physical modelling, simulation and evaluation possibilities. It further explains the physical principles of day and sunlight in terms of energy and visibility to the human eye, e.g. illuminance, luminance and wavelength as well as the interaction between light and surface material properties such as transmission, reflection, diffusion, roughness, albedo, etc.

Chapter 3 Large (Span) roofs

The third chapter describes the distinction between large span and large roof, their societal importance also in relation to daylighting design. It further introduces the issue of use individual versus collective use of people and the consequences in terms of approaching daylight design. A vital part is also to highlight the different functions under large (span) roofs such as infrastructural, commercial, cultural, recreational and sports. All these different functions have specific lighting requirements due to building regulation, safety, usability and user-user but also user-building interaction.

Chapter 4 Adaptive and Static

This chapter introduces adaptive and static architectural design. Here several definitions in terms of building components, reaction and Interface are looked at. Most importantly for this thesis a clear distinction is made in both static and adaptive architecture terms with respect to geometry and materiality or mix of both. The material and geometric properties always play a major role in daylighting in relation to incoming light and how light is “processed”. In addition, a new definition is worked out of Static Contextual Buildings, buildings which are designed via environmental design parameters however do not change. Here the two categories are Adapted Geometry (Smart Geometry) and Materials & High-Performance Materials. This is equally defined for Adaptive Buildings, being Kinetic Architecture by Adaptive Geometry and Statically Dynamic Architecture by Smart Materials.

Chapter 5 Case studies

Chapter 5 analyses several designs in form of case studies being own design solutions or existing ones in terms of large (span) roofs and daylight performance. This is done according to the categories coming from chapter 4 Static Contextual Buildings – Adapted Geometry & High-Performance materials and Adaptive Buildings – Kinetic Architecture by Adaptive Geometry and Statically Dynamic Architecture by Smart Materials.

The case studies are:

- Kimbell Art Museum (Louis Kahn)
- Origami Roof Structure (own)
- External shades based on Origami Roof Structure (own)
- Smart Energy Glass (TU Eindhoven)

All the case studies are researched, designed and evaluated according to the following categories:

- Context
- Function and Layout
- Lighting requirements
- Design process
- Geometrical & Material Aspects - Technical solutions & systems
- Lighting Analysis and Alternatives
- Conclusion

Chapter 6 Design Method

Based on the findings from chapter 5, this chapter derives a Design Method which gets later applied in chapter 7. Initially Top Down and Bottom Up (Design Exploration) design trajectories get explained also with the use of several examples. The previous case studies get further classified what design trajectories where prevalent in the design process itself. As a next step boundary conditions relevant for daylighting are introduced. These are building's function, location & climate, quantitative aspects of daylight and qualitative aspects of daylight. Design tools are introduced, the way they operate, the physical principles which apply. Here Parametric Design, Simulation, physical prototypes and ways of evaluation and feedback into the design system are explained. The final step of the fully fleshed out Design Method gives a step by step design guideline and a preview of the fully applied Design Method.

Chapter 7 Fully applied Design Method – Adaptive Liquid Lens

Here the final design result of this thesis is displayed in form of and Adaptive Liquid Lens being a daylight altering and redirection device. Like in the previous chapter explained it describes the Top Down and Bottom Up - Design Exploration elements and how the design came into being also with respect to design tools. It also shows the potentials and limitations of using simulations versus building prototypes and how such a daylighting system can be applied in 1:1 scale. The measured results get then evaluated and further design and research suggestions especially with respect to Smart Material applications are made.

Chapter 8 Conclusions

Offers conclusions, evaluations on the state of Adaptive Buildings and gives recommendations for future research. It also evaluates the proposed design Method, its applicability, etc.

2

Performance Driven (Daylighting) Design

Current design practices employ digital design tools in all its facets, from generating representative images, doing calculations and simulations, 3-D modeling, model making, to shop drawings, BIM etc. Performance Driven Design or performative design is not necessarily related to computational tools, since the notion is much older than our current computational possibilities. However, CAD programs which were first introduced in the early 1960s in form of Sketchpad by Ivan Sutherland, commercially available simulation software packages and Parametric Design which was theorized over the at least past 20 years and found its mainstream application around 5 years ago make it possible to employ Performative Driven Design as a common tool for architects and designers. One could say that within the application of Parametric Design several notions or line of thoughts were developed. One for instance is *Parametricism* (Schumacher, 2010) which promotes Parametric Design as a style or manifesto versus Performance Driven Design which aims for a more scientific rigor (quantifiable) in the application of design parameters and leans more towards an engineering side. In the latter, it is also important not only to clearly communicate the nature and basis of specific design parameters but also how those are linked with each other including various disciplines involved in the building process. Performance Driven Design further advocates testing and iterative improvement of designs via feedback but again not for the sake of merely generating variations or discreet elements but for the sake of optimization towards a design goal.

2.1 Definition Performance Driven Design general

Performance Driven Design nowadays seeks to define and integrate more specific design goals and the evaluation thereof in earlier design stages as a tool for designing rather than a later assessment or affirmation when major parts of the design are already developed, and certain design decisions are irreversibly locked. It further advocates the earlier integration of vertical transformations rather than only lateral transformations (Meniru, et al., 2003). Lateral design transformations can be related to lateral thinking (de Bono, 1970) which describes as creative and indirect approach and can be interpreted as traditional architectural design process which is imaginative, intuitive and nonlinear. Here in succession or parallel different design options are worked out and less suitable ones are discarded. The integration of vertical transformation means to simultaneously look more closely, rational and factual into the potential of design options which at the same time need to be developed specifically with a clear design goal in mind. The issue however is that considering several options simultaneously and more detailed, while evaluating e.g. geometrical and material combinations, this not only leads to a combinatorial explosion, thus the management of data and a challenging evaluation process of one set of designs versus another but eventually results in an increased design duration. The increased design duration not only poses a strain to the design team, but also other disciplines involved as well as communication of results with the client, since time is one of the most limited resources during the design process. Therefore, it is only possible to carry out such a design trajectory with the help of computational tools, which can help to generate design variations swiftly (parametric design), evaluate them (simulations and prototypes), communicate them with other disciplines (BIM) and reach a for the client understandable conclusion and recommendation matrix.

It is therefore required to get a clear picture about several performance-related aspects of the design process beforehand:

- Multidisciplinary range of performance aspects and impact/conflicts
- Range of performance assessments qualitative and quantitative aspects
- Performance measurement
- Kinds of performance
- Long term short term needs
- Human & functional needs
- Environmental factors

2.2 Performance Driven Daylighting Design

Performance Driven Daylight Design intends to bring natural light into buildings for a user or group of users according to their tasks in the best possible way. Here design objectives can be but are not limited to aesthetics, occupant's health, comfort, energy savings, safety and visibility of objects or other people. It is therefore required to identify several design boundary conditions, be it external and internal to get a better understanding for the design task at hand and develop Daylight design evaluation criteria to test whether a design or design options/variations matches these criteria.

External parameters

- Location on earth, thus
- Climatic conditions
- Atmospheric conditions, sunlight and daylight availability during the day and year
- Surrounding and eventually obstructions

Internal parameters

- Function of the building
- Inhabitants
- Safety and visibility
- Building regulations and codes
- Comfort
- Energy savings

A large (span) roof, as the envelope of the building acts as interface or mediator between existing and current light conditions on the outside and internal functional and user needs. It does that via three different but related and equally important design aspects: Geometry – Materiality – Time. The thesis is thus set up in such a way to elaborate in the later chapters in form of case studies and design method on the interplay of geometrical, material and adaptive systems in relation to changing daylight conditions. Since daylight, as an ever-changing design parameter and the processing of it through the building envelope is always influenced by the material-geometry system it is required to get a basic understanding of the relationship and interplay of these elements and the external and internal boundary conditions or design parameters.

2.2.1 Location, climate & atmospheric conditions

A building design needs to be linked to location, its specific climate and atmospheric conditions.

Location

It is not only important to see how the sun's vector in relation to the earth's surface normal changes during day and season but also whether there are potential obstructions in form of higher buildings casting eventually shadows on top of the roof during certain times. The incoming sun vector depending on the latitude on the planet plays a major role due to daily rotation of the earth around its axis, the orbit around the sun for one year and in relation to the axial tilt or obliquity of the rotation axis. Depending on the position e.g. the more on the northern or southern hemisphere a building is located (latitude), the more elaborated are the differences in available hours of daylight and seasonal extremes. A building which is located nearby the equator will have sunlight coming in from North in the months around June and South direction in the months around December. The difference between the altitude angle between the summer and winter solstice have a larger impact the more north or south a building is located due to available hours of sunshine and thus passive energy gains. On the northern hemisphere, the sunlight will always come from the south no matter whether it is summer, or winter and the maximum and minimum altitude angles differ depending on the latitude of the northern hemisphere. On the southern hemisphere, this is the other way around. To know this information is not only important for being able to design a geometry in response but also to understand whether passive heat gains during the various season are desirable or not and at what times the sun raises and sets, etc.

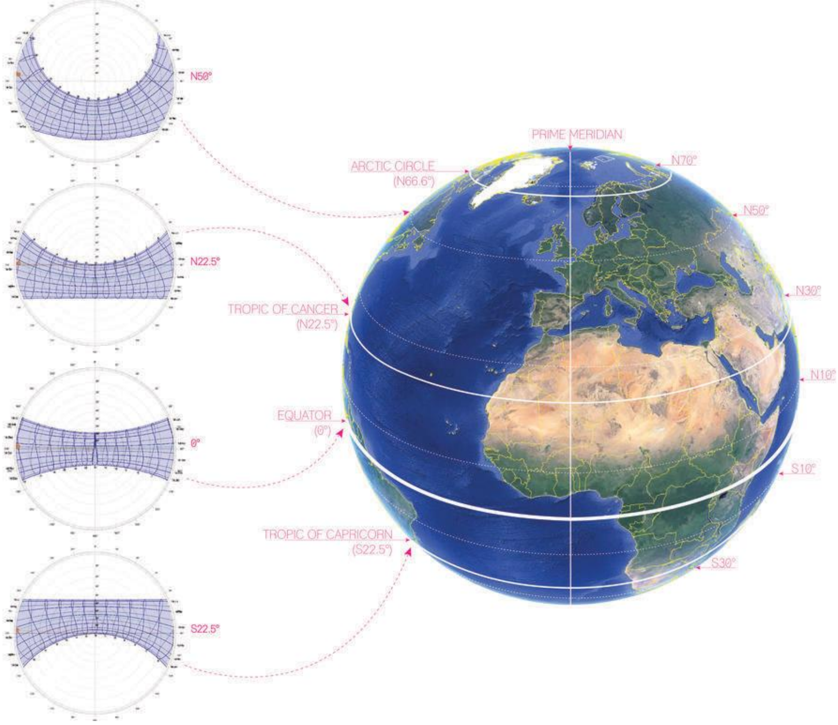


Figure 5. Sun charts illustrating the variation in the sun's movement in relation to latitude. Image source: AutoDesk

Climate & atmospheric conditions

It is furthermore important to understand the climatic conditions of a location from several viewpoints. When there are large seasonal fluctuations in terms of outdoor temperature a passive heat gain from sunlight during colder winter months could be desirable. However, this can pose a challenge in terms of visual comfort during winter months. When one deals with e.g. a tropical climate then shading throughout the year to prevent the building from overheating is essential. As a result, this can pose a challenge in getting sufficient visible light into the interior. Thus, the daylighting strategy must go hand in hand with the design approach for climate aspects. Among others, annual temperature charts but also the Köppen-Geiger climate classification should be considered to define boundary conditions for the daylight design strategy.

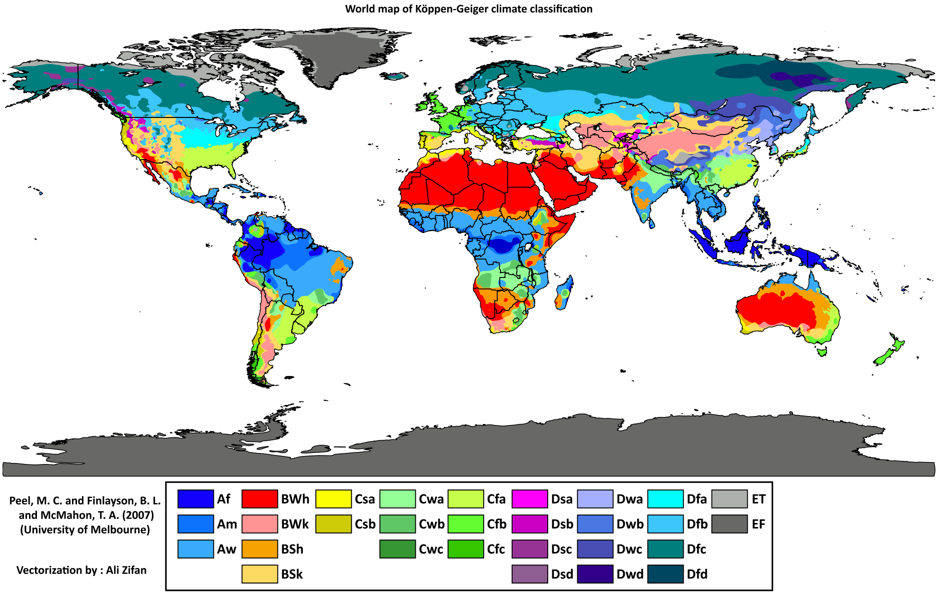


Figure 6. World map of Köppen-Geiger climate classification, image source: University of Melbourne

Another issue to look at are the prevalent atmospheric conditions. Regions with a high precipitation in opposition to regions with an arid and dry climate have more cloudy sky conditions, thus less illuminance yet more diffuse natural light is available. The sky conditions need to be considered and a daylighting strategy needs to be developed accordingly in the way how daylight gets transmitted into the interior. Directed sunlight can be reflected better into the interior, whereas diffuse light demands larger openings on the roof, all under the premise of (intentional) passive solar heat gains but also generally lower u-values of glazed surfaces versus opaque ones. Therefore, again it is necessary to look at the *Köppen*-Geiger climate map but also consult charts of monthly precipitation, rainy days, monthly hours of sunshine, etc. Information regarding this can be easily found via internet like the US Department of Energy (EnergyPlus, 2018) and be used in daylight simulation software.

2.2.2 Building's functions and daylighting demands

In this step, it is crucial to define the building's functions in relation to their daylighting demands. The questions to be asked are what sort of building is going to be designed, for what sort of inhabitants and what are the requirements in terms of lighting and daylighting.

Functions can be:

Market hall, football stadium, Olympic stadium, swimming pool, atrium in a larger compound, airport terminal, train station, museum, convention center, trade fair, entertainment-plex, etc.

If one takes the airport terminal as example one can immediately see, that there are several sub functions and requirements in daylighting at hand. The top most priority in terms of lighting design regarding passengers is the safe and unhindered passage. Airports are frequented by many people, either arriving, departing or changing airplanes but also people working there in administrative functions or doing logistic and maintenance work. In that sense, an airport can be perceived as a flow of people, goods and machinery with various interfaces of exchange. The two main groups of passenger area and service facilities are considered separated due to security requirements and the interface of these "flows" are present in form of service facilities either integrated inside the spaces for passengers underneath the roof or near the envelope. The overall layout of an airport is in most cases flat horizontal where a central terminal building spreads out in a tree like structure to form the various gates. The whole building design is guided by logistics in terms of fitting airplanes of various sizes, maintaining, loading and unloading them and bring the passengers to their destinations within the building. Depending on the airport layout and size, it forces passengers to walk from the security check to their gate for quite some time or in some cases take additional means of transport like light rail. The passengers are often in a hurry, sometimes anxious or stressed and tired. That requires a lighting design for the airport halls which supports way finding and visibility of signage, gates and other people. Therefore, an evenly lit surrounding with little glare due to backlighting and harsh contrasts is required. It also needs to perform well independently from outside lighting conditions caused by seasons, times of the day or atmospheric conditions. Airports also operate from early morning hours till late at night and artificial lighting will play a major role since the lighting requirements cannot be met all the time by natural light. In opposition to train stations rush hours during morning and evening times play much less of a role but can be more subject to seasonal peaks. With carefully analyzing the requirements and how people interact with the build environment a set of design criteria or guidelines can be worked out which the upcoming design must meet.

2.2.3 Quantitative aspects of daylight – regulations and certificates

Illuminance

It is required to consult local regulations and sustainability certificates for requirements in illuminance. However, this should be regarded as a minimum to reach, or as guidelines, since the idea of adaptive daylighting systems is to strive for better. Looking e.g. at the European Standard EN 12464-1 (with regards to large roofs) where values of illuminance are set in relation to tasks of the inhabitants, then it becomes quite clear that some of the values are easily reachable with natural light, but others are more challenging. In such cases or due to sub-optimal boundary conditions, or seasonal circumstances in terms of daylight availability it will be required to employ artificial lighting.

The following table shows maintained illuminance ($\bar{E}_m$) requirements from EN 12464-1:

Airports

Ref. no.	Type of interior, task or activity	$\bar{E}_{m,}$ lux
8.1.1	Arrival and departure halls, baggage claim areas	200
8.1.2	Connecting areas, escalators, travellators	150
8.1.3	Information desks, check-in desks	500
8.1.4	Customs and passport control desks	500
8.1.5	Waiting areas	200
8.1.6	Luggage store rooms	200
8.1.7	Security check areas	300
8.1.8	Air traffic control tower	500
8.1.9	Testing and repair hangars	500
8.1.10	Engine test areas	500
8.1.11	Measuring areas in hangars	500

Railway installations

Ref. no.	Type of interior, task or activity	$\bar{E}_{m,}$ lux
8.2.1	Covered platforms and passenger subways (underpasses)	50
8.2.2	Ticket hall and concourse	200
8.2.3	Ticket and luggage offices and counters	300
8.2.4	Waiting rooms	200

Table 1. EN 12464-1

Staying with the example of airports and looking at the above listed functions and how those are situated inside the building, one can distinguish between zones underneath a large roof with ample ceiling height and zones either situated at the perimeter, or where people enter another area (e.g. security check), or functions which are in free standing cubicles. The zones for waiting or transfer require an illuminance between 50-200 lux. Areas where a one on one communication between staff and passenger is required it goes up to 500 lux, which is like the requirements for office spaces. One can see that functions with lesser requirements in illuminance are mostly situated under the large roof whereas those with higher requirements at the. Therefore, for the unobstructed functions under the large roof with lesser lighting requirements, it should be possible to be lit entirely by natural light.

Without going further into detail, other functions require different values in illuminance, especially considering professional sports. Thus, regulations and requirements must be checked before the actual design starts and needs to be defined as boundary conditions.

Other criteria

Another performance aspect are green building certificates such as LEED, BREAM, DGNB, DGBC, etc. LEED for instance is promoting a daylight factor as criteria for a sufficiently lit building interior. However, this poses several challenges, like it uncritically being applied as a design tool while it merely shows lighting potentials rather than an actual situation for a certain moment in time (Reinhart and LoVerso, 2010) and is therefore inadequate to design adaptive solutions. For example, the daylight factor is intended to a ensure minimum in indoor lighting conditions. It calculates how much percentage of the outside light reaches a certain point in the interior via a sky component, externally reflected component and internally reflected component (Reinhart, 2011). This does not say anything about the quality of light e.g. whether it is directly or diffusely transmitted, but it promotes a “the more the better” approach and skips individual situations during the year. For adaptive daylighting design is required to test the system’s performance for several and varying scenarios during the year and carefully assess, whether the indoor lighting situation is performing sufficiently or not for a specific building function. This is especially important since the geometric or material configuration within an adaptive solution changes with respect to the changing environmental conditions, thus one is not able to work with statistical means or averages but needs to consider the actual situation.

2.2.4 Qualitative aspects of daylight – User oriented

Other criteria for daylighting also play a role which are not only defined by having sufficient amount of light available but qualitative aspects. The list below describes some of the qualitative aspects of daylight in the interior.

The EN 12464-1 defines qualitative aspects such as:

- Agreeable luminous environment
- Harmonious luminance distribution
- Adequate illuminance for the interior areas, task areas or activity areas listed in the tables "Schedule of lighting requirements"
- Good uniformity
- Limitation of direct and reflected glare, including veiling reflections
- Correct directionality of lighting and agreeable modelling
- Appropriate color rendering and color appearance of the light
- Avoidance of flicker and stroboscopic effects
- Quality of daylight
- Variability of light

2.3 Daylight Fundamentals

Among others, two easily accessible publications (Ryer, 1998), (Rensselaer, 2000) give basic insights in the way how light works and interacts. Without the understanding of the basic physical principles it will be difficult to come up with new designs or be able to use light simulation software and interpret the results in a meaningful way. It is therefore advised before starting with own design solutions to go through these basics thoroughly.

Light and electromagnetic radiation

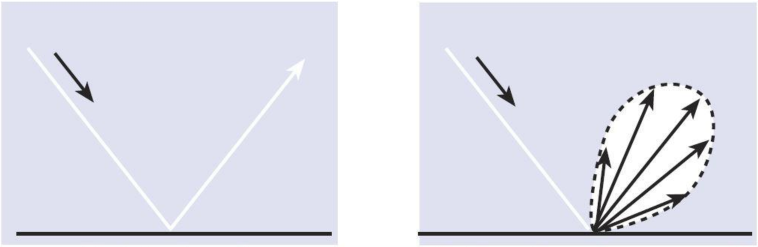
Photometry is about measuring the optical radiation as seen by the human being. Light is a small part of electromagnetic radiation with the most relevant part for daylighting is the for human visible segment ranging in wavelength from about 380 to 780 nanometers situated between the ultraviolet and the infrared spectrum. Ultraviolet radiation, especially the UV-B component which is not filtered by the atmosphere is dangerous for humans but also pigments in artworks, thus in case one designs a daylighting system for museums which displays paintings, the UV radiation needs to be taken care of (see case study 5.1, Kimbell Museum). On the other side of the visible spectrum, the IR radiation needs also taken to be care off since it causes passive heat gains inside buildings which from case to case can be desired or needs to be blocked depending on the overall climatic situation (see case study 5.2 Origami Roof Structure). Since the human eye has developed in response to natural light available on earth, daylighting has not to deal with negative aspects of artificial light emitting only partial segments of the visible light spectrum falsifying color information. However, discomfort glare in form of direct light blending or too high contrast needs to be evaluates much more.

Color

The human brain’s interpretation of colors due to optical receptors within the eye depends on which segments of the visible light spectrum is either reflected, transmitted, absorbed or filtered by surfaces which are surrounding us. Therefore, it is necessary to look at how surfaces interact between light and the human eye.

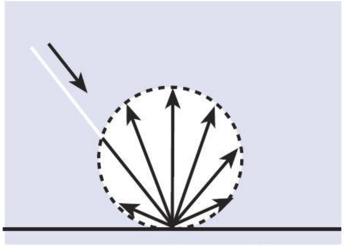
Reflection

Three kinds of reflections are possible: specular, diffuse or spread. A polished surface like glossy paint or a mirror has specular reflection. That means light is reflected outwards in the same angle as the light hits the surface (incident angle=reflected angle). Rough concrete, wood surfaces which are untreated or matte paint have a diffuse reflection. Light is reflected in a scattered way. Spread reflection depending on the material is in varying ranges in between specular and diffuse reflection. Light is reflected in a scattered way but still in general light angle in response to the incident light angle. Materials which have spread reflections are some metal surfaces, leather, or semi-gloss paint.



a. Polished surface, specular

b. Rough surface, spread



c. Matte surface, diffuse

Figure 7. Types of Reflection, image source: Illumination Fundamentals (Rensselaer, 2000)

Refraction

Light traveling from one material to another changes velocity and as a result the incident angle is deflected inside the next material according to Snell's law. The effect is stronger, the thicker a material is. Examples for visualizing the effect are: An object cast in resin or seeing a fish inside water appearing dislocated from their actual position. The object appears in a different location since light travels much further inside resin or water in comparison to an object sitting behind a regular window. For glazing and windows, the effect is negligible but still present because glass panes are only 2-4 millimeter thick. Thus, an object behind a regular window only appears to be the same position where it is located because the effect is rather small. Also, light rays when leaving the glass panes into air the angle changes back to the previous incident angle which adds, that the effect is hardly noticeable. The formula for Snell's law is the following:
n = speed of light in vacuum/speed of light in the material = c/v

Relationship between incident angle and refractive index:

$n_1 \sin \theta_1 = n_2 \sin \theta_2$

n_1 = the refractive index of medium 1
n_2 = the refractive index of medium 2
θ_1 = the incident angle of the light ray (with respect to the normal)
θ_2 = the refracted angle (with respect to the normal)

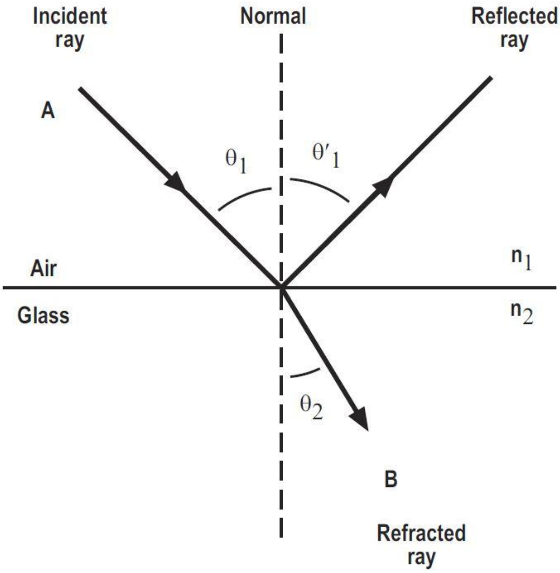


Figure 8. Snell's Law, image source: Illumination Fundamentals (Rensselaer, 2000)

In architecture and optical engineering Snell's Law plays a major role in optical devices such as light redirecting prisms, the glass domes of light pipes (prismatic or Fresnel), Fresnel sheets or lenses in Lighthouses or Lenses as such (see chapter 7 Fully applied Design Method – Adaptive Liquid Lens). However, one must be careful using lenses or prisms because materials have different index of refraction in relation to different wavelengths which causes chromatic aberration. This means light is split up visibly into its different color components (rainbow). Another aspect which can be potentially used for daylighting is the critical angle θc. If light hits the inner surface from a higher index of refraction to a lower one (e.g. light tries to leave glass into air) and reaches the critical angle θc, it does not leave but travels along the surface plane. If the angle is larger than the critical angle θc, total Internal Reflections will occur. This effect is made use of in e.g. glass fiber cables.

Different materials especially liquids and solids have a great range of Indexes of Refraction and can be employed for design purposes accordingly.

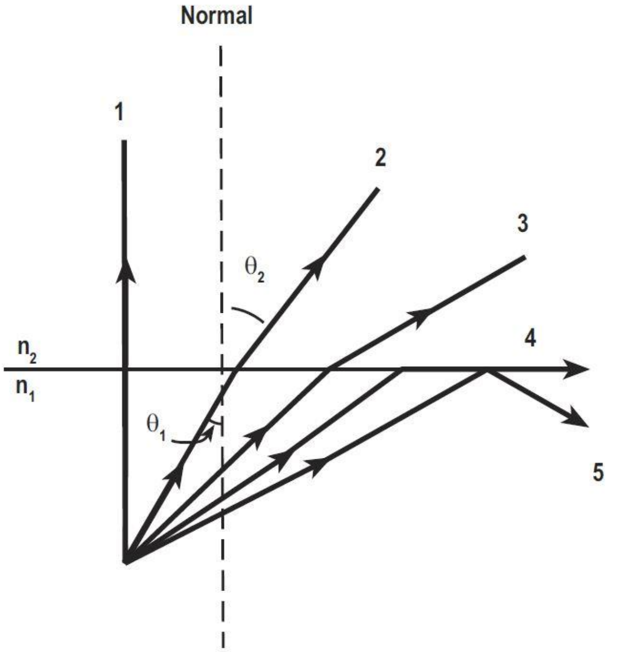


Figure 9. Critical angle and internal reflections, image source: Illumination Fundamentals (Rensselaer, 2000).

Reflection due to index of refraction

A transparent surface never transmits all the incoming light due to the change of velocity of light even at a surface normal incident angle. That is the reason why glass can never be truly transparent but always remains visible. This happens according to Fresnel's law for incident angle:

$R_\lambda=(n_2-n_1)^2/ (n_2+n_1)^2$

r_λ = the reflection loss
n_1 = the refractive index of medium 1
n_2 = the refractive index of medium 2

The more the incident angle of light deviates from the normal angle (0°), meaning the bigger the incident angle is, the more light gets reflected.

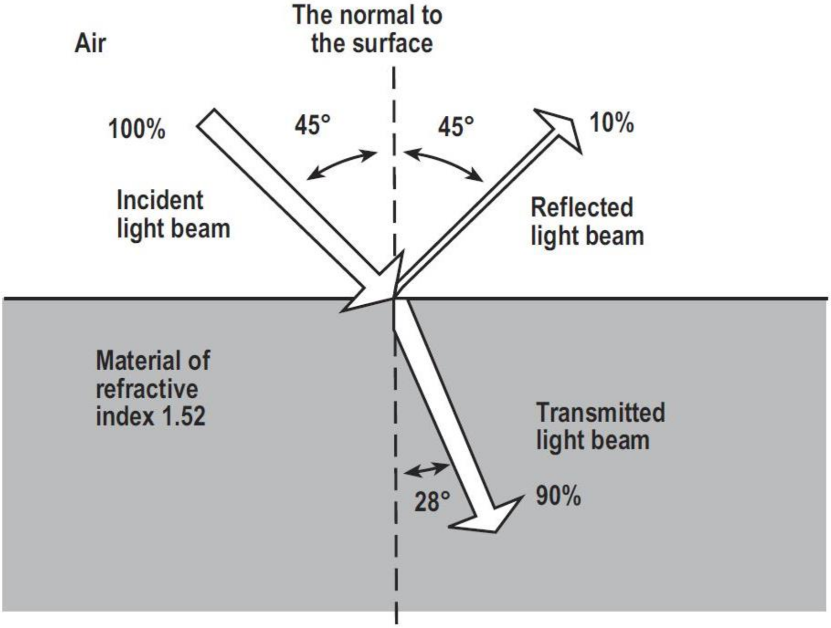


Figure 10. Light transmittance according to incident angle and index of refraction, image source: Illumination Fundamentals (Rensselaer, 2000)

Transmission

The act of light passing through a material is called transmission. This is affected by previously shown refraction, reflection but also absorption, diffusion and filtering

Absorption

Materials can partly absorb and transmit light. Some materials only absorb a certain wavelength which is called selective absorption. Lambert's Law of absorption states that equal thicknesses of the same material absorb the same fraction of light.

$I = I_0 e^{-\alpha x}$

I = intensity of transmitted light
I_0 = intensity of light entering the material (excluding surface reflection)
α = the absorption coefficient in inverse length units.
x = the thickness of the sample (measured in the same unit for thickness as α).

Furthermore, Beer's law splits the absorption coefficient α into two variables, β an absorption per unit concentration coefficient and c, being the concentration of the material. Like Lambert's law this means that equal amounts of absorbing material, absorb equal fractions of light.

$I = I_0 e^{-\beta c x}$
I = intensity of transmitted light
I_0 = intensity of light entering the material (excluding surface reflection)
β = absorption per concentration coefficient (inverse length per inverse grams or moles per liter)
c = the concentration of the absorbing material.
x = the path length (length)

This is insofar important when the design intends to reduce the Intensity of transmitted light or filter certain wavelengths for protective reasons. Chapter 5.3 High Performance Materials – Aerogel deals with this effect in form of change of Visual Light Transmittance (VLT) throughout several layers of light absorbing materials as well as chapter 5.4 Statically dynamic Architecture by Smart Materials Energy. Here, Smart Glass can switch the Solar Heat Gain Coefficient (SHGC) to alter the passive heat gains.

Diffusion

Like diffuse reflection, there is diffuse (scattered) light transmission. This happens when e.g. sunlight hits a layer of clouds, parts get absorbed and the rest is transmitted in a diffused way. Same goes for e.g. frosted glass. Two factors are relevant for the diffusion of light: difference in refractive index between the materials. Wavelength of light compared to the geometry and size of particles in the diffusing material.

Filtering

Transmissive and reflective filters absorb certain wavelengths and transmit and reflect others. Looking at some window panes which appear to have a blue-green hue looking from the outside absorb or transmit the longer wavelengths of light and reflect the shorter ones. Same goes for sunglasses which give an orange/warm color. They absorb or reflect the more of the shorter wavelengths but transmit more of the longer ones.

Basic Radiometric and Photometric units

There are several common radio- and photometric quantities. In this research the most often used units to describe certain daylighting outcomes are illuminance and luminance.

Illuminance (E_v)

It is the photometric flux per unit area received by a surface or visible flux density. It is measured among others in lux (lm/m^2). This measurement is insofar of relevance since various building codes and regulations describe a minimum requirement in illuminance for a certain function which needs to be met.

According to e.g. EN 12464-1 lighting requirements for indoor work places, depending on the work task to be carried out, a maintained Illuminance E_m (average) is required on the work place surface where the values should not fall below the threshold value. Here office work needs to maintain a value of 500 lux. As comparison on a sunny summer day in Central Europe outdoor surfaces receive about 100.000 lux whereas on a cloudy winter day the outdoor surface receives about 9.000 lux. By knowing the minimum requirements, it is possible to design and evaluate the outcome accordingly.

Luminance (L_v)

Luminance is the illuminance per unit viewing solid angle and measured in lm/m^2/sr or the luminous intensity per unit area in cd/m^2. This means luminance is the density of visible radiation in a certain direction and comes closest to a measurable quantity which resembles a human's perception of brightness coming from any surface in the surrounding someone is looking at.

By using e.g. Radiance software ray-traced images can be made which show the appearance of space (rendering) and it is possible to overlay luminance "brightness" values. Therefore, it is also possible to evaluate visual disturbances in form of glare. Furthermore, luminance values are used by the industry e.g. to characterize the brightness of various displays.

A table of photometric Si units can be found in Appendix A – SI units and tables

3

Large (Span) Roofs

Daylighting for large roofs is fundamentally different from bringing daylight into functions behind vertical facades. Firstly, larger roofs cater for the need of a larger amount of people situated inside one single space than most singular rooms behind vertical facades do. Therefore, it is not possible to treat individual inhabitant’s needs, but it is required to look at the specific function a large roof has and derive from that daylighting requirements and a design approach. Secondly, the orientation of large roofs is in principle horizontally above ground which means that during the day, not taking obstructive high-rise structures nearby into consideration, the roof’s surface is lit from the moment the sun rises till the moment the sun sets. Vertical façades on the other hand are oriented, that means that a façade which is mainly oriented to the south has different requirements in e.g. shading than a façade which oriented towards north, east and west. For Large (Span) Roofs, all these orientations and changing sun angles in form of altitude and azimuth are to be taken into consideration during the whole day and year simultaneously. This also means large roofs in terms of daylighting face different problems then vertical facades do. Set the case a large roof surface is the only way to bring daylight into the building because its vertical facades are closed or obstructed while looking at more extreme situations during e.g. early morning hours or during winter noon at the northern hemisphere the daylight which is transmitted through the roof is not ending up directly on the floor underneath but on the far side. That means the light is not arriving at the location where it is needed but somewhere else. Thus, redirecting the sunlight can be a great concern for large roofs.

Figure 11. Roof transmitting daylight, Louvre Abu Dhabi, Ateliers Jean Nouvel, image source: Paasikivi

3.1 Distinction between large roof and large span roof

The difference between large roofs and large span roofs is of how the structural system is designed and whether the span over parts of the functions underneath or over the whole building. Both however can host similar programs. Large roofs have a column support underneath whereas large span roofs span from one side to another freely. Those will be employed when absolutely no columns should interfere with the functions underneath, i.e. swimming pools or sports halls. Different structural systems of large span roofs are cable-, textile-, pneumatic-, arch-, truss-, space truss-, beam-, frame, folded plate- or shell structures. Some of them can have column support underneath and will then be large roofs, others can only be designed as large span roofs. It is therefore important to think of a daylighting strategy in relation to structural and material elements or if possible to select a design strategy which gives the most flexibility for daylighting design. It makes a big difference to think of daylighting strategies for e.g. active thin concrete shell structures or a regular truss system. The first can be relatively thin and daylight could easily be transmitted without any obstructions but poses structural challenges, because adding holes and extra weight influences the force equilibrium, thus the geometry and material thickness must be changed. The latter truss system is structurally easier to design but its girder height acts as obstructive element for transmitting daylight into the interior. Notable design examples not only structurally but also in terms of daylighting are Felix Candela's tilted concrete umbrellas which when grouped together form a sort of saw-tooth (large) roof. Another version at the former High Life Factory in Mexico has integrated glass blocks to transmit daylight. A further example is Ingenhoven Architects' and Frei Otto's proposal for the Stuttgart main station (under construction) where a form found minimal surface structure integrates the daylighting strategy with the column system (large span none the less).

Figure 12. High Life Textile Factory, Mexico, Felix Candela, image source: Princeton University

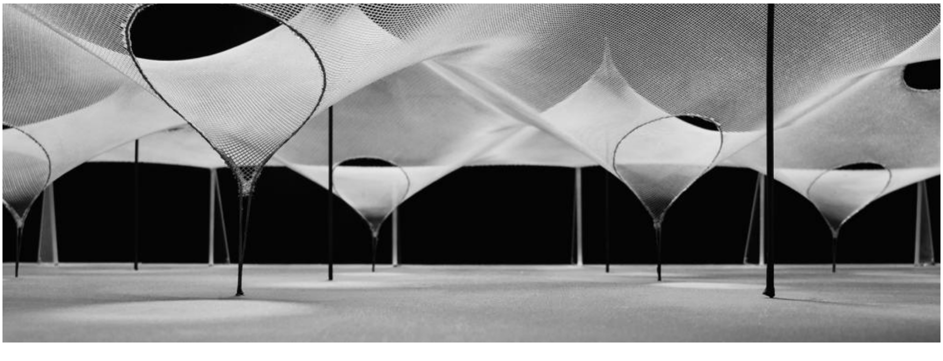


Figure 13. Stuttgart Main Station, Ingenhoven Architects, Frei Otto, image source: ZKM

3.2 Aspects of use –collective and individual

Peter Sloterdijk in Spheres III (Sloterdijk, 2004) makes a clear distinction between cohabitation, the role of the apartment related to the individual and in opposition to the upcoming democratic ideas of the French Revolution the need for gathering many people in form of collectors (buildings). These various forms of housing people are so fundamentally different from each other that the earlier can lead to vertical stacking seen in high rise buildings whereas the latter leads to horizontally laid out buildings. Thus, the most important interface between inside and outside be it apartment or office space is the vertical wall whereas the collector which houses a crowd of people is the (horizontal) roof. However, their purposes are different. Large (span) roofs do not take individual needs in consideration but facilitate the interaction between people or people and building's internal function rather than establishing a visual connection to the outside. In that respect a vertical façade in form of windows are not only important in terms of daylight but are the interface between the individual and the outside world. A large (span) roof on the other hand forms an envelope and due to the visual field of humans being wider in the horizontal plane vs. the vertical acts more as a background and not the focus point of attention, nor does it need to establish a visual connection to the outside in the same way vertical facades do, simply because in general there is not much else to see other than the sky. In some cases, like early shopping mall designs in the 1950s in the USA a visual connection to the outside is even unwanted since it potentially distracts the customer from shopping.

3.3 Examples of large (span) roof functions and the role of daylight

Sports

- Sport Stadiums
- Sport halls
- Swimming pools

Regarding sports it is important to determine whether the sport activities are for training purposes, recreation, smaller competitions, or professional competitions. Each country's regulations provide a set of rules to ensure minimal levels of illuminance. Professional sports with their respective professional organizations have more strict requirements due to TV broadcasting necessities and need to ensure that both teams playing against each other have the same conditions and one team is not in a disadvantage due to e.g. glare. Therefore, based on the specific sports activities and level of public interest, artificial lighting can play a more important role than natural lighting. In any case illumination highlights are not desired but an equal and homogenous light distribution is required. It is also important to note that not only diffuse light with equal lighting distribution is desired because human's 3-dimensional perception of objects or people in space is required. Since swimming is an activity which happens in or under water the athletes are not relying that much on visibility of objects in space. Therefore, diffuse lighting situations can be found in swimming pools. Notable projects regarding large roofs and sports function in relation to daylight are Olympic Swimming Pool in Munich or the National Swimming Center (Watercube) in Beijing by PTW Architects both with membrane roof elements which transmits daylight in a diffuse way. In chapter 5.3 as part of the case studies an example of membrane roof structure in relation to sports and daylighting will be explained more thoroughly.

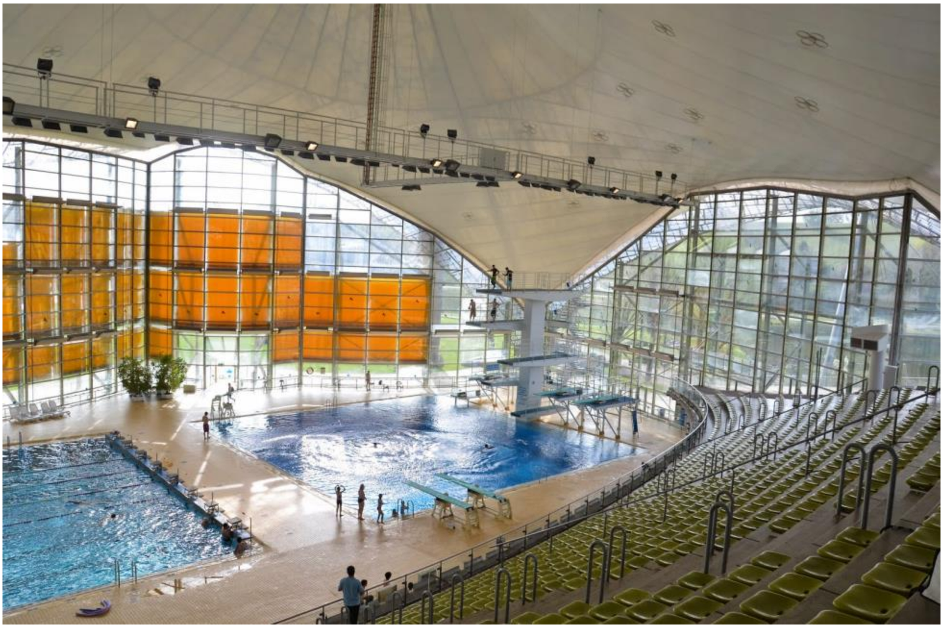
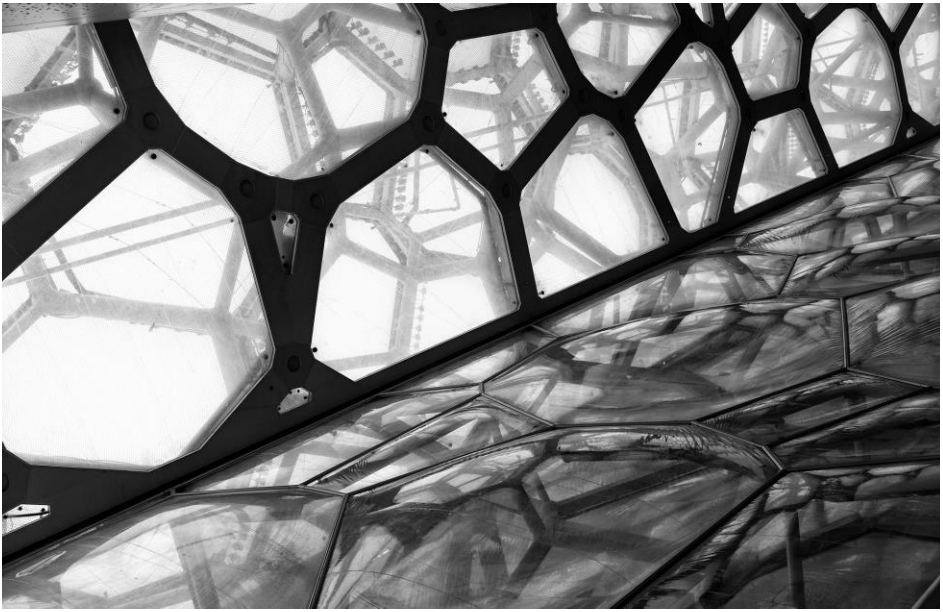


Figure 14. Olympic Swimming Pool, Munich, Frei Otto, image source: Dr. Helga Wäß



15. National Swimming Center – Watercube, Beijing, PTW Architects, image source: See-ming Lee

Culture

- Multifunctional halls & Convention centers
- Museum & Exhibitions
- Concert halls

Multifunctional halls as the name suggests need to cater for various uses and thus needs. Larger ones can be used for congresses, exhibitions but also TV shows. That means a Multifunctional hall needs to be flexible enough in terms of lighting design to be able perform for different requirements but also times of usage. Here a highly adaptive artificial and daylighting strategy is required. Concert halls on the other hand are often closed containers with little to no visual and lighting connection to the outside since major concerts happen during the evening hours. Here the acoustic qualities especially for classic concerts are the main design parameter. Museums are the more demanding building design tasks in terms of daylighting. Depending on the content some of the exhibited pieces like paintings and their permanency of pigments can be rather sensitive towards the UV component of daylight. Therefore, a lighting design strategy is also required to be implemented right from the beginning. Notable examples of large (span) roofs in this category are Kimbell Art Museum which is thoroughly analyzed in chapter 5.1, OMA's Kunsthal in Rotterdam, Frei Otto's Multihalle in Mannheim, Shigeru Ban's pavilion for the Hannover Expo 2000, his Centre Pompidou in Metz, the below ground situated Frankfurt Städel Museum extension by Schneider+Schuhmacher, or the Singapore Esplanade theaters.

Figure 16. Kunsthal Rotterdam, OMA, image source: Jacco van Giessen

Commercial

- Shopping malls
- Lobbies & Atria

Shopping malls, Lobbies and Atria are less restrictive in terms requirements of large roof design and daylighting strategy. Since they often house hospitality functions like restaurants too and are enclosed by various functions a visual connection to the outside at least in recent years is desired. Here the spatial atmosphere of the design and wellbeing of visitors plus iconic architectural elements play a major role. It is necessary to take care that the passive heat gain due to solar radiation is manageable. In combination with e.g. indoor gardens, direct light or a 1:1 daylight relation between inside and outside is desired. Galaxy Soho in Beijing by Zaha Hadid Architects, the Louvre pyramids shaped lobbies, etc. by I.M. Pei are notable examples just to name a view.

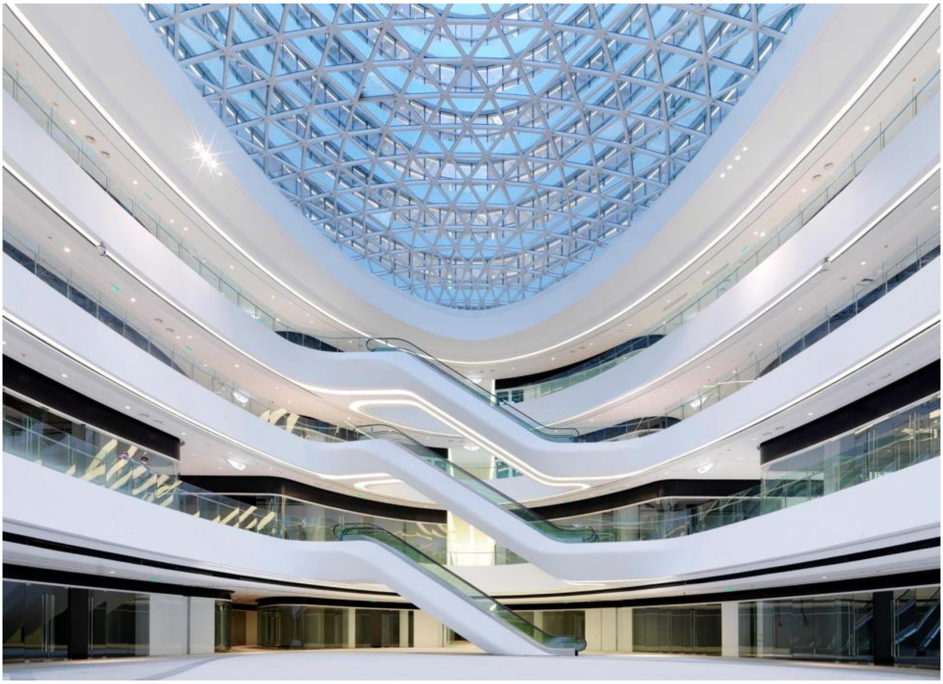


Figure 17. Galaxy Soho, Beijing, Zaha Hadid Architects, image source: Jonathan Leijonhufvud

Transportation

- Train stations
- Bus terminals
- Airports
- Ferry/Ship terminals

Buildings with large (span) roofs for infrastructural purposes and logistical operations also due to their spread-out layout (airports) need to foremost ensure that passengers are guided in a safe and simple way to their destination. These types of buildings also underlay different degrees of security measures. In general transportation buildings can be regarded as a more linear sequence of functions with different requirements like Entrance hall – Commercial zone – Terminals/platforms. The entrance hall serves as first orientation for people leaving or arriving directly connected to ticketing, information counters, check-in counters, other means of (public) transportation and people gathering or meeting upon departure or arrival. It also acts a sorting zone where then travelers get distributed into different terminal arms or platforms. Lighting for the different zones underlays local regulations for safe passage. The commercial zones after the initial security check, check-in or ticketing are dedicated to hospitality where travelers bridge their time before embarking. The final step is then distributing passengers on different means of transport be it plane, ship or train. The arrival/departure hall is rather well connected via a vertical façade to the outside. However due to its depth and dimension a daylighting system integrated in the roof can be necessary. Here visibility of signage, information boards and faces of people is important. The commercial zone between hall and terminals is less connected to the outside and has a similar purpose in terms of lighting like the earlier described commercial buildings. Train station platforms and arms of airport terminals are insofar different, because the earlier mentioned are compacted together and are arrayed under one large roof whereas the later are a branched system due to the large width of airplanes thus are narrower and therefore have vertical facades with view to the airfield outside. In any case visual disturbances like glare be it too bright by too high contrasts, especially between closed roof and vertical glass façade as backdrop should be avoided. Chapter 5.2 with the origami daylighting systems describes a form of spatial programming with daylight for various purposes e.g. in a building for transportation purposes. Further notable examples are Shenzhen Airport by Fuksas, Rotterdam Central Station, Queen Alia Airport by Foster & Partners and Birmingham New Street Station by FOA (formerly).

Figure 18. Rotterdam Central Station glass roof above platforms, image source: Jannes Linders

Industrial

- Storage facilities
- Factories

Industrial buildings which house a large array of machinery and facilities can also serve as historical examples like the application of saw-tooth roofs. Those were oriented towards north to only let diffuse daylight pass. Storage facilities where less people work simultaneously can none the less benefit from daylighting. In general cost efficiency to cover large areas and logistics are major considerations rather than architectural design aspects. A contemporary example is the BMW Werk Leipzig central building of the factory by Zaha Hadid Architects which connects several more conventional Industrial buildings and serves as hub of industrial flows in between. Daylight can enter via an array of glazed roof elements following the overall flowing geometry of the building. However, since various functions are stacked above each other like crossing conveyor belts daylight is obstructed, and artificial lighting is required.

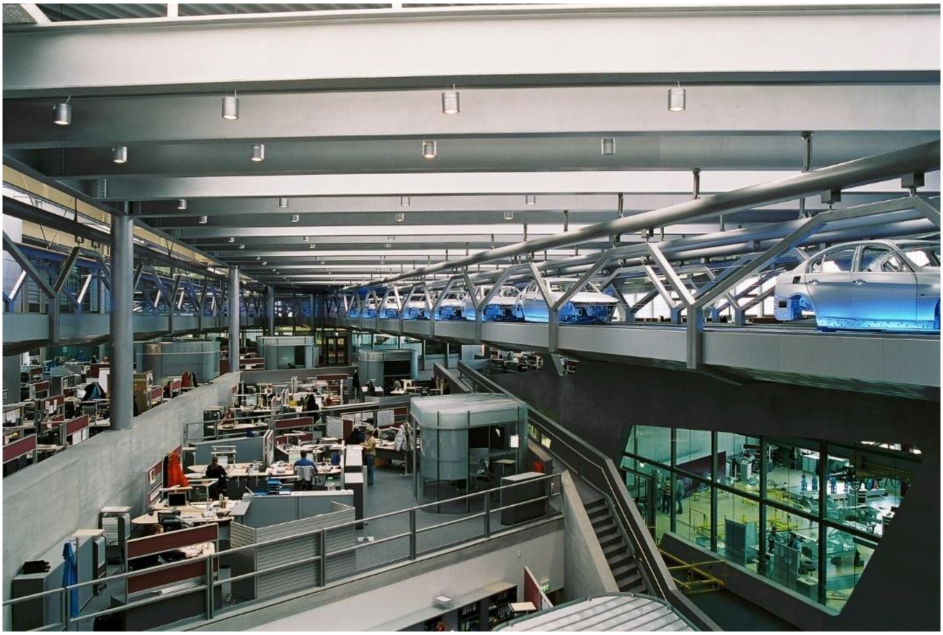


Figure 19. BMW Werk Leipzig, Zaha Hadid Architects, image source: Magnus Manske

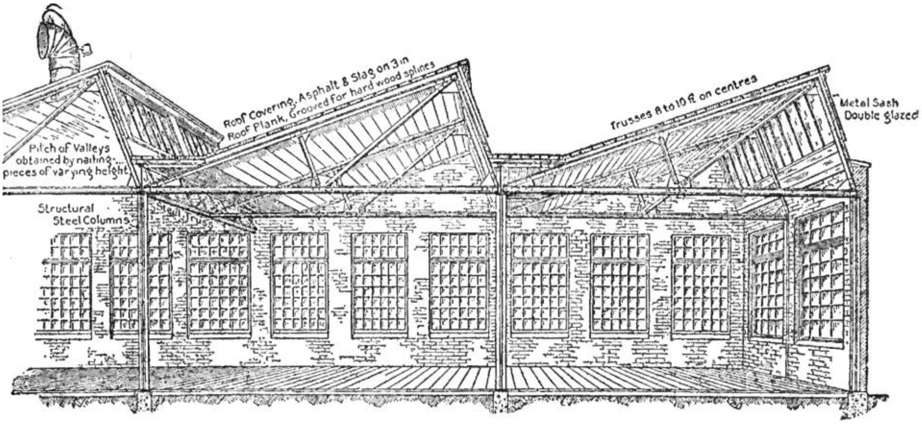


Fig. 159. Light Machine Shop—Saw-Tooth Roof Construction.

Figure 20. Saw tooth roof, image source: Radford's Cyclopedia of Construction by William A. Radford (1909)

4

Adaptive and Static

The reason for researching a design method for adaptive daylight system in large roofs is related to improvement of the buildings performance respectively. Performance driven daylight design as described in chapter 2 is hence the motivation to investigate and compare adaptive architecture and building components with non-adaptive ones. For that reason, it is necessary to understand different notions of adaptivity and their specific relevance for the current research work.

4.1 Motivation for Adaptivity

According to Schnädelbach (2010), cultural, societal, organizational and communication domains are motivators and drivers for adaptive architecture.

Cultural

Adaptive daylighting for large (span) roofs covering cultural buildings and especially museums it is important to assess the daylighting strategy from the perspective of visibility aspects of the to be exhibited artifacts. However, it is required to figure out beforehand whether the exhibited samples need protection from direct UV light such as paintings or intended to be displayed under changing lighting conditions such as e.g. sculptures. The first case would *ask for* an adaptive daylight system which is able to equally distribute light and filter out UV rays and cope with changes in the daylighting situation in real time to enhance the visual quality and show all the details of the painting. The later would not necessarily require any adaptive daylighting solution since the appearance of 3-dimensional sculptures through their materiality, e.g. glossy or rough surface thus quality of reflection of light, or the way they cast shadows under different lighting conditions is essential to the work and the artist's or curator's intention. However, it would be interesting to design an adaptive daylight system which is able to generate various lighting situations be it direct light or diffuse light under the same daylight condition to highlight and show sculptures in a varied way independently from the external lighting conditions.

Societal

Beyond talking about environmental or energetic aspects Schnädelbach (2010) writes about life style and highlights several examples such as the Japanese residential houses which would require adaptivity. This is rather difficult to compare or draw parallels since large roofs naturally facilitate a rather diverse group of people with different interests instead of a more homogenously structured family or individual. In this case however it can mean that immediate functional or programmatic changes which influence the way we interact with the building can be the motivator for an adaptive daylight system. In case we talk about more long-term changes in occupation or changing circumstances it would fall under the organizational category.

Organizational

Change in lighting requirements is not tied only to daily and seasonal external changes in daylight conditions but also to the building's changing requirements for functions. As example, one could think of a trade fair hall, where an adaptive daylight system can cater to the needs of specific exhibitors for the time being.

Communication

Flow management is stated as one of the drivers. Terminal buildings be it most notably airports but also train stations require to guide people safely to their destinations like gates or platforms within the building. Here not only a constant quantity of light but also a specific quality like even distribution is required. An adaptive day light system designed specifically for way finding and setting highlights where needed while achieving visibility, safety and spatial structuring can facilitate that. This again could be done to cope with changes in the external daylight conditions in real time but also due to organizational changes like e.g. a train arrives at another platform like originally intended. The change is usually announced via often difficult to understand loudspeaker announcements but could be enhanced by temporarily highlighting the new platform destination.

Further Schnädelbach (2010) illustrates the need to understand in reaction to what architecture needs to be adaptive which he describes as inhabitants, interior and exterior environment and objects. This is already covered in examples in this chapter. However, it is relevant to note once more and especially relevant for large roofs: "*Designing for adaptiveness for groups of individuals can be a real challenge in turn.*"

4.2 Building Components adaptive and non-adaptive

Regardless whether architecture or parts of it are adaptive or not, one must clarify which elements of the building are active in terms of their performative aspect and specifically regarding daylighting for the current research.

A way to describe buildings' components is based on building layers with different time scales or life expectancy (Brand, 1994).

- Site – The geographic setting
- Structure – The foundation and load bearing elements
- Skin – Exterior surfaces
- Services – HVAC, etc.
- Space plan – The interior layout
- Stuff – Furniture, kitchen appliances, etc.

Another way to describe elements (of adaptation) is by the categories surfaces, components, modules and spatial features (Schnädelbach, 2010)

a. Surfaces, external (facades) and internal (image projection/information)
  - Mechanical adaptations
  - Lighting and display technologies

b. Components and modules
  - Re-use
  - Adaptive internal partitions
  - Components/Units that can be removed and relocated

c. Spatial features
  - Location
  - Form
  - Typology
  - Orientation
  - Link between inside and outside
  - Internal partitioning

Brand describes more of a long-term adaptation related to change of use, etc. However, looking at both descriptions regarding large roofs and large span roofs it becomes clear that the research is dealing with skins (Brand, 1994) and surfaces (Schnädelbach, 2010) as focus point and the structure or spatial features as secondary aspect. This means for this research that the roof surfaces in form of perforations or a population of elements which constitute the whole roof are adaptive in either their geometry and/or material property to manipulate the transmitted daylight. The secondary aspect which are the structural elements do not necessarily be adaptive. They hold the skin into place. Obviously, the distinction in functional aspects as well as elements is not that simple when one deals with large span roofs like shells where the skin itself becomes the load bearing structure. In addition, Schnädelbach (2010) describes retractable roofs as a link between inside and outside and places it under spatial features. With respect to the link between inside in outside one can argue that surfaces and skins should also be attributed with this feature. It is important to note that retractable roofs are not part of this research because of their lack of ability to manipulate the transmission of daylight. They are either closed which can be regarded as total absence of light or opened where in that case one gets 1:1 the same lighting condition in the interior as at the exterior. Change in the lighting condition or manipulation of daylight does not really happen.

4.3 Static contextual buildings

Before going into adaptive buildings, one must investigate regular, static buildings regarding their potential performance aspects and the way those are designed and the differences. The Kimbell Art Museum is a good example where the geometry and material selection are done under direction of daylight performance aspects/parameters and is described in more detail in chapter 5.1. The static contextual building can handle changes in the environment in form of a general solution dealing with all eventualities, in this case daylight but does not change itself to do so. Here, performance aspects of buildings are directly related to their context and environment they are placed in. The environmental aspects form the design parameters which drive design decisions and become the generative medium. In terms of daylighting this has to do with the sun's altitude and azimuth angles during the day and year but also atmospheric conditions and light quality. No matter if one is designing a static contextual building or an adaptive one in both cases the application of design parameters is essential. The difference however, is the way how these parameters are understood and handled. In a static building where the building or elements thereof are not able to cope with changes in real time, one uses a specific condition to be met (e.g. worst case) or statistical means as design parameters. This means during the design process one is not dealing with the actual but tests the design performance during peak moments or worst-case scenarios, deducting that all the other situations will be covered (more or less).

A specific condition can be a certain sun altitude and azimuth during the year when heating periods are changing in spring and in autumn and daylight can directly penetrate the skin and passive heat gains are desired. This potentially performs most of the time well but when there are extreme conditions which fall out of the frame of the design parameter, the static building cannot cope with that situation.

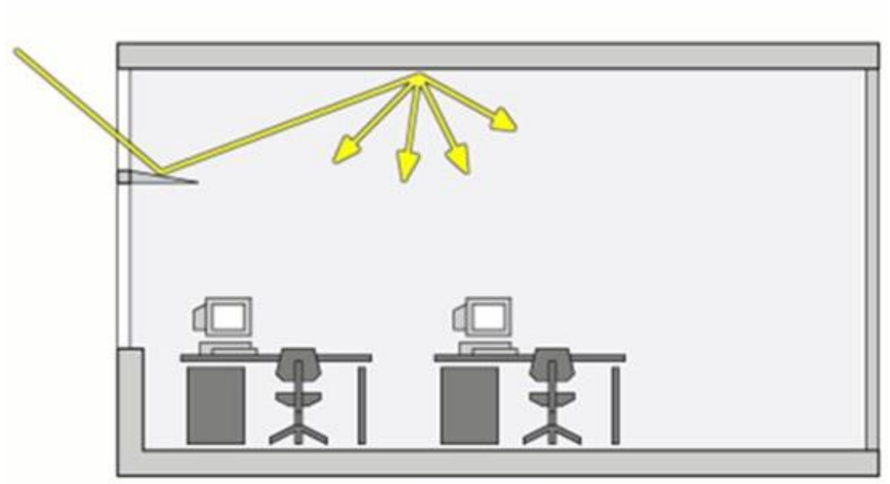


Figure 21. Light shelf, image source: Schorsch

A statistical mean as design parameter can be a merging of several different conditions of the same design space which covers the whole ranges between the extremes or boundaries. Thus, a design solution will always perform somehow. An example of this is a Sun Tunnel. Albeit a very complex and well thought geometry in terms of curvature and Fresnel refraction, a specific sun angle does not matter, because sunlight is always redirected into the interior, just not the maximum of which is possible.

Figure 22. Sun tunnel, image source: Velux

4.3.1 Geometry and Materiality

In daylighting the interaction of material as well as geometrical properties are relevant. The former determines for instance how daylight is transmitted or reflected like diffuse or specular, the latter is important with respect to how much light or energy for example is transmitted or reflected due to angular relations between the surface itself and the sunlight. Both can alter the qualitative and quantitative properties of light. The distinction is important to highlight not only due to achievements in recent material research and design development in form of digital design tools including manufacturing possibilities but also to understand how the two properties are contributing to the performance of a building. For instance, in terms of insulation and thermal resistance the geometrical aspect of a wall element is much less important than the material one. In case of structural performance and in the case of daylighting one can argue that both aspects are equally important. In terms of design effort of adaptive architecture geometrical and material aspects will have even a higher impact than static buildings since either material properties and/or geometrical configuration can change over time and all eventualities for those different configurations with respect to the changing boundary conditions need to be taken into consideration.

4.3.2 Adapted Geometry (Smart & static geometry)

Looking into geometrical aspects of a static contextual building, a known example could be a shell structure, where due to the “dome” like geometry of the surface the load travels along it in form of compression. The shape was specifically designed, or form found to be able to do so, thus it adapted. As a result, the roof can span a much larger distance with lesser material use than with a regular structure.

4.3.3 Materials and High Performance materials

Regarding materials and High Performance Materials (Addington, Schodek, 2005) which do not adapt or change according to an environmental stimulus, are static, thus always have the same material properties. High Performance Materials perform however better than their regular counterparts or a tailored for specific tasks. This can be for instance Ultra High Performance Concrete for the case of shell structures where one could make even thinner shells, or vacuum insulation panels where much less thickness is required to insulate sufficiently, or aerogel insulation which besides the thermal performance additionally transmits light.

4.4 Adaptive buildings

4.4.1 Reaction

The reaction-based classification of adaptive architecture explains in what way the building element is reacting in its physical state. In the case of this research it is dealing with skins and surfaces in forms of openings to transmit daylight. These openings can basically be manipulated in two different ways either in form of a geometrical change where systems are described under reconfigurable/kinetic Architecture (Kirkegaard, Foged, 2011), (Zuk & Clark, 1970) or a change in material properties which falls under Statically Dynamic Architecture (Turrin, 2014).

4.4.1.1 Kinetic Architecture by Adaptive Geometry

Several researches which are dealing with reconfigurable or kinetic architecture make a distinction between various aspects of what changes within a building. This can be related to the scale, to building elements or components to technical systems. The following section gives an overview of various classifications and what it means for the current research.

Technical processes (Zuk & Clark, 1970)

- Kinetically controlled static structures (controlling deformation in structures)
- Dynamically self-erecting structures (Example self-erecting crane or tent)
- Kinetic components (movable partitions, roofs, rotatable buildings)
- Reversible architecture (container architecture, demountable)
- Incremental architecture (growing according to need, not pre-thought)
- Deformable architecture (form change as a whole, e.g. scissor systems)
- Mobile architecture (building moves as a total unit)
- Disposable architecture

Intelligent kinetic responsive systems (Fox, 2002)

- Embedded (in fixed location but controlling the whole building)
- Deployable (temporary location)
- Dynamic kinetic structures (in fixed location but controlling parts of a building)

Based on means of kinetic structural solutions (Kirkegaard, Foged, 2011)

- Pneumatic
- Chemical
- Magnetic
- Natural
- Mechanical

Earlier classifications talk especially about the elements of the building which are changing and their contribution in form of functionality and life span but already imply performative aspects. Since material sciences were not that far yet, the systems which are described by Zuk & Clark (1970) were of pure mechanical nature. Later research describes a geometrical morphological change which is not only of mechanical nature but also mentions processes based purely on materials. For the sake of the dissertation it is important to state that kinetic Architecture can be actuated mechanically as well as exclusively on a material level but in either case, they have an impact on the geometry on the building component scale. In plain words the user can observe moving parts whether they are mechanical, pneumatic or on the material level is not important. In the case of daylighting one can imagine an aperture opening and closing with the help of Smart Composites based on shape memory polymers (Lelieveld, 2013) purely based on internal material mechanical properties and not hinges. However, in this case the material's surface does not change its microscopic surface structure and how light is reflected but undergoes a visible geometrical change of the angular relation between incoming light and reflecting surface.

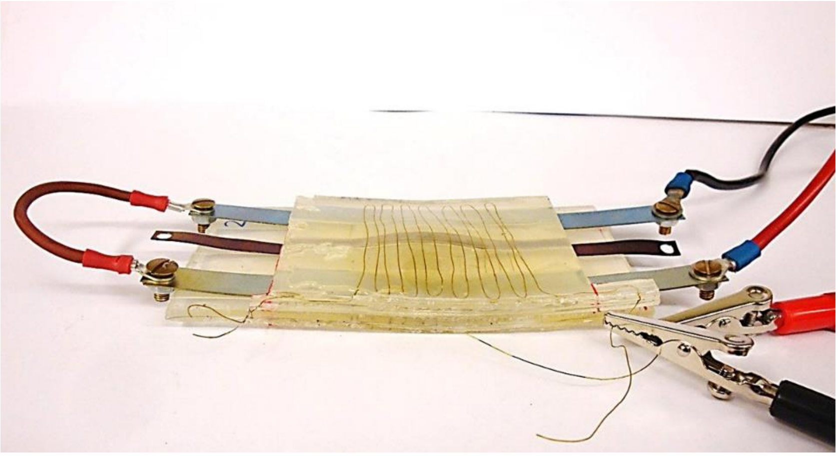


Figure 23. Smart Composite, image source: Charlotte Lelieveld

4.4.1.2 Statically dynamic architecture - by Adaptive (Smart) Materials

Smart Materials are not only described by what causes the change in the material properties (sensing), but also how they change, what of their properties are changing and level of smartness or intelligence. Michela Turrin (2014) coins the term statically dynamic architecture in her PhD dissertation and describes systems which are not undergoing a geometrical change but within material properties only. For daylighting this is a rather important aspect to investigate materials which can alter the way how daylight is transmitted, e.g. diffuse, spread, specular, or collimated (unchanged parallel direct sunlight) or converged/diverged (bundled rays), the way they are reflected e.g. diffuse, spread or specular and finally the change of quantities (absorption) and alteration of bandwidth of wavelengths being transmitted.

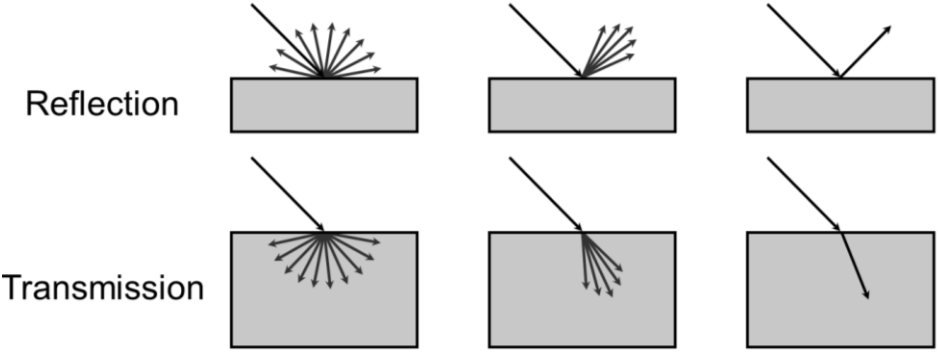


Figure 24. Light reflection and transmission, diffuse, spread, specular, image source: Elemental Ray

Statically dynamic architecture has a great potential since only building's or the element's static geometry and the relation of the surface to the sun's path must be considered and not a geometrical change itself. That can result in a greater design freedom and a reduced complexity because the performative aspects can be regarded in a more traditional and separated way according to layers of building physics performance and eventually they do not impose a certain aesthetics or style. This is especially relevant for a European context also in relation to the last financial crisis where less new buildings are done but more focus lies on renovation, improved energy efficiency and (re)use of the existing building structure. That means that the energy and daylight performance of a historical monument can be improved by e.g. smart glass without drastically changing the building’s appearance.

Figure 25. Amsterdam Central Station, image source: Tommy Farnsworth

The clear distinction between kinetic architecture and statically dynamic architecture is not intended as a dogmatic stance of either or but serves as a model for understanding. In many cases it is possible to think about hybrid systems of both especially considering the design of adaptive daylighting systems for new buildings.

4.4.2 Interface

This chapter deals with the interface between inhabitant, external natural lighting condition and the skin or more specifically daylighting device as mediator between both the internal requirements and the external givens.
Due to the nature of large roofs, the individual user interaction is not so much of relevance but taking the lighting need of a larger group of people into account who are simultaneously occupying the space as well as programmatic aspects. To illustrate the example in terms of lighting one can look at two cases, office room and station hall.

The office room's program is working at a desk in front of a computer, thus sufficient illuminance of 500lux (EN 12464-1, 2002) is required on the table. Glare between window screen, office background and computer screen in form of high contrast as well as glare from direct light entering should be avoided. The space is occupied by a small group of people or an individual which in addition would like to have a visual relation to the outside. Since personal preferences are varying, the occupant in general demands to be able to adjust his environment according to his/her needs. The interface must be designed in such a way to allow the input of the occupant. Therefore, the design parameters are quantity of light, quality of light, visual comfort, outside view and individual interaction. In terms of user interface this could be solved in various degrees of automation (Turrin, 2014).

- Passive adaptive: Louvers and blinds which are operated by the user manually
- Semi passive/semi active: Automatic louvers and blinds which react to the light conditions in an automated way but can be overridden by a switch.
- Full automation: Automatic louvers and blinds which can be programmed or know the user's preference by learning

The station hall is the lobby of the train station welcoming travelers as well as directing them safely and efficient towards the platforms. Not only sufficient illuminance of about 150lux (EN 12464-1, 2002) on the floor is required but also an even light distribution and high visibility of signage and passages which can be established by diffused light. Also, high contrast for visual comfort should be avoided. However, the individual preference of the traveler in terms of lighting outside view are marginally relevant. Sufficient quantities of light and qualitative aspects stemming from safety demands are the leading design parameters. An adaptive daylight system within the roof must mediate between daylight availability and quality and functional requirements which goes so far that once sufficient illumination levels cannot be reached by natural means, artificial light must be turned on. Since needs of individuals are not relevant nor intended passive adaptive systems or semi passive/semi active systems of automation are excluded and full automation is the only possible solution.

- Full automation: Sensing of exterior and interior lighting conditions which automatically adjust the roof openings, possibly in relation with artificial lighting, climate control and emergency measures.

Since one can conclude that full automation is the only solution for interfaces in adaptive daylighting for large span roofs, the next question would be how this is to be achieved? Here the work of Adington & Schodek (2005) as well as Velikov & Thün (2013) give several answers by defining the terms and making a distinction between Smart or Intelligent architecture.

Intelligent (Addington, Schodek 2005)
"Intelligent is the ability to acquire knowledge, demonstrate good judgment, possess quickness in understanding"

Smart (Addington, Schodek 2005)
"'Smart' implies notions of an informed or knowledgeable response, with associated qualities of alertness and quickness."

Smart & Intelligent (Velikov, Thün 2013)
"The biggest difference, therefore, between terms "smart" and "intelligent" is that in the case of the former functionality results from intrinsic material properties, whereas in the latter performance is primarily controlled through computation and automation. The performance profile of intelligent envelopes is typically more variable than that of smart skins; the operation of smart skins is typically binary and more limited in control, while intelligent envelopes typically require external power to achieve their goals. Hence, when committed to overall building energy reductions, intelligent envelopes should ideally be developed with smart materials that are self-powering and self-actuating."

Smart skins/envelopes based on smart material systems have the nature like beauty that sensing, processing and actuation can be entirely integrated within the material itself and are often not distinguishable as separate entities. This makes solutions based on material systems also resilient and compact. However, that also means that during the design phase the performance criteria must be exactly defined because once the adaptive properties of materials are "baked" into the final configuration changing them afterwards is hardly possible. That also means that building skins which are designed for certain functions or programs in mind have difficulties to evolve over time according to general changes in functionality. This is most critical especially when sensing, processing and actuation happen within the material. To illustrate that, two different smart materials are described:

Latent heat storage in form of Phase Change Materials or so called PCMs (James, Delaney, 2012): Like ice turning into water, turning into vapor, PCM does the same just at different temperature points which are suitable for applications in the built environment. Here the phase change from solid to liquid is utilized and while this happens thermal energy is stored inside the material while the temperature of the material and indoors does not rise. This effect can be used in light building constructions which lack thermal storage capabilities of heavier constructions such as brick or concrete to buffer thermal energy between inside and outdoor temperatures. The critical aspect in terms of design is choosing the volume and melting temperature of the PCM in relation to the climatic conditions present at the location where the building is to be situated. After the building is finished changes in the thermal profile due to climatic changes or internal loads are difficult to deal with due to the inability of the material to alter its melting temperature accordingly.

Smart Glass with LCD coating (Khandelwal, Loonen, et al., 2015) can change their solar heat gain coefficient (SHGC) due to the possibility to acquire different tints or a third translucent state via switchable broadband infrared reflector using polymer stabilized cholesteric liquid crystals. The three different states are stable only requiring an external electric current to switch from state into the other. Smart Glass can be categorized as Smart Material because the change in properties happens due to "flipping" of molecules and not mechanical elements. However, sensing, processing and actuation are separate systems. That also means that smart glass can be integrated into a larger coherent home automation system which potentially can learn or is able to be regulated in a much more sophisticated way.

As already suggested by Velikov and Thün (2013) the aim within the research for adaptive daylight systems in large roofs is to find intelligent skin/envelop solutions because lighting is not a discipline which can be seen separated but has a close relationship with other disciplines which are mostly climate related. In that sense natural lighting is plugged into a larger building environmental context where several aspects come together and must be adjusted in relation with each other. Such buildings have a much larger potential to learn or evolve not by changing material layers but by the alteration of the programming, implementation of more sophisticated software or integration of databases and self-learning algorithms.

5

Case studies

In the following chapter several case studies of existing buildings or building components and own design proposals & research are analyzed with respect to the in chapter 4 explained differentiation of Static contextual buildings – Adapted Geometry & High Performance Materials and Adaptive Buildings – Kinetic Architecture & Statically dynamic Architecture.

Static contextual buildings

a. Adapted Geometry
  - Kimbell Art Museum
  - Origami Roof Structure

b. High performance Materials
  - Aerogel Insulation – Membrane structures

Adaptive buildings

a. Kinetic Architecture - by adaptive geometry
  - External shades (Origami)

b. Statically dynamic architecture - by Adaptive (Smart) Materials
  - Smart Energy Glass

Each of the Case studies will be explained out of several perspectives to make the reader understand how those were designed or in case of products how those can be applied and under which circumstances. In some cases, there will be a suggestion of how to improve or alter a design and how to come up with an adaptive solution.

Structure of Analysis:

- Context
- Function and Layout
- Lighting requirements
- Design process
- Geometrical & Material Aspects - Technical solutions & systems
- Lighting Analysis and Alternatives
- Conclusion

5.1 Static Contextual Buildings – Adapted Geometry – Kimbell Art Museum

5.1.1 Context

Historical

The Kimbell Art Museum by Luis Kahn located in Fort Worth, Texas, United States of America was designed and executed from 1966-1972. The exhibition of art ranges from pieces of antiquity to contemporary pieces. During the design process in terms of general layout roof shape and natural lighting solution, several options were developed, and the design process was finished in September 1968. Natural light was an important design parameter right from the beginning and was a concern of the Kimbell's first director Richard Brown (Park et al., 2007).

Figure 26. Kimbell Art Museum, view from South-West, image source: Carol M. Highsmith

Figure 27. Kimbell Art Museum, North gallery, image source: Michael Barera

Environmental

Fort Worth is in North Central Texas at 32°45’26,49”N 97°19’59,45”W and has a humid subtropical climate (Cfa) according to Köppen climate classification system. Cfa stands for: Warm temperate – fully humid – hot summer. The highest average high temperature is around 35,2° Celsius in July and the wettest month is in May with an average of 9,3 precipitation days with 130,8 mm of precipitation. In terms of natural lighting cloudy and overcast sky conditions with diffuse natural light are to be taken in consideration. Potential overheating of the building during the summer months can be an issue.

Date	Altitude	Azimuth
21.06	78,49°	140,75°
21.12.	33,44°	163,28°

Table 2. sun’s altitude and azimuth at 12:00

That means during the design one must deal with a delta of around 45° in sun’s altitude between summer and winter time.

5.1.2 Function and Layout

The Kimbell Art Museum went through several design iterations (Park et al., 2007). In its final form the museum consists of sixteen 100 feet or 30.5-meter-long, in north-south direction extruded vaults organized in three rows of six, four and six vault elements. The most western column of vaults is a roof covering an outdoor area. The middle row with four vaults house the entrance with stepped courts and is connected via the street and the Modern Art Museum of Fort Worth on the east side to a park on the west side. All major exhibition spaces, auditorium, lobby museum shops, etc. are on the ground level and secondary functions are located one floor below.

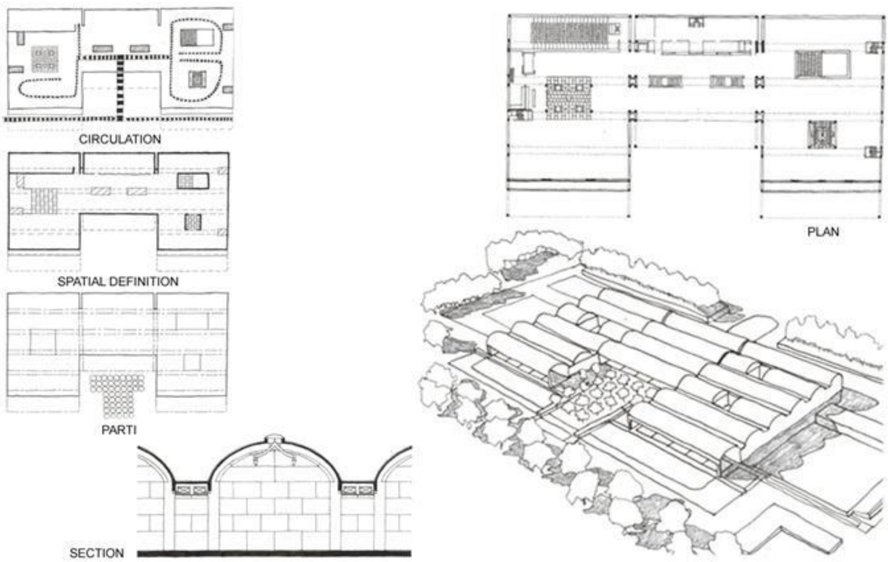


Figure 28. Kimbell Art Museum, plans, section and perspective image source: Chad Boardman

5.1.3 Lighting requirements

In terms of functional requirements for art exhibitions, the intention (Park et al., 2007) was to make use of natural daylight which is often not desired in museums showing pieces of art since the UV component of the sunlight causes massive damage in the pigments of paintings. Apart from UV protection it also required to have an even, constant and diffuse light distribution for the legibility of paintings.

5.1.4 Design Process

The design process started in 1967 and the final scheme was derived in September 1968. During the design process several general building layouts were looked at starting from a square with courtyard to an H-layout and finally the C like arrangement in its current form (Park et al., 2007) was found. Also, the roof shape in cross section evolved during the design process. Kahn proposed in the beginning a polygonal design and later semi-circle, however Marshal D. Meyers project manager of the Kimbell found this solution obstructive in terms of height of the exterior appearance, thus the less high shape of the cycloid was developed and finally built (Park et al., 2007). In terms of lighting design Richard Kelly was from an early stage on involved (Oberkircher, 2001). This also included the advice to take care of the damaging aspect of the ultraviolet light coming through the sky lights. It was ultimately Kelly’s input which determined the shape, materiality and perforation of the wing shaped reflectors on the underside of the vault. One year later Isaac Goodbar working at Edison Price developed a computer program to calculate the position of the reflectors and light intensity hitting the underside of the concrete vault (Oberkircher, 2001).

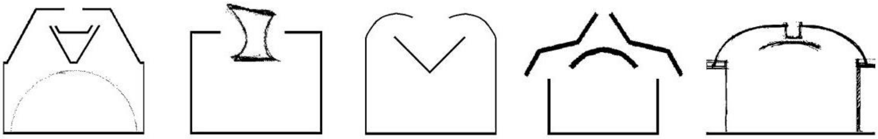


Figure 29. Design option vault cross section, image source: Park, et. Al.

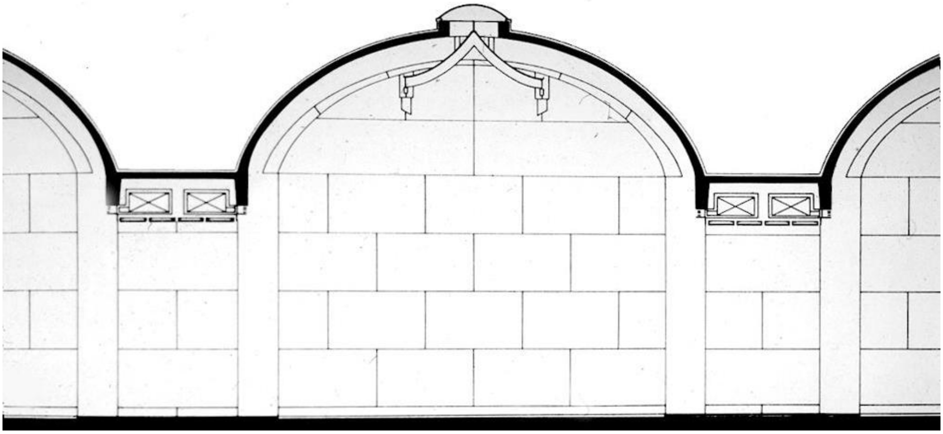


Figure 30. Cross section Cycloid vault and reflector, image source: Luis Kahn

5.1.5 Geometrical & Material Aspects - Technical solutions & systems

The resulting natural lighting scheme is an interplay of geometric and material aspects. According to Kelly (IESNY, 1993) the materiality and geometry of the reflector plays a significant role. The specific interplay of the top opening slit, the vault geometry and reflectors and their material properties for achieving the desired lighting outcome also in terms of the classification of Adapted Geometry is especially interesting for the research since these are the most obvious characteristics. During the design process a specific hierarchy of design parameters seems to be present. In the beginning Kahn experimented with several building layouts, roof shapes and reflector ideas to reach an even light distribution yet a distinguished readability of daytime projected into the interior. The top slit in the roof was already present at an early design stage. In a second stage the shape of the roof in form of the cycloid was designed and as response to that the reflectors were developed. It also was clear that the vaults would be made of concrete. In that sense a clear cause and effect relation is at hand. The slit and the vault materiality and geometry are given and as response to that the reflector geometry and materiality was developed. The reflectors are made from perforated (24% perforation) bent aluminum in a gull wing like section suspended from the ceiling. They are joined on the upper part by a folded lip extending into the opening slit to prevent direct sunlight from entering during low sun altitude angles. The aluminum reflectors are perforated, albeit less of the light will be reflected, the underside does not appear that dark and it was claimed that the visual coherence is more even since the visitor does not see a dark stripe up on the ceiling (IESNY, 1993). Also, a fraction of the daylight is in this way transmitted into the central part of the room. Although the Kimbell Museum is already well documented and researched in terms of daylight (Kacel, Benson, 2013), (Altmann, Apian-Bennewitz, 2001) the relative simple system the Kimbell presents an ideal case for studies because the complexity in design solutions can unfold in further research also in terms of adaptive systems and several “what if” scenarios are shown in a later stage.

5.1.6 Lighting Analysis and Alternatives

The analysis of the building and its lighting performance is a reverse engineering approach and consists of several steps.

- Parametric 2-dimensional sections of one vault
- 3-dimensional model and daylighting analysis of existing geometry and materials
- Design and analysis of alternative reflectors geometries and material properties
- Design and analysis of an adaptive reflector geometry and material properties

Parametric 2-Dimensional sections of one vault

The parametric section is set up in such a way to get a rough indication how the sunrays are reflected. This happens via in cross section projected vectors coming from the sun’s altitude and azimuth angle. With that it is possible to flexibly adjust any given sun angle throughout the year. The vectors according to their angular relation via the normal towards the reflector’s curve get reflected onto the vault where in a similar way the vector gets reflected into the interior space. This parametric section serves two purposes. Firstly, to understand in what way the rays get reflected and secondly for the later stage as early assessment tool to try out alternative reflector shapes and an adaptive system.

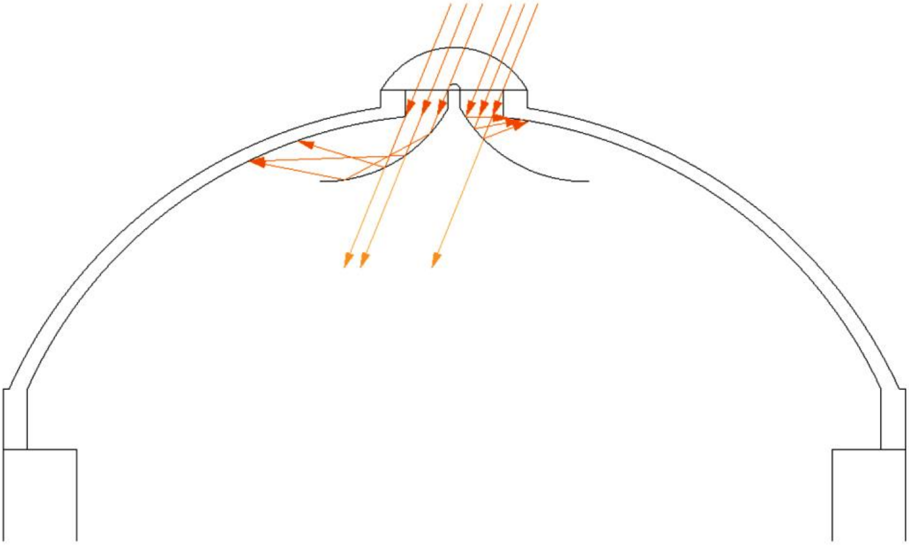


Figure 31. 2-D parametric section for estimation of sun ray reflection

3-Dimensional model and daylighting analysis of existing geometry and materials

The 3-dimensional model consist of one 30,5m long vault which is closed on both sides to see the effect of only the north-south oriented roof light in the interior. It is modeled after original drawings and the material properties are set according to the real materials within Radiance. Here several simulations were done for different times and seasonal settings.

Test 1

This simulation compares 5 cases on the 21st of June at 12:00 under clear sky condition in terms of illumination, luminance levels and visual comfort and most importantly natural light distribution. The 2-dimensional parametric diagram predicts that due to the incident sun angle the left side will have light reflected deeper into the vault.

This first set of tests is looking into the way how the existing reflectors are reflecting the incoming sunlight. With a specular reflection the light remains reflected parallel or in the case of the round shaped reflector trough converged. The diffuse reflector on the other hand has also a converging element, however the light rays are scattered much more.

The test also compares the material parameters of the aluminum reflector. Here a perforated one is compared to a solid one. One of the reasons is to evaluate the impact of the perforation as stated by the designers on visual comfort and lower contrast ratios between the underside of the aluminum reflector and adjacent concrete ceiling. Another aspect is to see the impact on illumination levels on the ground since part of the light in the perforated version is not reflected but transmitted according to the sun’s angle. Another issue is to find out whether it is feasible for further studies to entirely use a solid solution instead of the perforated one (for various reasons such as texture mapping specifics in Radiance). Within the Radiance simulation environment, the openings are not defined according to a UV mapping like in contemporary render engines which are able to e.g. cylindrically wrap a map with an alpha channel for openings around the geometry. Instead one must define a plane of projection where the openings are applied. With planar surface this is not much of a problem, however since the reflectors are curved extrusions this means that the perforation is more stretched the more the curvature goes in the z-direction according to the absolute coordinate system.

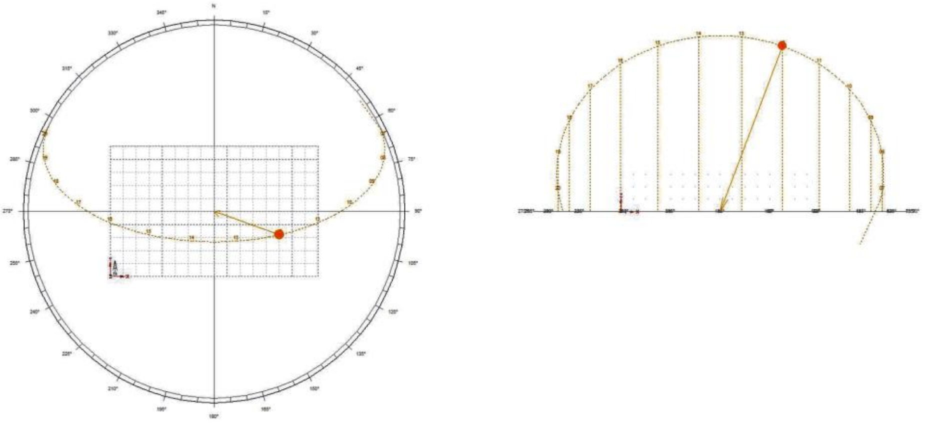
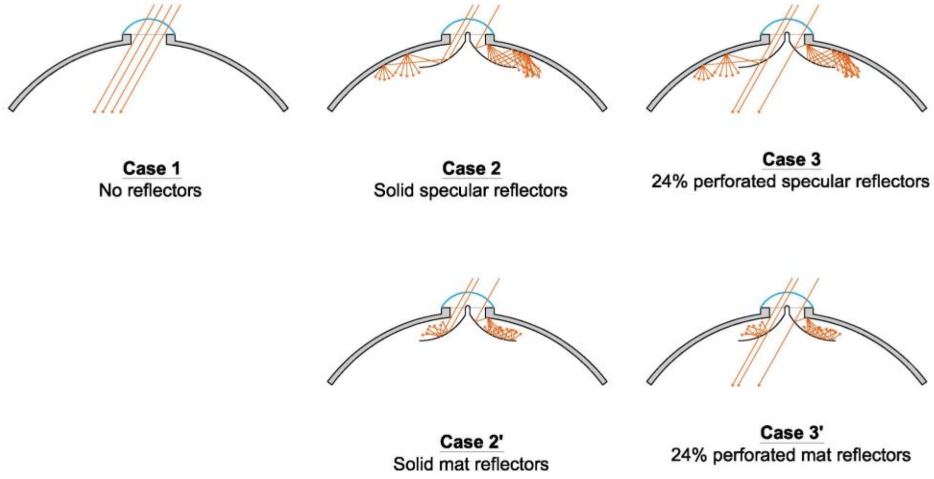


Figure 32. Fort Worth, Texas sun path, 21/06, 12:00

Floor	**Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)**
Walls (long sides)	Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides)	Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault	Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane	Single pane (0.962/ 0.962/ 0.962)
Case 2 Solid aluminum reflector specular	Aluminum (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Case 3 Perforated aluminum reflector spec.	Perforation -s 0.0025 perforation 24%
Case 2' Solid aluminum reflector ideal diffuse	Aluminum (0.9/ 0.88/ 0.88/ 0 / 0)
Case 3' Perforated aluminum reflector dif.	Perforation -s 0.0025 perforation 24%

Table 3. Material settings for daylight simulation Test 1



Case 1
No reflectors

Case 2
Solid specular reflectors

Case 3
24% perforated specular reflectors

Case 2'
Solid mat reflectors

Case 3'
24% perforated mat reflectors

Figure 33. Reflector cases 1,2,3,2',3'

Case 1

The first case has only the opening slit on top of the vault and no reflectors underneath to examine how the space would be lit without and to see how direct light is transmitted into the space. It is also of interest to compare especially levels of illumination but also luminance in the interior with the other results to examine the “loss” the reflectors are causing.

Case 2

The second case consists of the original shape of the reflectors with specular reflection properties of the aluminum and no perforation.

Case 3

The third case has the same material properties as case 2. However, the reflector is 24% perforated according to information found in literature.

Case 2’

This case consists of the original shape of the reflectors but has a diffuse light reflectance and no perforation

Case 3’

It has the original shape, the material properties of case 2’ but has 24% perforation.

Summer 21.06., 12:00, Clear sky with sun results

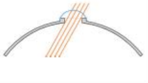
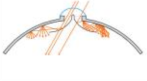
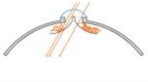
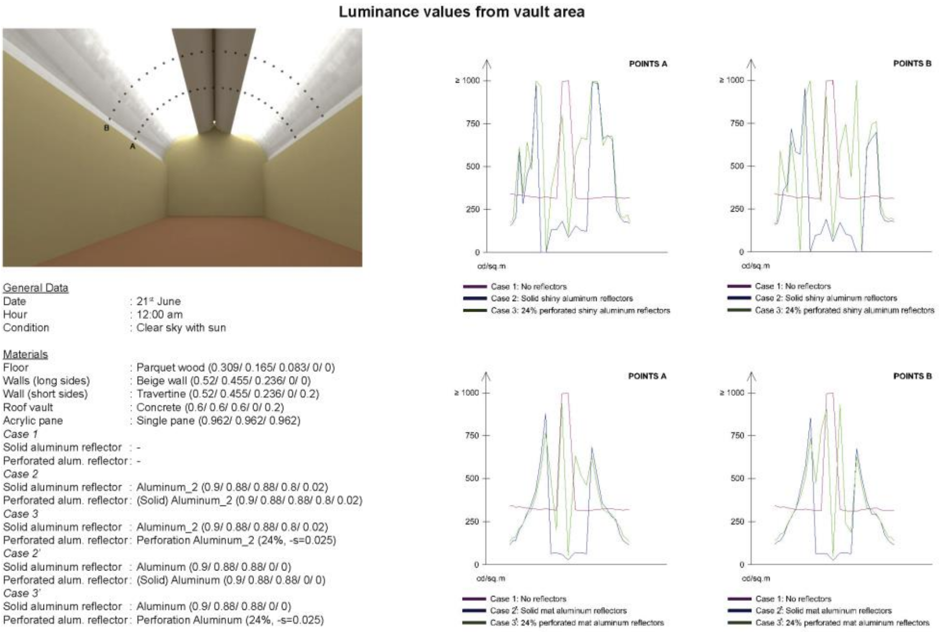
Conditions	**Clear sky with sun: 21-06, 12:00**				
Case name	**Case 1**	**Case 2**	**Case 2'**	**Case 3**	**Case 3'**
Description	No reflectors	Specular reflectors	Mat reflectors	Spec. reflectors 24% perforated	Mat reflectors 24% perforated
Mean illuminance (lux)	10.266	496	153	532	241
Max. luminance (cd/m^2)	7.115	7.311	2.598	7.170	6433
Min. luminance (cd/m^2)	43	16	4	10	6
Luminance W. wall (cd/m^2)	237	84	35	88	46
Luminance E. wall (cd/m^2)	176	84	33	93	43
Luminance floor (cd/m^2)	95	60	24	68	31
Daylight glare probability (%)	29	18	17	20	19
Section					

Table 4. Illuminance, luminance values, daylight glare probability of cases 1,2,3,2’,3’



General Data
Date : 21st June
Hour : 12:00 am
Condition : Clear sky with sun

Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Case 1
Solid aluminum reflector : -
Perforated alum. reflector : -
Case 2
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Case 3
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : Perforation Aluminum_2 (24%, -s=0.025)
Case 2'
Solid aluminum reflector : Aluminum (0.9/ 0.88/ 0.88/ 0/ 0)
Perforated alum. reflector : (Solid) Aluminum (0.9/ 0.88/ 0.88/ 0/ 0)
Case 3'
Solid aluminum reflector : Aluminum (0.9/ 0.88/ 0.88/ 0/ 0)
Perforated alum. reflector : Perforation Aluminum (24%, -s=0.025)

Figure 34. luminance values of cases 1,2,3,2',3 along vault 21st June, 12:00, clear sky

The detailed simulation results of each of the cases can be found in **Appendix B – Kimbell Art Museum**

Evaluation Test 1

Evaluation specular and diffuse reflection

Looking at diverse literature and existing photos it is not entirely clear which reflective properties the actual aluminum reflectors have. However, looking closer at photos and comparing them to the simulation results, the way daylight is reflected to the ceiling comes closer to the specular reflection pattern. In terms of daylight performance, the specular reflectors bring more daylight in and in any case the concrete vault reflects it further in a diffused way. It appears that the diffuse reflectors at the given time and date reflect more light back to the outside and/or have a higher level of absorption. No matter whether diffuse or specular reflection is considered, it does not have much of an impact on visual comfort.

Evaluation Perforated aluminum reflector versus solid reflector

The simulations do not confirm the claims of the designers to have a better visual comfort and reduced glare than solid ones. Whether this is due to flaws in the simulation or real phenomenon needs to be investigated further. Looking at the photos of the existing interior however, one can agree due to the slight transparency of the reflectors that they are visually less obvious. The perforations in fact transmits in total more daylight into the interior, which occasionally form direct light stripes on floor and ceiling. The perforation has a higher impact in terms of light transmittance in the case of diffuse reflection. For the further studies of alternative shapes and adaptive systems solid reflector will be used due to possible errors in the simulation and being able to assess better the geometrical aspects of solid reflectors and mapping/projection limitations as earlier stated in the radiance simulation.

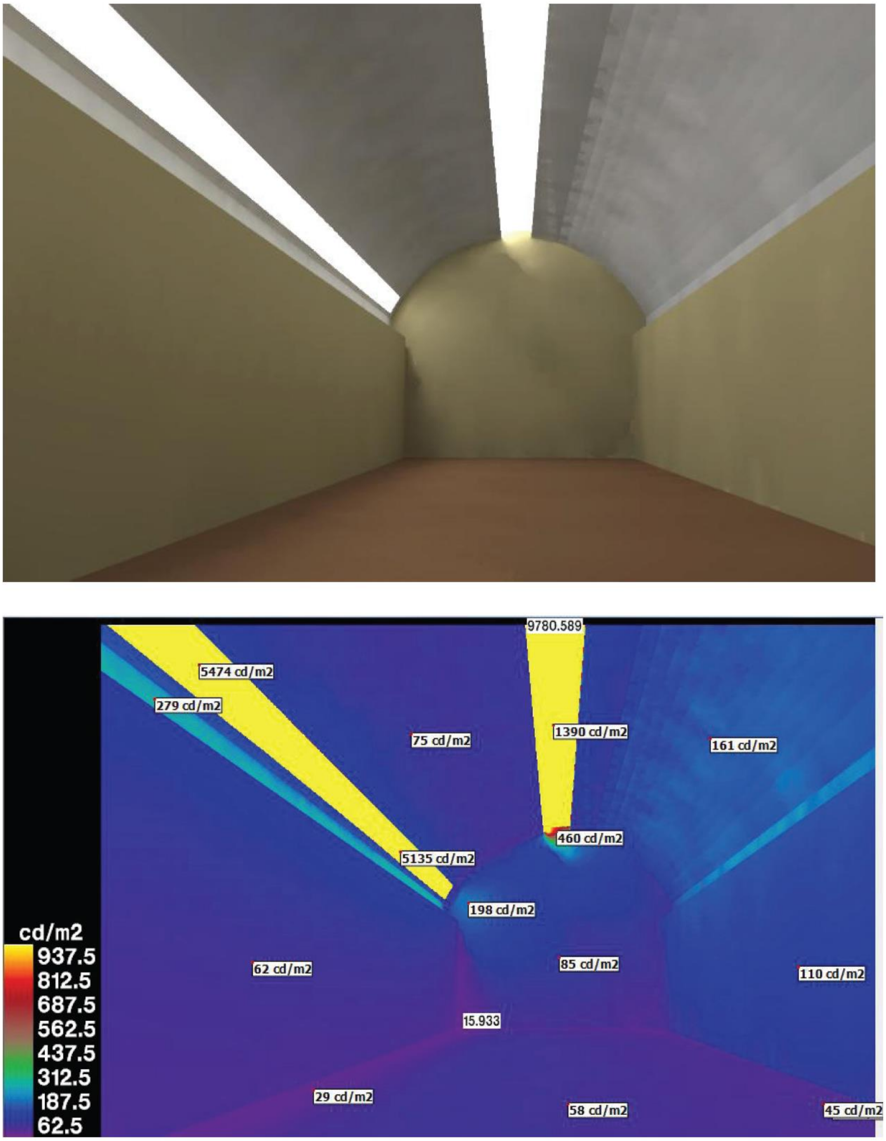
Test 2

In accordance with the results from the first test, the existing reflector configuration was tested in terms of daylight performance for the specular aluminum reflectors of the previous case 2 and as comparison how daylight would enter unhindered with no reflectors to also show the sun's angle in relation to the space. It is the aim to evaluate the dynamic properties of changing altitude and azimuth angles and sky conditions. The test 2 was done for 21st of June at 8:00, 10:00, 12:00, 14:00, 16:00, 18:00 as well as 21st of December at 10:00, 14:00, 18:00 and various overcast sky conditions. It is also stated by Louis Kahn that the design intention was to have connection in the interior with environment and light condition from the outside. Therefore, the test investigates in which direction the incoming sunlight is reflected into the interior.

Floor	Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides)	Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides)	Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault	Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane	Single pane (0.962/ 0.962/ 0.962)
Case 2 Solid aluminum reflector specular	Aluminum (0.9/ 0.88/ 0.88/ 0.8/ 0.02)

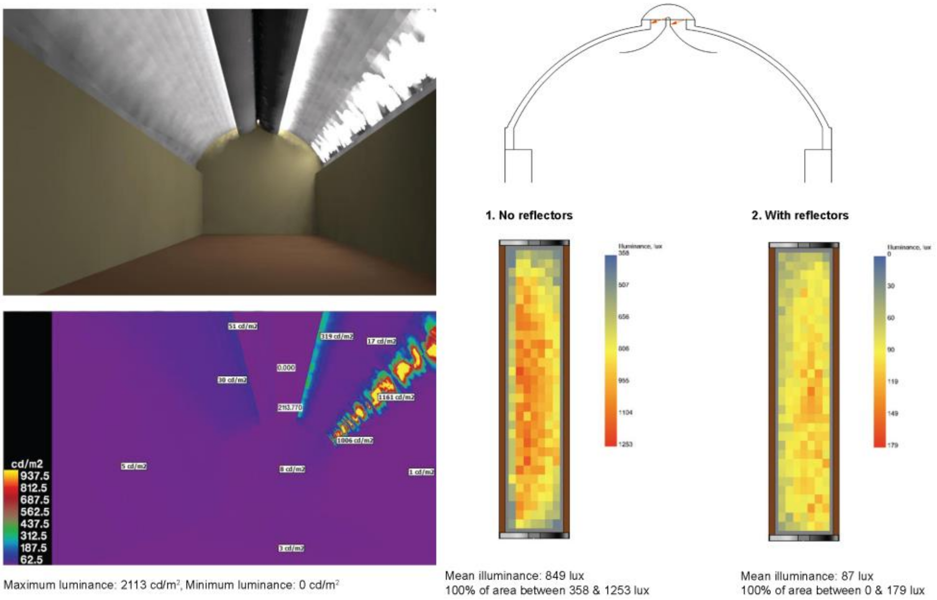
Table 5. Material settings for daylight simulation Test 2

Results Test 2



Maximum luminance: 9780 cd/m^2, Minimum luminance: 16 cd/m^2

Figure 35. Daylight simulation 21.06., clear Sky with sun, 8:00, without reflectors



Maximum luminance: 2113 cd/m², Minimum luminance: 0 cd/m²

Mean illuminance: 849 lux
100% of area between 358 & 1253 lux

Mean illuminance: 87 lux
100% of area between 0 & 179 lux

Figure 36. Daylight simulation 21.06., clear Sky with sun, 8:00, and Reflectors case 2

Time	No refl. Mean Illuminance in lux	Refl. Mean Illuminance in lux	No refl. Lum. wall (dark side) cd/m²	Refl. lum. wall cd/m²
8:00	849	87	110	5
10:00	1802	206	258	17
12:00	10266	496	138	48
14:00	9743	251	94	21
16:00	894	138	79	5
18:00	342	34	35	1

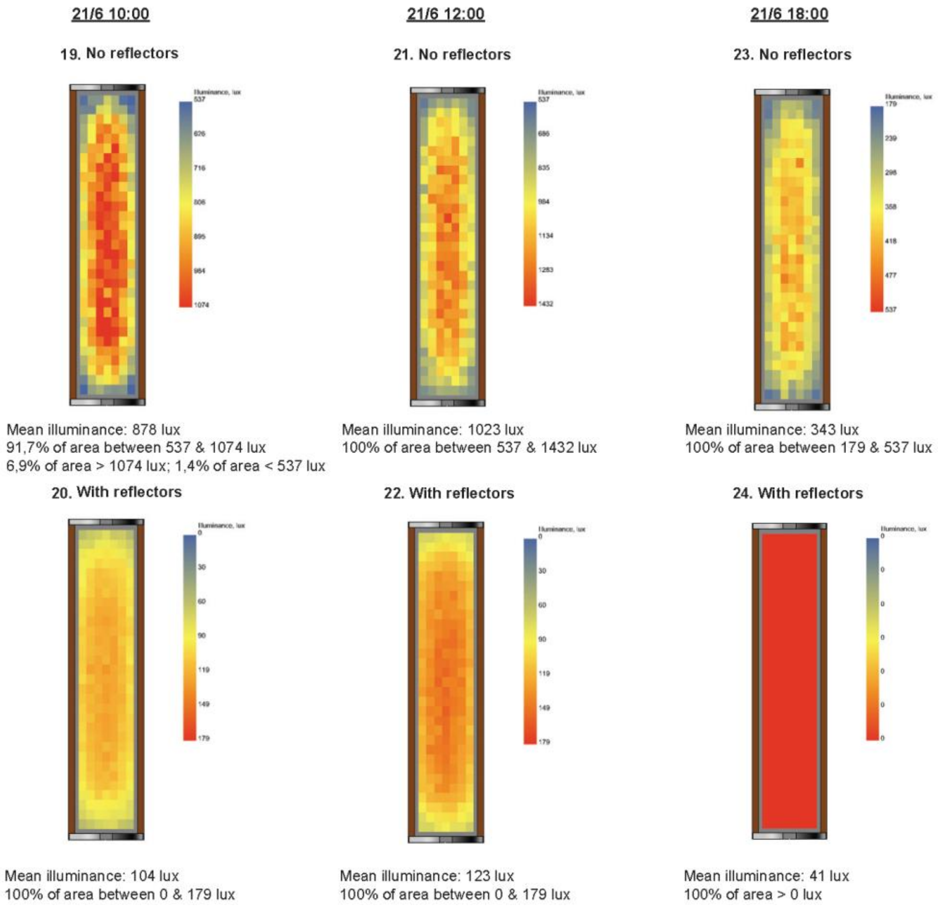
Table 6. Illuminance, luminance values for various hours 21.06. Clear sky condition

More detailed simulation results of each of each hour can be found in **Appendix B – Kimbell Art Museum**

Light projection during course of the day, daylight readability

Due to the geometry of the opening and the reflectors in relation to the sun's altitude between roughly 10:00 -16:00 the direction of the sun is portrayed correctly in the interior. Earlier or later the daylight is reflected on the opposite side of the incoming light.

Summer 21.06. Overcast sky



Mean illuminance: 878 lux
91,7% of area between 537 & 1074 lux
6,9% of area > 1074 lux; 1,4% of area < 537 lux

Mean illuminance: 1023 lux
100% of area between 537 & 1432 lux

Mean illuminance: 343 lux
100% of area between 179 & 537 lux

Mean illuminance: 104 lux
100% of area between 0 & 179 lux

Mean illuminance: 123 lux
100% of area between 0 & 179 lux

Mean illuminance: 41 lux
100% of area > 0 lux

Figure 37. Daylight simulation 21.06., overcast sky, during various hours and reflector conditions

Time	No refl. Mean Illuminance in lux	Refl. Mean Illuminance in lux	No refl. Lum. wall (dark side) cd/m²	Refl. lum. wall cd/m²
10:00	878 (1802)	87 (206)	104 (258)	0 (17)
12:00	1023 (10266)	206 (496)	123 (138)	0 (48)
18:00	343 (342)	496 (34)	41 (35)	0 (1)

Table 7. Illuminance, luminance values for various hours 21.06. Overcast sky condition, Clear sky in brackets

The detailed simulation results of each of each hour can be found in **Appendix B – Kimbell Art Museum**

Winter 21.12. Clear sky with sun

Time	No refl. Mean Illuminance in lux	Refl. Mean Illuminance in lux	No refl. Lum. wall (dark side) cd/m²	Refl. lum. wall cd/m²
10:00	426	66	72	1
14:00	876	108	109	5
18:00	32	5	4	0

Table 8. Illuminance, luminance values for various hours 21.12. Clear sky condition

The detailed simulation results of each of each hour can be found in **Appendix B – Kimbell Art Museum**

Evaluation Test 2

It appears that only under more ideal situations, while having direct light and clear sky, the amount reflected inside is sufficient without adding additional artificial light. During overcast sky situations the amount of illumination is not sufficient. In terms of daylight autonomy with respect to humid subtropical climate having often overcast sky conditions the existing solution appears to be sub optimal. However, the research looks exclusively into the top lights and neglects light from vertical windows. In addition, the design must be seen in its architectural design context and intention rather than merely from a quantitative viewpoint.

Test 3

Like stated earlier, “what if” scenarios were developed to investigate whether it is possible to alter or improve the reflectors’ daylight performance since this would be the simplest intervention.

What if one would change the shape, what would happen?

For that new shapes were defined with the help of the 2-dimensional parametric prediction tool. The new shapes do not deviate much from the original shape to also stay true to the historical context.

Modification 1 and 1’

Here the upper “lip” of the vertical reflector segment reaching into the top opening was removed to enable more daylight to enter. However, with this modification also direct light can enter the vault not diffused, thus this modification was early on discarded and not further investigated.

Modification 2 and 2’

Those are the closest to the original shape. In fact, it is an offset of the original shape with the main difference that they hang now lower under the vault and the vertical reflector element which blocks direct light from entering during shallow altitude angles is higher and the transition between this element and reflector cross sectional curve is adjusted. The prediction states that now the lower altitude angles get better reflected into the interior and the additional space created between reflector and vault brings the reflected daylight further inside the vault. The boundary condition to be met was that at no altitude angles, especially the higher ones around noon, direct sunlight can enter the interior directly. Like in the first test this is done for specular reflection in modification 2 and diffuse reflection in modification 2’

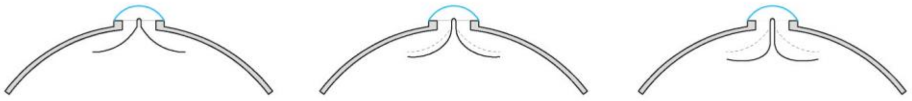
Modification 3 and 3’

Here the vertical element going down into the vault is much higher, the curve of the actual reflector is much shallower with the intention that low sun altitude angles during morning and afternoons but also winter times get via a double reflection better reflected onto the vault’s ceiling. It is estimated that this would work best with only specular reflection, however for the sake of completeness the diffuse reflection was also simulated.

What if the reflectors would be adaptive, can the daylight performance be improved?

Modification 4 and 4’

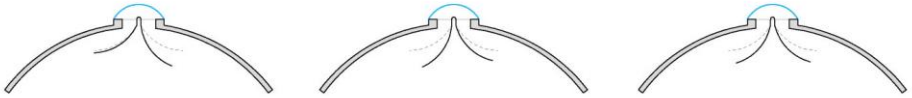
Several scenarios of adaptivity were discussed, ranging from change of reflector’s shape and curvature to height under the vault, etc. but finally it was decided due to the architectural boundary conditions to keep the original shape but make the reflectors individually rotatable along the inner edge of the reflector trough to adjust themselves according to the suns’ altitude angle with the help of the 2-dimensional parametric design tool. Again, the simulations were done for both specular and diffuse reflection.



Case 2/2'
Solid specular/mat reflectors,
original curve

Modification 2/2'
Solid specular/mat reflectors

Modification 3/3'
Solid specular/mat reflectors



Modification 4/4', 21/06, 10:00
Rotating solid specular/mat reflectors

Modification 4/4', 21/06, 12:00
Rotating solid specular/mat reflectors

Modification 4/4', 21/06, 16:00
Rotating solid specular/mat reflectors

Figure 38. Various reflector positions, shapes and adaptive kinetic solution

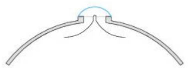
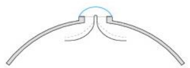
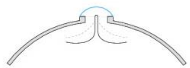
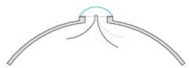
Floor	Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides)	Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides)	Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault	Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane	Single pane (0.962/ 0.962/ 0.962)
Case 2 Mod. 2,3,4 Solid aluminum reflector specular	Aluminum (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Case 2’, Mod. 2’, 3 ’, 4’ Solid alum. reflector ideal diff.	Aluminum (0.9/ 0.88/ 0.88/ 0 / 0)

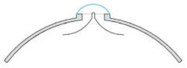
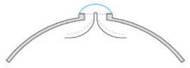
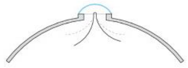
Table 9. Material settings for daylight simulation Test3

The simulations were run for the 21st of June under clear sky conditions for 10:00, 12:00 and 16:00 because earlier and later due to the opening slit on top of the vault and the construction related depth it is in any case difficult to sufficiently illuminate the interior. This can be referred to in the first test setting.

Results Test 3

Case 2 (solid reflector specular reflection) and 2’ (solid reflector diffuse reflection)
Modification 2 (solid reflector specular reflection) and 2’ (solid reflector diffuse reflection)
Modification 3 (solid reflector specular reflection) and 3’ (solid reflector diffuse reflection)
Modification 4 (solid reflector specular reflection) and 4’ (solid reflector diffuse reflection)

Conditions	Clear sky with sun: 21-06, 10:00							
Case name	**Case 2**	**Case 2'**	**Modification 2**	**Modification 2'**	**Modification 3**	**Modification 3'**	**Modification 4**	**Modification 4'**
Description	Original curve / specular reflectors	Original curve / mat reflectors	Steeper curve / specular reflectors	Steeper curve / mat reflectors	Middle vertical elements / spec. reflectors	Middle vertical elements / mat reflectors	Adaptive / specular reflectors	Adaptive / mat reflectors
Mean illuminance (lux)	206	91	437	146	289	157	312	179
Max. luminance (cd/m^2)	4.274	2.085	7.715	2.097	2.098	2.011	6.098	2.002
Min. luminance (cd/m^2)	0	3	0	3	0	1	10	5
Luminance W. wall (cd/m^2)	12	29	30	43	14	47	82	55
Luminance E. wall (cd/m^2)	17	22	12	31	6	35	63	47
Luminance floor (cd/m^2)	15	17	26	26	7	29	51	31
Daylight glare probability (%)	9	16	-	-	-	-	17	17
Section								

Conditions	Clear sky with sun: 21-06, 12:00							
Case name	**Case 2**	**Case 2'**	**Modification 2**	**Modification 2'**	**Modification 3**	**Modification 3'**	**Modification 4**	**Modification 4'**
Description	Original curve / specular reflectors	Original curve / mat reflectors	Steeper curve / specular reflectors	Steeper curve / mat reflectors	Middle vertical elements / spec. reflectors	Middle vertical elements / mat reflectors	Adaptive / specular reflectors	Adaptive / mat reflectors
Mean illuminance (lux)	496	153	541	224	382	244	509	470
Max. luminance (cd/m^2)	7.311	2.598	5.824	2.312	4.463	2.482	7.191	2.585
Min. luminance (cd/m^2)	16	4	0	4	0	2	13	9
Luminance W. wall (cd/m^2)	84	35	41	56	40	65	125	114
Luminance E. wall (cd/m^2)	84	33	36	52	24	62	114	92
Luminance floor (cd/m^2)	60	24	37	38	24	42	76	62
Daylight glare probability (%)	18	17	-	-	-	-	19	20
Section								

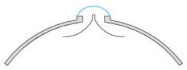
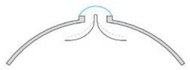
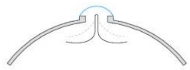
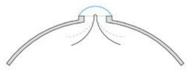
Conditions	Clear sky with sun: 21-06, 16:00							
Case name	**Case 2**	**Case 2'**	**Modification 2**	**Modification 2'**	**Modification 3**	**Modification 3'**	**Modification 4**	**Modification 4'**
Description	Original curve / specular reflectors	Original curve / mat reflectors	Steeper curve / specular reflectors	Steeper curve / mat reflectors	Middle vertical elements / spec. reflectors	Middle vertical elements / mat reflectors	Adaptive / specular reflectors	Adaptive / mat reflectors
Mean illuminance (lux)	138	55	339	85	220	83	242	88
Max. luminance (cd/m^2)	6.318	2.138	7.506	2.146	2.155	2.482	5.143	1.716
Min. luminance (cd/m^2)	0	2	0	2	0	2	8	3
Luminance W. wall (cd/m^2)	4	13	9	19	10	65	47	30
Luminance E. wall (cd/m^2)	5	19	18	27	6	62	56	30
Luminance floor (cd/m^2)	4	11	13	18	7	42	37	20
Daylight glare probability (%)	2	4	-	-	-	-	15	13
Section								

Table 10. Simulation results, Reflector Geometry, adaptive and static

Evaluation Test 3

All the modifications perform better in terms of illuminating the floor apart from modification 3 during noon. This is insofar not surprising because here the reflector has specular reflection properties but reflects part of the incoming light at a less optimal area of the vault and it was designed to transmit the lower sun angles better. Its diffuse counterpart of modification 3’ however performs second best in terms of illumination after the adaptive modification 4’. Even though modification 3 was intended to reflect more light from low sun angles, the other static modification 2 performs better in this respect. The results get turned around in respect to diffuse reflector modifications when looking at luminance values on the walls where the paintings are located. Here modification 3’ performs always better than case 2’ the original geometry, modification 2’ which in its specular counterpart 2 has the highest illuminance on the floor of all, or at one time at 16:00 it is better than the adaptive diffuse modification 4’. The adaptive modification 4 with specular properties is second best in terms of illuminance on the floor but best with modification 4’ diffuse reflection especially during steep sun angles during noon. Looking again at luminance values coming from the walls modifications 4 and 4’ (apart from the exception at 16:00) perform best of all in their material class. It is noteworthy to state that the original geometry of case 2 with specular reflection performs second best in terms of luminance from the wall after case 4 during noon.

Original case 2 and 2’

Lowest mean illuminance on the floor
Case 2 second best luminance from the wall during noon

Modification 2 (specular reflection)

Highest mean illuminance of the floor during all the times

Modification 3’ (diffuse reflection)

Second best mean illuminance of the floor in the diffuse class
Third best in two cases regarding luminance from the wall but not far off from the worst cases

Modification 4 (specular reflection)

Second best in terms mean illuminance on the floor
Best most of the time in terms of luminance coming from the wall

Modification 4’ (diffuse reflection)

Outstanding in terms of mean illuminance on the floor during noon in comparison to all other diffuse cases

5.1.7 Conclusion

Little changes in geometrical configuration can have a big impact in how the daylight gets transmitted into the interior. This is greatly dependent on the material properties in this case of the reflectors’ way of how light gets further distributed. The more specular the material is, the bigger the influence of the geometry. Diffuse reflection generates a softer gradient on the vaults ceiling without improvement of visual comfort, but since a lot of the rays get reflected in a less optimal direction, the result in terms of daylight performance is less than specular reflectors. This is insofar important as the reflectors themselves are the first in the chain of redirecting daylight and second is the concrete vault which acts as the actual diffusor or light source. That means it is important to keep the losses low till the light reaches its destination. To optimize light hitting the diffusing surface like the concrete vault in this case as second reflector, the geometrical properties together with the specular reflection play a major role. Here the adjustable angles of the adaptive configuration are most capable of maximizing the effect. For further studies other test setups of reconfigurable reflectors can be explored. This requires an early design assessment tool like in this case the 2-dimensional parametric visualization of the incoming sun rays and their reflection into the vault, because otherwise one is mainly busy evaluating a great deal of invalid design options with time-consuming radiance lighting simulations. Another advantage of the reconfigurable reflectors is the daylight performance during overcast sky conditions where any of the static, or fixed reflector configurations is not performing well. Here an adaptive solution can be folded vertically down to maximize access and not to obstruct the area underneath the slit in the roof and sky. Obviously, this must go hand in hand with fast response times and proper automation system including the system’s awareness of the current sun position which is able to react swiftly once an e.g. obstructing cloud moves in front of the sun.

5.2 Static Contextual Buildings – Adapted Geometry – Origami Roof Structure

5.2.1 Context

The Origami Roof Structure was the initial proposal for entering the PhD and was refined during further research. It relates itself partially to the authors study and research at the Berlage Institute during the Associative Design course in 2005-2006 with Prof. Peter Trummer and to the working experience and parametric design practice at the architecture office UNStudio van Berkel & Bos. Its underlying theoretical concept is that of hybridization instead of mono functional or functional layered design which is to be found in modernist architecture. In that sense the proposed roof also investigates the design of free form geometries, their structural performance and integration of constructive/manufacturing possibilities with one system instead of multiple functionally distinct or layered ones. It is the aim to be able to manage multi parametric designs with several different inputs with the help of one geometrical model while satisfying all the requirements simultaneously. The proposed Origami roof combines free form materialization aspects, structural aspects and daylighting. The focus within this specific research lies on the daylighting aspect and how the building skin can be utilized to program lighting scenarios for the interior.

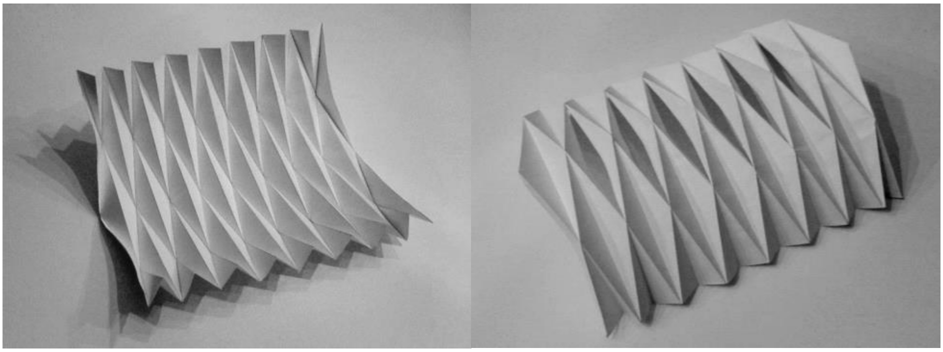
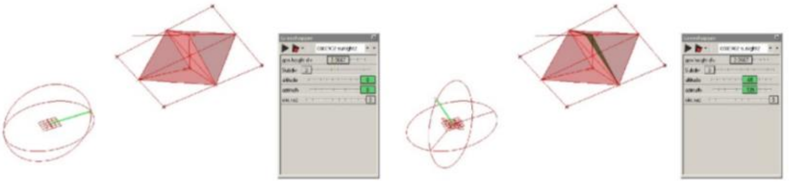


Figure 39. Yoshimura fold

Figure 40. Origami Roof, early design

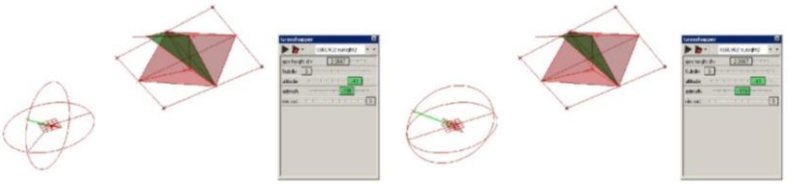
5.2.2 Function and Layout

The Origami Roof Structure is intended to be placed on top of buildings which cover larger surface areas such as trade fairs with little access to daylight by glass facades at the perimeter while protecting the interior from overheating during hot seasons while being able to program specific daylighting conditions in the interior. According to certain parametric design principles, the associative 3D model is set up in 2 stages, initially genotype and later phenotype. The genotype stage defines the not yet applied basic geometrical relations and design potentials but require environmental and functional input to acquire its final form (phenotype). The geometry is based on a Yoshimura origami fold which was selected because it can be applied to any surface geometry. Due to the spatial folding of flat elements and in combination with the overall geometry it receives locally structural height, thus structural performance. In regular alternations within the basic diamond pattern special geometrical components are introduced which function as openings like those found in shed roofs to enable daylight to enter. Those can be both oriented towards north or south and their opening sizes are dependent on function and lighting requirements of the building. Depending on the location of the building and whether passive heat gain during various seasons of the year are desirable, the south facing openings require shading extensions which are automatically formulated within the parametric design environment to block out direct light during specific time intervals. Those depend on a pre-selected sun vector according to annual temperature charts and climatic strategy. The opening size and spatial orientation of the individual opening on the roof itself are further input parameters for the shading elements. The final design becomes highly contextual since the designer can react to various climatic and functional contexts with the help of a parametric design model in an automated way during the design process.



Hood extension A

Hood extension B



Hood extension C

Hood extension D

Figure 41. Origami Roof, variation in shading extension according to sun vector

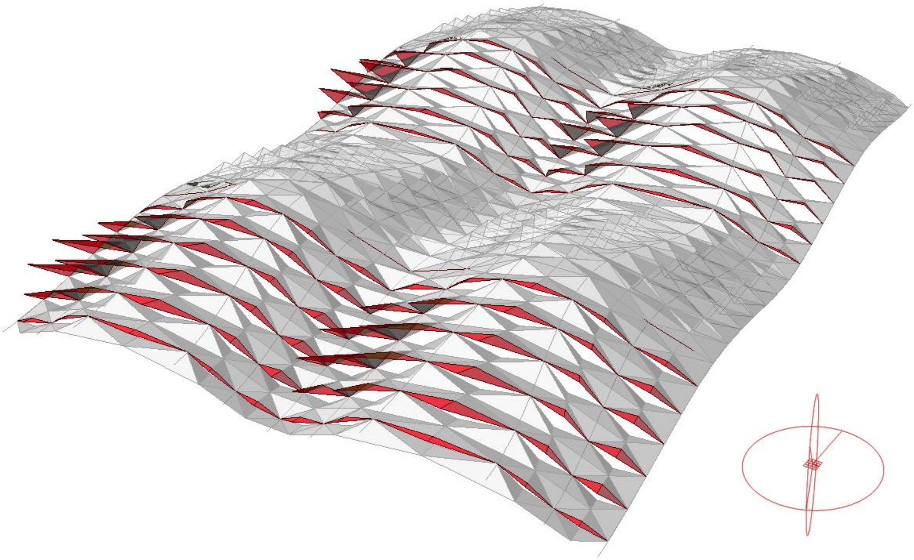


Figure 42. Origami Roof, shading extension formulation according to roof geometry and sun vector

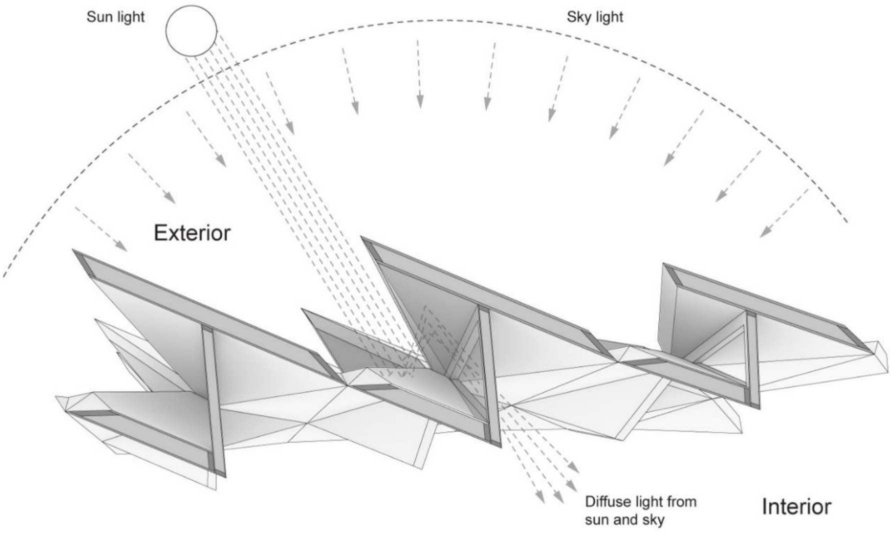


Figure 43. Opening and light redirection

5.2.3 Lighting requirements

The initial roof geometry is by design intention generic (genotype). Different daylighting solution can be found by researching lighting requirements for certain building types and functions. the research is applied in form of quantitative parameters for each individual building. The proposed geometry needs to be validated via daylight simulations whether it fulfills the requirements and possibly be readjusted via further design evaluations and iterations. The basic design and openings sizes are determined initially via a 3-dimensional graph surface and later via gradient black to white colored maps, where each brightness value represents an opening state of the roof above. That makes it especially easy for architectural design purposes to simply color areas in plan which require daylight and link it to the parametric model. The so received opening sizes can be further adjusted due to numerical offset input. The intention is to show designers a way to design with a similar strategy qualitative and quantitative lighting aspects simultaneously. The later Lighting Analysis and Alternatives chapter 5.2.6 shows designs and evaluations of various prototypical scenarios and their results in terms of daylight. In addition, it highlights the relationship not only between individual openings and their respective black and white map but also for various roof geometries and the influence those have in terms of daylighting.

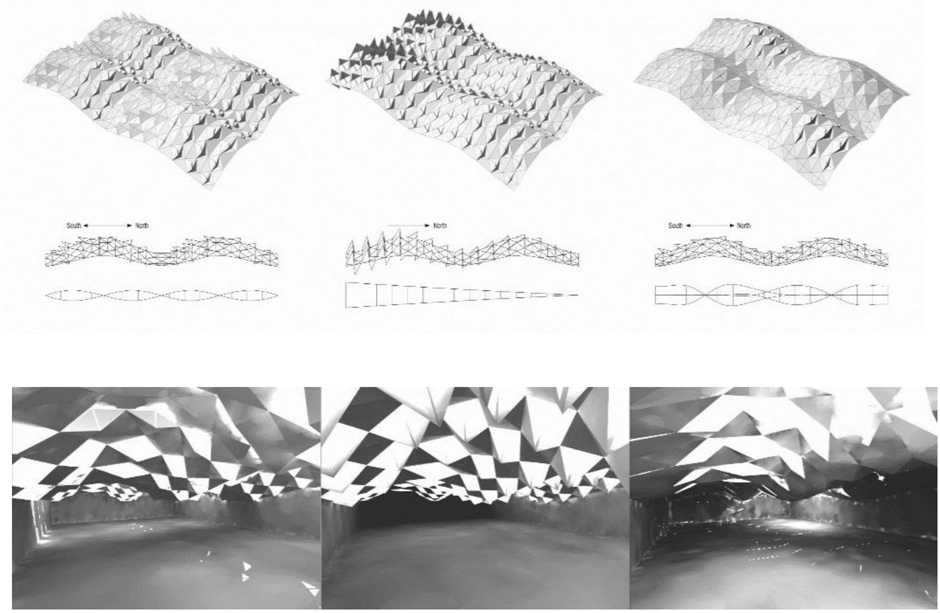


Figure 44. Origami Roof, variation in opening sizes driven by graph surface

Application scenarios

Northern and southern hemisphere with moderate climate

Passive heat gains during cold winter months and during spring time are mostly desirable. During this period direct sunlight can penetrate the roof due to lower sun altitude angles. This has a direct consequence for the interior lighting conditions. Part of the year direct light and hard shadows during sunny hours can be experienced in the interior but due to higher sun altitude angles during summer light will enter reflected in a diffuse way. In case glare due to visual comfort requirements is not desired and/or passive heat gains are not necessary the openings can be only oriented towards north and only diffuse atmospheric light can enter. As it can be seen later, the overall roof geometry plays a major role in terms of application of shading extensions because sun altitude differences are more extreme.

Hot climates and equatorial regions

In hot climates where passive heat gains are not desired the shading extensions are formulated in such a way according to the lowest sun altitude possible so that direct light is blocked. Throughout the whole year the interior receives exclusively diffuse daylight. At equatorial regions where sunlight comes from south and north both sides will receive shading extensions.

The possible scenarios in short:

- Passive heat gains desired, openings to both north and south, shading extensions required
- Passive heat gains and possible glare not desired, openings towards north only, no shading extension
- Passive heat gains not desired, openings both north and south, shading extensions depending on proximity to equator both on north and south.

5.2.4 Design Process

A designer who applies the parametric model could do it from 2 different starting points. Firstly, define a global roof shape geometry with the architectural boundary conditions in mind, then check the structural engineering requirements and define the daylighting parameters or secondly defining via form finding methods a structurally well performing global roof geometry and then apply the parametric model and daylighting requirements. In any case the overall global roof geometry is the basic input.

Design Steps

- The global roof geometry is subdivided into a set of splines which serve as further input for the parametric model where the components get applied.
- By loading in the gradient map according to lighting requirements, the individual opening sizes get formulated
- By looking into annual climatic data, a sun vector needs to be defined which serves as point where the interior will be completely shaded and does not receive direct sunlight
- Materials within the Radiance/Diva plugin will be assigned
- Starting the daylighting simulation and evaluation process
- Feedback of the results by fine tuning the gradient map

The latter analysis looks at different roof configuration for a prototypical setup in terms of different global roof geometries or shapes, their shading performance, different gradient maps and daylighting performance. Here it is necessary to understand how the various possibilities influence the results and how to manipulate them to receive desired results.

5.2.5 Geometrical & Material Aspects - Technical solutions & systems

Location test cases

As location for the test case the city of Munich as a representation for a Northern European climate was chosen. Here cold winters require passive heat gains and warm summers require shading and no direct sunlight transmittance. Looking at annual temperature charts, daily hours of sunshine the date of 10th of April was chosen so that from this moment on the interior is going to be shaded to reduce passive heat gains. The sun vector for the 10th of April at 12:00 will determine the formulation of the shading extension and the effect is shown in the "Lighting Analysis and Alternatives" section.

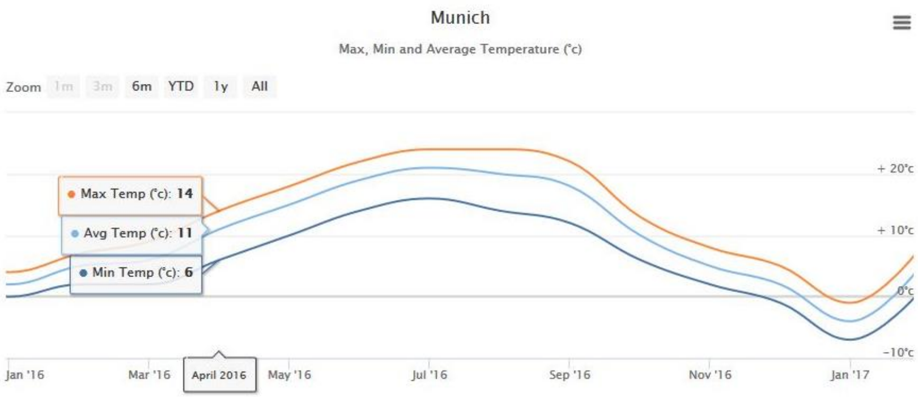


Figure 45. Temperature chart 2016 location Munich, image source: Worldweatheronline.com

Basic geometry of the roofs

It is the intention not only to show the influence of the local openings on the daylighting outcome but also that of the overall roof geometry. This can happen in two ways. Firstly, the geometry due to spatial expansion or contraction (height development of the roof), enhances or restricts the daylighting performance. Secondly, a very elaborated surface curvature simply possibly starts to self-shade and sunlight cannot reach the interior anymore at lower sun angles at certain times. This also influences the shading possibilities of the shading extensions due to the general inclination of an opening component in relation to the sun angle. At a certain moment, openings simply become not shade-able anymore.

The basic dimension of the chosen roof layout is 40m x 20m with an eaves height of 6m. The 40m direction is north-south oriented to see possible lighting effects on the walls. The proportion of 2:1 in north-south direction is chosen to generate spatial orientation/direction to develop several lighting scenarios.

The geometries of the roof for testing are the following

- Flat
- Barrel vault like, single curved, monoclastic
- Shell like, double curved, synclastic, slightly anticlastic at the edges
- Free-form, double curved, synclastic and anticlastic
- Lighting informed freeform, double curved, synclastic and anticlastic

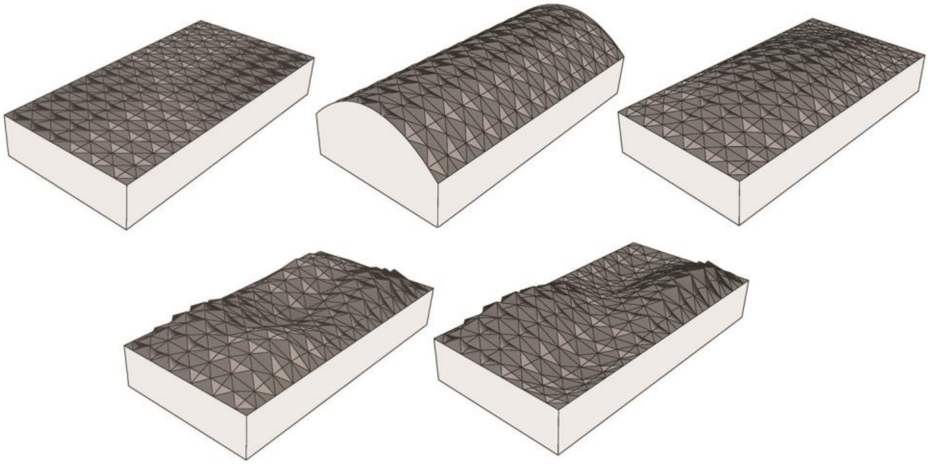


Figure 46. Basic roof shapes

Geometry of the openings

The size and location of the openings are determined via black and white gradient maps. Here several lighting scenarios and their interplay with the overall roof geometry were developed

Completely open

As a basic setting and initial comparison, a complete white map resulting in 100% opening size was chosen

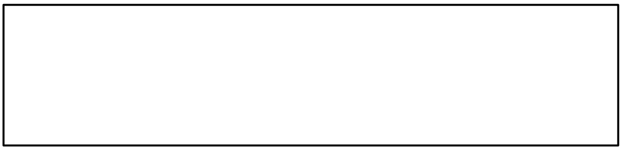


Figure 47. White map, all open

Linear path 1

The first linear path is gradient map with a white stripe and lit path to support human movement. The edges of the map are grey to have slight opening at the sides.

Figure 48. Linear path grey map

Linear path 2

The second linear path gradient map also intended to guide people. Here the edge is black to have the related roof components closed for more focus on the central part stripe.

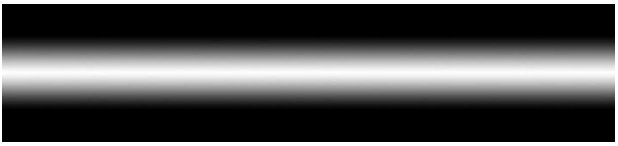


Figure 49. Linear path closed sides map

Central area

The gradient map has 100% opening in the middle, gradually closing to all sides. This is intended for a place to where people should slow down.

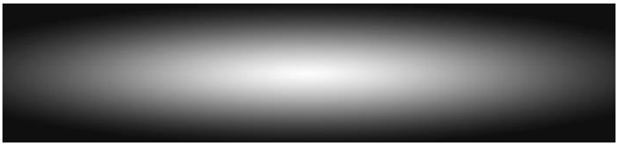


Figure 50. Central openings map

Two accents

This gradient map generates diagonally opposing two opened areas in the roof to place spatial accents. With this, special attention can be drawn to specific areas of interest.

Figure 51. Two accents map

Floor	GenericInteriorWall_50 Percent Reflectance (0.5/ 0.5/ 0.05/ 0/ 0)
Walls	GenericInteriorWall_50 Percent Reflectance (0.5/ 0.5/ 0.05/ 0/ 0)
Shades	Clear_white_mat (0.728/ 0.899/ 0.842/ 0/ 0)
Reflectors	Aluminum 2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
GLazing	Double pane (0.705192/ 0.705192/ 0.705192)

Table 11. Material selection for daylight simulation

Floors and walls have a 50% diffuse reflectance representing a middle value. For the external skin aluminum reflectors with specular reflection were chosen to get direct sunlight reflected into the interior and toward the shades. The shades reflect in a diffuse way to avoid bright light spots in the interior. For glazing a double pane setup was chosen, because this represents a minimum energy saving requirement in Europe. The materiality in any daylight simulation obviously plays a major role. Therefore, it is intended with the general selection of materials to be balanced in order not to overtly exaggerate the transmission and reflection of daylight. For a final building design, the materials need to be further specified. Here the glazing and transmission of daylight is a major factor which can have a great influence on opening sizes and geometry to fulfill lighting requirements.

5.2.6 Lighting Analysis, Alternatives and Application

Shading and shadow pattern

To proof that the shading is working during different times of the year, the various roof shapes earlier described in combination with the individual openings and a white map (100% open) were mapped via the sun's vectors in form of polygons within the parametric grasshopper environment. The 10th of April was the point for location Munich that no direct sunlight should enter the interior. This was done for the 4 basic roof geometries.

Flat

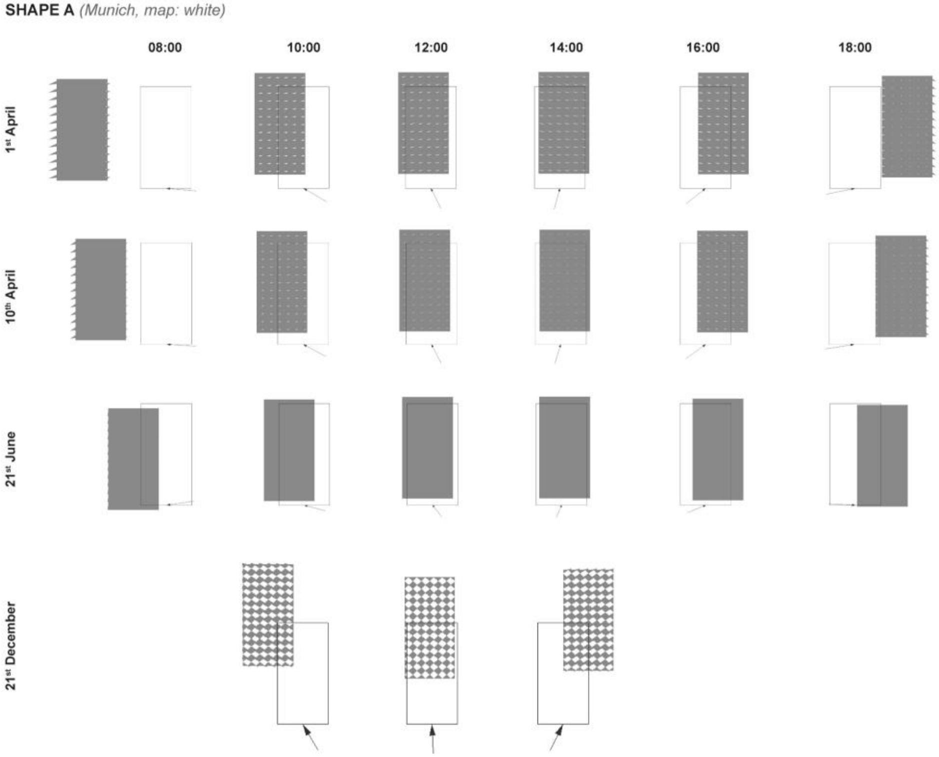


Figure 52. Shadow pattern flat roof

The other shadow studies can be found in **Appendix C – Origami Roof Structure**

Evaluation Shading & shading in relation to roof curvature/geometry

In general shading works well, especially with the flat roof. Here on the 10th of April a negligible area of direct light is transmitted into the interior during the whole day. After the moment the interior is completely shaded. This is somewhat different with the other roof shapes, albeit the effect is still little. The components which are in areas of the overall roof geometry where its surface normal is facing more towards the incoming sun angle at the given moment are shading perfectly, the other side does not. That means e.g. with the barrel shaped roof, during morning hours the east side of the roof is shading well but the west side is not. This has to do with the fact, that it is geometrically impossible to shade here especially between 10:00-12:00 unless one closes the openings completely.

Light simulations

All the simulations are done via Rhino and the Diva plugin which uses Radiance for the simulation. It shows the results directly in Rhino for illuminance values on the floor or for luminance in form of false color images via an external window.

Initial comparison – white map

The first set of tests investigate illumination and luminance of the interior when all the components on the roof are opened with the same total area of openings where the white map defines each individual glazing element as being maximal opened. Here it shows the influence of the overall roof geometry and the shading extensions especially in terms of resulting quantities. This was done for the 4 basic roof geometries.

Flat

- Barrel vault like, single curved, monoclastic
- Shell like, double curved, synclastic, slightly anticlastic at the edges
- Free-form, double curved, synclastic and anticlastic

All simulations were done for each of the 4 roof geometries for the location Munich on the 21.06. at 12:00 for clear and overcast sky conditions, for the 21.12. at 12:00 also for clear and overcast sky conditions in two separate sets. One with the shading extension applied and without it.

Summer 21.06. 12:00, Flat roof comparison shades, no shades

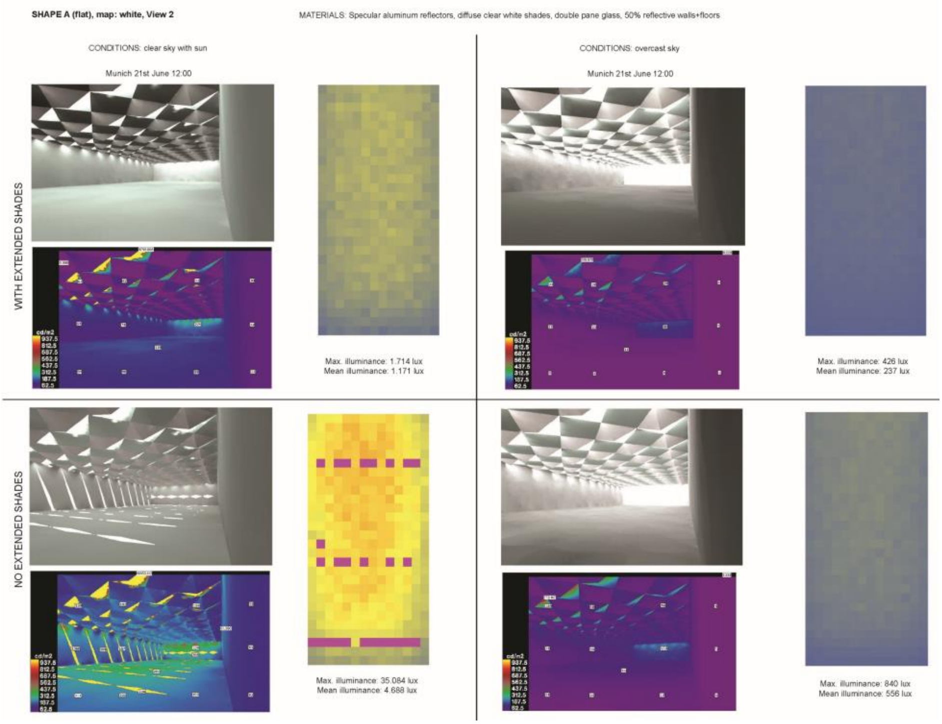


Figure 53. Luminance and illuminance during clear and overcast sky conditions, 21.06, 12:00

Winter 21.12. 12:00 Flat roof comparison shades, no shades

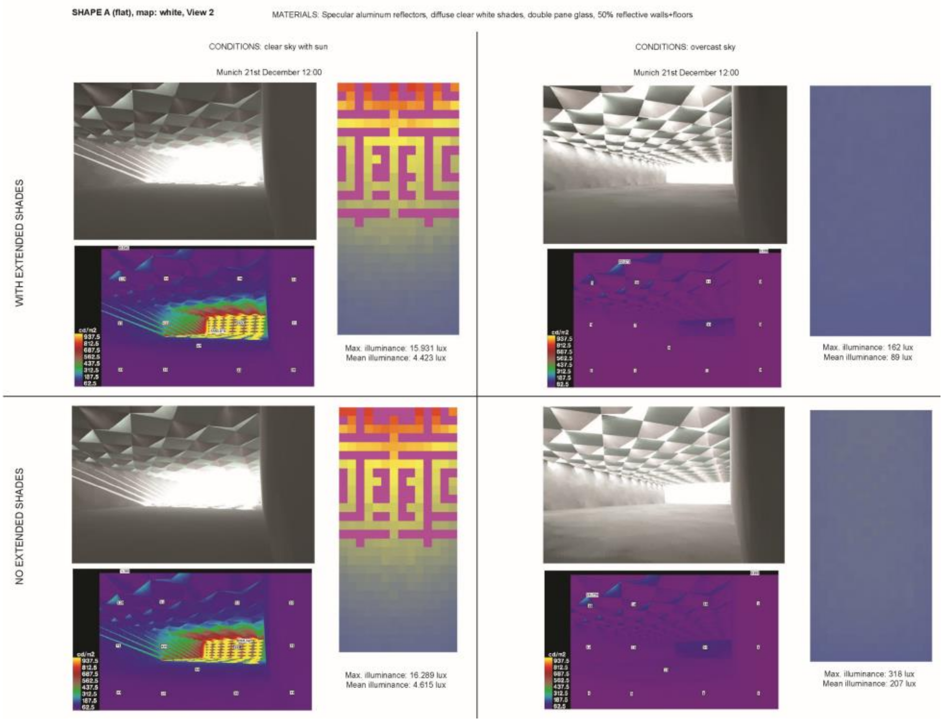


Figure 54. Luminance and illuminance during clear and overcast sky conditions, 21.12, 12:00

The rest of the luminance and illuminance maps can be found in **Appendix C – Origami Roof Structure**

Evaluations white maps

Shading extension vs. no shading example flat roof
The shading extension like intended and previously shown block out direct light during summer. They have however an impact in terms of light transmission and illuminance in the interior.

- In winter 12:00 during clear sky, the mean illumination of the shaded flat roof is significantly higher than in summer as it was expected (4423 lux vs. 1171 lux)
- In summer during clear sky, the shading extension reduces the mean illumination to 25% of the unshaded one (1171 lux vs. 4688 lux)
- In winter during clear sky, there is no significant difference in mean illumination between shaded and non-shaded version due to the geometrical layout of the shades and the low altitude of the sun being able to enter the interior (4423 lux vs. 4615 lux)
- During summer and winter in overcast sky conditions the shading elements reduce the mean illuminance by half. That is 237 lux (summer) and 89 lux (winter) vs. 556 lux (summer) and 207 lux (winter)

Impact of the roof geometry

The roof geometries also have a significant impact on the illumination on the interior. This comes mostly from the fact that as soon as the roof is developing upwards and downwards the overall geometry becomes self-shading. This can be seen best in the comparison between flat roof and the arched vault which has the most difference in height and inclination. The results in realization, that not only the opening sizes but the roof shape itself can therefore be utilized to manage the amount of daylight reaching the interior and deliberately create lighter and darker zones.

For example, the values of the mean interior illumination during clears skies in summer at noon are:

- Flat 1171 lux,
- Barrel vault 768 lux,
- Shell like 1035 lux
- Free-form 783 lux.

During overcast sky conditions and the multidirectional nature of the incoming light rays, the roof geometry itself has not so much of an impact anymore. For example, the values of the mean interior illumination during overcast skies in summer at noon are:

- Flat 237 lux,
- Barrel vault 185 lux
- Shell like 222 lux
- Free-form 198 lux

The table on the next pages shows more detailed information about the interior lighting conditions.

Shape	**Shape A** (flat)							
Location	Munich							
Case name	With extended shading				No extended shading			
Date & Time	21st June, 12:00		21st December, 12:00		21st June, 12:00		21st December, 12:00	
Conditions	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky
Mean illuminance (lux)	1.171	237	4.423	89	4.688	556	4.615	207
Max. illuminance (lux)	1.714	426	15.931	162	35.084	840	16.289	318
Max. luminance (cd/m^2)	9.756	619	5.851	251	19.964	773	6.306	282
Min. luminance (cd/m^2)	1	1	11	0	67	2	17	1
Luminance E. wall (cd/m^2)	32	1	21	0	93	3	21	1
Luminance floor (cd/m^2)	89	4	23	1	193	17	26	6

Shape	**Shape B** (cylinder)							
Location	Munich							
Case name	With extended shading				No extended shading			
Date & Time	21st June, 12:00		21st December, 12:00		21st June, 12:00		21st December, 12:00	
Conditions	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky
Mean illuminance (lux)	768	185	3.029	69	4.110	480	3.148	181
Max. illuminance (lux)	1.253	358	16.289	121	34.905	716	16.468	358
Max. luminance (cd/m^2)	7.451	745	5.858	277	13.481	714	5.905	280
Min. luminance (cd/m^2)	7	1	28	0	34	2	29	1
Luminance E. wall (cd/m^2)	16	1	31	0	43	2	34	11
Luminance floor (cd/m^2)	36	3	33	1	109	11	35	11

Shape	**Shape C** (double-curved)							
Location	Munich							
Case name	With extended shading				No extended shading			
Date & Time	21st June, 12:00		21st December, 12:00		21st June, 12:00		21st December, 12:00	
Conditions	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky
Mean illuminance (lux)	1.035	222	3.353	83	4.291	517	3.777	191
Max. illuminance (lux)	1.602	372	15.527	139	35.081	871	16.128	327
Max. luminance (cd/m^2)	5.845	636	12.019	206	12.867	684	5.919	259
Min. luminance (cd/m^2)	3	1	17	0	57	2	21	1
Luminance E. wall (cd/m^2)	23	1	21	0	72	3	22	1
Luminance floor (cd/m^2)	77	3	26	1	167	15	31	6

Shape	**Shape D** (free-curved)							
Location	Munich							
Case name	With extended shading				No extended shading			
Date & Time	21st June, 12:00		21st December, 12:00		21st June, 12:00		21st December, 12:00	
Conditions	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky	Clear sky with sun	Overcast sky
Mean illuminance (lux)	783	198	2.320	74	3.274	475	3.043	177
Max. illuminance (lux)	2.008	339	13.525	126	49.129	772	14.440	305
Max. luminance (cd/m^2)	7.317	530	9.237	229	13.997	681	6.280	281
Min. luminance (cd/m^2)	2	2	30	0	35	2	30	1
Luminance E. wall (cd/m^2)	12	2	31	0	47	3	35	1
Luminance floor (cd/m^2)	48	4	58	1	107	15	66	5

Table 12. Comparing roof shapes and openings under various lighting conditions

Further studies, various roof geometries and opening maps.

In this step the previously shown maps which define the opening sizes were applied to a specific roof geometry to generate and support certain usage scenarios in the space underneath. Here, spatial qualities rather than quantities were of concern. It links flow of roof geometry, interior ceiling height and opening sizes thus lighting conditions with each other to show how to be able to program functions with daylight. The studies were done for clear sky conditions for both 21st of June and 1st of April (start of blocking direct light) at 12:00 noon again for both applied shading extensions and without. Only the shaded version at 21st of June are shown. The rest can be found in the Appendix.

Flat

As previously seen this case due to absence of self-shading transmits most of the daylight into the interior. Due to the neutrality of shape any of the maps for different usage scenarios can be applied. However, despite the fact of providing the highest quantity in daylighting, the shape due to is generic form does not enhance an intended spatial and functional effect.

The first map applied is the linear path map 1 with grey edges. That means the central components are opened maximal and the edges are opened 50% to also bring light to the perimeter. As result, the linear path is not that well visible. For that reason, this map was discarded for further studies

Figure 55. Flat roof, linear map, luminance and illuminance, 21.06, clear sky with sun

The second map applied is the linear path map 2. Here the edges are fully closed. As can be seen in the luminance and false color perspective the effect of generating a guiding element for people is much stronger. The mean and maximum illuminance got reduced but would be still sufficient for being a passenger guiding system e.g. in train stations. Due to the flat shape of the roof the underside of the ceiling does not receive much light and will appear dark. This can only be solved with a change of the roof geometry itself.

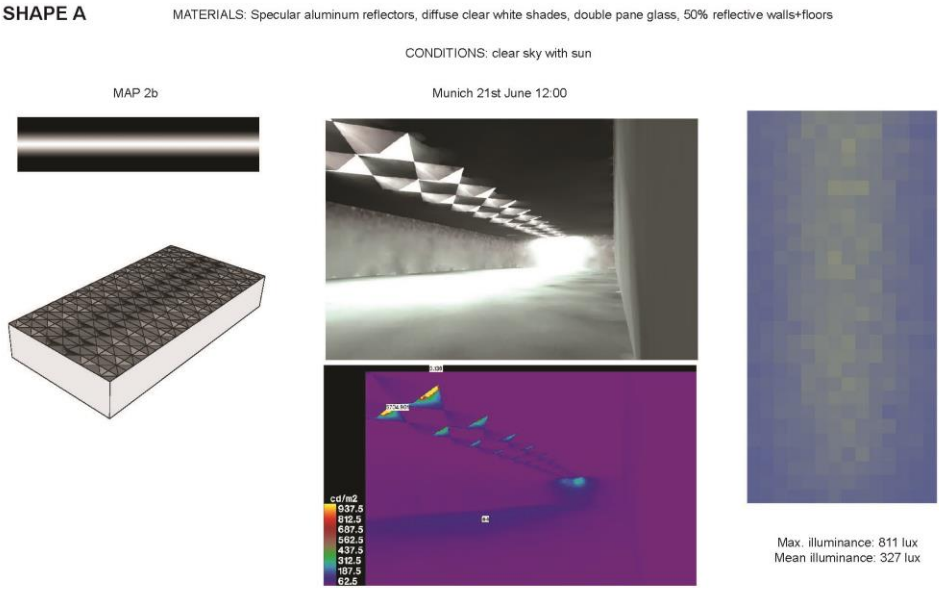


Figure 56. Flat roof, linear map 2b, luminance and illuminance, 21.06, clear sky with sun

Barrel vault

Map 2 was applied to the barrel vault geometry enhancing the spatial effect of linear path and movement. Now the change in luminance on the ceiling is less abrupt (in comparison to the flat roof) due to the inclined components adjacent to the opened also receiving light. The path is further enhanced due to the difference in room height.

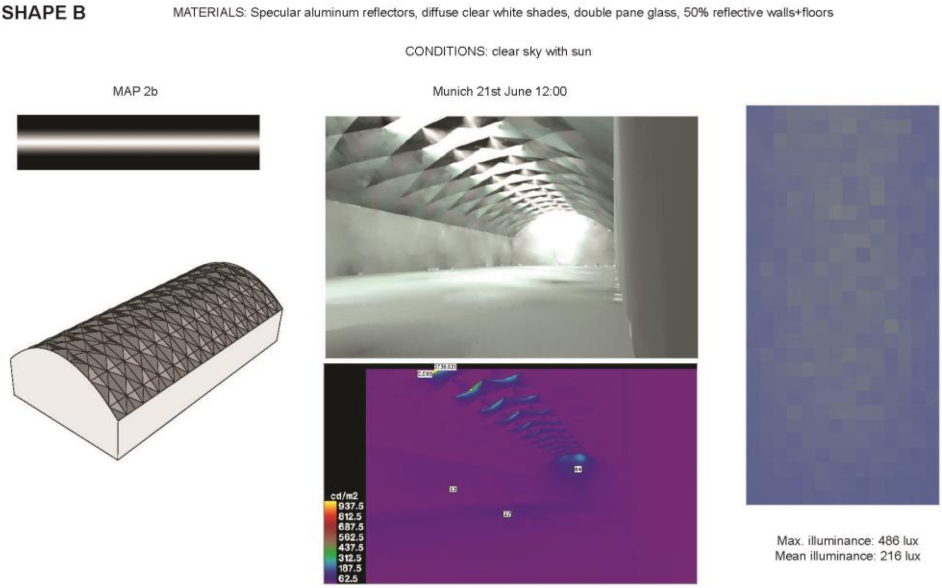


Figure 57. Barrel vault roof, linear map 2b, luminance and illuminance, 21.06, clear sky with sun

Shell like

In the next steps maps got applied which match the overall roof geometry. Therefore, the shell-like roof shape is combined with the central area map 3. This is applicable for meeting points or places for hospitality like cafes, etc. It is also possible to generate several linear paths leading towards this spot and the central area functions as daylight enhanced local hub.

Figure 58. Shell like roof, central map 7, luminance and illuminance, 21.06, clear sky with sun

Free-form

The free form geometry is intended to be used to highlight relatively small areas. It could be interesting to generate zones for exhibitions to draw attention towards certain areas. However, learning from the previous studies and seeing how the gradient maps need area to develop (otherwise the lighting effect gets disturbed) instead of 4 highlights matching with the roof geometry, 2 diagonally opposing ones in form of the two accents map were applied.

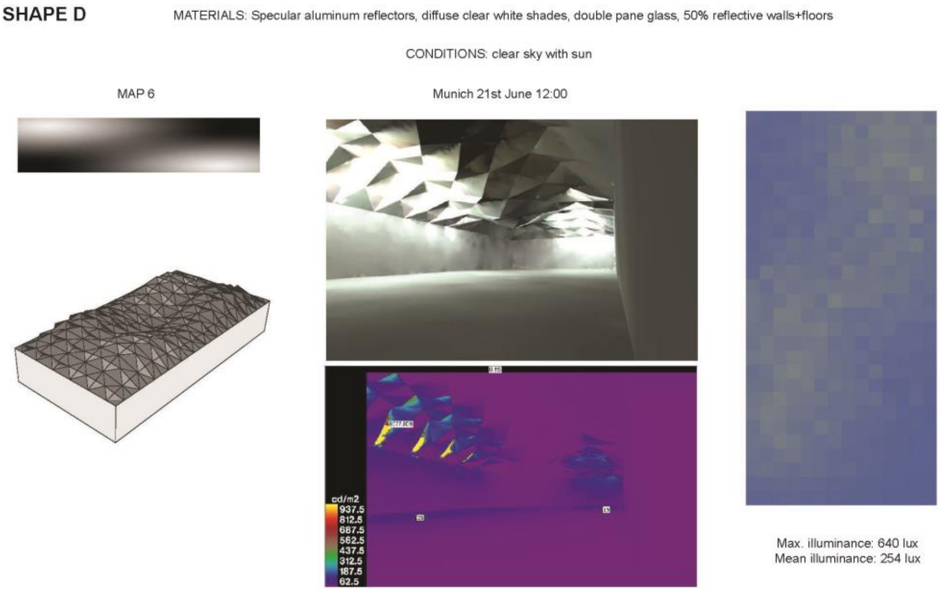


Figure 59. Free-form roof, two accents map 6, luminance and illuminance, 21.06, clear sky with sun

Since the roof geometry is not matching the lighting scheme, the free-form geometry was updated in to match it. Due to the curving downwards of the roof geometry and directionality of incoming daylight, the lowest height of the roof above ground receives little light. However, the effect of spatial compression and opening can be perceived well.

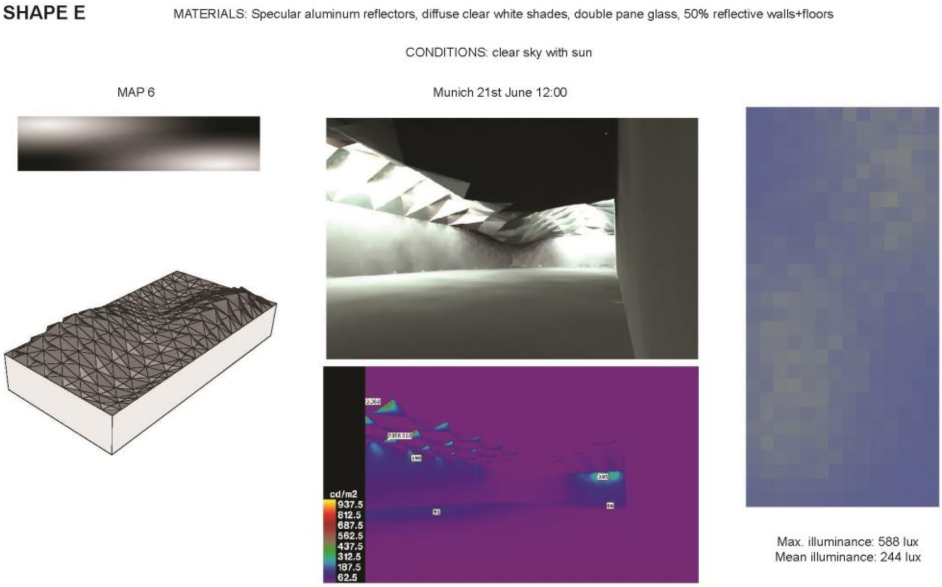


Figure 60. Free-form roof adjusted, two accents map 6, luminance and illuminance, 21.06, clear sky with sun

To reduce the effect of having dark ceiling parts, one needs not only to take into consideration the general direction and the movement of natural light but also where the inhabitants enter the space. Taking that into consideration the map and roof geometry were mirrored to reduce the effect of darkened parts of the ceiling to be perceived from one side.

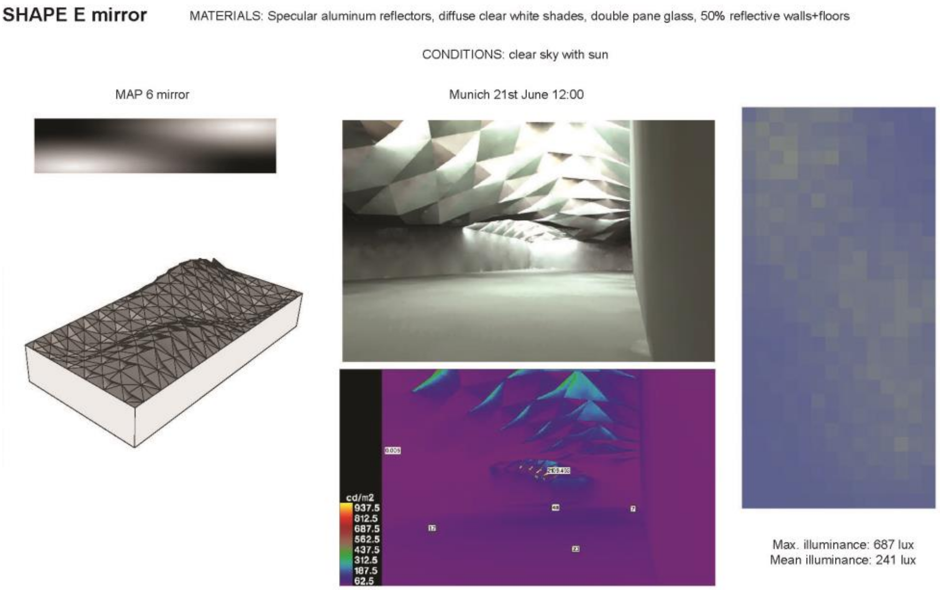


Figure 61. Free-form roof mirrored, two accents map 6 mirrored, luminance and illuminance, 21.06, clear sky with sun

Evaluation daylighting roof geometries and matching opening maps

This step is done to move away from a general approach towards more applied design scenarios with specific cases. The shown examples illustrate how a usage scenario can be linked with a spatially defining roof geometry and daylighting scheme for enhancement. Seeing how other factors in terms of daylight like glazed vertical façades come into play a specifically designed roof geometry and maps were made for the Neue National Gallery in Berlin as replacement for the existing roof.

Applied Case Neue National Gallery Berlin

The New National Gallery in Berlin is the only building which was realized by Mies van der Rohe after the Great War in Germany. It was the first museum which was realized in the Kulturforum nearby Potsdamer Platz. For the design two previously not realized designs like the administration building for Bacardi in Santiago de Cuba and the Museum Georg Schäfer in Schweinfurt which also have a free spanning roof carried by eight columns served as template. For the application of the origami roof the upper hall was looked at. The current situation in terms of daylighting, according to the location Berlin in Germany is analyzed and subsequently a new roof taking the layout and in inner functions in consideration is designed. Apart from the roof, the other existing materials are kept.

Figure 62. Neue National Gallery Berlin, aerial photo, image source: Raimond Spekking

Design Intention by Mies van der Rohe

Universal space

The spatial configuration is defined by a clear unobstructed volume which is encased by a transparent glass skin thus establishing a continuous relation between inside and outside, the inner floor and the outer ground. This is further enhanced by showing and emphasizing the roof construction which is presented in form of a beam grid stretching equally into both directions and thus enhancing the spatial continuum by its perspectival lines of flight. The eight vertical columns on the outside upholding the roof, are also defined in form by their constructive functions and purposes. They are materialized as crosses in section which are slender enough to almost visually disappear. The strong horizontal lines of the sharp edges of the seemingly floating roof enhance the relation of visitor inside and framing the vista to the outside. The square shaped roof having 8,4m floor to ceiling height is dimensioned 64,8m by 64,8m surrounded by a glass façade which is set back 7,2 m letting at certain times during summer no direct light into the interior. The roof is constructed via 19x19 beams which form 324 cassettes on the ceiling.

Figure 63. Neue National Gallery Berlin, interior photo, image source: Dirk Verwoerd

Materiality

The most obvious materials are the black painted steel beams on the ceiling and the natural stone flooring material. For the daylight simulation the existing material values were transferred to Diva/Radiance. Because of not being able to clearly determine the material properties of the flooring material and visual clarity the floor was not simulated as a specular reflecting one but as diffuse material.

Ceiling elements, columns, frames:	**Black-steel (0.05 0.04 0.03 0.3 0.02)**
Facade glazing	DoublePane_Clear_64 (0.705192 0.705192 0.705192)
Floor	GenericInteriorWall_50PercentReflectance (0.5 0.5 0.5 0 0)
Walls	Beige_wall (0.52 0.455 0.236 0 0)
Pillars	Green_marble (0.032 0.059 0.057 0.3 0.2)

Table 13. Material settings for daylight simulations

Daylighting

The ceiling and floor appearing as darker elements in photographs albeit enhancing the focus on the panoramic view add contrast to the interior due to backlighting, reflection on the floor close to the glazed perimeter and lack of other natural light sources from the roof. It is questionable whether this space can function due to low illuminance values as seen in the daylight simulation, as exhibition space due to reduced legibility of exhibition pieces. The exhibition would have to be set up close to the glass façade facing the exterior leaving the center empty unless artificial light sources would be implemented. In contrast to initial expectations also with respect to personal experience and photographs the horizontal light bands do not pose an issue in terms of glare as shown in the fisheye image of the point in time daylight glare probability (DGP).

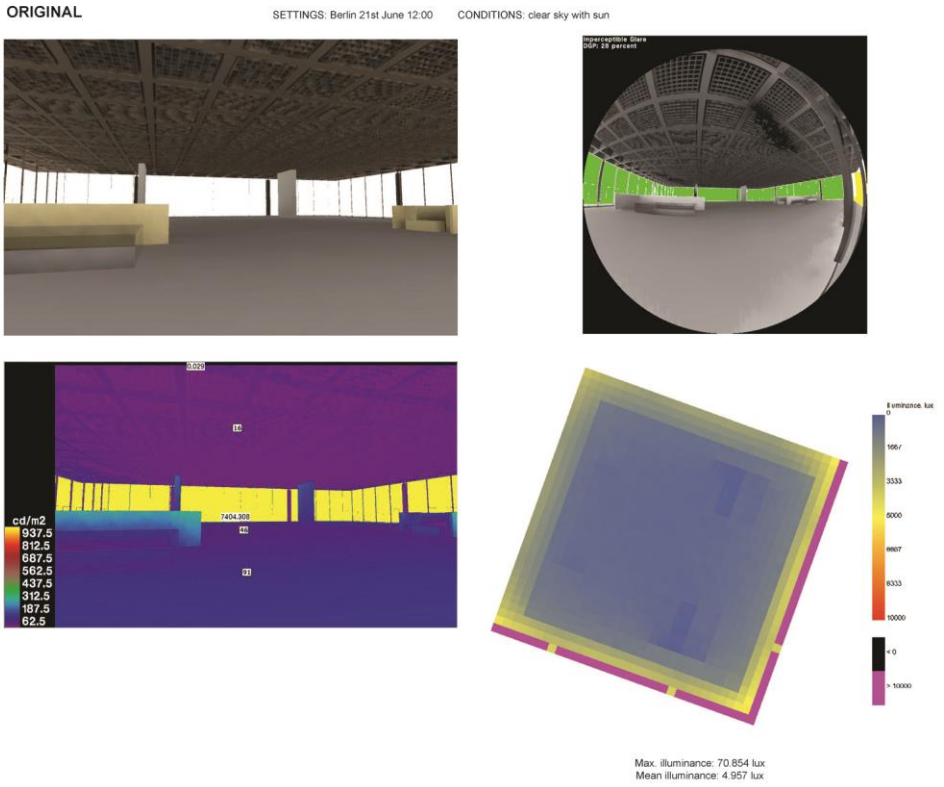


Figure 64. Neue National Gallery Berlin, original roof, 21.06., 12:00 clear sky with sun, luminance and illuminance

Application of the Origami roof

The new roof was designed in such a way to respect the original design to a certain degree but implement a new spatial interpretation according to entrance zones and floor plan layout. The edges of the roof remain horizontal and straight in order not to influence the outer appearance of the building. Looking at the floor plan and the simple layout three major elements symmetrically arranged were identified. Firstly, entrance zone and close to that the stairs and volumes for accessing the exhibition space underneath as second element. Finally, the back area with two vertical massive pillar elements forming a hall. The roof geometry as such was designed to introduce in accordance with the notion of spatial continuum a more differentiated gradually changing space related to its functions becoming thus less universal but more specific. The entrance area stays flat due to its proximity to the edge, flow of curvature and transformation into the back part. Above the staircases the roof flows down, however not touching the floor and not dividing the space radically but to introduce a downwards motion. The back part with the largest area receives a shell-like geometry, having the largest room height and emphasis on its importance within the whole building layout. The map was designed in a similar way having openings above the entrance connecting linearly to the back part with the largest area of openings, also needed to illuminate the exhibition space and increase the usability.

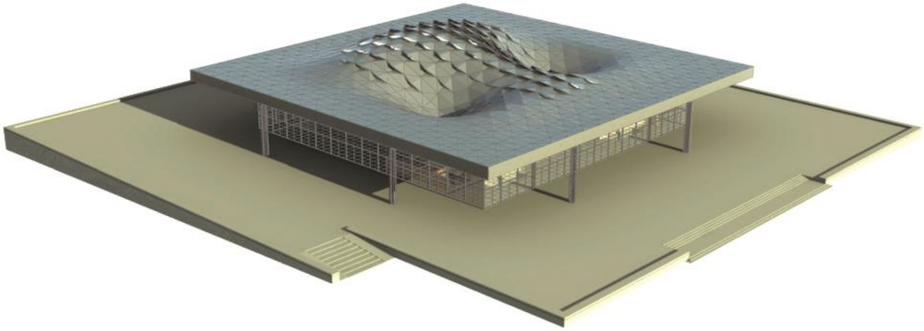


Figure 65. Neue National Gallery Berlin, test case new origami roof design

The previous material settings were kept, but the settings for the roof were changed according to earlier Origami roof settings.

Roof shades	**clear_white_mat (0.728 0.899 0.842 0 0)**
Roof reflectors	aluminum_2 (0.9 0.88 0.88 0.8 0.02)
Roof glazing	DoublePane_Clear_64 (0.705192 0.705192 0.705192)
Columns, frames	Black-steel (0.05 0.04 0.03 0.3 0.02)
Facade glazing	DoublePane_Clear_64 (0.705192 0.705192 0.705192)
Floor	GenericInteriorWall_50PercentReflectance (0.5 0.5 0.5 0 0)
Walls	Beige_wall (0.52 0.455 0.236 0 0)
Pillars	Green_marble (0.032 0.059 0.057 0.3 0.2)

Table 14. Material settings for daylight simulations

Daylighting

Looking at the daylight simulations two different effects occur but are working against each other. The illuminance values in the interior due to the openings in the roof improved and the space would be usable for exhibitions during daytime. Additionally, no direct light can enter the space and the shading extension function as intended. Due to the increased light reflection of the ceiling material, the edges close to the glass façade also reach higher illumination values in comparison to the original design. However, the perimeter in this case has higher lux values than the central spot which in a way reduces the architectural effect to be able to highlight and draw attention to the central space as shown in the previous general example shell-like roof combined with central area map. Glare at 12:00 on the 21st of June with 30% DGP is slightly higher than the original state but still categorized as imperceptible.

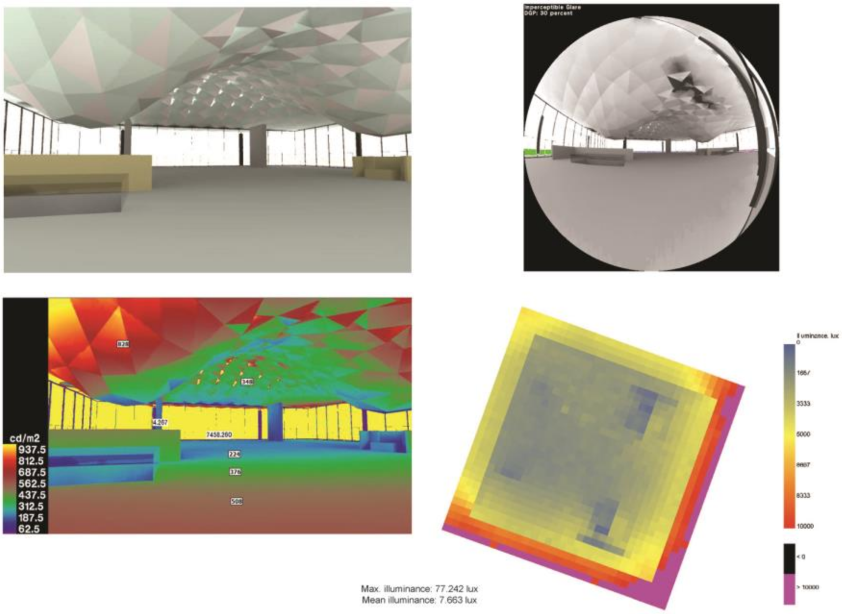


Figure 66. Neue National Gallery Berlin, origami roof, 21.06., 12:00 clear sky with sun, luminance and illuminance

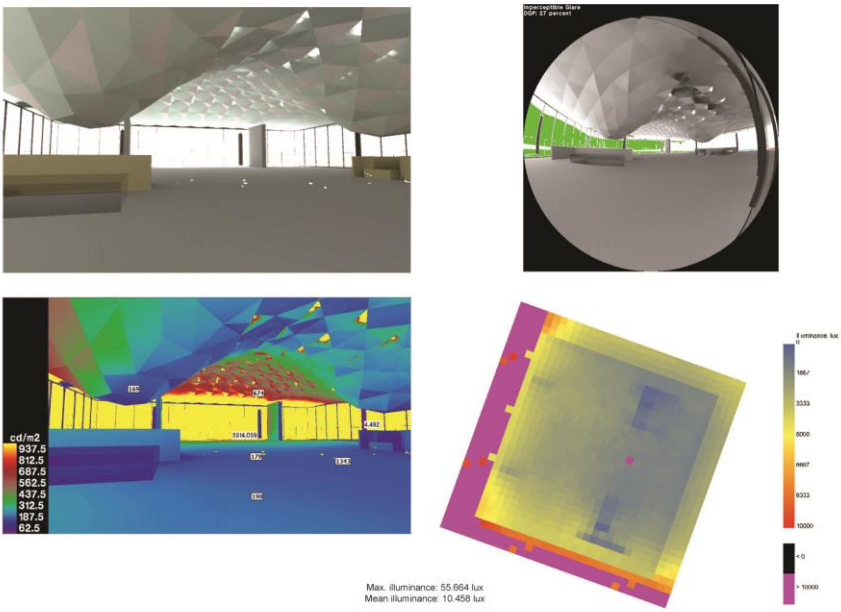


Figure 67. Neue National Gallery Berlin, origami roof, 21.06., 17:00 clear sky with sun, luminance and illuminance

Evaluation daylighting and comparison original state and origami roof application

The origami roof is successful in making the space more usable but the architectural design intentions to give more accents to the central space by daylighting strategies should be rethought, simply because the glazed perimeter receives higher luminance values as the floor underneath and ceiling. This starts to change in the late afternoon once sunlight comes from the west in a lower altitude angle. It appears, that the two light sources in form of openings in the roof and the vertical glass façade compete not in terms of illuminating the space but setting accents/highlights for architectural and spatial purposes. For enhancing an architectural effect either reflectivity of the flooring material should be reduced (reducing the luminance surface at the perimeter), or it should be accepted that like the original design the perimeter and view to the outside draws most attention. Otherwise another example should be found where there is little to no daylight being transmitted from the periphery. This could be for instance the California Institute of Science by Renzo Piano which already displays with its roof geometry a comparable approach.

Figure 68. California Institute of Science, Renzo Piano, image source: WolfmanSF

5.2.7 Conclusion

The shown approach in the category of adapted geometry has advantages in comparison to conventional design methods but also disadvantages in terms of daylighting. It is very well possible to be able to program space for certain functional requirements to a much higher degree than conventional design methods. However, it takes more time to develop and come up with appropriate geometrical and material configurations and several design iterations need to be made to result in an optimal solution.

The origami roof structure serves here as an example and case study. That means that other designers can and should come up with their own geometrical and material proposal but can use the presented work as almost step by step guideline. In recent years similar concepts in form of projects like the Shenzhen Bao International Airport building in China were realized but costs and effort due non-standardization in form of construction as well as design and planning procedures are extraordinaire.

Figure 69. The Shenzhen Bao International Airport building, Studio Fuksas, image source: Yida xu

The disadvantages of adapted geometries as shown in the case study come from the fact that the result is not very flexible but very specific in terms of use and function and changing lighting requirements can hardly be incorporated. This is simply due to the nature of this sort of parametric design approach. Making proper use of parameters and translating those into a geometrical and material model all the aspects must be clearly defined, and the boundary conditions become rather tight. Therefore, that a design solution cannot be anything else than specific for a certain more narrowed down task otherwise it would not perform at all but also suboptimal outside the predefined framework. The issue here lies also in the fact that external lighting conditions are changing but to come up with a static geometrical and material solution averages or mean values must be taken as parameters and checked against several different daylighting conditions to ensure the intended performance for the intended function over a longer period. For that reason, as already suggested by the title of this dissertation an adaptive solution would be required.

5.3 Static Contextual Buildings – High-Performance Materials - Aerogel

5.3.1 Context

Membrane roofs are not only used as outdoor shading devices but when used as complete buildings also to let natural daylight into the interior of the building like the well-known examples of Frei Otto's Multihalle in Mannheim or the Olympic swimming arena in Munich. Since membrane roofs transmit light in a diffused way this makes them especially suitable for functions which require an even light distribution like infrastructural or sport facilities without having the negative effect of glare through high differences in contrast. One disadvantage of the earlier described examples however, is that those were built during times when energy regulations were laxer, therefore no thermal insulation was present. This case study investigates whether it is feasible to apply Aerogel as insulation to textile structures, improving the thermal performance while keeping as much as possible daylight transmissions. Looking Visual Light Transmittance (VLT) values of textiles as such, one realizes that materiality, manufacturing process, tensile strength and manufacturer have a great impact. PTFE-coated glass fabric for instance depending on its thickness and weavings can have a light transmittance between 5-25% (Hightex, 2013)

The case study looks specifically at the application of Aerogel in combination with membrane structures to evaluate the potentials for natural day lighting. However, the combination of Aerogel insulation with membranes further reduces light transmittance but an estimated value of 5%-7% of Visual Light Transmittance would be sufficient to replace artificial lighting in sports halls for non-professional sports and reduce running costs during daytime for the case study location Munich which is also used for the later shown daylight simulation. The application of Aerogels for new buildings, especially for large span membrane roof structures located in cold and moderate climate conditions looks promising but needs to be evaluated comparing initial costs in relation to daylight performance and savings for artificial light.

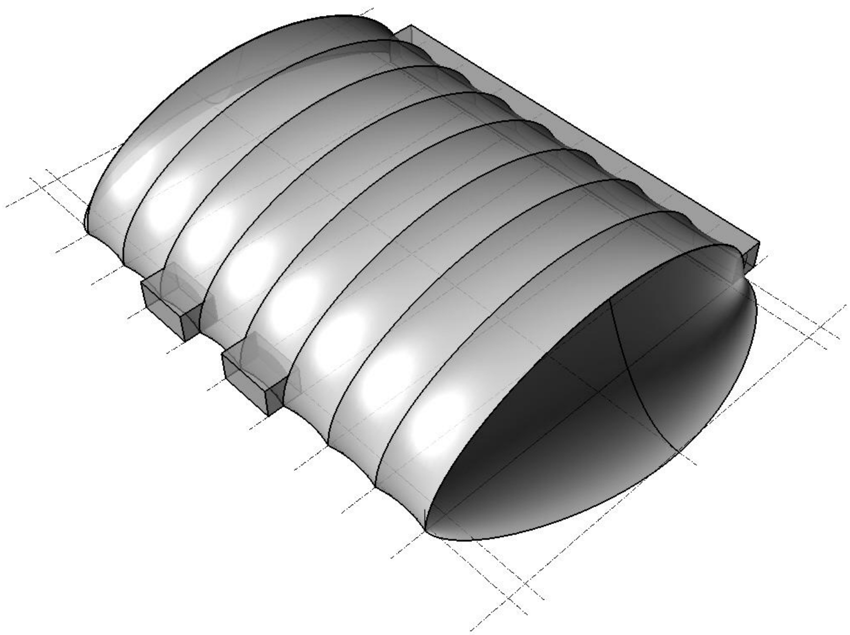


Figure 70. Design Tennis Hall

5.3.2 Lighting requirements

According to the requirements of the EN 12464-1 (European Standard, 2002). certain minima in illumination levels must be met. The classes shown differentiate between school and club sports (class III), competition and training for intermediate levels (class II) and professional competitions (class I). Since a lot of membranes structures are used for covered tennis courts which are used publicly for non-professional sports, the later shown assessment orients itself to meet the illumination value of 300 lux (class III).

Class	Description	Illumination
I	competitions serious sports, training serious sports	500-2000lux
II	competitions average level, training average level	300-1000lux
III	competition simple, common training, sports at school	200-300lux

Table 15. Lighting requirements according to EN 12464-1

5.3.3 Design Process

The reference which the case study is based on is a tennis hall with dimensions of 40m*70m and is an actual prototypical design (Heinzelmann, Teuffel, 2013) with further possibilities to be used for several applications.

5.3.4 Geometrical & Material Aspects - Technical solutions & systems

Aerogel and insulation

Apart from the unique material properties of Aerogel being translucent, a good sound insulating material and hydrophobic, Aerogel displays superior insulation qualities. Depending on the treatment of Aerogel being either packed granules, compressed, or as a fleece it has different thermal conductivity (λ-value) also depending on the respective product manufacturers.

Silica aerogel (AEROGEL.ORG, 2013) is the most common type of aerogel. Aerogels are open-celled, mesoporous, solid structures of a 95-99% gas content, produced by the removal of the liquid component from a gel, without its shrinkage to occur. They are produced by the supercritical drying of silica gel and thus the resulting solid framework of silica aerogel is composed of nanoparticles of silica—the oxide of silicon. It is hydrophilic due to the unreacted silanol (Si-OH) groups on the framework's surface, but chemical processing of silica gel before the stage of supercritical drying can convert the final product to 100% hydrophobic. One of the most know attributes of silica aerogels is the high optical transparency and low thermal conductivity of values as low as 0.012 W/(m*K). Silica Aerogel has a very high compressive strength to weight ratio, but it is very brittle. This could pose insofar a problem since membrane structures have a double curved geometry but also are flexible (mechanical strain) and react on changing load conditions.

The lower the thermal conductivity value the better is the performance. As general indication Aerogel as such has a relatively low thermal conductivity which is only surpassed by Vacuum Insulation Panels (VIP). Applying a 7 cm layer of Aerogel block (λ-value 0.012 W/(m*K)) would result in a U-value of 0.193 W/(m^{2}K). As a comparison this value would be reached with 20 cm of mineral wool (λ-value 0.04 W/(m*K)), 3 cm of VIPs (λ-value 0.04 W/(m*K)) or 90 cm of reinforced concrete (λ-value 1.8 W/(m*K)). The advantage of applying Aerogel for textile buildings is its lightness with 60-80kg/m^3 but also the fact that it can be applied in relatively thin layers while having good insulation properties. This should keep the enclosing envelope slender, which is essential for membrane structures.

The following table shows a comparison of different insulation materials in terms of thermal conductivity, layer thickness and U-value.

Material	λ-value W/(m*K)	Thickness (mm)	U-value W/(m²K)
Aerogel block	0.012	70	0.193
Aerogel granule	0.018	70	0.25
Mineral wool	0.040	200	0.19
VIP	0.006	30	0.22

Table 16. Thermal conductivity & thermal transmittance (u-wert.net)

The above shown table only takes thermal conductivity but not transparency into consideration. It is also a rather idealized view on Aerogel, because it is necessary to look more closely at specific manufacturers and their products not only in terms of performance but also in terms of pricing and applicability for membrane structures. The following table compares several products.

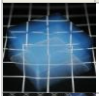
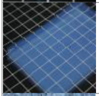
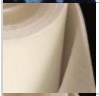
IMAGE	PRODUCT	COMPOSITION	DIMENSIONS	λ (W/m*K)	PRICE	TRANSPARENCY	MANUFACTURER
	Classic Silica Block	Aerogel Block	2,5cm*2,5cm*1cm	~0,012	60$	90-93% per cm	Aerogel Technologies, LLC
	Classic Silica Tile	Aerogel Tile	5cm*7,5cm*0,7cm	~0,012	200$	90-93% per cm	Aerogel Technologies, LLC
	Lumira™ Aerogel	Aerogel Granules	Granule size range 0,07-0,4cm	0,018	10$ per 100cm^3	91% per cm	Cabot
	Lumira™ Aerogel Blanket	Lumira™ Granules within non-woven polyester and polyethylene fibers	Available thicknesses: 0,35/0,6/0,8cm	0,023	-	20% per 0,8cm	Cabot
	Thermal Wrap™	Lumira™ Granules within non-woven polyester and polyethylene fibers	Available thicknesses: 0,35/0,6/0,8cm	0,023	25$ per piece: 30,5cm*27,4cm*0,6cm	20% per 0,8cm	Cabot
	Spaceloft® Blanket	Silica aerogel and reinforcing fibers	Available thickness: 0,5/1cm	0,014	40$ per piece: 30,5cm*30,5cm*1cm	0%	Aspen Aerogels

Table 17. Comparison of different Aerogel based products. (Cabot, 2013) (Aspen Aerogels, 2013)

From the list only the Lumira Aerogel blanket with embedded aerogel granules in non-woven polyester and polyethylene fibers or the Thermal Wrap are immediately usable for membrane structures. Those two are also feasible because of their transparency. Here, the readily available Tensotherm composite system (Birdair, 2013) with an outer layer of glass fiber PTFE Membrane uses Lumira. Pure Aerogel granules which are also cheaper than the brittle Aerogel block would have a lower thermal conductivity and superior light transmittance in comparison to the Lumira blanket. However, the granules cannot be applied immediately without being integrated in some sort of carrier mat or layer.

Material settings for daylight simulations

As location Munich was chosen to conduct the daylight simulation. Here it is required to design membrane structures according to class 3 (Forster, Mollaert, 2004) because of snow and wind loads. This also poses a more challenging case in terms of day-lighting because the stronger the tensile strength of a membrane, the less daylight can be transmitted. For the tennis hall with the dimensions of 40m*70m and a girder distance of 6,5m while fulfilling class 3 requirements, the membrane needs to have a tensile strength of around 560daN/5cm (Heinzelmann, Teuffel, 2013)

In terms of energy requirements and resulting demands in thermal transmittance, the German law for energy preservation in buildings (EnEv, 2009) is taken as basis for defining the thickness of the Aerogel insulation. In accordance with the indoor temperatures requirements of 15°C-20°C for sport halls (EnEv, 2009) lowered values in thermal resistance are applied. Compared to a massive constructive system for a sports hall which would have 10%-20% of glazed surfaces (to have a similar daylight performance) the resulting mean u-value is around 0,66 W/(m^{2}K) which serves as a target for the layering of aerogel.

For the membrane itself various products are available. Only a couple of them match the requirements in terms of tensile strength and light transmittance.

PRODUCT	**COMPOSITION**	**TRANSPARENCY**	**TENSILE STRENGTH** warp/ weft (N/5cm)	**TEAR RESISTANCE** warp/ weft (N)	**WEIGHT** (gr/m^2)	**MANUFACTURER**
Précontraint 1202 T2 back PVDF	Woven polyester base cloth, Exterior surface treatment: Fluotop T2 (High concentration PVDF), Interior coating: weldable PVDF	10%	5600/5600	800/650	1050 (1250)	Serge Ferrari
Duraskin B 18089	Glass Fibre EC 3/4 fabric with PTFE coating	14% (at 550nm)	7000/6000	500/500	1150	Verseidag
Duraskin B 18656	Glass Fibre EC 6 with PTFE coating	34% (at 550nm)	5000/4500	450/500	700	Verseidag
Sheerfil II-HT	Fiberglass and PTFE	12,5%	6874/4904	331/289	1432	Saint Cobain
Sheerfil II-A	Fiberglass and PTFE	16,0%	5604/5604	267/331	1414	Saint Cobain

Table 18. Comparison of different membranes (Ferrari, 2013), (Verseidag, 2013), (Saint-Gobain, 2013)

Several daylight simulation test cases were set up to compare material settings within the simulation environment (case 1), existing products which already combine aerogel insulation material with a membrane layering (case 2 & 3) and check earlier estimated light transmission requirements (case 4)

Case 1

Control simulation to determine the difference between glass and trans material in terms of illumination levels under clear sky and overcast sky conditions.

Case 2

The Thensotherm Lumira (Birdair, 2013) membrane composites found in the product sheet give a range of light transmissions, u-values, etc. according to the layering variations. The selected product for case 2 has an outer, mechanical layer consisting of a Saint Gobain Sheerfill glass fiber PTFE membrane, sandwiched inside are 4 layers of 8 mm Lumira Aerogel sheets and in the inner layer consists of an acoustic liner. This specific combination fulfills the requirement of a U-value of 0.65 W/(m²K) has a light transmission of 2.48% but does not match the structural requirements. It was none the less chosen to compare it with case 3 which fulfills all the requirements but has a lower light transmission.

Case 3

Another Tensotherm Lumira product which has the same inner layering like in Case 2. It was not clearly stated by the product specification sheet which exact membrane layer is used in the product. However, by comparing several product data sheets (Saint-Gobain, 2013), (Birdair, 2013) it became apparent that the outer, mechanical layer is a Saint Gobain Sheerfill II-A glass fibre PTFE membrane due to the light transmission of 16%. This combination fulfills both the requirements for tensile strength of 560/560 daN/5cm according to class 3 and U-value of the membrane composite of 0.65 W/(m²K). The light transmission is 1.72%.

Case 4

Estimation case of 6% daylight transmission.

Case	**light transmission in %**
1. *trans* material, control case	20
2.Tensotherm 32mm,	2.48
3.Tensotherm 32mm, class3	1.72
4.Estimated case	6

Table 19. Light transmission layered membrane (Birdair, 2013)

The other building components like floor or walls were defined according to available material lists within *Radiance.*

Opaque material	50% reflectance
Interior floor	20% reflectance
Outside ground	20% reflectance

Table 20. General material properties for the DIVA simulation

It is important to note that for other cases in other locations, the required values for illumination, thermal resistance and tensile strength must be checked in relation to the local building codes individually for each country where a membrane structure will be built. For this case study German codes were used. The aim is to get a constant illumination of 300 lux throughout the year to achieve daylight autonomy and limit the use of artificial lighting to early morning, evening and winter months.

5.3.5 Lighting Analysis and Alternatives

The daylight simulation is done from the *Rhino 3D* modeler using the *DIVA* plugin which utilizes the *Radiance* engine for light simulation. The material chosen for the membrane within the simulation is based on a *glass* material in opposition to translucent *trans* material definition since it is not possible to determine the diffuse and specular transmittance as well as the total light transmittance of the chosen material mix by the manufacturer data only. To receive precise information this would have to be done by physically laboratory testing via a spectral-photometer according to DIN. However, this poses not so much of a problem since the main interest is to investigate the quantities of daylight transmitted rather than the qualitative aspects. Since the membrane is spread all over the usable surface of the hall the light is in any case equally distributed and scattered. To proof that this approach is valid a test run was done with a *trans* material which was readily available in the *Radiance* material library and the properties are based on actual material measurements (albeit different from the to be tested cases).

Usually the zone of measurement is situated 0.85m above ground to check for workplace illumination levels on top of tables. Since this is not relevant for a tennis hall, the current set of simulation points of measurement are situated 5cm above ground since the end fields of the membrane are inclined and some of the simulation grid points would be located outside the membrane and would falsify the result.

The simulations were run based on the following geometry with the dimension of 40m*70m. The chosen dates were the extremes during summer solstice and winter solstice and a situation in between representing a spring/autumn condition.

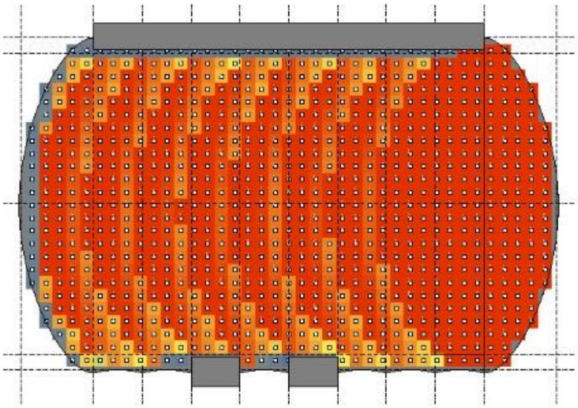


Figure 71. Case 4, 21.09. 12:00, clear sky

Case 1 *trans* material 20% light transmission
Location Munich, 48°8′0″N 11°34′0″E

Date/time	Sky condition	Mean illumination in lux
21.12./12:00	clear sky with sunlight	3437
21.12./12:00	overcast sky	807
21.09./12:00	clear sky with sunlight	8020
21.09./12:00	overcast sky	1671
21.06./12:00	clear sky with sunlight	11882
21.06./12:00	overcast sky	2238

Table 21. DIVA simulation results mean illumination case 1 for Munich, Germany

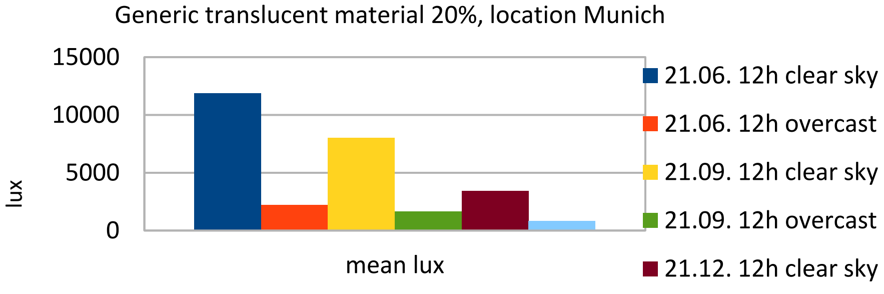


Figure 72. DIVA simulation results mean illumination in Munich, Germany

Case 2 Tensotherm 32mm Lumira, 2.48% light transmission
Location Munich, 48°8′0″N 11°34′0″E

Date/time	Sky condition	Mean illumination in lux
21.12./12:00	clear sky with sunlight	323
21.12./12:00	overcast sky	95
21.09./12:00	clear sky with sunlight	800
21.09./12:00	overcast sky	195
21.06./12:00	clear sky with sunlight	1286
21.06./12:00	overcast sky	261

Table 22. DIVA simulation results mean illumination case 2 for Munich, Germany

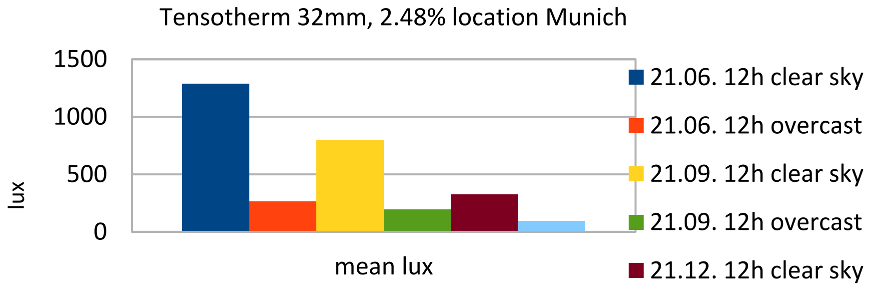


Figure 73. DIVA simulation results mean illumination in Munich, Germany

Case 3 Tensotherm 32mm Lumira, 1.72% light transmission
Location Munich, 48°8′0″N 11°34′0″E

Date/time	**Sky condition**	**Mean illumination in lux**
21.12./12:00	clear sky with sunlight	213
21.12./12:00	overcast sky	62
21.09./12:00	clear sky with sunlight	524
21.09./12:00	overcast sky	128
21.06./12:00	clear sky with sunlight	850
21.06./12:00	overcast sky	171

Table 23. DIVA simulation results mean illumination case 2 for Munich, Germany

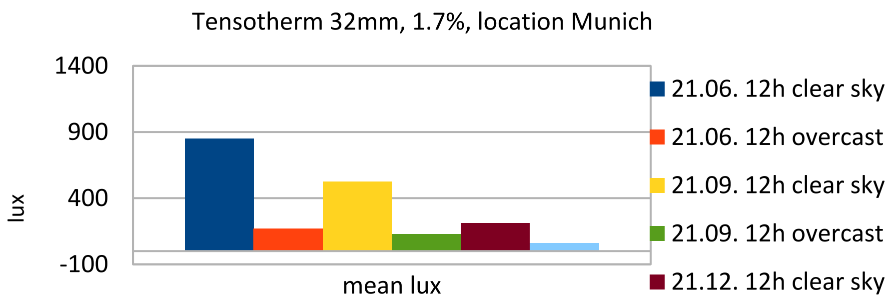


Figure 74. DIVA simulation results mean illumination in Munich, Germany

Case 4 Optimal solution, 6% light transmission
Location Munich, 48°8’0”N 11°34’0”E

Date/time	Sky condition	Mean illumination in lux
21.12./12:00	clear sky with sunlight	816
21.12./12:00	overcast sky	241
21.09./12:00	clear sky with sunlight	2061
21.09./12:00	overcast sky	499
21.06./12:00	clear sky with sunlight	3236
21.06./12:00	overcast sky	668

Table 24. DIVA simulation results mean illumination case 2 for Munich, Germany

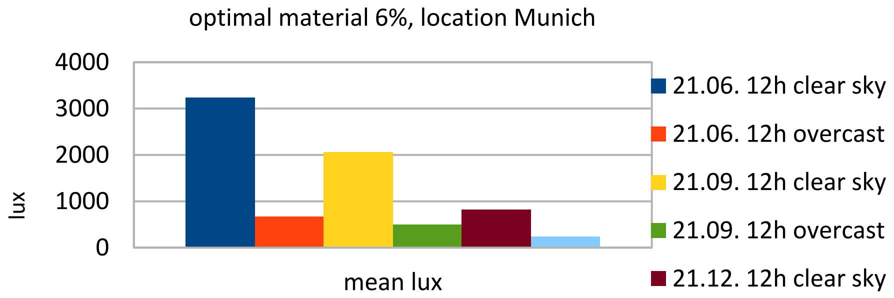
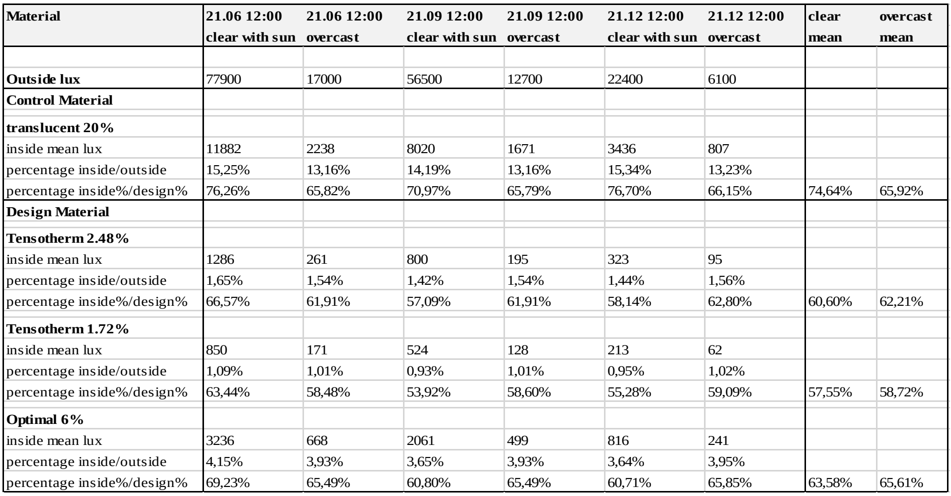


Figure 75. DIVA simulation results mean illumination in Munich, Germany

Comparison *glass* and *trans* material



Material	21.06 12:00 clear with sun	21.06 12:00 overcast	21.09 12:00 clear with sun	21.09 12:00 overcast	21.12 12:00 clear with sun	21.12 12:00 overcast	clear mean	overcast mean
Outside lux	77900	17000	56500	12700	22400	6100		
Control Material								
translucent 20%								
inside mean lux	11882	2238	8020	1671	3436	807		
percentage inside/outside	15,25%	13,16%	14,19%	13,16%	15,34%	13,23%		
percentage inside%/design%	76,26%	65,82%	70,97%	65,79%	76,70%	66,15%	74,64%	65,92%
Design Material								
Tensotherm 2.48%								
inside mean lux	1286	261	800	195	323	95		
percentage inside/outside	1,65%	1,54%	1,42%	1,54%	1,44%	1,56%		
percentage inside%/design%	66,57%	61,91%	57,09%	61,91%	58,14%	62,80%	60,60%	62,21%
Tensotherm 1.72%								
inside mean lux	850	171	524	128	213	62		
percentage inside/outside	1,09%	1,01%	0,93%	1,01%	0,95%	1,02%		
percentage inside%/design%	63,44%	58,48%	53,92%	58,60%	55,28%	59,09%	57,55%	58,72%
Optimal 6%								
inside mean lux	3236	668	2061	499	816	241		
percentage inside/outside	4,15%	3,93%	3,65%	3,93%	3,64%	3,95%		
percentage inside%/design%	69,23%	65,49%	60,80%	65,49%	60,71%	65,85%	63,58%	65,61%

Table 25. Comparison trans versus glass material

By looking closer at *trans* material and *glass* material simulations as earlier stated being relevant for understanding the difference of a diffuse (trans) and direct (glass) light transmission, it shows that there is a gap in comparison in terms of percentage of design value of light transmittance and simulated value which reaches the interior. The difference between *trans* and *glass* material in percentage of reaching the interior becomes larger the smaller the design value of light transmission gets. This is less favorable especially for case 3 Tensotherm 1.72% material. Especially looking at the more critical overcast sky conditions throughout the year and increasing the illumination values by 7%, the Tensotherm structure will not meet the required illumination of 300lux.

Evaluation

Case 2 with a light transmission of 2.48% is not taken into consideration since the mechanical layer does not meet the class 3 requirements. Case 3 with the earlier stated difference in daylight simulation results regarding *trans* and *glass* material requires a more differentiated view. During the whole year under clear sky conditions the structure would perform well. However, under overcast, meaning cloudy sky conditions where a fraction of daylight reaches the ground the situation is different. Here even in summer the interior would not be sufficiently lit, and artificial light would have to be used. The roof needs to perform better considering the amount of overcast or rainy days in Germany.

Case 4 with a light transmission of 6% is satisfying this demand, reaching 240 lux in worst case scenario 21.12. under overcast sky conditions. 7%-8% would be even better to reach the full 300 lux and cover more of the morning and afternoon hours. There is currently no product available on the market which simultaneously fulfills the requirements in thermal resistance, mechanical properties and light transmission.

5.3.6 Conclusion

As earlier stated the daylight performance is greatly dependent on mechanical and thermal requirements which the membrane structure should meet according regulations but also on atmospheric conditions thus daylight availability at a certain location. Further the use or function of the hall also plays a great role, e.g. in case a vapor barrier or other layers are required this would additionally reduce the light transmission. This case study should add a new perspective towards future product developments also in terms of improved daylight performance. By looking at Aerogel granules only, the light transmission of a layer of 1cm is 91%. The Lumira Aerogel blanket in comparison with a thickness of 8mm has 20%. Here lays untapped potential to further optimize translucent insulations towards an increased light transmittance. This is even more important under the consideration that the above shown simulations just met the minimum requirements in terms of thermal resistance according to the EnEV 2009 with reduced inside target temperatures. That means if one considers building a daylight performing membrane hall under tighter regulations in terms of thermal requirements or a low-energy hall, the layer thickness of the insulation must be increased thus the light transmission will decrease. Again, looking at the sole Aerogel granules versus the Lumira blanket (table 4) the difference in thermal conductivity 0,018 W/(m*K) versus 0,023 W/(m*K) is not that huge, meaning improvement in terms of thermal performance of a new product and reduction of insulation thickness will not be that drastic. Therefore, one must look for another way to embed Aerogel granules into a flexible blanket or sheets where the carrier material (which prevents the granules from accumulating and forming thermal bridges) transmits more daylight. Here the research by Markus Holzbach (2009) which proposes to embed Aerogel granules into a so called *Inversmatrix* shows a promising direction. Finally, the costs of Aerogel products must be considered. The cost difference between Aerogel granules and the Thermal Wrap (table 4) is drastic. This is due to the fact the Thermal Wrap embodies less volume of Aerogel granules (thus lowered thermal resistance).

The only way to make future Aerogel products more appealing to the building industries and bring the initial cost versus the running cost (electricity saving for artificial lighting) into an economic balance is by being able to produce Aerogel more cheaply. According to predictions, in 2050 (Aerogel, 2013) aerogel will be commonly and widely applied (equally to plastics today), significantly contributing to the solution of future environmental problems. Although the raw material for the silica aerogel production is among the most abundant elements in earth, silica aerogel is still very expensive. The high cost is mainly related to the supercritical drying production technique that requires the development of high temperatures and pressure and produces in relatively small batches. There are several researches on the way which claim to be able to reduce manufacturing costs of Aerogel by 80%-90% soon. Here Maerogel, an aerogel made of rice husk developed at the Universiti Teknologi Malaysia (MIGHT, 2013) or Quartzene by Svenska Aerogel AB (Aerogel, 2013) are some of the developments to keep an eye on.

5.4 Adaptive Buildings - Kinetic Architecture by Adaptive Geometry & Statically Dynamic Architecture by Smart Materials

This relatively short chapter dealing with both adaptive geometry and statically dynamic architecture (smart materials) simultaneously in opposition to previous chapters where geometric and material aspects were dealt with separately is an intermediate step to develop the design method. The fully worked out case study for adaptive buildings will be presented in chapter 7.

5.4.1 Context

The case study for kinetic architecture by adaptive geometry as well as the statically dynamic architecture by adaptive smart materials is an early follow up research and design proposal based on Origami Roof structure case study (Heinzelmann, 2009). The geometry which is based on the Yoshimura Origami fold principle is thought in two scenarios:

- **Kinetic Architecture by Adaptive Geometry:** How would the structure be enabled to become adaptive and responsive towards its environment by actuation of its geometry and how would that perform in terms of daylighting and for what functions could it be used? This leads to **Case 1 External adaptive shades**
- **Statically Dynamic Architecture by Smart Materials** (Turrin, 2013)**:** In a similar way, how would the daylight performance be if the geometry remains static, but the material properties are changing in terms Visual Light Transmittance? This leads to **Case 2 Smart Glass**

Both cases investigate an application of smart skins (Klooster, 2009) which can react towards changes in environmental conditions, specifically solar incident radiation and irradiance.

5.4.2 Function and layout

Since the case study investigates design principles and usage scenarios in terms of daylighting a more generic shape was chosen. The test case roof is based on an arc shaped extrusion with the length of 27m and width of 14m. This geometry also has little interference with the daylighting outcome due to geometric simplicity while it covers the sides of the building.

5.4.3 Lighting requirements

There are no concrete lighting requirements set up since the case study’s main purpose is to examine design potentials and possible applications. Thus, the latter daylight simulation serves as documentation and input for further design steps. However, due to the arrangement of textile blinds and various modes of operation it is intended that there are constantly diffuse light conditions in the interior for Case 1. Case 2 made from Smart Glass which similarly transmits exterior lighting conditions into the interior.

5.4.4 Design Process

Out of the original Origami structure two case studies where developed which take the same geometrical principle as a starting point but are thought of in two different material systems and are later compared in terms of daylighting performance.

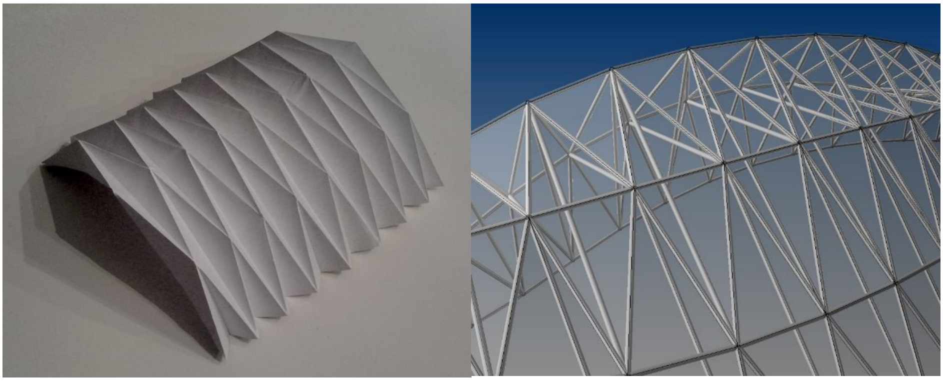


Figure 76. Yoshimura fold and translation into linear members with outer skin

The ridges and grooves forming Yoshimura fold were reinterpreted from being a structural active surface towards linear structural elements. By doing that, the surface area of the skin in comparison to the Yoshimura fold is reduced which as a result also reduces thermal loss. The outcome of the resulting structure reminds of works of Buckminster Fuller while the structure itself could be executed with the Mero system (Kneel, et al., 2008), or a welded steel frame construction which is clad with glass panes.

Case 1 External adaptive shades

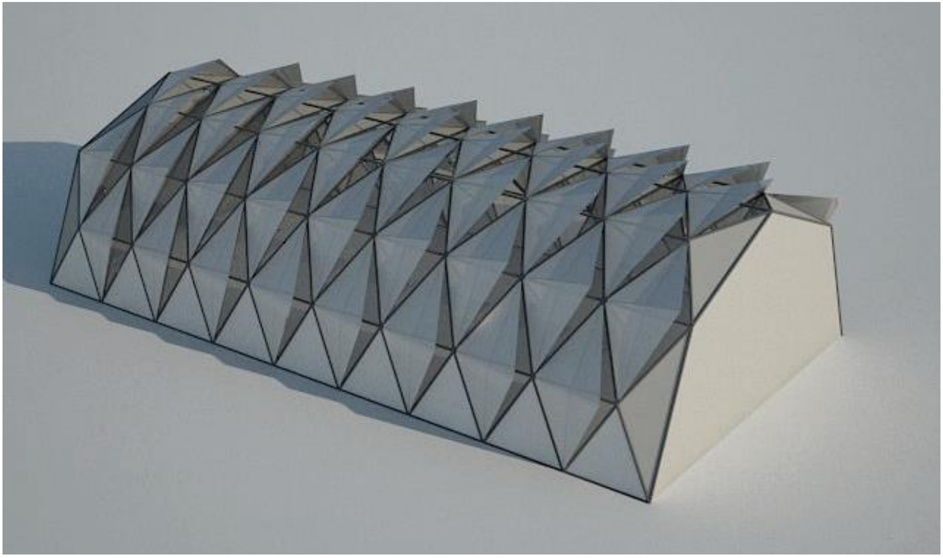


Figure 77. Case 1 External adaptive shades

Case 2 Smart Glass

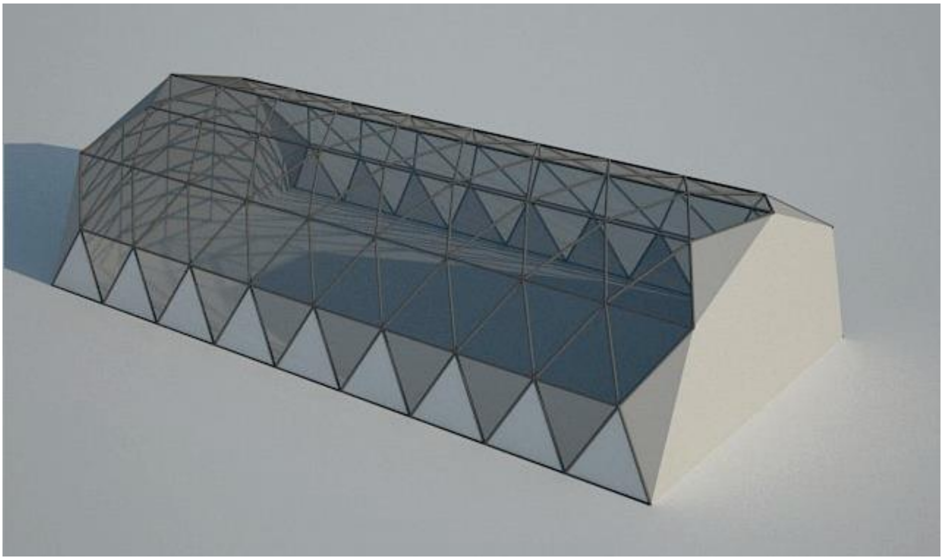


Figure 78. Case 2 Smart Glass

5.4.5 Geometrical & Material Aspects - Technical solutions & systems

5.4.5.1 Case 1 External adaptive shades

The external adaptive shade is a multi-layered system consisting of an assembly of different high performance or smart materials. Those are moveable external textile shades actuated by various material possibilities. Underneath comes a glazing layer and an internal layer of translucent PCM blinds protecting against glare. The textile shades are intended to be closed over the glazing skin when a high amount of solar radiation like i.e. in sunny summer conditions is available and moved in an opened state when lesser radiation and daylight is present. In opposition to saw tooth roofs, the openings are oriented towards south since one of the main ideas is also to increase passive heat gain during winter times. There are four different basic parameters thought of which as result have an impact on the geometric configuration. During cloudy sky conditions throughout the year, the external shades are completely opened so that diffuse skylight can enter as much as possible. When the heat impact is too high, especially during hot summer months and direct illumination the external shades close. This is predicted not to have a negative outcome in terms of daylighting because the textile shades have a certain amount of daylight transmittance paired with the fact that during summer the outside illuminance is much higher than during cloudy sky conditions or in winter. Since the roof is made from independently operating elements it is expected that there are differentiated states of being open or closed due to overshadowing of e.g. neighboring buildings.

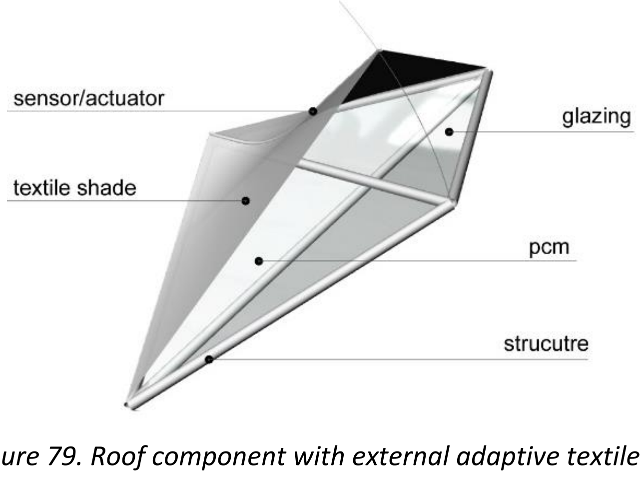


Figure 79. Roof component with external adaptive textile shades

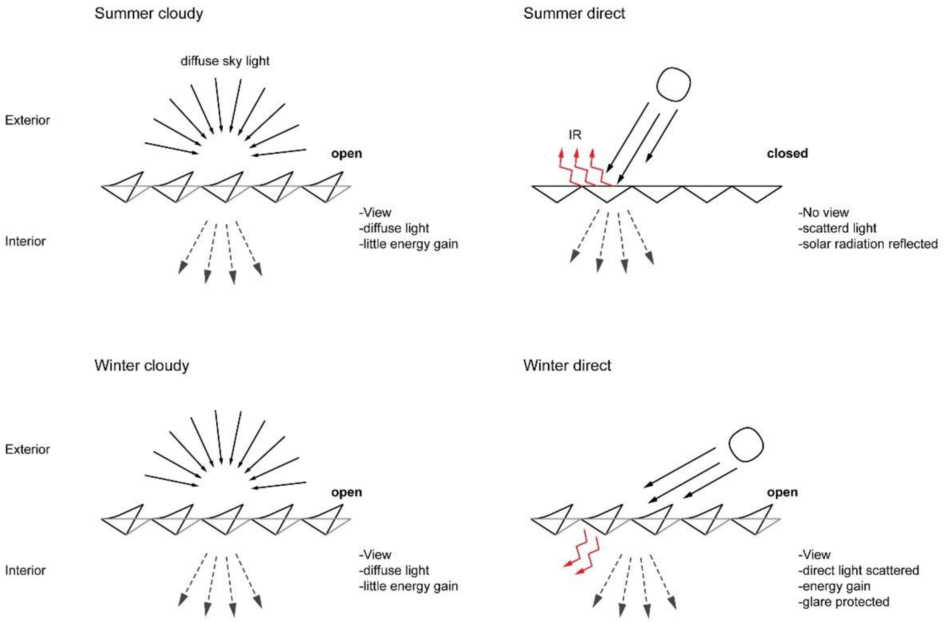


Figure 80. Adaptive behavior

External textile components sensing and actuation

Sensor/Actuator kinetic material system

In principle there are two different possible approaches for sensors or actuators. These could be active systems consisting of separate sensor and actuators like i.e. servo motors. Those would require wiring and connection to external energy sources. The energy issue could basically be covered by the integration of photovoltaic cells into the textile shades as a decentralized system. None the less such an approach would lead to quite some maintenance and installation efforts and is therefore not considered further.

A more promising approach is to look at various smart materials which act as be sensor and actuator simultaneously. This means, that the intelligence and computing as well as the kinetic abilities lie within the material properties themselves and do not need any additional information or energy input facilities. They “merely” react to external stimuli coming from a change in environmental conditions. The designer must therefore be rather careful in determining the range of operation for a specific environment and define and design the material properties accordingly.

Shape Memory Alloy (SMA)

Shape Memory Alloys with a two-way effect could be interwoven into the external shades (Addington, Schodek, 2005). Through the change of temperature at the outside air and additional incident solar radiation and resulting temperature change within the material the textile shades open and close accordingly. Above a certain temperature when direct sunlight is received, the alloy has an austenitic crystal lattice structure and moves into the closed position. Below this temperature by lack of direct sun and lower outside temperature, the material becomes soft and in its martensitic state is easily deformable. By cooling the material, it returns into its original shape supported by the force which is inherent in the stretched textile shades. Here the temperature range of operation at a certain location must be carefully researched to get the expected behavior.

Expansion Materials (EM), Thermal expansion Material (TEM)

The thermal expansion abilities of liquids are i.e. used in thermometers and have a wide range of application but on the downside have slow response times though. Those liquids are further used in sprinkler systems or heating thermostats where the liquids are usually contained in pressure resistant vessels which drive through expansion a piston outward. One concept in an architectural scale for the applications of EM working elements as linear actuators can be seen in the kinetic room installation for the Bath Festival self-constructing tower (Linnet, et al., 2010). Since the liquids react like SMAs on temperature changes a system of pistons could operate the opening and closing of the external textile shades based on the heat gained through the solar incident radiation.

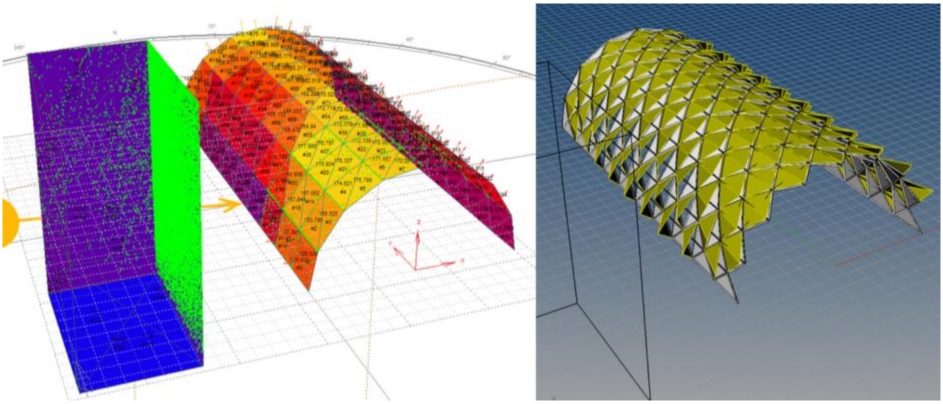


Figure 81. Solar incident radiation calculated in Ecotect and linked with Grasshopper which formulates differentiated opening sizes caused by an obstruction.

Phase Change Material (PCM) blinds

Since the low altitude of the incoming winter sun during sunny days causes glare PCM blinds are integrated in the interior space frame structure. Those help additionally to improve the thermal behavior of the roof structure. Manufacturers (GlassX, 2010) provide a semi-transparent solution where a salt hydrate solution is embedded in transparent polycarbonate containers in their glazing product. The phase change from solid to liquid state stores a great deal of energy. During the summer this helps to cool the interior during the day and in winter the heat energy of direct sunlight entering through the outer glazing layer and hitting the PCM blinds would be stored and released during the night. In the solid state of the salt hydrate the structure is crystalline, translucent and light scattering while the heating up turns the salt hydrate into a liquid state and the solution becomes more transparent.

In the later light simulation, the effect of the whole system on the interior is described in a more detailed way.

Material settings for daylight simulations

The designer has a choice from a wide range of available textile materials for the exterior application. To be usable for external movable shades as it is thought in this case the material must be stretchable or needs a stretchable boarder. The main interest in the textile material is the possibility to transmit light in different ways. This depends on its basic materials, the coating, the overall thickness and way of weaving or braiding etc. (Addington, Schodek, 2005). Another aspect is the possibility to apply a low-E coating on the textile (Holzbach, 2009) while having a high visible light transmission (VLT) and direct light scattering abilities (Ritter, 2007) A coating could be also used on the inner side of the textile which would additionally prevent the heat exchange/heat radiation between different heat environments (inside and outside). For the reflection of the incoming long-wave heat radiation possible materials for coatings are Aluminium, Silver, Gold, or Titan layers whereas the thickness of the applied layer determines the performance. Flexible PV cells could further be integrated into the textile like the project Soft House (Kennedy, Violich, 2013) exemplifies. The textile shades therefore not only become a lighting and energy protection device but also generate energy and transgress therefore from being a high-performance material to a smart material.

For harvesting a sufficient amount of daylight while protecting the building against heating up in summer the textile should ideally display a low radiation transmission T_s value, a high radiation reflection R_s value and a low radiation absorption A_s value, while having a high light transmission T_v value to become independent from using artificial light sources during the day. As initial test, different material settings for the external blinds were examined. For the latter testing of the system with *Radiance* transmission T_v values are set to the following values.

Material settings

External shades:
Colour Red/Green/Blue: 0.5 0.5 0.5
Specularity/Roughness: 0.0 0.0
Diffuse transmission/Specular transmission: 0.35 0.1
Internal blinds:
Colour Red/Green/Blue: 0.5 0.5 0.5
Specularity/Roughness: 0.0 0.0
Diffuse transmission/Specular transmission: 0.5 0.1

5.4.5.2 Case 2 Smart Glass

One can think about daylight control not only in terms of a moveable external shading devices but being done by the ability of the skin to change its solar heat gain coefficient (SHGC), translucency and visual light transmission (VLT). That means it is possible to regulate the incoming energy as well as the nature of the visible daylight by either letting it be transmitted completely or scattering it while diffused light will enter. The elegance in such a system lies in the fact it potentially can be rather simple and made up from less number of different components.

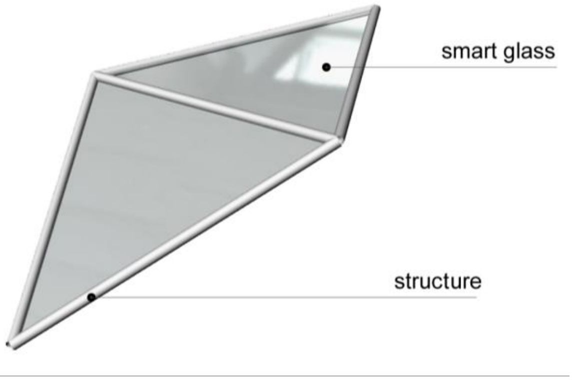


Figure 82. Roof component with smart glass

LCD technology

Possibilities of switchable glasses which are based on different technologies are extensively researched (Haase, 2004). Another research based on similar principles was done at the TU Eindhoven and is currently developed into an upcoming product by Peer+ B.V. Smart Energy Glass in collaboration with different industry partners. A thin coating on the glass which is based on the Liquid Crystal Technology (LCD) can change the tint and transparency by applying an electric current. In terms of tint two different states are possible, changing the solar heat gain coefficient (SHGC) and visual light transmittance (VLT). A further state which is called privacy mode makes the glass appear hazy and no direct view is possible. Here the direct light is also transmitted scattered. One advantage of those systems is, that only the switching process itself consumes energy while the three different states remain stable without any further energy input. The LCD layer in combination with the underlying glass is intended to work as a concentrator and transmits the incoming light to the sides of the glass pane where it can be harvested by photovoltaic cells, thus making the switching process energy independent and even producing an energy surplus. With that each glass pane can be operated independently and individually via wireless switches. Therefore, different patterns of tints or orientation towards direct incoming sunlight would be possible. Since it is an ongoing research and the product is in development final physical values are not available. Peer+ none the less aims for the "dark state" with a SHGC of 0.2 and a VLT of 0.3. For the "light" state a SHGC of 0.3 and a VLT of 0.6 is aimed for. For the "private" state no data was available at this point (Waagenar, 2010).

Figure 83. Smart Energy Glass, different states. Image source: Peer+ B.V.

Material settings

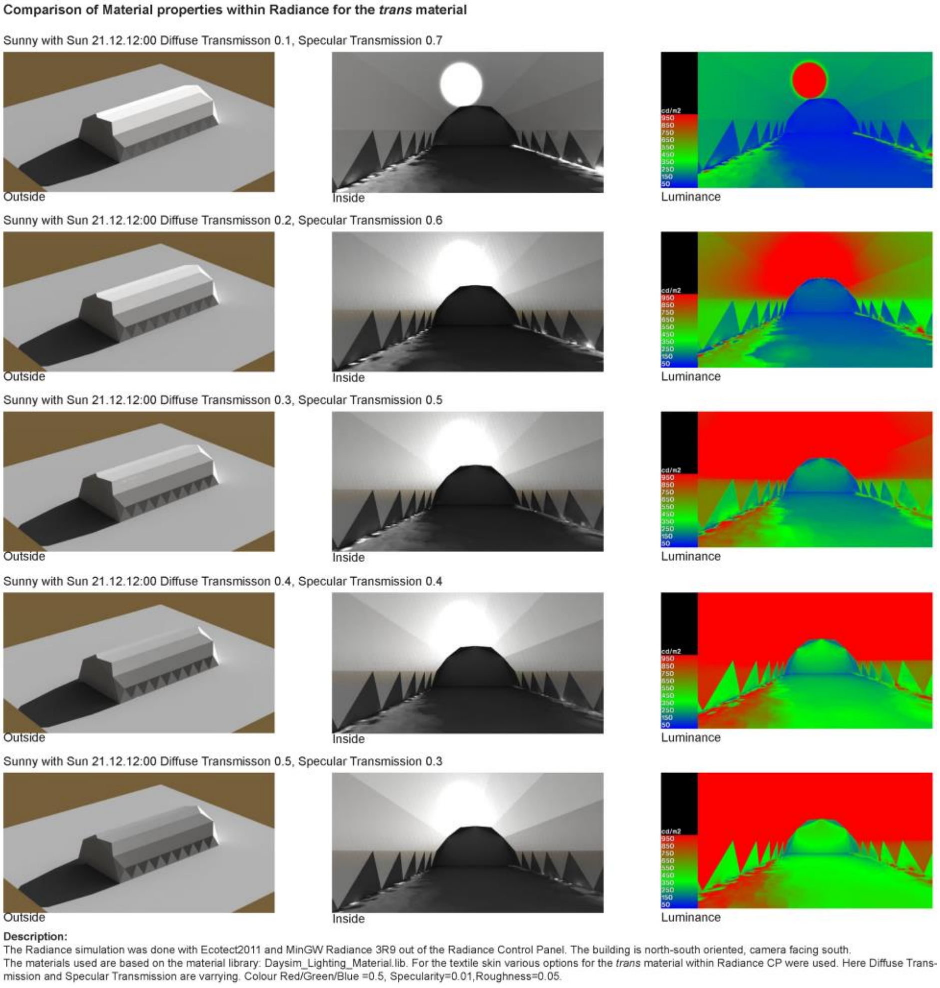
The values were defined within *Ecotect* and translated in *Radiance* into color values.
Lower SHGC/VLT value (dark state): 0.2 0.3
Color Red/Green/Blue: 0.327 0.327 0.327
Higher SHGC/VLT value (light state): 0.3 0.6
Color Red/Green/Blue: 0.654 0.654 0.654

5.4.6 Lighting Analysis and Alternatives

The geometries were exported via *Ecotect 2011* to *Desktop Radiance* and the light simulation was done in combination with *MinGW Radiance 3R9*. As material library for all opaque materials the daysim_lighting_material.lib file was used. All textile materials where defined within *Radiance* as *trans* materials.

The simulations were run for the location Munich. Here the sky conditions are diverse ranging from sunny summer to overcast winter sky conditions. For the date 21.06., at 12:00, Intermediate sky and Sunny sky condition with direct sun were simulated. For the date 21.12., at 12:00, overcast sky CIE with no direct sunlight was simulated. The two cases display the daylight availability and quality for the most extreme situations having most daylight and sunlight available in opposition to the least amount.

5.4.6.1 Case 1 External adaptive shades



Comparison of Material properties within Radiance for the *trans* material

Sunny with Sun 21.12.12:00 Diffuse Transmisson 0.1, Specular Transmission 0.7

Sunny with Sun 21.12.12:00 Diffuse Transmisson 0.2, Specular Transmission 0.6

Sunny with Sun 21.12.12:00 Diffuse Transmisson 0.3, Specular Transmission 0.5

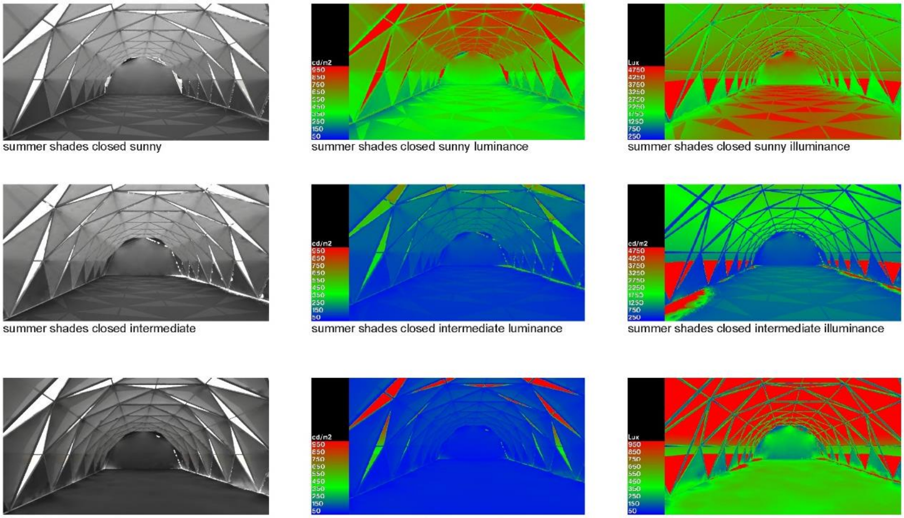
Sunny with Sun 21.12.12:00 Diffuse Transmisson 0.4, Specular Transmission 0.4

Sunny with Sun 21.12.12:00 Diffuse Transmisson 0.5, Specular Transmission 0.3

Description:
The Radiance simulation was done with Ecotect2011 and MinGW Radiance 3R9 out of the Radiance Control Panel. The building is north-south oriented, camera facing south.
The materials used are based on the material library: Daysim_Lighting_Material.lib. For the textile skin various options for the *trans* material within Radiance CP were used. Here Diffuse Transmission and Specular Transmission are varrying. Colour Red/Green/Blue =0.5, Specularity=0.01,Roughness=0.05.

Figure 84. Radiance comparison of different trans material settings and light transmission results

Visual impacts of different sky and sun conditions for a system with moveable external textile shades and internal blinds at 12:00



summer shades closed sunny

summer shades closed sunny luminance

summer shades closed sunny illuminance

summer shades closed intermediate

summer shades closed intermediate luminance

summer shades closed intermediate illuminance

winter shades opened overcast

winter shades opened overcast luminance

winter shades opened overcast illuminance

Description:
The Radiance simulation was done with Ecotect2011 and MinGW Radiance 3R9 out of the Radiance Control Panel. The building is north-south oriented, camera facing south.
The materials used are based on the material library: Daysim_Lighting_Material.lib. The external textile blinds were defined with a diffuse transmission of 35% and a specular transmission of 10%. The inner blinds were set with a diffuse transmission of 50% and a specular transmission of 10%

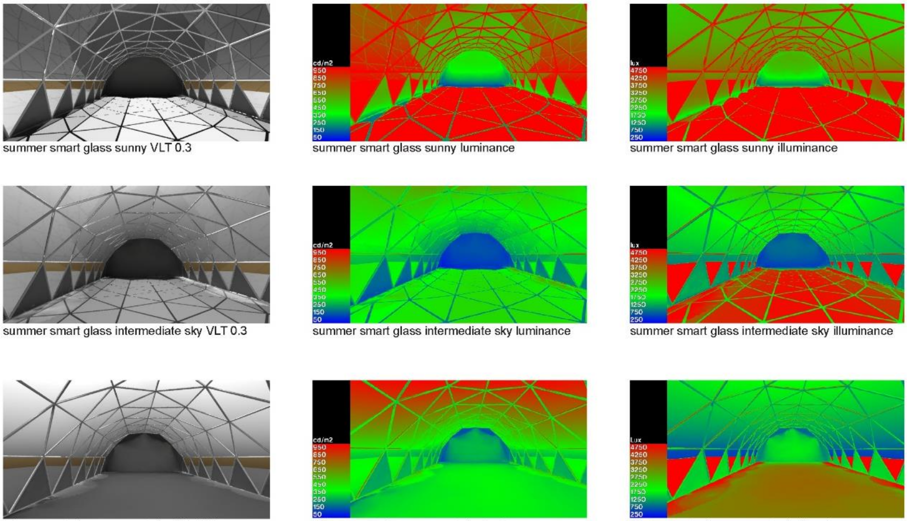
Figure 85. Radiance daylight simulation external adaptive textile shades

Evaluation External adaptive shades

Independently from the outside light condition, the interior light quality remains similar through all states due to the diffusion of the light when the external textile shades are closed. The light is evenly distributed as well as the space underneath is more evenly lit where fluctuations of the external light source don’t have a big impact. This makes such a roofing system more suitable for functions which are underlying a high degree of regulation in terms of visibility and security. According to technical specifications of the interoperability regarding „limited mobile people“ in conventional trans-European Railways (UWS, 2010) obstacle free pathways within train stations have to have at least 100 lux at the floor surface. The illuminance at the ground floor with an overcast sky condition displays between 460lux -520lux. With these values other functions like office workspaces could be suitably lit without any extra artificial light sources (European Standard, 2002). Therefore, there is no or little view to the outside. People within this space are more disconnected from the external environment. This makes the roofing system useful for functions which do not really require or even reject outside view or have the possibility to provide view via a transparent facade at the perimeter by having the roof system elevated.

5.4.6.2 Case 2 Smart Glass

Visual impacts of different sky and sun conditions for switchable Smart Glass at 12:00



summer smart glass sunny VLT 0.3 | summer smart glass sunny luminance | summer smart glass sunny illuminance

summer smart glass intermediate sky VLT 0.3 | summer smart glass intermediate sky luminance | summer smart glass intermediate sky illuminance

winter smart glass overcast sky VLT 0.6 | winter smart glass overcast sky luminance | winter smart glass overcast sky illuminance

Description:
The Radiance simulation was done with Ecotect2011 and MinGW Radiance 3R9 out of the Radiance Control Panel. The building is north-south oriented, camera facing south.
The materials used are based on the material library: Daysim_Lighting_Material.lib. The switchable smart glass was defined in Radiance for the sunny and intermediate summer conditions with a visual light transmittance of 30% for the overcast sky condition with 60%.

Figure 86. Radiance daylight simulation Smart Glass

Evaluation Smart Glass

The main concept behind such a system is to generate as much as possible view, relation and light from the outside while minimizing solar energy gains for the building. That also means that the space underneath could be over-illuminated for certain tasks such as making electronic display panels legible. The outside light condition, while being reduced in its intensity is one to one represented in the interior. That also means that glare due to high contrasts on the interior surfaces or due to a low sun altitude could become disturbing. This sort of roof system would be more suitable for inner courtyards which then provide view to the sky and the building volume protects the interior against a low sun altitude at the mornings or evenings. Such a roofing system would further be used for functions which require a certain atmosphere and hospitality which would invite people to stay.

5.4.7 Conclusion

5.4.7.1 Case 1 External adaptive shades

The initial results are promising, however further studies need to be done to be able to completely evaluate different translucent textile materials. As already mentioned in chapter 4.3.3 about Materials and High-performance materials, individual products need to be tested under laboratory conditions in to verify manufacturers' material properties but also to come up with valid material parameters which can be used for the daylight simulation. Furthermore, a lot of material testing and prototyping needs to be done to make sure that the technical system in terms of actuation and sensing either with Shape Memory Alloys or Thermal Expansion Materials is working in the intended way. This could prove rather difficult not only in terms of adjustment that e.g. the shades are closed when they need to be closed but also for every location with a different climate it would be required to set up and test the system again since the specific behavior of shape change is related to a specific temperature. However, the beauty and elegance of a material which to sense and actuate by itself without any further technical devices attached is not to be dismissed because the building skin would be truly smart and operating in an organic way. In case there was a mistake in design or long-term changes in building usage occur, it is impossible to incorporate these issues because sensing and actuation is baked into the material properties itself. Despite the elegance it thus needs to be concluded that such a system is not very resilient due to combinatorial explosions during the design phase and no possibility to change operation parameters once the system is built.

5.4.7.2 Case 2 Smart Glass

The main concept behind such a system is to generate as much as possible view, relation and light from the outside while minimizing solar energy gains for the building. That also means that the space underneath could be over-illuminated for certain tasks such as making electronic display panels legible. The outside light condition, while being reduced in its intensity is one to one represented in the interior. That also means that glare due to high contrasts on the interior surfaces or due to a low sun altitude could become disturbing. This sort of roof system would be more suitable for inner courtyards which then provide view to the sky and the building volume protects the interior against a low sun altitude at the mornings or evenings. Such a roofing system would further be used for functions which require a certain atmosphere and hospitality and would invite people to stay.

6

Design Method

6.1 Introduction Design Method

The overall product of this dissertation is a design method which serves as a design tool for the design of adaptive daylighting systems in large (span) roofs. The proposed systematic consists initially identifying whether the design trajectory is leaning towards a Top Down or Bottom up approach. This has mainly to do with how well defined a design task is beforehand in terms of applicability, costs and time to design and what components are designed or applied in which order. The previously presented case studies serve as examples on how to start up a design process and explore its validity. The designer should be able to link one of the categories found in the case studies from chapter 5 like e.g. Adaptive Building with his/her own design intention and follow step by step the development of a concept towards a worked-out design. It is important to note that a design process always consist of Top Down and Bottom Up design aspects. Therefore, it is necessary to understand how these processes are defined, how they work and how they are combined and what are their strengths and weaknesses to establish a more target-oriented none the less innovative way to design. It is also required to be aware of the processes and their relevance within design steps to be able to set up a coherent design sequence.

In this chapter also design tools, their workings and application will be described leading to the actual Design Method.

6.1.1 Top Down and Bottom Up design

In current design processes, it is not possible to only use abstraction or only a theoretical framework to design (Terpenny, Nnaji, et al., 1998). The Top Down approach is using abstraction and is driven by functional requirements while developing design options but cannot assure that those will be valid solutions in terms of being realizable in an e.g. economical feasible way. The Top Down approach is a decomposition in sub-systems where each sub system with its own specifications will then be refined and designed accordingly and later put together to form a whole. At the Bottom Up approach designs are built from known and existing components and are combined with each other, thus the Bottom Up design approach investigates from the sub systems into the whole. Here a potential problem is that overall, or global functional requirements of the resulting, sometimes emergent design cannot be met due to the combinatorial complexity in larger systems.

In architectural design there are two main issues at hand. Firstly, being able to identify clearly what are Top Down and Bottom Up design aspects, meaning what part is designed according to which input and output trajectory and how to clearly identify the nature of input and output parameters being either Top Down or Bottom Up and as a result how to make best use of it during the design process. Secondly in architectural design theory with regards to emergent systems, file to factory approaches, parametric design practices, etc. there seems to be a different definition of Bottom Up and Top Down approach especially with respect to innovation.

Therefore, two simplified examples from industrial design regarding Top Down and Bottom Up approach the space suit and car design are highlighted. A space suit is designed in a Top Down manner. Here the design tasks are broken down and e.g. entirely new fasteners are required thus designed and if material properties are not matching the requirements, new materials must be invented. With car design, especially regarding the use of the same platform for different models, existing engines, brakes, shock absorbers, etc. (off the shelf) are assembled Bottom Up, from the component into the whole. This seems to be in opposition to the architectural understanding of Top Down and Bottom Up design at least in terms of innovation.

Therefore, in this research work with respect to architectural design the Top Down and Bottom Up design aspects need to be clearly (re)defined and an additional category is introduced as following:

Top Down

The clear definition of design boundaries which act as design guideline and splitting the design task in separated design disciplines. This does not necessarily lead to new inventions like with the Industrial design case of the space suit, but the application of e.g. known typologies is possible.

Bottom Up

The pure application of readily available materials or products which are combined into the whole (building). This can also be e.g. known and existing housing typologies which are multiplied into a larger urban configuration. Here the definition follows more that of Industrial Design case of the car.

Bottom Up - Design Exploration

Working from the single element into the whole without knowing the result in an explorative way. This can lead to iterative and time-consuming design exercise yet producing novel solutions.

6.1.1.1 Identifying Top Down and Bottom up in Architectural Design

The following example is reduced in its complexity in comparison to real design tasks to make the Top Down and Bottom Up aspects of the design process as clear as possible. Also, for the following description Top Down will be abbreviated with (TD) and Bottom Up with (BU)

Top Down - designing a sports hall

According to functional requirements like which sort of sports and activities be it training purposes or competitions should be housed, the raw dimensions of the interior will be determined (TD). This also has an impact on further functional and programmatic requirements, like entrance situation, e.g. ticketing, or amount and size of changing rooms or seating for spectators. It will further have an impact on lighting requirements in terms of illuminance levels and quality of light like being diffuse rather than direct (glare and contrasts). Once these parameters are defined it will become clear that the roof on top must span a larger distance and some form girder or beam structure must be designed which does not impair the sports field’s usability and flexibility by interrupting it with columns. It becomes also clear in terms of input parameters that some form of roof lighting which lets natural pass must be integrated to increase visibility but also reduce the use of artificial lighting while minimizing visual discomfort in form of glare for the players (TD). The design task can be split up in several components where each step can be designed almost independently from each other and combined in a later stage (TD). Firstly, the perimeter which encloses the sports field and houses all additional functions defines the span of the roof. For the design of all the sub-systems e.g. the roof structure a more Bottom Up vs. a more Top Down approach is possible. In any case the whole process starts mostly Top Down by defining the boundary conditions and requirements due to rules, regulations and functional aspects into different sub domains.

Bottom Up – designing a roof

Assuming the case there is a manufacturer who sells “Off the shelf” roof systems which match all the requirements for structural engineering, costs, etc., the installation of e.g. Skylight products and both can be adopted and integrated to meet the boundary conditions and fulfilling the design task, this can be considered a Bottom Up approach. The design of the roof is perceived from various existing components into the whole (BU) whereas the main design and performance parameters are predefined (TD). Since the designer is relying on standardized products, the result won’t be overtly specific in terms of architectural design and probably less performing regarding lighting and energy, thus being less innovative. In the case of daylighting this means that the designer chooses a product which can be firstly integrated into the roof structure and secondly meets the design criteria to enable sufficient quantities in illuminance but also qualities like glare and visibility with respect to usability as sports hall. The advantage of such an approach however is that the time to design and assess the performance of roof and building will not require as much time as designing everything from scratch.

Bottom Up - Design Exploration

Looking at publications of recent years regarding computational design or design by research using e.g. material properties as starting point and comparing it with the above described processes, the claim for producing innovation from the viewpoint of industrial design seems reversed. This sort of Bottom Up approach does not use readily available stock products and combines it into a final assembly but tries to explore via looking e.g. into basic material properties or ways of manufacturing to create new systems and possibilities for architectural design. Here the sum of the parts should create more than the capacity of the individual element, explore novel ways of design and manufacturing and the resulting design systems should display in the best case emergent qualities (the change of a system into something radically new and not preconceived). This approach is often regarded in direct opposition to traditional design approaches which are labeled Top Down and criticized for lacking innovation. However, here lies a misunderstanding. Of course, more traditional practices are using Top Down methods like the initial idea (limiting design variations beforehand), or more clearly defined boundary conditions for the design but are also making extensive use of traditional Bottom Up approaches by employing well known typologies, construction methods, standards or available products. However, without the definition of boundary conditions in which a design must perform it is nearly impossible to design something useful. In addition, it is more a matter of being willing to engage with a design problem on a deeper level and whether the design team can handle larger complexities. Thus, the question is not so much about whether Top Down or Bottom Up was employed since both are always present, but in what way does it generate innovation and how does the result perform? In any case design exploration can happen from both starting points. The difference is whether there are tighter boundary conditions for applicability present right from the beginning (TD) or do those need to be defined by the designer during the design exploration process (BU).

6.1.1.2 Summary Bottom Up & Top Down

It is necessary to make a distinction between defining the boundary conditions which frame the design exercise, the materialization of a building and the design approach itself whether it can be Bottom Up or Top Down. Defining the boundary conditions, specifying various design tasks into categories, framing the design space and thus setting limitations is a Top Down act. Also, in the rarest cases will design practices or Architects work in form of a Top Down approach and define material property criteria and design new materials which meet tightly specified criteria. This is mostly reserved for research institutions or companies which have a research and development budget and which in the end can sell a new product in larger quantities. In most cases they will use existing materials or products in a Bottom Up way and innovation can be achieved by applying these products or materials in a novel way. The design work itself can be either Top Down or Bottom up, or a combination of both. How the design goal is met is entirely up to the designer’s preference, resources at hand and capabilities.

6.1.1.3 Combination Top Down & Bottom Up in Architectural Practice

Architectural design works have in varying degrees bottom up and top down designed elements. The bottom up design exploration can be the creative motor to search for novel solutions whereas the top down elements defines the boundary which the design must meet and acts as a control in form of an overall vision, design brief or sets of objectives where the individual design elements can be always tested against. This is a reciprocal process where both components will influence each other. For a concrete design project, the top down component acts out stronger in the beginning of the design process due to analyzing the task and deriving in a set of design rules and the bottom up component plays a greater role during the actual design process and new findings will influence, question and refine the preset rules.

As an example of an architectural design task for any given building the top down element is presented in form of a brief which describes the function and required elements the building must contain. Also, the existing regulations, urban context act as top down element. Here e.g. building height allowance, regulations about distances to the neighboring building, access to view and daylight define an envelope and the building must be designed within it. In that sense the boundary conditions act out as control mechanism that in an e.g. urban low raise setting one does not design a high raise building. However, directly working with the program of functions like amounts of individual rooms and their relationship with each other is the bottom up-design exploration element. By testing various configurations in form of topological relations various potential building layouts can be explored. During this explorative work while bringing the individual elements in relation with each other, new functional relationships, impact on other disciplines in form of construction consequences, or even meanings can be found. Once those are discovered and made explicit they can be formulated and added to the design brief or architectural vision and act now as top down element, meaning any further design exploration must meet now a new set of criteria or boundary condition thus the top down and bottom up design exploration process becomes reciprocal.

6.1.2 Classification of case studies

Kimbell Art Museum

The design process itself by Louis Kahn consists mostly of a set of top down rather than bottom up factors. Herby the focus for this research lies in the way a daylight solution was found. One of the leading top down factors was the first director Richard F. Brown which requested having daylight to illuminate the museum's interior, despite certain difficulties. That results in several design criteria or boundary conditions, about how to protect the art from decay due to the sun's ultraviolet radiation while transmitting daylight suitable for an art exhibition. After several studies (Bottom Up – Design Exploration) in terms of building layout and form, Kahn came up with the C arrangement of the 18 vaults oriented in north south direction which act as a further Top Down aspect for designing the roof and daylighting mechanism within a now given system. Since no direct light but indirect light for legibility of the art pieces was needed, over the course of the design process several roof and reflector shapes were developed ranging from polygonal till the final cycloid roof shape was derived and approved. During the roof shape development as a response and the fact that roof, openings and reflectors form one system, the reflectors in its final shape and materiality were developed due to the input of Richard Kelly and computational studies of Isaac Goodbar. The experimentation with geometry and materiality of vault and reflectors albeit explorative was still a Top Down approach since they were clearly defined earlier.

For the further design research and to understand the interaction of the components for daylighting and latter proposal for alternative shapes and the proposed adaptive system by the author, the boundaries were clearly set by the building itself, the historical value and thus are regarded pure top down approach. The cycloid vault's geometry and materiality and the materiality of the reflectors were accepted as given (historical value) and within that narrow boundary alternative reflector shapes and the adaptive system for improving indoor lighting conditions were sought.

Origami Roof

The Origami Roof came out of architectural practice experience, while working at UN Studio, interest in parametric design tools, façade performance argumentation and freeform geometry and is the seed for starting this PhD research. It represents a Bottom Up - Design Exploration where a single roofing component in form of a fold or pleat is multiplied into a whole roof and acts as a device to program space for certain purposes via daylight. Here several test setups were made and evaluated to understand the interaction of roof geometry, local opening sizes and form and how the whole roof plays out its potential for different usage scenarios. With the insight gained it is then possible to flip the process around and be able to approach a specific design task in a top down manner like shown with the application of the Origami Roof at the Neue Nationalgallerie in Berlin.

Aerogel

Since the research into aerogel as translucent insulation material was a contracted research in form of a feasibility study with respect to initial costs versus gains in terms of daylighting and daylight autonomy for the specific case of Munich, the work is defined in a top down manner. The structural system, spans, loads, climatic conditions and application for sports of the membrane roof were clearly formulated right from the beginning. The application of aerogel was tested against a set of clearly defined criteria. However, once the results were clear, it showed that the current insulation material being available on the market do not fully harness the potential in terms of daylight transmittance of the pure aerogel granules and looking from out the material properties a new product solution was suggested.

External shades Origami

By starting to consider the possibility of changing the Origami roof from an adapted geometry (rigid) into an adaptive system, two possibilities were researched. An adaptive geometry – via kinetic external shades and a statically dynamic architecture by adaptive (Smart) materials were developed in parallel. This a Top Down approach by using the previously developed Origami geometry further and investigate its performance potential as adaptive system. The boundary conditions in terms of geometry were tight (TD) but the choice of possible existing materials, sensors and actuators had to match the existing design (BU).

Smart Energy Glass

When the Smart Energy Glass Peer+ was developed at TU Eindhoven by the Department of Chemical Engineering and Chemistry. It was the aim to develop a switchable glass which fulfills certain energetic criteria in terms of switchable Solar Heat Gain Coefficient (TD) while being energy stable in the three states. Referring to the research of the earlier presented case study within this work, it can be described as Bottom Up approach, because an existing material system was analyzed and applied. The Top Down aspect by using the existing Origami Roof Structure geometry as starting point is insofar marginal within the research, because the overall geometry be it e.g. dome like or vault like nor the subdivision into triangles or quads do not have a large effect on the daylighting outcome.

6.2 Design Tools

There are several digital and physical possibilities which provide a designer with a powerful set of tools to be able to handle, manage and tie various design parameters together and generate options, variations and especially different states for adaptive design solutions in this case for daylighting. As already earlier mentioned the issue with adaptive solutions is the requirement to be able to test and verify the changing configurations, be it of material or geometrical nature in response to the changing boundary conditions, e.g. functional requirements or daylight conditions. It is required to test each state for a specific design condition. However, this can lead to an overtly complex and high effort in testing and simulating, which leads to an increase in simulation results and loss in overview. It is therefore advisable to develop a design strategy which makes the complexity manageable.

A starting point is to define the above-mentioned boundary conditions well (TD) or Bottom Up – Design explore different options and derive from that a design task and boundary conditions. The next step is to start with a limited set of starting conditions and variables and work from a rougher estimation towards more detailed designs and evaluations. In case of daylighting this means to test and simulate the most extreme conditions and note down whether the performance criteria are met. The most extreme conditions can be e.g. lowest daylight availability in winter during clear but also overcast sky conditions as well as most daylight availability in summer for several different hours during the day. If there is a radical change in the way a daylighting system needs to perform e.g. seasonal requirements, those need to be tested in addition.

Here can be referred to the origami roof structure case study. The system is tested during the most extreme daylight situations in the year like lowest and highest sun altitude to see in what way and quantities daylight can enter in relation to opening sizes. However, it is one design requirement (TD), that passive heat gains are only possible during winter, meaning direct sunlight is transmitted but the structure shades the interior during summer. Consulting outdoor temperature charts in this case for the location Munich and determining a time window during the year when passive heat gains are desired or not is required. This moments when performance should switch from one state to another also need to be tested. In this case it is the geometric formulation of the shading extension which were generated in accordance with a specific sun altitude and azimuth angle. Afterwards shading studies were done to confirm whether the geometry performs as intended.

For design and evaluation there are several design and simulation tools at hand which proof useful and are described in short.

6.2.1 Parametric Design

For all the case studies the software *Rhinoceros 3D* (MCNeel, 2017) in combination with the associative and parametric plugin *Grasshopper* was used. With *Grasshopper* it is possible to link several inputs, be it geometrical, or numerical e.g. coming from an external excel file together and have it displaying and changing in real time within the *Rhinoceros 3D* environment. For that matter a visual programming environment in form of a canvas is provided where components like lines, surface but also mathematical operations are dragged and dropped inside and linked by "pulling cables", meaning establishing a flow of data.

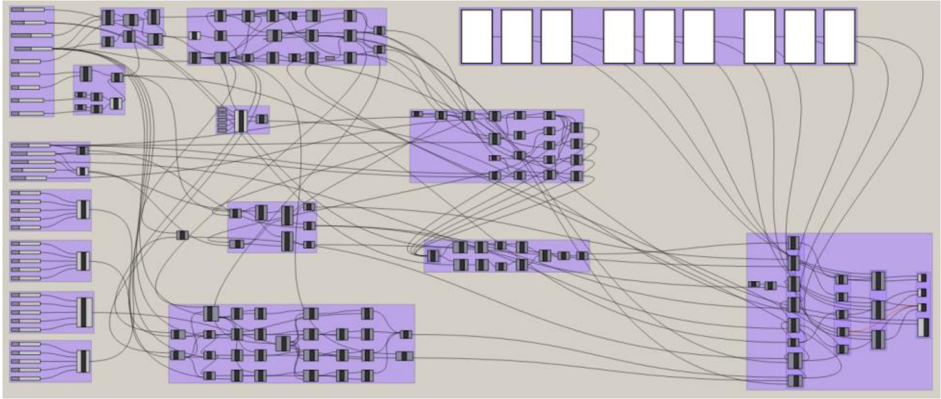


Figure 87. grasshopper canvas

With that it is possible to generate any sort of geometry or calculation and is only limited by the designers understanding of data and parametric requirements and how those must be combined. A simple example is drawing a line. In usual CAD environments one draws a line by clicking a start point and an endpoint. The basic information which defines the start end endpoint are not associated with the line in the CAD system, but this information only remains with the designer. Once the start and endpoint of the previously drawn line changes, the CAD environment will not automatically update the line since it does not have the information stored. Therefore, the person making the drawing must update the line manually. In associative, parametric design it is required to define the start and endpoint of the afore mentioned line explicitly and link the data input to the line component inside the canvas. Each placed component is in association with its input parameters, hence the term associative design. Once the boundary conditions like position of points change, the line gets automatically updated in real time.

With this it is possible to establish a linked chain of (geometrical) operations in a hierarchical manner of cause and effect where all the data gets computed and trickles from the inputs towards the components at the end of the chain of information and automated, complex configurations are possible without the designer having to draw them individually. This is essential for dealing with adaptive design solutions since each state related to the change in boundary conditions/input is generated instantaneous. Another advantage in using *Rhinoceros 3D* in combination with *Grasshopper* is it being relatively cheap in prize und therefore widespread among designers from various disciplines but also educational institutions. That led to a well-documented and supported software package, a vast community of users but also a manifold of different modules developed by individuals often in an open source and free to use way. That means that (aspiring) designers have easy access to how to use the software but also to tailored software solutions which they are not able to program themselves in many cases. This ranges from solvers, to structural analysis integration but also tools and packages dealing with daylight. One of the daylight solutions which also is extensively used within this research is *DIVA* (Solemma, 2017) for Rhino. It combines several existing software packages like *Radiance, Daysim*, or *Evalglare* and integrates them into Rhinoceros 3D and Grasshopper. With that it is possible to establish a seamless and integrated flow of information and output within the parametric design environment.

6.2.2 Simulation

There are several software packages on the market for doing daylight simulations (Velux, 2018). Some of them are scientifically or from official side validated to be able to acquire sustainability certificates (ArchEcology, 2018). It is not in the scope of this work to compare the diverse software tools and make recommendations other than the previously named software packages which were used during design and research. As already described all simulations were done in *Radiance* which was integrated by Solemma via *DIVA* into the *Rhinoceros 3D* and *Grasshopper* 3D modelling environment which means that there is no need to manually export geometries into another software package.

About *Radiance*:

Radiance is a suite of programs for the analysis and visualization of lighting in design.

Input files specify the scene geometry, materials, luminaires, time, date and sky conditions (for daylight calculations). Calculated values include spectral radiance (i.e. luminance + color), irradiance (illuminance + color) and glare indices. Simulation results may be displayed as color images, numerical values and contour plots.

The primary advantage of Radiance over simpler lighting calculation and rendering tools is that there are no limitations on the geometry or the materials that may be simulated. Radiance is used by architects and engineers to predict illumination, visual quality and appearance of innovative design spaces, and by researchers to evaluate new lighting and daylighting technologies.

Further:

Radiance includes many of the features of popular computer graphics rendering programs with the physical accuracy of an advanced lighting simulation. This combination of flexibility and accuracy makes it unique in providing realistic images with predictive power for architects, engineers and lighting designers. Its flexibility is demonstrated in applications as diverse as forensics (ie. roadway accident reenactment by Failure Analysis and Associates, CA) and aerospace (ie. space station design by NASA, Goddard).

Radiance has been compared to other lighting calculations, scale model measurements and real spaces to validate its capabilities. No other lighting calculation has undergone a more rigorous validation.
(Radiance, 2017)

It must be noted however that Radiance for windows is not capable of sufficiently simulating geometrical-optical material configurations like light refractions within prims, lenses, etc. For that a photon mapping extension is required (Schregle, 2004) which is only available within the UNIX OS environment. This issue will be become important in chapter 7. It should also be noted that the use of translucent materials in Radiance simulations requires extra attention (Reinhart, Andersen, 2006) and transferring existing material properties into the simulation is not simple and needs actual physical testing. In any case, it is required before doing simulations that the user gets familiar with daylight simulations (Larson, Shakespeare, 1998) (Jakobs, 2014), lighting physics (Rensselaer, 2000) (Ryer, 1998) and can correctly interpret the simulation results.

For adaptive design solutions, documentation and data management is even more important than for more common design approaches. Since a lot more simulations need to be done by assessing different states of geometrical and/or material configurations in response to daylight conditions it is essential to document the findings properly otherwise the sheer amount and complexity of results is not manageable.

6.2.3 Physical prototypes and testing

It is also possible to use physical models for validation instead of/or in addition to simulations. The advantage of physical models in comparison to e.g. structural engineering is that with lighting the results are perfectly scalable. However special attention is required towards material properties due to the thickness of model elements. For instance, opaque elements should also be perfectly opaque when used for a model too. Glazing elements in real scale will reduce the light transmitted, especially due to reflection at acute-angled light hitting the surface. This needs to be taken into consideration for a physical model where the openings are either left open or a substitute material is used for glazed parts.

Measurements can be taken via lux meters to measure illuminance values. Luminance pictures can be taken with specially adjusted cameras where software like *Photolux* process them further into false color images to make different levels of luminance perceptible. The models should be also big enough in scale to be able to use equipment for measurement inside.

Measurements can be made outside and the result will be one to one in comparison to an actual building. However, this can be rather time consuming having to wait for perfect atmospheric conditions or sun position to take the required measurement. It is therefore also possible to use a sunlight simulator for direct sunlight and an artificial sky for overcast sky situations. In terms of sunlight simulator this has the advantage to be able to adjust several different sun altitude angles in short order and with that it is not only possible to test light transmittance or redirection but the performance of the adaptive system as such in an accelerated fashion. In both cases measuring outside or using physical simulators it is required to measure e.g. illumination levels in the beginning without obstructions to have a control value and especially for the latter to be able to scale up values to match real outside conditions since the artificial light source of the sun simulator delivers lower illuminance values.

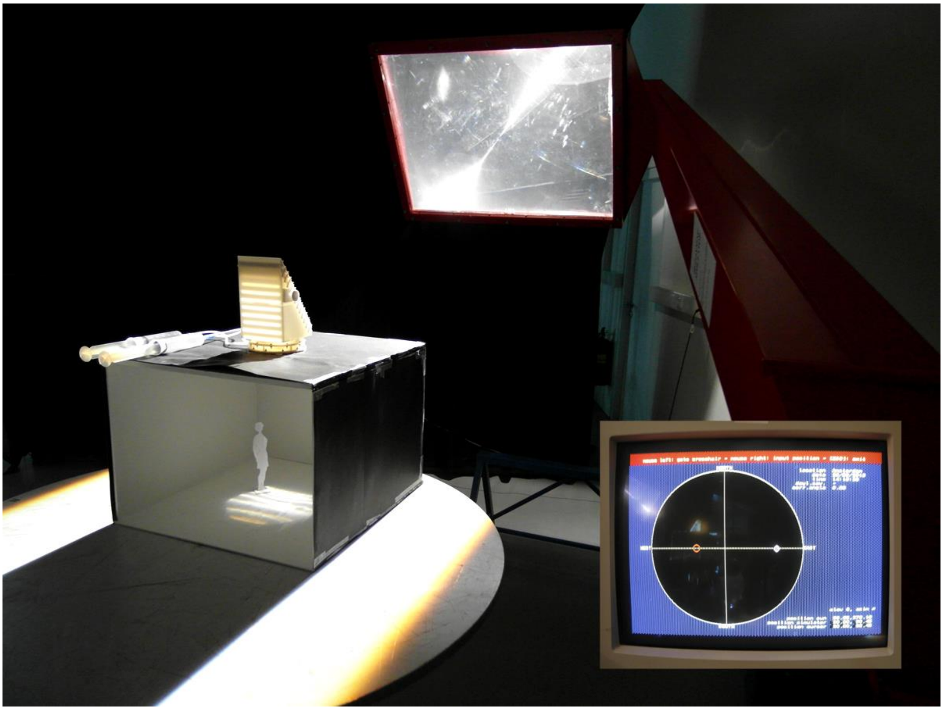


Figure 88. Sun simulator TU Eindhoven

6.2.4 Evaluation, feedback loop, conflicts

After testing the performance of the adaptive daylight system via simulations or physical prototypes, the results need to be interpreted and assessed how the design performs not only in absolute terms but especially regarding e.g. a certain design task (TD) or existing design solution (BU). In case the system performs sub-optimal strategies must be thought of how to increase the performance. In case this is only possible with an unreasonable effort or by compromising the design solution, the design as such must be evaluated whether it is valid or not. Otherwise the design and formulation of the components in terms of size, operation or materiality must be readjusted in form of a feedback loop and then tested again. Especially this iterative process can lead to a conflict with other disciplines e.g. structural engineering when the lighting design loses track of other requirements. Here a hierarchy can help to determining which discipline has the lead.

6.3 Design Method

6.3.1 Overview

In the first part of this chapter Top Down, Bottom Up and Bottom Up- Design Exploration has been identified. It was also established that in design processes both Top Down and Bottom Up- Design Exploration aspects are employed most of the time. The pure Bottom Up design scenario is left out, because in architectural design practices, it does not lead to design innovation. Furthermore, it is necessary to further specify and detail an actual design task for adaptive daylighting in large span roofs. Thus, the design process is broken down into several steps. The following step by step guide elaborates on three design scenarios where the decision-making process is visualized via a flowchart below. The three scenarios are derived from common design approaches and tasks which can be found in practice and education. However, they are boiled down into “typical” cases to distinguish them from each other more clearly.

Top Down, Top Down
This process starts with a concrete design task (Top Down) as well as an existing roof design where a solution for daylighting must be sought within a tight set of boundary conditions (Top Down) e.g. building layout, construction method, roof geometry, structural system, etc. This case describes that of a consultant to the architect who faces relatively final and fixed design specifications.

Top Down, Bottom Up- Design Exploration, Top Down
This process also starts with a concrete design task (Top Down). However, there is no design solution yet. That means roof form and structure, materiality and daylight solution is sought after in relationship with each other and the functional requirements (Bottom Up-Design Exploration). After several design options are found and evaluated, the findings will become fixed design parameters for the final design solution (Top Down). This process describes a target oriented, yet holistic and multidisciplinary approach where the different disciplines work tightly together.

Bottom Up- Design Exploration, Top down
This process is a more academic case, which can be found in architectural design education, where there might not be a design task for a concrete building, yet a specific brief or topic for exploring towards a design solution. The (re)search is open and not bound, thus can be developed in any direction (Bottom Up-Design Exploration). Eventually some valid design solutions emerge which can be tested, further specified and refined to solve an actual design problem (Top Down).

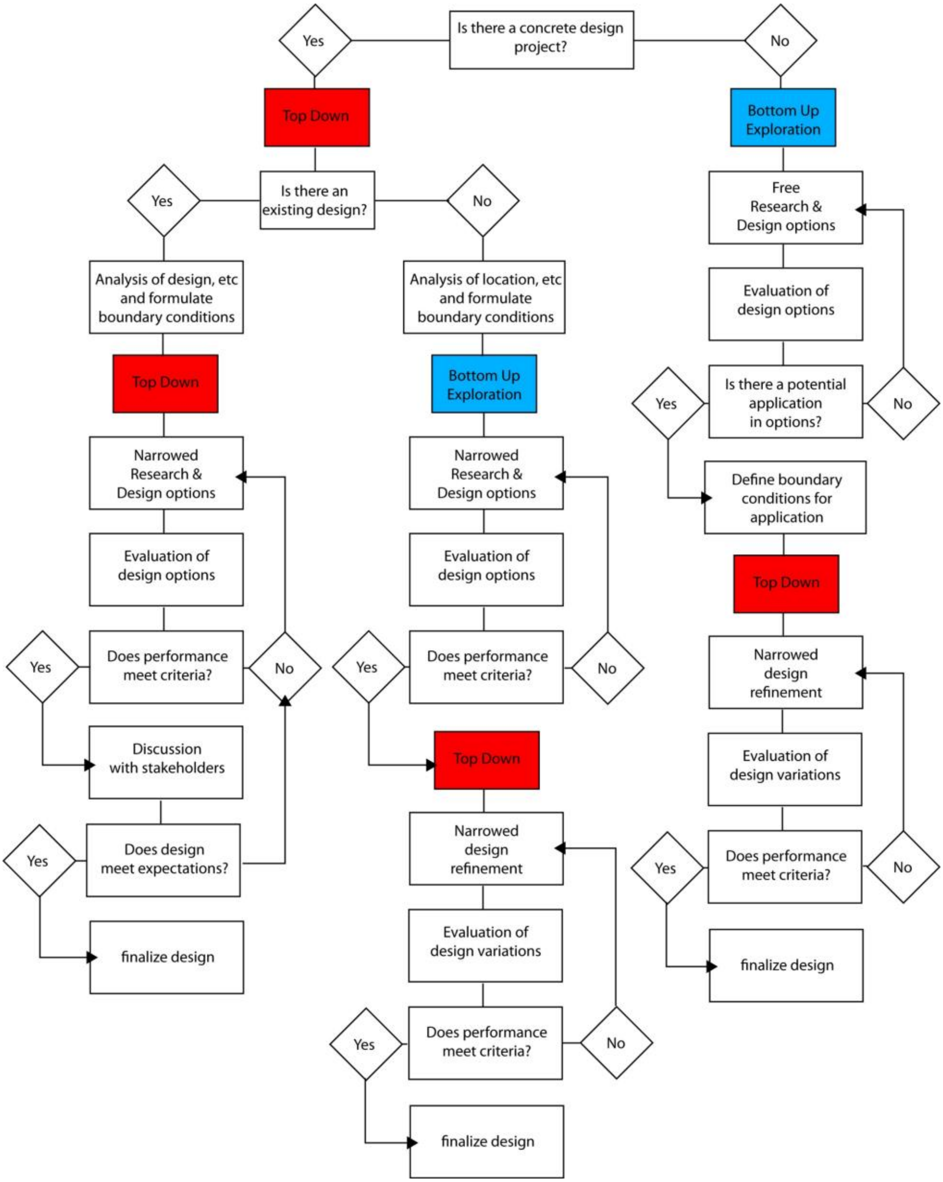
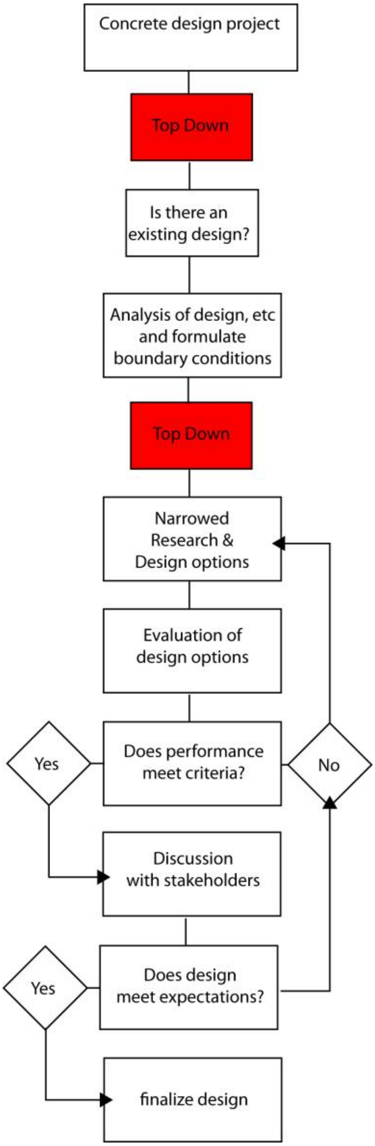


Figure 89. Design flowchart

6.3.2 Step by step, How to Design

All the following scenarios are describing how to design an adaptive daylight system in large roofs. However, they are general enough to be applicable to other design tasks. It also must be noted that in real life situations the design trajectory will be messier and less clear and the above shown design diagram presents an abstraction.

6.3.3 Top Down, Top Down



Left Figure 90. Design flowchart Top Down – Top Down

Top Down (Clearly defined design task) Since a clearly defined design task exists, the large roof and integration of an adaptive daylight solution is set immediately against a set of irrevocable set of parameters and boundary conditions like:

- Location/site
- Climate
- Orientation
- Typology & Functions
- Surroundings

Analysis of the design, etc. and formulation of boundary conditions A concrete design is given for a specific location due to an architectural design concept or an existing building needs to be retrofitted with adaptive daylighting components (e.g. the function has changed). This scenario represents the most constraint variant. In terms of case studies this design scenario is shown by the research and design work on the Kimbell Art Museum in the previous chapter. The above listed boundary conditions will be complemented by the following:

- Materialization
- Roof structure and construction
- Building layout, accessibility and circulation (topology)
- Historical value (in case)
- Design intention (architect)

Both sets of boundary conditions will determine the requirements of lighting quantities and qualities indoor but also sets the context in terms of daylight availability. The existing materials defines how the light is internally reflected or distributed and can give conclusions in an early stage how the light needs to be distributed. The given structure, geometry and materialization of the roof define how much space is available for integrating a solution or how much additional weight the structure can bear. Out of this, the designer should derive a design brief which forms a rather tight design space in which the solution must perform and operate and thus forms the second Top Down design part.

Top Down

Narrowed research and design options

The writing of the design brief and an initial assumption and evaluation will rule out several options for not being feasibly applicable. One way to start the design is too look whether there are built references or products on the market which deal with a similar design task. Otherwise the designer musty come up with own solutions. In both cases the design options can be evaluated in the coming steps and tested against the required criteria.

Evaluation of design options & does performance meet the design criteria

Here the potentials of the options for application are looked at. All options need to be prepared in such a way that those are 1:1 comparable vs. each other. Apart from daylighting issues the designer should also come up with evaluation methods to check the other criteria which were defined in the design brief. In case simulations are used it would be best to 3D model the building and prepare easily exchangeable daylighting mechanisms as options. To keep the results comparable, the fixed elements and building components, their arrangement and materiality need to remain constant. After doing several daylighting simulations which need to be done for each option at exact the same dates, points in time, it will become clear that some options will perform better than others, some sub-optimal or not at all. Those which perform not all can be ruled out. In case all the options are performing sub optimal or not at all the designer must go back and start the design process again integrating his findings into further design or redesign steps.

Discussion with the stakeholders

Whether there is a predefined design or existing building, the proposed design solution(s) need to be discussed with the other stakeholders be it architect, structural engineer, the client or the responsible municipal body, etc. This can lead to finalizing the design or going back into the design and evaluation trajectory and incorporate the requested changes.

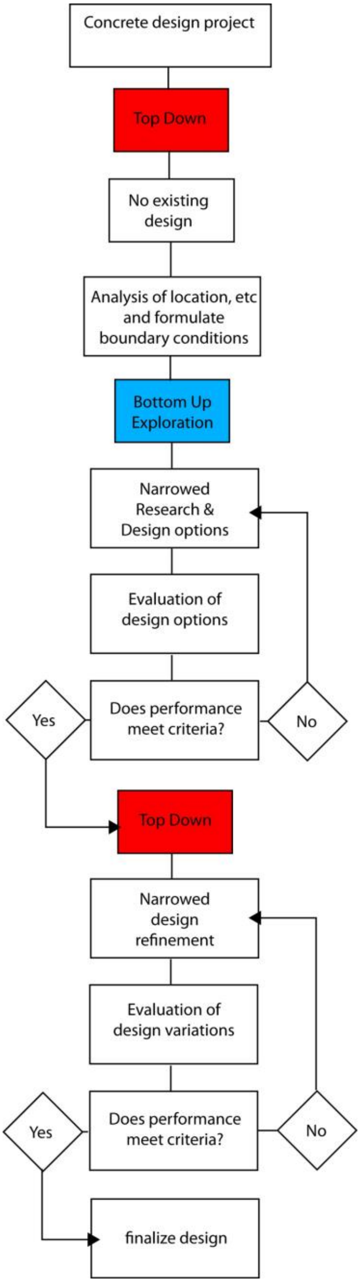
Work out details and finalize design

In general, this will be a classical bottom up approach because readily available products will be used to fit into the existing building configuration, e.g. the application of top lights. For adaptive daylighting elements, this will be more difficult since not many off the shelf products exist but even a novel design will be manufactured from existing components available on the market.

Summary

The “Top Down, Top Down” design trajectory is an initial definition of the design task in a very detailed way, where the design must match exact specifications (TD) and in a later stage the working out of the how to make it.

6.3.4 Top Down, Bottom Up- Design Exploration, Top Down



Left Figure 91. Design flowchart Top Down, Bottom Up- Design exploration, Top Down

Top Down (Clearly defined design task)

Similarly, to the first described design trajectory, a clearly defined design task is also present. Since there is no predefined design existing and the adaptive daylight design task is part of a more integrated design approach, there are less irrevocable sets of parameters, but the initial boundary conditions remain the same:

- Location/site
- Climate
- Orientation
- Typology & Functions
- Surroundings

Analysis of location and formulation of boundary conditions

Through a thorough analysis of above stated boundary conditions, design potentials can be emphasized, and design obstacles can be avoided. For instance, when the design task asks for an indoor sports hall, especially where two teams play against each other, a daylighting strategy is sought after which eliminates glare from low sun angles to prevent one of the team having an advantage.

Bottom Up- Design Exploration

The adaptive daylighting system must be developed in a multidisciplinary way or at least with all design aspects in mind because the various design elements will influence each other, possibly in a reciprocal way due to discoveries along the design trajectory. Communication within the design team is a key element to adjust towards each other and eventually resolve design conflicts between the different disciplines. The makes a key difference to the previously described Top Down, Top Down approach. Because the different disciplines work much closer with each other and the design task is not split up that much into realms of expertise, adjustments will happen along the way of design rather than having separate coordination meetings and time intensive design adjustments.

Narrowed down research and design options

The narrowed down research and design options are more flexible, and form lose boundary conditions which need to be fixed in a later stage. The site, location, purpose of the building is clear which needs to be defined as design parameters. However, the exact dimensions of the building, materiality, structure, or architectural concept is not. Ideally at the end of the design trajectory all these elements fall into place and form a coherent whole. It is therefore necessary to explore design options with different possibilities of layout and roof structure in mind. This can lead to a combinatorial explosion and management and documentation of options, design constants and change of parameters is key. It is required to define the key function and purpose of the adaptive daylight system right from the beginning. The selection in the following list can give suggestions in which direction the design exploration should go (TD):

Building occupancy

- Safety issues (visibility)
- Energy saving artificial light
- Energy saving passive heat gain (intended or not)
- Individual user or crowd
- UV ray sensitivity

This leads to possible:

- Integration of artificial lighting
- Requirement in illuminance and light distribution (visibility)
- Light redirection
- Shading during certain times and seasons
- Individual adjustability vs. automatically controlled
- Light filters

With that several functional requirements can be defined to be the starting point for the design exploration.

Evaluation of design options

In a similar way to the above in chapter 6.3.3 described Top Down, Top Down design trajectory, the potentials of the options for application need to be looked at. For that, all options need to be prepared in such a way that those are 1:1 comparable vs. each other. However, the main difference is that there are less design constants and more flexibility in terms of parameters like materialization are present. The design options will also be developed and evaluated in a multidisciplinary way. This means not only daylight performance aspects are important but also the requirements coming from the architect, structural engineer, clients, etc. For keeping the design complexity to a minimum, design constants like e.g. same floor materiality need to be kept throughout all design options for the sake of comparability.

Out of the evaluation process a decision will made based on recommendations and requests of all parties at hand. If there is no agreement on a design option, the input of these discussion need to be documented to redesign and develop more options. In the other case the input becomes a Top Down requirement for refinement and the being further worked out in variations rather than distinct options.

Top Down

Narrowed design refinement

In this part of the design trajectory the previously laid out specifications act as new target which must be met no matter what. All the stakeholders at this point of the design process rely on the previous agreement to be able to finish their work without causing major conflicts between the different disciplines. For the chosen option variations like geometrical alterations and materiality will be prepared.

Evaluation of design variations

The variations need to be evaluated in form of simulations and/or physical prototypes and compared among each other which of them suits the design requirements most. There can be several phases of evaluation by presenting the findings to the stakeholders until the requirements are met.

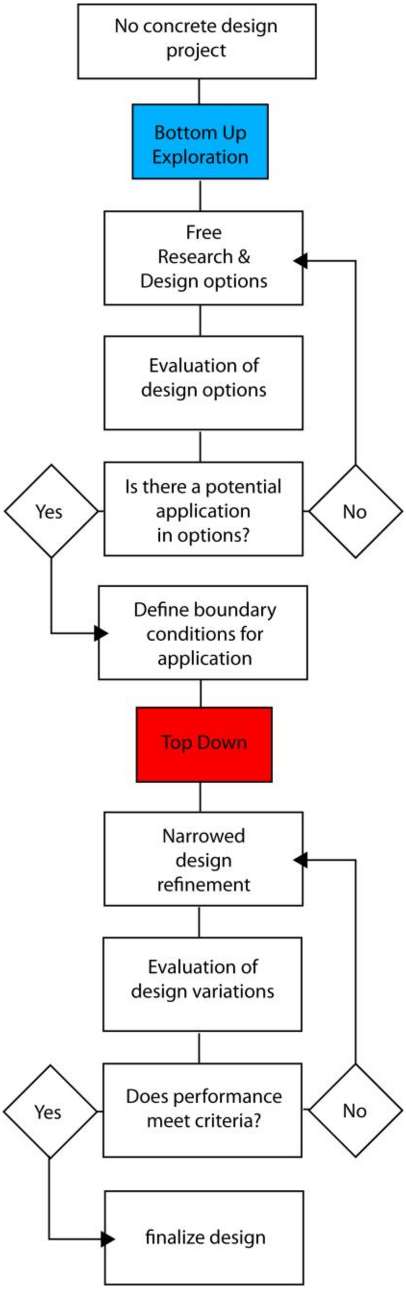
Finalize design

Since the final design variant is already worked out in a much greater detail in terms of dimension, design integration, materiality, etc. finalizing the exact design requires less effort than the “Top down – Top down” approach. This means at this point a functioning prototype is present and it needs to be worked out to be manufactured an implemented.

Summary

The “Top Down, Bottom Up- Design exploration, Top Down” design trajectory defines loose boundary conditions and criteria in the beginning where design must operate within. During the Bottom Up- Design Exploration several options are worked out more detailed. The last Top Down design aspect is used to refine one design option till it is ready for application.

6.3.5 Bottom Up- Design Exploration, Top Down



Left Figure 92. Design flowchart Bottom Up- Design Exploration, Top Down

Bottom Up- Design Exploration

This design trajectory can start with a found material or an interest of what can one to develop a new way of dealing with adaptive daylight solutions. It is not clear from the beginning where this trajectory leads and whether the result is useful, performs well (enough) or not. It is design research and experimentation.

Free research & Design options

At the beginning an extensive research phase is required which e.g. considers already existing daylighting solutions, evaluating their strengths, etc. or it is also possible to investigate other disciplines like product design and find materials or systems which have not been used for architectural application. It is further possible to look e.g. biomimicry and adopt strategies for own design purposes which emerged in nature. Design options are developed according to the potential rather than immediate application and usefulness. Therefore, it is required to work out principles which are less detailed and evaluate options according to potentials for further design exploration.

Evaluation of design options

Here it is not directly required to use daylight simulations instantaneous but project potential functions via physical principles. When those are understood, and the design suggests that it can be worked out in a certain direction, options which show the most potential for being realizable are continued in greater detail.

Is there a potential application?

Instead of knowing beforehand how to solve a specific design problem, in this approach the design problem is discovered along the way of designing and by evaluating several options. As an example, serves the earlier case study of the Origami roof. Here it was discovered that such a surface-active roof structure has the potential to program the function and space underneath specifically for certain tasks and purposes by daylighting. The parametrically generated options or design variants need to be evaluated with the help of daylight simulations to discover the potential for application. Is there is no discovery the search trajectory must continue. Otherwise the findings of what change in the system is causing what effect, be it geometrically or material wise in relation to lighting outcome need to be precisely documented. Now the design process can be flipped around and through the discovery of potential design applications can become a Top Down approach by defining the boundary conditions.

Define boundary conditions for application

By discovering that the design could potential be used for a certain purpose, it is required to look now specifically into these requirements. For instance, by applying a linear gradient map to the Origami roof structure a pedestrian guiding system by daylight can be made. However, if one wants to apply that for an actual design it needs to be known for which sort of building and what are the necessary levels of illuminance requirements.

Top down

Evaluation of design variations

With the help of the newly established boundary conditions, the initial design can be adjusted and newly evaluated to match the requirements. This is an iterative process where one should consider changing only one design parameter at a time e.g. geometry configuration to be able to clearly see and document the outcome this effect produces. With this learning and understanding process of the capabilities of the design system, the designer is now able to manipulate the design and/or its parametric relations to reach an intended effect. Once it is clear what cause what, what are the limitations of the system and are performance criteria met, a final design application can be done.

Finalize design

Again, in the case of the Origami roof structure and due to its theoretical nature potential buildings for application were looked at. In this case it is the Neue Nationalgallerie in Berlin. The roof structure is specified that it matches the size of the cassettes in the roof, bulges down where the stairs are and changes its overall shape at the back above the upper exhibition space to give more headroom. The openings were defined via gradient maps to generate variance of illuminated zones to mark the entrance and give most light to the exhibition space.

Summary

The “Bottom Up- Design Exploration, Top Down” design trajectory starts from a very loose design intention or research interest and tries to discover design potentials. For that reason, this is an economically not feasible and often too time-consuming approach for design practices, which work mostly commission based, hence also have a design brief already at hand. However, it is none the less possible that Bottom Up- Design Exploration can happen intentionally in form of design e.g. workshops to broaden the horizon of the staff or unintentionally and coincidental as a byproduct of regular design work. For the latter, the challenge is to be able to track, filter and edit valuable results and it is highly dependent on the staff’s ability to bring those findings to attention. For academic and teaching purposes however, it is a valid approach for discovery of novel solutions. Once those are found the Top Down aspects defines the scope of application and the design is refined in an iterative process till it matches certain criteria and it can be potentially applied.

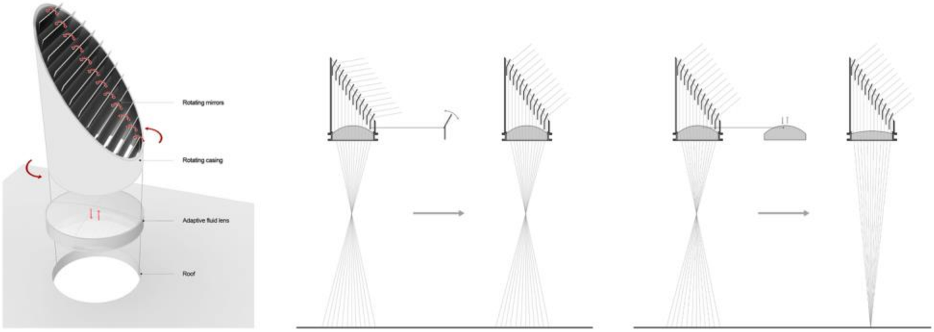
7

Fully applied Design Method – Adaptive Liquid Lens

The design and research for the Adaptive Liquid Lens serves as an example for a fully applied design method. It falls into the category of “Top Down, Bottom Up- Design Exploration, Top Down” approach. After working on the case studies where the whole roof acts as daylighting device it is worthwhile to follow another direction and design a more product like adaptive daylighting device which has a wider range of application. The aim which is also the initial Top Down constraint, is to develop a design which can be easily applied, like a window. The innovation can be found in the design and workings of a single device but also in the interplay of several such devices in one roof.

7.1 Overview & Design Principle

The liquid lens consists of two elements a sunlight redirection device consisting of rotatable mirrors (towards sun’s altitude and azimuth) and a lens housed in a casing which can kinetically & adaptively change its geometry via a flexible membrane. Here liquid is pumped in or out and deform the lens in various, seamless stages from convex to concave thus converge or diverge the sunrays. For the sunlight redirection, an array of mirrors which orient themselves towards the general horizontal sun direction (azimuth) and individual rows of mirrors which are rotated in the same angle according to the sun altitude. The altitude orientation is done in such a way that the incoming sunrays are reflected downwards into an aperture which houses the adaptive lens. The adaptive liquid lens is located underneath the sunlight redirecting mirrors. The lens itself consists of a transparent horizontal lower surface, a casing and on top an elastic deformable and transparent membrane. By changing the internal volume via pumping a clear and transparent liquid the shape of the membrane can be changed from concave to convex and continuously all the stages in between, thus being able to diverge or converge direct light according to Index of Refraction and Snell’s law (Taylor, 2000).



Adaptive fluid lens & rotatable mirrors

By controlling the rotation of the mirrors and their casing, sunlight can be redirected to the lens perpendicularly to its bottom surface

By altering the curvature of the len's upper surface through pumping in and out liquid, the focus of sunlight in the interior changes

Figure 93. Description of the proposed system.

7.2 Application of Design Method

The starting point, as predefined design brief, thus first Top Down component for the Bottom Up-Design Exploration was to come up with a product which has a wide range of application possibilities (functional and lighting performance) and can later be applied by any architect. The reason for this choice is the following: A lot of clients and are not able to afford, or willing to spend on a time intensive and therefore expensive design trajectory which results in an equally costly and complex roof structure like the Origami roof or Fuksas Shenzhen Airport (chapter 5.2), simply due to the fact that the to be designed large roof needs to fulfill other requirements and/or should not impose a certain style. Therefore, daylight performance paired with design freedom resulting in functional separation of the building's envelope layers rather than hybridization becomes a requirement. With the examples of Origami roof or Shenzhen Airport not only parts but the whole roof acts as daylighting device and needs to be designed a as such. Here the lack of design flexibility in terms of design sturdiness as a direct result of the requirement to simultaneously determine every single aspect by each design discipline involved is seen critically within the research. Moreover, these bodies of work also represent a certain design thinking and with their geometric expression end up becoming a style or design ideology which ultimately is subject to a designer's personal preference. Designing a product which is generic in enough in terms of its expression and integrates better with the architectural design makes it an easier choice for many more architects to select this product since it leaves them their room for individual design choices. In this sense, the application of the liquid lens into a roof represents a classical modernist and functionally separated design approach. However, the design for the liquid lens itself as a product does not.

7.3 Top Down 1

7.3.1 Analysis and formulate boundary conditions

The current design process according to chapter 6.3 Design Method is a “Top Down, Bottom Up - Design Exploration, Top Down” approach. Since the design brief asks for a general applicability for any building, the context, like location and climate, etc. is not known yet. The Top Down design requirements are:

- The product is generally applicable for a wide range of uses
- The product should be applicable by any architect or designer and thus should not impose a certain style or school of thought in its formal expression
- The product is to be applied on flat roofs/shallowly inclined since those represent the most generic case and do not pose any further requirements in terms of daylighting due to geometric specifications (self-shading, etc.)
- The product should impose as little constraints as possible with respect to the constructive system of the roof. It should be applicable in a large span roofs as well large roofs (column support)
- Daylight needs to be with whatever technical solution redirected into the interior to be useful thus needs to be adaptive
- Daylight should be used in a maximized way during a broad range of weather conditions and times during the day and year thus it needs to be adaptive
- Daylight transmitted to the interior should be able to be altered in terms of intensity but also quality like direct light or diffuse light to be able to cover a broad spectrum of functions and uses. Therefore, an adaptive solution needs to be found.

This set of design constraints narrows down the possible design space. In more practical terms it was concluded that the design should be a punctual opening (some form of window) and not being applied over the whole surface. Otherwise this would limit the designer of the building in terms of constructive system but also material choice. With this decision, there are also lesser issues in terms of thermal energetic aspects like u-values and resulting insulation performance like heat loss and passive heat gain. Obviously, the question is where then to start for the upcoming Bottom Up-Design Exploration?

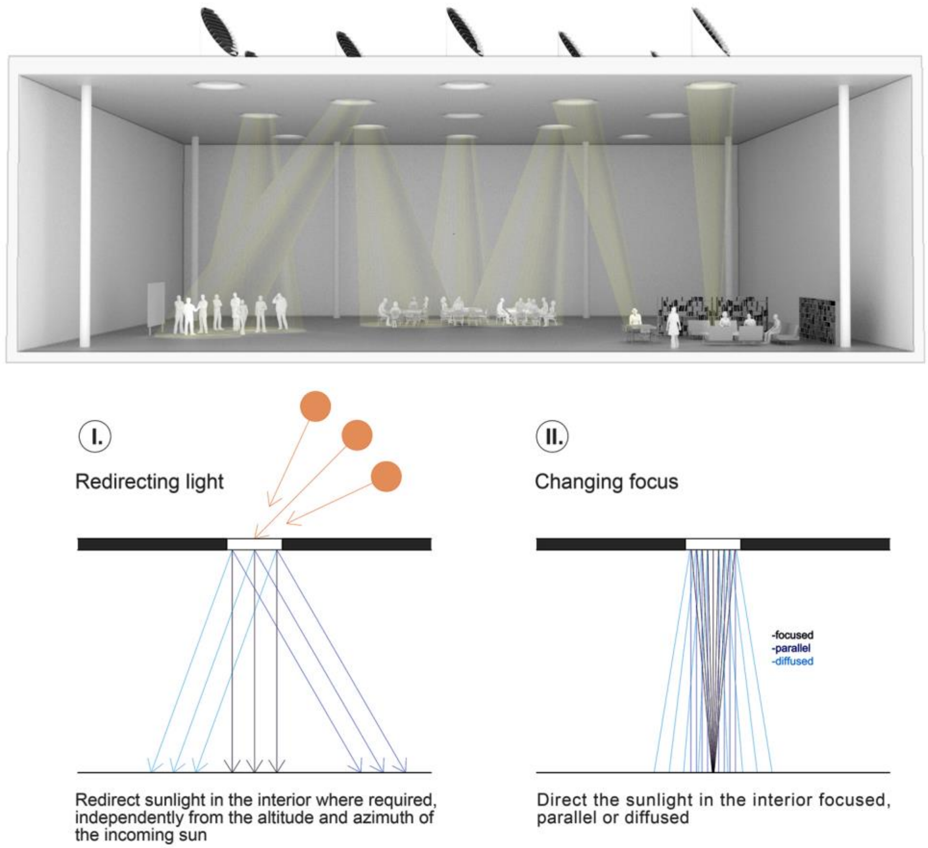


Figure 94. Objective of the adaptive liquid lens and sunlight redirection system.

7.4 Bottom Up –Design Exploration

7.4.1 Narrowed Research & Design Options

The first step was to look at lighting physics on a fundamental level. Optics and related physical principles became of special interest and several physical principles like light redirection via reflection and refraction were tested and evaluated whether they could be used for a potential design solution. To check applicability of physical principles like Snell's law or Fresnel's equation (Bennett, 1995) several associative files were set up in the Rhino/Grasshopper environment to see the effects of light refraction, transmittance, absorption or reflectance of various geometry/material combinations and evaluate the possibilities for sunlight redirection and alteration. For the final candidate which is worked out in greater detail, the Adaptive Liquid Lens Snell’s Law is most relevant (Taylor, 2000).

Associative sectional (2-D) models

Adaptive Prism

Several physical laws like Snell’s and Fresnel’s law were translated into associative 2-D sectional drawings. The first design option consists of a set of adjustable and geometrically changing prisms. This possibility was discarded after careful evaluation albeit sunlight could be redirected vertically down into the building. This was decided because of the relationship between incoming sunlight angle (altitude) towards the glass pane according to Snell’s Law. The glass pane’s angle towards the incident sunlight angle would be rather shallow and more sunlight would be reflected away than transmitted into the interior. This mean would cause a greater loss in daylight harvesting at certain moments during the day. The principle however was reconsidered in a later stage for sunlight redirection in combination with the liquid lens. Other reasons for discarding the solution of an adaptive prism were the technical challenges of how to change a prism geometry adaptively while no further possibilities in terms daylighting other than light redirection would be achievable.

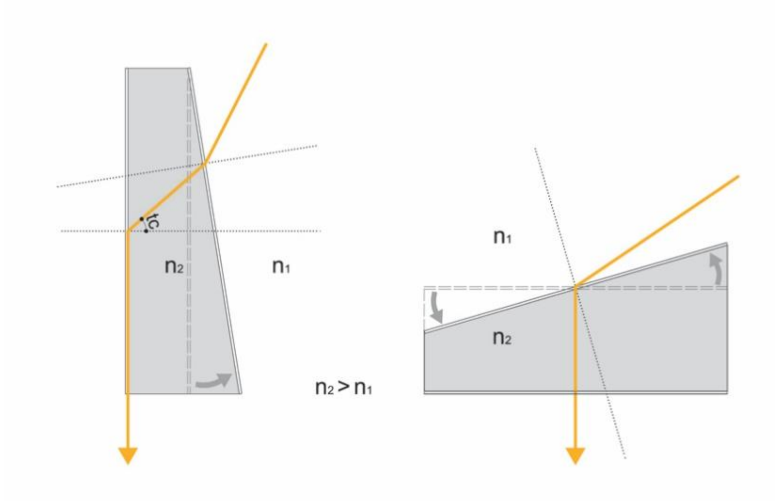


Figure 95. Adaptive prism and (internal) reflections.

Liquid Lens

The second approach was to think about a lens which could change its geometry. Early on, the possibility of a Liquid lens was imagined via water filled balloons which have a convex surface and it was projected that this could work as lens if the balloon's skin would be transparent. Later research also showed that Liquid Lenses are currently researched as space saving zoom devices for cameras in e.g. mobile phones with little to no moving parts (Kuiper, Hendriks, 2004). In an initial step, an adaptive lens system was set up in grasshopper which can change the radius of an upper and lower lens and Index of Refraction of the contained liquid according to material properties of existing fluids and Snell's law to focus or diffuse light. Later it a became clear that in the lens' concave state light does not get diffused as envisioned but diverged and thus remains directional. For the adaptive lens drawing, an array of vectors is refracted by applying the formulas and angular calculations within the lens and made visible via a bundle of lines to serve as design and early evaluation tool. It further became apparent that a lower flexible membrane is not suitable due the weight of the liquid, resulting in not controllable bulging.

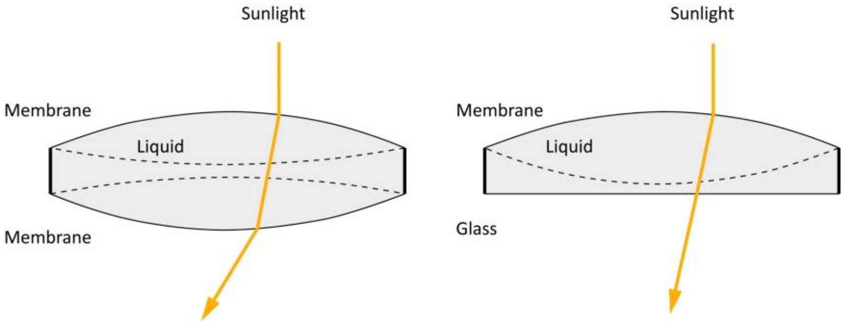


Figure 96. Liquid lenses with lower membrane and solid glass plate

Nonetheless, light can still be altered sufficiently by only changing only the upper membrane. A change in altitude angles of the sun leads to the requirement of continuously changing the focal point of the lens so that the refracted light area hitting the ground remains constant. This means for keeping the light e.g. diverged for a constant area, size the membranes geometry must be continuously changed by pumping liquid in or out due to the resulting change of the focal point in relation to the sun's changing altitude. It also showed that the general redirection possibilities of a lens are limited. Due to prospect of having to continuously pump liquid and the lens' limited possibility of light redirection into the interior a secondary system for light redirection is required.

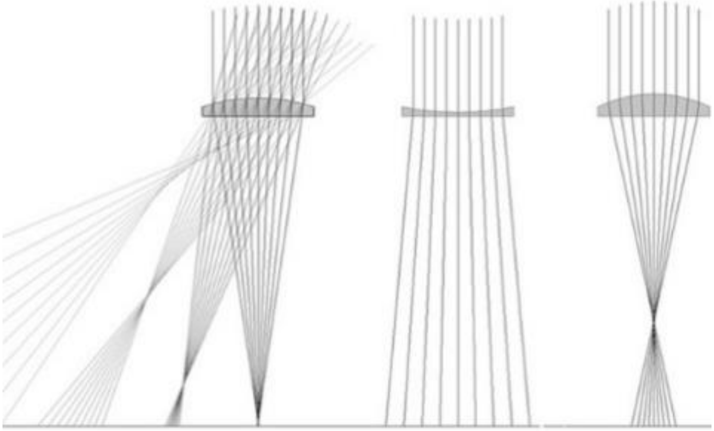


Figure 97. Adaptive lens' possibilities. From left to right. Lens geometry constant – change of focal point due to sun angle, concave lens – diverging light rays, convex lens – converging light rays

At this stage, a first physical non-adaptive prototype was made to draw early conclusions about the performance of a Liquid Lens as well as starting to think about technical and constructive solutions.

Figure 98. First prototype consisting of transparent petri dish and clear plastic wrap filled with water

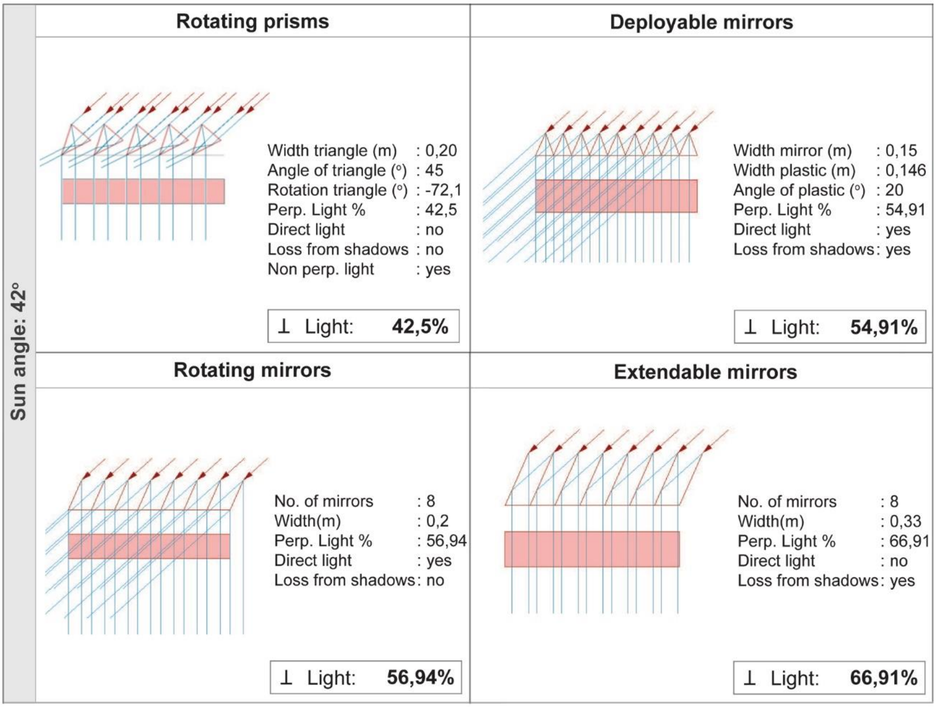
7.4.2 Evaluation of design options

The adaptive prism design option was discarded early on due to expected technical and practical difficulties in building a functional prototype but also due to limitations in applicability for daylighting. Because of the potentials shown by the associative 2-D drawings, the first physical prototype and the novelty of employing a Liquid Lens system in the built environment, it was deemed that the Liquid Lens design trajectory is worth further following up. Since, the Liquid Lens option shows that the performance criteria are not exactly met, and it is required to find a secondary system for sunlight redirection to be able to make full use of its daylighting potential, the Bottom Up-Design exploration proceeds further.

7.4.3 Further Bottom Up Design Exploration for Sun redirection

The earlier findings of the adaptive Prism were reconsidered for sunlight redirection. Several options like trapping light by internal reflections (glass fiber principle), a rotatable prism system or plain mirrors were evaluated. The system of rotating mirrors was favored, because this proofed to more “straight forward”, sturdy and more promising in terms of being able to redirect light under a greater variety of sun altitude angles. To have less high mirror system builds, located on top of the lens, an array of mirrors was chosen instead of one larger mirror.

It became clear, that a light redirection device in any case would have to follow the sun's azimuth. Therefore, the only relevant design parameter regarding the sun’s changing angles is the altitude one. As a result, the 2-dimensional, sectional approach of design and evaluation was continued. It turned out, that using an array of mirrors instead one large single element poses several challenges. At a certain moment all the elements of the horizontal mirror array begin to overshadow each other. Furthermore, there is a relation between sun's altitude angle and mirror array angle as response, resulting in different quantities of redirected daylight. To find optimal configurations and dimensions for the horizontal mirror array, the Galapagos genetic algorithm solver (Rutten, 2010) was used. The Genetic algorithm solver, changes randomly the value of a defined design parameter and maps the results for each changed value, in this case amount of daylight transmitted vertically downwards. Letting the solver run for a certain amount of time and generations, the most “fittest” and optimal design option becomes apparent. For systems like prisms, design parameters like sun altitude and prism geometry, distances, and rotation was evaluated. For the mirror system, sun altitude, width of individual mirror lamella, mirror lamella distance, etc. were examined and evaluated. Since it was only possible to run single parameter changes and not multiple ones, the final comparison between systems, etc. was done manually. Furthermore, the initial results were not satisfactory in terms of amount of daylight redirected due to overshadowing especially at lower sun altitudes. It turned out that there is no universal system which works equally well in every situation.



Rotating prisms

Width triangle (m) : 0,20
Angle of triangle (°) : 45
Rotation triangle (°) : -72,1
Perp. Light % : 42,5
Direct light : no
Loss from shadows : no
Non perp. light : yes

⊥ Light: **42,5%**

Deployable mirrors

Width mirror (m) : 0,15
Width plastic (m) : 0,146
Angle of plastic (°) : 20
Perp. Light % : 54,91
Direct light : yes
Loss from shadows : yes

⊥ Light: **54,91%**

Rotating mirrors

No. of mirrors : 8
Width(m) : 0,2
Perp. Light % : 56,94
Direct light : yes
Loss from shadows : no

⊥ Light: **56,94%**

Extendable mirrors

No. of mirrors : 8
Width(m) : 0,33
Perp. Light % : 66,91
Direct light : no
Loss from shadows : yes

⊥ Light: **66,91%**

Figure 99. Grasshopper study on the percentage of sunlight redirected perpendicularly to the floor according to different scenarios based on prisms or mirrors.

Therefore, it is necessary to take a closer look at several design parameters and become specific about location, the respective available hours with sunshine, the annual and daily sun path and the prevalence of certain ranges of sun altitude angles and times of occupancy of the building. By matching these parameters, it is possible to narrow down the target range of altitude angles where the redirection of sunlight is working close to hundred percent.

As a result, design parameters need to become more specific and act as final Top Down design requirement.

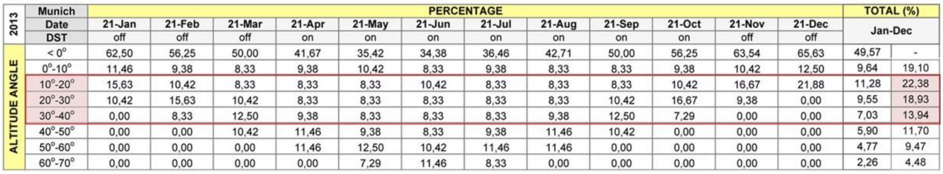
7.5 Top Down 2

The Bottom Up- Design Exploration trajectory showed that it was possible to come up with a functioning design principle. This stage remained on purpose more generic to discover a more general understanding of the mechanisms, but it also showed the limitations of the system, especially with respect to the sunlight redirection. The system can only work optimally in terms of performance criteria within a certain range. To develop a fully worked out design it is now required to limit the range of applications and come up with a usage scenario with respect to building function, occupancy, location, etc.

7.5.1 Narrowed Design Refinement

By choosing a design example in Munich and as function a train station which is heavily frequented during the rush hours, lower sun altitude angle ranges, which occur more frequently during mornings and evenings but also during spring, autumn and winter become more relevant. It also represents a usage scenario which can as a building typology and daylighting requirements in terms of illumination (EN 12464-1, 2002) greatly benefit from a liquid lens system. For that reason, sun altitude occurrences over the year were listed and a range of 10 to 30 degree was chosen to be most relevant for this design case.

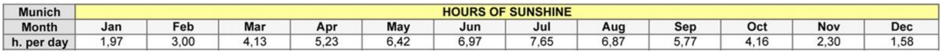
Percentage of the day that the altitude of the incident sunlight is at a specific angle range



2013	Munich	PERCENTAGE												TOTAL (%)	
	Date	21-Jan	21-Feb	21-Mar	21-Apr	21-May	21-Jun	21-Jul	21-Aug	21-Sep	21-Oct	21-Nov	21-Dec	Jan-Dec	
	DST	off	off	off	on	on	on	on	on	on	on	off	off		
ALTITUDE ANGLE	< 0°	62,50	56,25	50,00	41,67	35,42	34,38	36,46	42,71	50,00	56,25	63,54	65,63	49,57	-
	0°-10°	11,46	9,38	8,33	9,38	10,42	8,33	9,38	8,33	8,33	9,38	10,42	12,50	9,64	19,10
	10°-20°	15,63	10,42	8,33	8,33	8,33	10,42	8,33	8,33	8,33	10,42	16,67	21,88	11,28	22,38
	20°-30°	10,42	15,63	10,42	8,33	8,33	8,33	8,33	8,33	10,42	16,67	9,38	0,00	9,55	18,93
	30°-40°	0,00	8,33	12,50	9,38	8,33	8,33	8,33	9,38	12,50	7,29	0,00	0,00	7,03	13,94
	40°-50°	0,00	0,00	10,42	11,46	9,38	8,33	9,38	11,46	10,42	0,00	0,00	0,00	5,90	11,70
	50°-60°	0,00	0,00	0,00	11,46	12,50	10,42	11,46	11,46	0,00	0,00	0,00	0,00	4,77	9,47
	60°-70°	0,00	0,00	0,00	0,00	7,29	11,46	8,33	0,00	0,00	0,00	0,00	0,00	2,26	4,48

Data collected from: Solar elevation angle (for a day) calculator, http://keisan.casio.com/exec/system/1224682277

Hours of sunshine per day

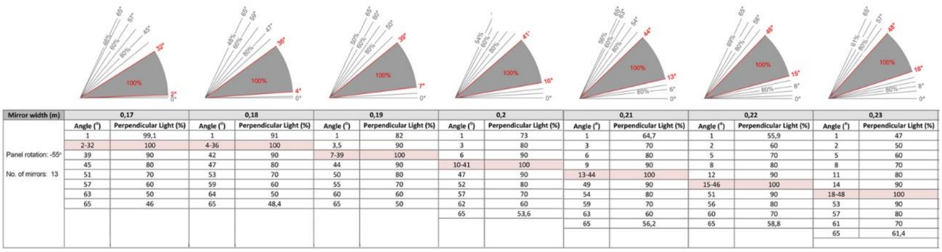


Munich	HOURS OF SUNSHINE											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
h. per day	1,97	3,00	4,13	5,23	6,42	6,97	7,65	6,87	5,77	4,16	2,30	1,58

Data collected from: Climatedata.eu, http://www.climatedata.eu/climate.php?loc=gmxx0087&lang=en

Table 26. Sun altitude occurrences for Munich.

By applying Galapagos to generate and validate variations of the fixed inclination of the whole mirror array, a set of design solutions is produced for different distances, sizes and amounts of individual mirrors which all redirect sunlight altitudes within a range/Δ of thirty degrees a hundred percent. It is then a matter of selecting the configuration which is most suitable for the design task at hand. In the example of Munich, a mirror configuration was eventually chosen which operates perfectly between 10-40 degrees.



Mirror width (m)	0,17		0,18		0,19		0,2		0,21		0,22		0,23	
	Angle (°)	Perpendicular Light (%)	Angle (°)	Perpendicular Light (%)	Angle (°)	Perpendicular Light (%)	Angle (°)	Perpendicular Light (%)	Angle (°)	Perpendicular Light (%)	Angle (°)	Perpendicular Light (%)	Angle (°)	Perpendicular Light (%)
	1	99,1	1	91	1	82	1	73	1	64,7	1	55,9	1	47
	2-32	100	4-36	100	3,5	90	3	80	3	70	2	60	2	50
Panel rotation: -55°	39	90	42	90	7-39	100	6	90	6	80	5	70	5	60
	45	80	47	80	44	90	10-41	100	9	90	8	80	8	70
No. of mirrors: 13	51	70	53	70	50	80	47	90	13-44	100	12	90	11	80
	57	60	59	60	55	70	52	80	49	90	15-46	100	14	90
	63	50	64	50	60	60	57	70	54	80	51	90	18-48	100
	65	46	65	48,4	65	50	62	60	59	70	56	80	53	90
							65	53,6	63	60	60	70	57	80
									65	56,2	65	58,8	61	70
													65	61,4

Table 27. Relation between mirror's width and delta of sun altitude angles which are redirected perpendicularly to the ground a 100%.

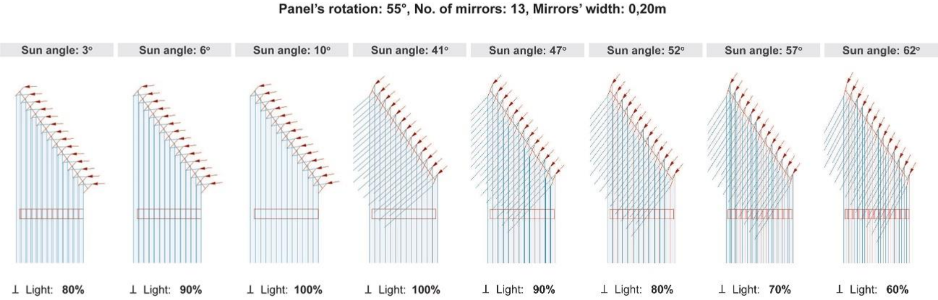


Figure 100. Grasshopper study on the percentage of sunlight redirected perpendicularly to the floor according to the sun altitude.

Associative 3-D models

After evaluating the design principles in the earlier steps associative three-dimensional files were set up to further evaluate the behavior of the lens and mirror system also to have a geometrical input for later daylight simulation. Regarding visualization of the redirected sun rays the solar tool of the Rhino Grasshopper/Diva plugin (Solemma) proofed to be valuable.

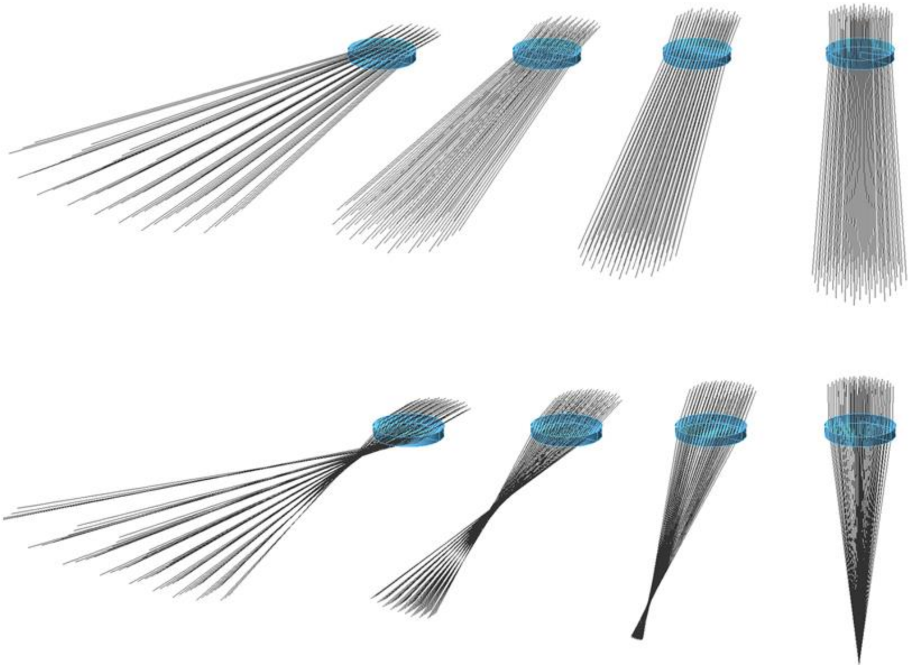


Figure 101. 3-D Associative lenses and light rays

7.5.2 Evaluation of design variants

Simulation

For Evaluation and feedback, the simulations were done via Diva/Radiance and the VRay renderer (Chaos Group) also available for Rhino 3D. The Radiance simulation was initially regarded as being important because it can show physical values like illumination in lux or luminance in cd/m². This would enable to check the performance for actual conditions and requirements as stated in e.g. building codes. However, the various simulations done proofed to be not accurate since Radiance for windows is not able to calculate optical effects with dielectric material properties properly (Jacobs, 2012). This must be done in the Linux environment with the help of a photon mapping module, which was developed by the Fraunhofer ISE (Schregle, 2016). This approach for simulating several different and adaptive geometries and the consequence to manually input the data in Radiance for Linux defies the seamless integration of parametric modelling and simulation. As point of reference contemporary render engines such as VRay can calculate caustic effects (Chaos Group) with physically correct material properties and Index of Refraction but are not able to display physical values such as Illuminance, etc. It was therefore decided to design and manufacture physical prototypes for the performance evaluation in accordance with the earlier findings from the associative 2-D and 3-D models. Light measuring instruments are readily at hand, the measured results are less prone to misinterpretation and a physical prototype gives much more insight and inspiration for further research. One should also not underestimate the fact that having something tangible immediately increases the creditability also to a larger audience.

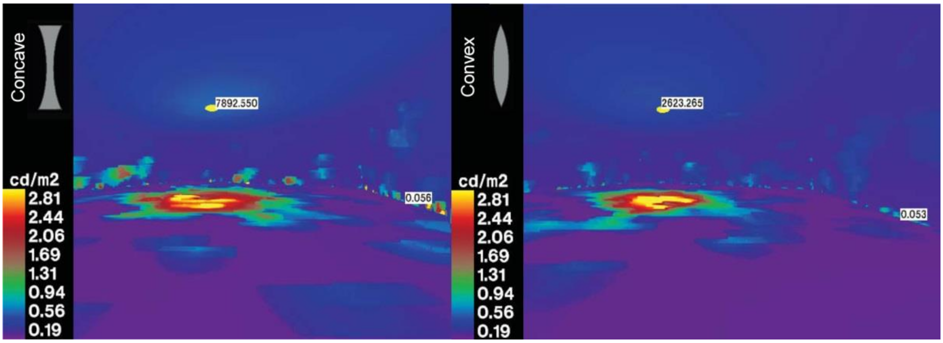


Figure 102. Radiance for windows luminance simulation. Convex and Concave Lens do not display the predicted difference.

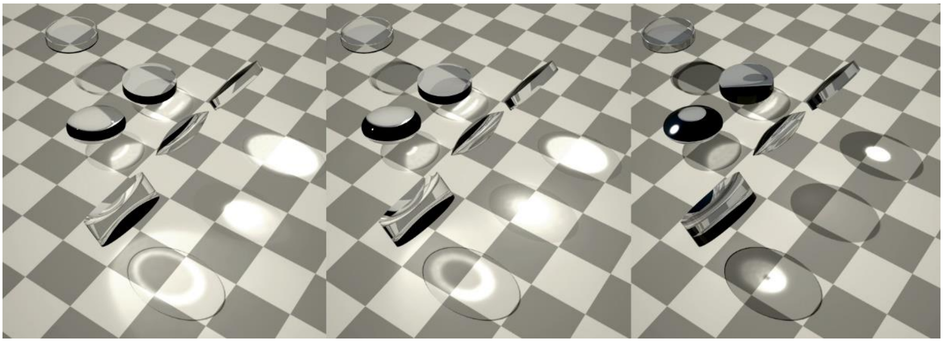


Figure 103. Caustic effects of various lenses with different index of refraction settings with constant parallel light source

Prototype

The first prototype consisting of transparent plastic petri dishes and clear plastic wrap displayed the expected optical behavior as any lens would. Due to the intended use and nature of household kitchen foil namely, being mainly plastically deformable and not elastically, the initial prototype was not adaptive yet. Later prototypes were built with the focus on adaptability in terms of lens membranes and the elasticity and sunlight redirection possibilities of the mirror system.

During the design process for the prototype, research was done for lens diameters, change of volume and therefore weight on the roof for a 1:1 case. In general, it can be concluded that the higher a roof is situated above ground the less of a shape change in the lens must occur to achieve a desired effect of converging or diverging light. By studying these parameters, it was decided that a lens with a diameter of 1 meter would be optimal for many applications in terms of weight and required volume change within the lens.

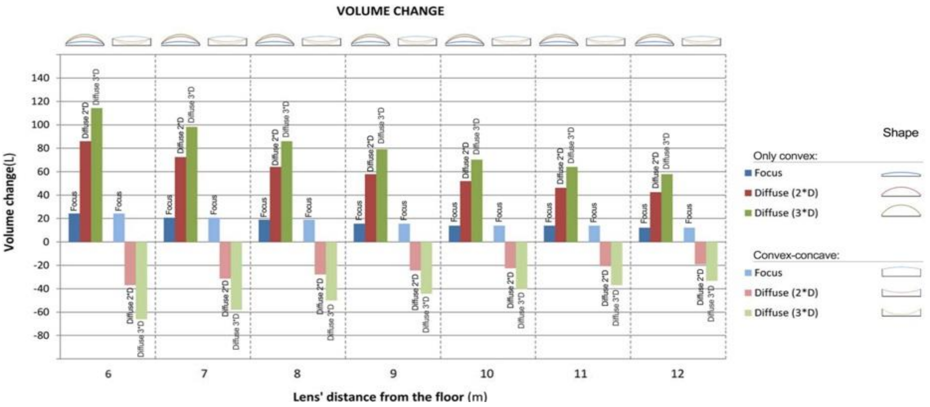


Figure 104. Volume change required for the convergence and divergence of light in relation to the room height with a lens of 1m diameter

The final prototypes which serve as proof of concept and are used for daylight performance measurements were manufactured in the scale 1:10. Most parts including the mechanical parts like gears and cog rail for the sunlight redirection device are made of white ABS plastic and 3-D printed by a Fused Deposition Modeling (FDM) printer. For the mirrors 3M™ Solar Mirror Film 1100 was applied on the rotatable ABS fins. The membrane for the lens turned out to be the most difficult part to make. After several unsuccessful material-tests a self-cast and baked Polydimethylsiloxane (PDMS) membrane provided by Michael Debije at Functional Devices research group of the Department of Chemical Engineering and Chemistry was used.

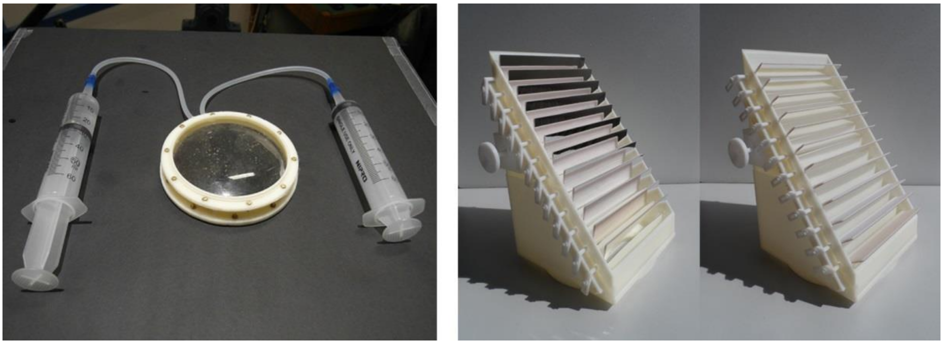


Figure 105. Adaptive liquid lens and sunlight redirecting system prototype in 1:10 scale.

The rest of the parts like syringes and hoses are standard shop ware. As a liquid water with an Index of Refraction of 1.33 (Lide, 2009) was used. Other liquids like colorless and transparent oils are also thinkable. However it is important to consider those for the prototype as well as for the final product under several viewpoints.

- Costs: Some of the found optical liquids are even in small amounts extremely expensive.
- Combustion: Intended for the built environment a liquid used needs to fullfil requirements in terms of fire regulations.
- Index of refraction: Apart from a few exceptions, Liquids with a higher Index of refraction also have a higher viscosity. That means that less pumping and change of volume, thus lens' change in shape is required in order to produce a similar optical effect. However the pumper needs to be stronger.
- Material Interaction: Not only should the membrane have a similar transparency and index of refraction as the liquid but it is also importnat that one material is not reacting with the other and the liquid disolves the membrane.
- Phase change: Since the liquid and the membrane are at the outer layer of the building it is important that the liquid is not freezing or boiling at common outside temperatures during winter and summer. Otherwise an additional layer would be required to protect the systems.

Material	**Index of refraction** at 20 °C	**Viscosity** (mPa*s)	**Density** (Kg/m^3)	**Freezing point** (°C)	**Flash point** (°C)	**Solubility in**
Water	1,33	1 (at 20° C)	1000	0	Not flammable (Boiling point 100)	Water
n-Butanol	1,399 (at 20° C)	3	810	-90	35	Water
Glucerol 60%	1,412	10,68	1153	-37,8	160 (solid glycerol)	Water
Calcium Chloride 32 %	1,418	4,035	1303,6	-49,7	Not flammable	water, acetone, acetic acid, ethanol
Ethylene Glucol	1,438	16,1	1113,2	-12,9	111	Water
Calcium Chloride 40 %	1,44	8,99	1395,7		Not flammable	water, acetone, acetic acid, ethanol
Glucerol 80%	1,443	59,9	1208,5		160 (solid glycerol)	Water
Carbon Tetrachloride	1,45	0,95 (at 20° C)	1586,7	-22,92	Not flammable	Alcohol, ether, chloroform, benzene
Mineral Oil	1,46	34,5 (at 40° C)	≈ 800	-30	depends: 129-195	In volatile oils, ether. Insoluble in water, alcohol
Safflower Oil	1,466	50 (at 23° C)	880	-17	167	Alcohol (80°C)
d-Limonene	1,47	0,9	841,1	-74,35	50	Nonsoluble in water
Castor Oil	1,475 (at 25° C)	615-790 (at 25° C)	961	263,2	285	Alcohol (ethanol)
Silicone oil	1,50-1,52	10 (at 25° C)	930	-55	316 (Boiling point: 140)	slightly soluble in water
Wintergreen Oil (Methyl Salicylate)	1,528 (at 25° C)	1,535	1174	-8,3	101	Alcohol, paraffin oil. Slightly in water

Table 28. List of transparent liquids.

Final measurement of prototype

The physical experimentations with the 1:10 scale prototype aimed at testing the performance of the system under clear sky with sun (Test 1-3) and cloudy sky conditions (Test 4). For the simulation of the clear sunny sky, a Solar Simulator was used, providing directional light, while for the overcast sky, an Artificial Sky Simulator was employed, to achieve diffuse lighting conditions. Through all test series, illumination measurements were done using a Hagner Digital Luxmeter EC1 and lumination pictures were taken with a Canon EOS 60 D and further processed in Photolux 3.2. (Photolux).

Figure 106. Left: Solar Simulator at a 90^o altitude (Test 1). Middle: Solar simulator inclined at a 30^o altitude (Test 3). Right: Set up for Test 4, using the Artificial Sky Simulator.

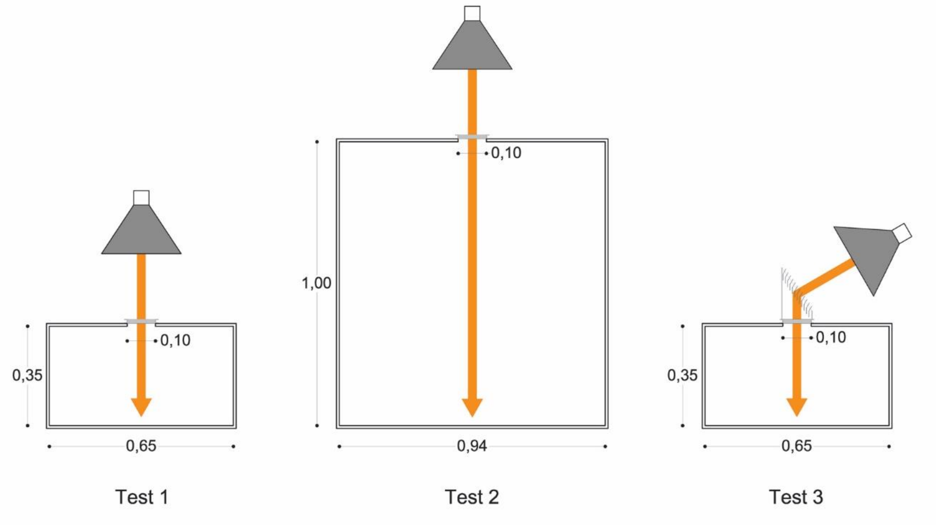


Figure 107. Left: Test 1 settings, solar simulator at a 90^o altitude. Middle: Test 2 settings, solar simulator at a 90^o altitude. Right: Test 3 settings, solar simulator inclined at a 30^o altitude.

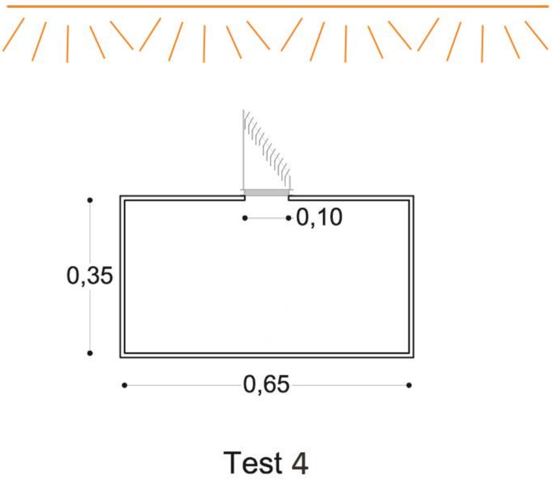


Figure 108. Test 4 Artificial sky

Clear sky with sun, Test 1&2 set up

The first two series of tests (Test 1&2) focused on the performance of the adaptive liquid lens alone under clear sky, supposing an ideal situation of 100% incoming perpendicular to the floor light which would occur if the sun redirection systems functioned perfectly. To simulate the above, the altitude of the solar simulator was set to a 90° angle. Two different in size closed boxes (Test 1: 0,5*0,5*0,35m, Test 2: 0,7*0,7*1m) with a circular opening at the center of their top surface for the 10cm diameter liquid lens to be placed over, were used as room models. Water was pumped in and out of the two syringes connected to the lens, to reconfigure its shape from neutral to convex and concave. These tests simulate the performance of a 1m diameter liquid lens in a 3,5m and 10m high room respectively.

Test 1 & Test 2 observations and comparison

The tests showed that under clear sunny sky conditions the light is indeed diverged or converged according to the configuration of the membrane and similarly to the predictions from the grasshopper models. Comparing the two room scenarios and scaling up the results to 1:1, it shows that a lens of 1m diameter is more efficient over a 10-meter-high room in comparison to a 3,5m high room. More specifically, in the case of the 1m box, the removal of 55ml of water from the lens in neutral mode causes a circular lit area on the floor of 0,46m diameter while the addition of 12ml produce a focal point on the floor of 0,01m diameter (in full scale the values are 10m, 55L, 4,6m, 12L 0,1m accordingly). At the 0,35m high box however, when an almost equal water volume (58ml) is removed from the neutral lens, a lit area of approximately half diameter (0,22m) is produced. Furthermore, to achieve focused light on the floor at a point of 0,005m diameter, 26ml of water need to be added to the neutral lens (in full scale the values become 3,5m, 58L, 2,2m, 26L and 0,05m accordingly).

At the concave mode, the lens is acting as a spotlight spreading out the received sunrays. The light hitting the floor surface and reflected by it causes the formation of soft shadows by the scaled human figures placed at the periphery inside the box. On the other hand, when the light is focused at the floor level, the flux density is so high that in fact the focal point acts as a point light source itself, casting hard shadows by the figures. The choice of a white shinny material for the floor surface is contributing to the intensity of these hard shadows as a significant amount of light landing on the floor gets specularly reflected. Finally, at the lens' neutral state it is observed that the incoming light is projected back to the lens' surface.

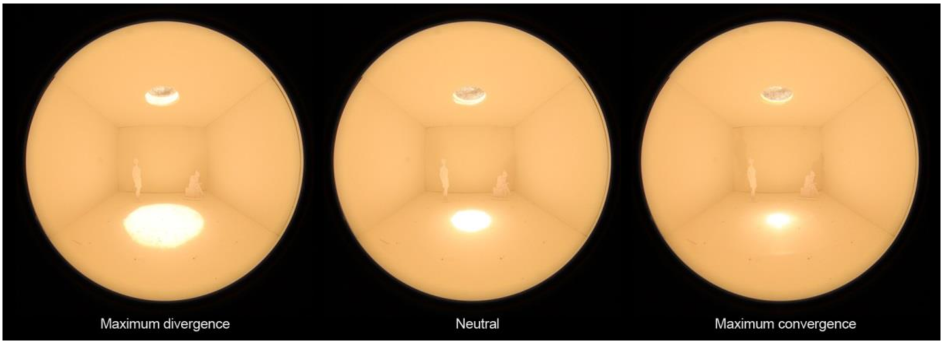
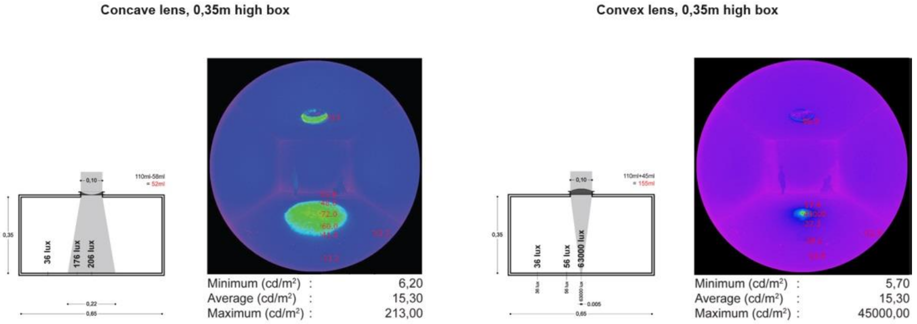


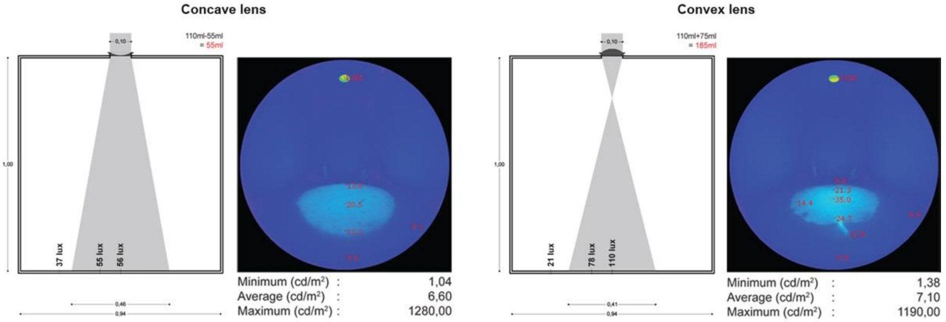
Figure 109. Differences in the quality of shadows from the diverged to the converged mode of the adaptive liquid lens.

Considering the focused mode, the flux density at the center of the floor surface (63.000lux for Test 1 settings) is excessively high in comparison to the density measured at the periphery (36lux for Test 1 settings). Given the fact that in Test 1 the sun simulator produces a value of 908lux at the floor center and scaling up the findings, we can assume that on a clear sunny day in summer where 100.000lux reach the ground (Flesch, 2006), the flux density will be 6.940.000lux at the center and 4.000lux at the periphery, when the liquid lens is at the focused mode. Even more, a 99,96% decrease of the brightness levels is observed at a distance of 0,1m from the center in the case of the 0,35m high box (1m at full scale). Such concentration of light is responsible for high contrast ratios in the room that not only exceed the acceptable contrast thresholds for visual comfort but also surpass the 1:1000 ratio which is the range of brightness the human eye can perceive (Green, Allen, et al., 2008). Further analysis needs to be conducted to evaluate the presence of discomforting or blinding glare in the interior regarding the different lens configurations. Moreover, the tests should be repeated to determine the reduction of these contrast ratios when a floor of increased surface roughness and darker color is selected, to increase the diffuse reflection (light reflected in all directions) and minimize the specular one (light reflected at a defined angle).


Concave lens, 0,35m high box

Convex lens, 0,35m high box

Figure 110. Comparison between the diverged and converged mode.


Concave lens

Convex lens

Figure 111. Test 2, light diverged via a concave and a convex configuration of the adaptive liquid lens.

Test 3 set up

Test series no. 3 examines the effectiveness of the sunlight redirection system on a clear sunny day. For these tests, the 0,5*0,5*0,35m box from test 1 was used as a room model and the solar simulator was set at 30° sun altitude, where the sunlight redirection system is expected to be 100% efficient according to the Grasshopper/Galapagos models. The system was placed over the liquid lens at the top of the box and the mirrors were rotated as such, to direct the received light perpendicularly to the ground.

Test 1 & Test 3 observations and comparison

Although the sunlight redirection system manages to redirect the light perpendicularly to the ground, the system in combination with the lens performs suboptimal in bundling all the rays in one focal point but in fact a linear series of focal points is noticed. This deviation is caused by imperfections of the mechanical system controlling the rotation of the mirrors. Given the fact that for an opening of 1m diameter and a 3,5m high room, a gradual angle difference between the first and the last mirror of 5,8 degrees increases the directly lit area by 400%, it can be derived that even minor deviations of the mirrors from the correct inclination can direct the light in a non-desired direction. In addition, it is assumed that deviations from the ideal light redirection model are also caused by the material used for the mirror surfaces of the prototype. The 3M™ Solar Mirror Film 1100 is not producing a perfect specular reflection but is in fact scattering a small portion of the incident light. The light scattering can be further enhanced if the film is not properly attached over the ABS lamellas, meaning that parts of the film are not stretched forming a perfectly straight surface but tend to curve. The imperfections at the rotation mechanism are also responsible for the presence of shadows on the floor cast by the row of mirrors. Minor shadows are of course expected at the neutral and diverging modes of the lens due to the thickness of the mirrors but not to the observed extent.

It was also observed that although the incoming redirected light has a circular footprint on the floor, within the bright spot itself, there is a difference in the levels of illumination which should not occur. This can be partially explained by considering that the inverse square law is applicable for the solar simulator and therefore light is expected to be dimmer as the light source (the light reflected from the mirror) is farther from the floor (13cm farther in our case). This phenomenon is not to be expected under sun light, where such differences in distance are considered negligible regarding the strongly directional light emitted from the sun.

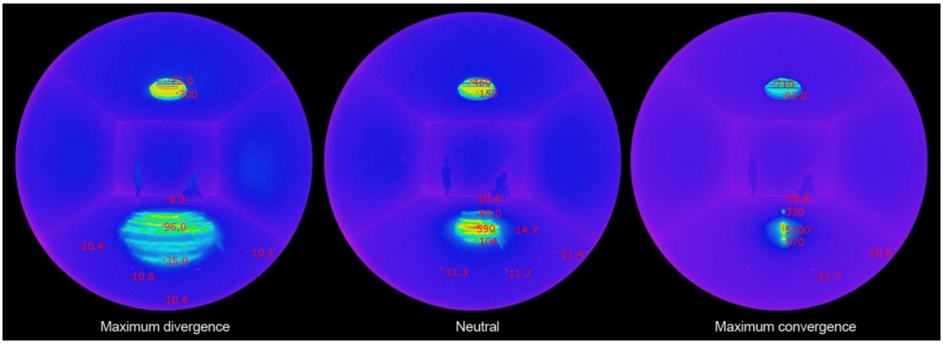


Figure 112. Test 3, different lens configurations.

Final Evaluation

Light redirecting possibilities

The prototype showed that initial expectations in terms of light redirection capabilities of the systems were by far exceeded. In the Test 3 configuration it was possible to redirect light within the sun's azimuth alignment until reaching the wall. In the other direction, it was possible to reach 90% of the space (0,5m*0,5m) with the spot which would be 5m x 5m in 1:1 scale. The Test 2 configuration in combination with the redirection device did not fit under the sun simulator. However, it should be noted that, the higher the ceiling, the larger the distance will be which the redirected light can travel, thus the range and performance increases. It is also important to note that due to the height of the redirection device, size of the opening in the roof, the area of illumination is more reduced the further the light beam is astray from the vertical redirection configuration. Furthermore, it will also be interesting to see the interaction and lighting design possibilities of several devices together.

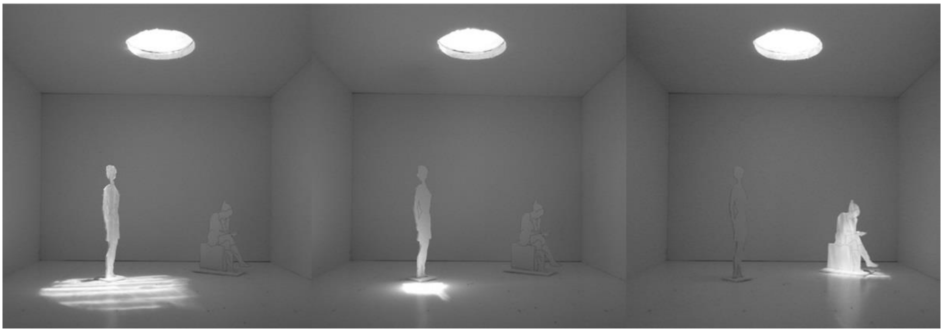


Figure 113. Adaptive daylight in the interior.

General findings regarding the liquid lens under clear sky conditions

The light and heat absorption by the water volume is another issue worth to be discussed as during clear sky conditions, the lux value on the floor surface under the opening is reduced in both Test series 1 and 2 by 3,1% when the lens at its neutral state is placed over the opening. The Beer-Lambert Law explains the logarithmic relationship between the transmission of light through a substance, the thickness of the medium and the wavelength of the light, proving that the intensity of light decreases exponentially with the increase of the water depth (Ryer, 1997). Taking into account that the light absorption coefficient of water for violet light (380nm wavelength) is 0,00011 cm^{-1} and for red light (725,5nm wavelength) is 0,01678 cm^{-1} (Pope, Fry, 1997) and by applying the Beer-Lambert law for a water depth of 1,4cm (water depth at the neutral state of the prototype), it can be concluded that 0,035% of violet light and 5,26% of red light will be absorbed by the water volume. Considering the full-scale lens however, the occurring light absorption will increase due to the 10 times higher water depth. Indeed, calculations show that 0,35% of violet light and 41,77% of red light will be absorbed by the water volume. This will result in a total reduction of the incoming light. Moreover, due to the selective color absorption property of water, the light exerting the lens will have a slight blue hue.

In addition, the light absorption coefficient of water for wavelengths of 1.000nm to 1.000.000nm ranges from 0,339 cm^{-1} to 128,2 cm^{-1} meaning that water is strongly absorbing infrared (Zolotarev, Mikhilov, et al., 1997) Of the radiant energy emitted from the Sun, approximately 50% lies in the infrared region (Fu, 2003). Regarding that this energy is to be perceived as thermal energy, absorption of the infrared light leads to the reduction of the amount of heat entering the room from the lens. Due to the high specific heat index of water, the lens is expected to act as a thermal mass that absorbs, stores and releases heat according to the surrounding temperature and reduces the heat gains as the penetration of heat is delayed.

Regarding the quality of the incoming light, it was found that trapped air in the water volume affects the uniformity of the incoming light as the occurring air bubbles cast shadows on the floor surface. Although in full-scale this phenomenon is expected to be less apparent, the minimization of the air content is considered important.

Cloudy sky

Test series 4, conducted in the Artificial Sky Simulator, study the performance of the system in the worst-case scenario, that of a cloudy winter day. For these tests the 0,5*0,5*0,35m box was used first with the liquid lens alone at its top opening (Test 4A) and then with the sunlight redirection system placed over (Test 4B). According to the findings, the incoming light is evenly distributed rather than diverged or converged.

When comparing Test 4A and 4B it can be concluded that the sunlight redirection system is reducing the amount of incoming light by 47,8% at the area under the opening (flux density is reduced from 53lux to 28lux) and by 57,5% at the periphery of the space (from 46lux it becomes 19lux). To scale up the measurements to real overcast conditions, a typical flux density at ground level on a cloudy winter day of 4000lux (Flesch, 2006) is considered and related to the 962lux measured outside next to the box. This results in 220lux at the center of the floor area and 191lux at the periphery when only the liquid lens is present, and in 116lux and 79lux respectively when the sunlight redirection system is added.

7.5.3 Finalize design

Technical system in 1:1 scale

The adaptive liquid lens at the current prototype is operated via hoses and attached syringes. When considering a final design to be placed in a building several other aspects are important.

Actuation

It is intended to have several lenses and mirrors working together but the system should be able to address each of them individually to have an interplay of several lens systems. This could be achieved via a hydraulic system where the liquid reservoir and pump is an extra unit which is stored at a central location. All the lenses would be connected by a system of pipes and individual change of the lens geometry would have to happen via individual valves either shutting the lenses off the hydraulic array or changing the hydraulic resistance accordingly. This seems not to be the most efficient way due to the increased installation effort due to the number of pipes as well as hydraulic, automation control engineering. It not only needs to regard pipe lengths and resistances due to flow of liquids in curves, but the whole hydraulic interaction with individual valves and resistances. Therefore, it is aimed to have a system of individual and hydraulically not connected lenses (decentralized) where actuation and storage of liquids is integrated in the perimeter of the lens body. That would also make maintenance less of an effort.

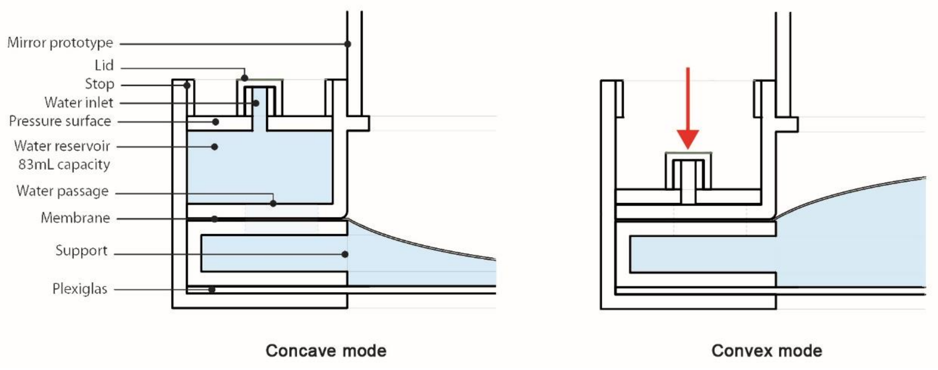


Figure 114. Liquid lens with actuation and storage of liquids integrated in its perimeter.

Feedback and further design considerations

Choosing for an adaptive lens that is based on the movement of liquids naturally raises questions regarding the imposed load on the roof and the absorption and quality of light reaching the interior and is paired with construction complications related to leakage and the vulnerability of the exterior membrane. Thus, alternative solutions based on multiple moveable lenses or on smart materials were considered and compared to the initial proposal.

Interaction of multiple lenses

This proposal is based on the principle of zoom lenses in photographic cameras. These usually consist of multiple lenses of different focal lengths that are moved close or apart of each other to alter the size of the light-beam or to focus the light.

Likewise, the proposed system is based on 2 or 3 interlocking glass lenses of 1m diameter, with the upper one being fixed while the rest can move downwards. Several scenarios were examined with parameters the number of moving lenses and the focal length of the lenses. For the assessment of the scenarios, a 2-D parametric file was built in Grasshopper.

All the studied cases proved to achieve considerable changes between diverged and converged light, the interior lens must significantly descent. Specifically, in a room of 10m height, to alter the light from parallel to converged by 3 times more than the initial diameter, at least 0,9m of downward movement is required. This causes problems regarding the height of the total system and more importantly the ability of the system to work when the incident sunlight is not perpendicular to the ground. A 1m distance between the two lenses could lead to significant light loss when the light enters in a shallow angle. More importantly the additional height in comparison to the thinner liquid lens also impairs the possibility to redirect light because the rays will illuminate the light pipe rather than the interior.

Regarding the weight of the system, this solution is much heavier than the adaptive liquid lens proposal, with a set of two glass lenses weighing up to 300 kg and a set of three 600kg. Acrylic glass was also considered, resulting to a system of 2 lenses that weigh 135kg. To further reduce the mass, the system was calculated using acrylic Fresnel lenses of the same focal length. The mass was reduced to 82,5kg which is still 12,5kg more than the maximum mass of an adaptive liquid lens of 1m diameter in a 10m height room.

The above limitations and disadvantages led to the discard of the multiple lenses approach.

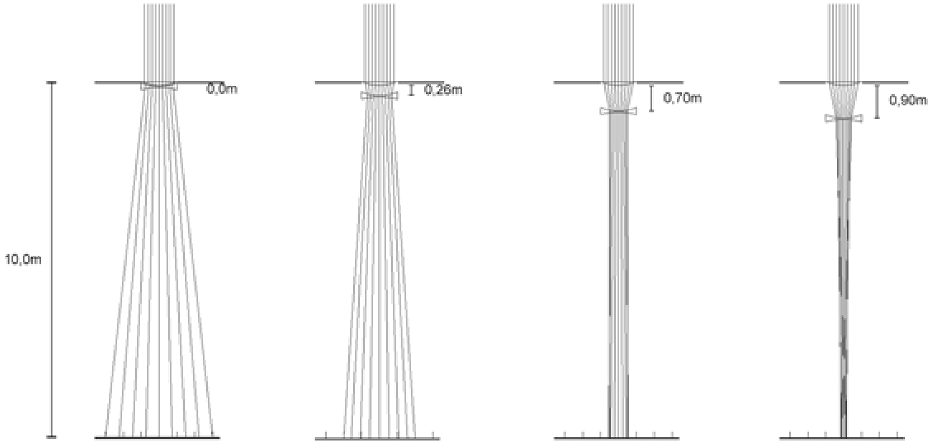


Figure 115. Grasshopper calculation of light redirection for a system of two moving lenses.

Smart materials

Further research led to the investigation of the possibility to use smart materials to achieve the convergence and divergence of sunlight and the redirection of the sunbeams. Ideally, the same smart material should perform all the above functions, minimizing therefore the total mass of the lens, it's system complexity and the energy costs required for its operation.

Extensive research has been conducted regarding tunable focus micro-lenses that find applications in cameras for cell-phones, endoscopy systems, etc. The apparatuses are divided in two main categories related to the method they adjust the focus: by changing the refractive index and by changing the curvature of the lens. Changes in the refractive index can be achieved with liquid crystals and the application of voltage (Ren, Fox, et al., 2007) while for the change in curvature different systems exist grouped in 4 categories according to their cause of change: fluidic pressure (actuators: syringe, servo-motor, piezoelectric, artificial muscle, voice coil actuator, thermo-pneumatic (Ren, Wu, 2012), (Zhang, Zappe, et al., 2014), thermal effect, electrowetting, and dialectrophoresis. In many of these research projects smart materials such as thermo-stimuli hydrogels (Dong, Agarwal, et al., 2006) are used to change the volume of the liquid in the lens, resulting thus to a change of its curvature. Research on hydrogels is also conducted at the Department of Chemical Engineering and Chemistry at TU Eindhoven with the aim of constructing responsive surface topographies (Liu, 2013). Hydrogels are polymer networks that can absorb hundreds of times their mass in water when triggered by a specific change in the temperature, light conditions, pH, humidity or electric field. The swelling capacity of the hydrogels can be controlled according to the degree of crosslinking of their network, therefore the researchers aim at creating inhomogeneous surfaces of different cross linker distributions along the hydrogel film, which will non-informingly swell, forming thus 3D microstructures.

In consultation with Prof. Dr. Broer and Dr. Debije a concept for an adaptive lens and redirection system out of light responsive hydrogels based on poly (*N*-isopropylacrylamide) (pNIPAAm) has been developed. When the lens' surface temperature is lower than the critical (34°C), it remains flat, while when incident light is heating it over the limit, it swells forming a fresnel lens that diverges the sunlight. The sunlight redirection system consists of triangular pNIPAAm beams with a highly reflective foil attached to one of their surfaces. According to the changes in the incident sun-angle, the hydrogel is expected to swell or de-swell changing the angle of the film and thus the redirection of the sunlight. Next steps could include the development of the smart material proposal together with the Functional Devices research group of the Department of Chemical Engineering and Chemistry at the TU Eindhoven. Particularly interesting will be to investigate the possibility to develop a similar functioning system without any moving parts involved.

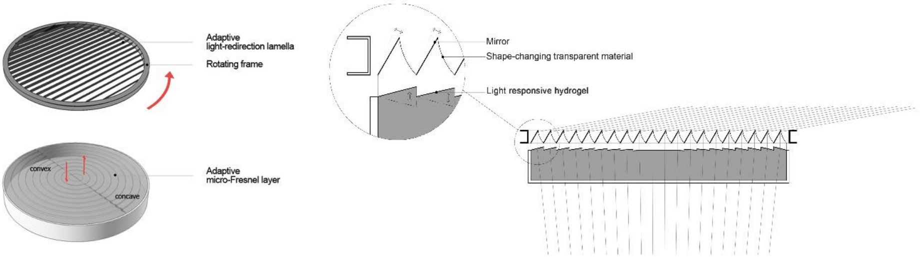
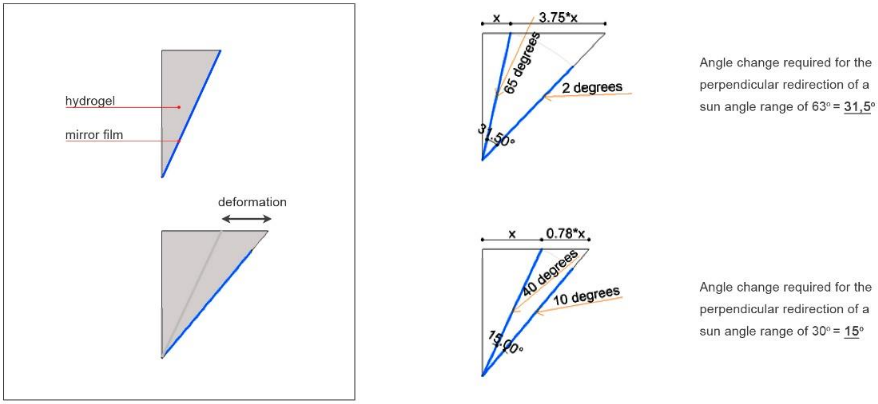


Figure 116. Adaptive lens and sunlight redirection system proposal based on light responsive hydrogels and shape-changing polymers.



Angle change required for the perpendicular redirection of a sun angle range of 63° = 31,5°

Angle change required for the perpendicular redirection of a sun angle range of 30° = 15°

Figure 117. Adaptive sunlight redirection system proposal based on light responsive hydrogels and mirror films.

Energy production

The extreme converging mode of the lens and bundling the light into one spot may not be applicable for lighting the interior but could be interesting in combination with photovoltaic as a concentrator system while the space underneath is less frequented or occupied by the inhabitants. The photovoltaic elements could be mounted as a relatively small device close to the ceiling and would therefore not disturb the flow of light otherwise. It would be also possible to employ a more expensive but highly efficient photovoltaic cell since the surface area is far less while being more protected from any outdoor influences like dust and rain.

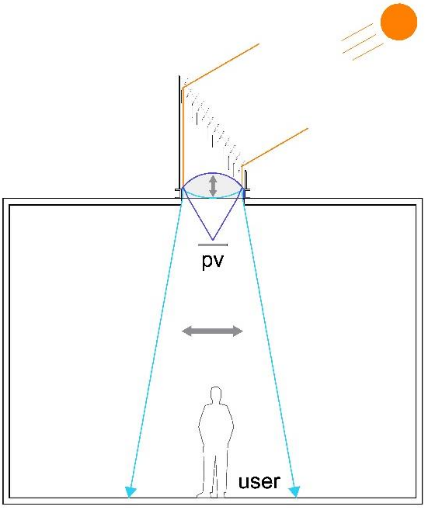


Figure 118. Adaptive lens that converges light for energy production when the room is not inhabited and converges light when the user is present.

7.6 Conclusion Liquid Lens Design

The physical experimentations prove the ability of the system to quickly adapt not only to converge/diverge the sunrays but also to redirect the incident light according to the needs of the interior space. The system successfully proved to be able to function as a daylight spotlight which can adaptively react to the moving sun position as well as interior lighting requirements. The changes between different modes occur gradually rather than abruptly and thus are not disturbing to the user.

However, concerning the high contrast ratio observed in some of the tests and the probability of glare, it is required to evaluate this further. Also, the illumination of the interior, when more than one adaptive sunlight redirecting modules are installed in proximity must be determined. The performance under worst case, cloudy sky conditions appears to be sub optimal. Here other non-adaptive solutions must be evaluated to understand at which square meter threshold of glazed roof surface daylight autonomy is guaranteed. This would either determine a certain number of lenses required on the roof or would suggest an application at a location with a high number of sunny hours. Therefore, by applying the system at the more southern hemisphere it would not only be more effective in terms of direct sunlight but also in terms of heat absorption and reduced heat gain. In general, the system is useful for interiors which require directed light and are not affected by contrasts. This could be suitable for Atria, large markets, shopping malls or restaurants to place dynamic daylight accents and highlight certain spots. If a more even and diffuse light distribution like in train stations, etc. is required an additional adaptive light diffusor must be thought of.

Alternative solutions

The stacked multiple lenses solution, although simple in concept, requires complicated engineering and over a meter height, to work. Its increased weight and inability to work with low solar-incident angles lead to the discard of the proposal. Implementing smart materials shows a much more promising path, but the technology is still in a very experimental stage and there are only indications that light responsive hydrogels will have the desired results once applied in a component of architectural scale. The two alternative approaches which were studied in addition to the Liquid Lens, in fact confirm that the current approach with contemporary technology at hand is a feasible way for product development. In more practical terms sensing, actuation and the digital interface should be thought of, as well as more material research for a product application must be done. The requirements for a high degree in precision in redirecting sunlight needs to be further considered.

7.7 Conclusion Application Design Method

The Design Method Top Down, Bottom Up-Design Exploration, Top Down is also the most often applied one within the author's own design practice. It has shown to be a healthy mix between defining design constraints, thus control mechanisms guiding the design exploration not being led astray yet producing innovation. The crucial part for successful application is to make the first Top Down aspect narrow enough to be guiding, yet open enough not to limit the design process. At the second step of the design exploration it is important to realize the moment when something meaningful is discovered and again being able to flip the design approach around by fully understanding the potentials and finalize the design according to the inherent potentials for application. The critical point within the design trajectory of the liquid lens was to realize that the relatively early discovery of a liquid lens requires a secondary system in form of light redirection device to make full use of its design potential and not discard it prematurely. The challenge while designing however is to realize in which phase one is at a specific moment and whether a more guided or open design approach is required. In design practices, this very often decided by other factors like design time/deadlines or cost for salaries and not necessarily what is good for the design. Therefore, having an awareness of the different phases one goes through, correlated to a schedule makes it possible to achieve design innovation.

8

Conclusions

8.1 Evaluation and discussion of Design Method

Working towards a Design Method from existing and self-created Design examples via Research by Design proofed a valuable approach. It directs one to become objective about creative and research processes and how design decisions are linked from several standpoints and design objectives. The Design Method frames how design is executed during various stages.

Although the Design Method is tightly linked to the research of Adaptive Daylight Systems in large (span) roofs it is general enough to equally help with other related design tasks.

The Design Method provides:

- Offers a clear guideline with flow chart
- Helps to gain an objective (external) view on the design process
- Describes the flow of Design processes
- Helps to manage the design process
- Serves as a decision-making tool

The proposed Design Method offers a clear guideline by identifying Top Down and/or Bottom Up Design Exploration starting points and how to operate within the respective trajectories. With that it enables a designer to gain an objective and external viewpoint on the design process. This is insofar essential, because design processes can be messy, which means one could be lead astray. With the raised awareness, designers can take a step back, evaluate and bring the design process back into track. It also describes the flow of the Design process and what sort of possible stakeholders are involved. With that it helps not only to manage the design process, but it serves as a decision-making tool.

The Design Method does not provide:

- How to come up with ideas, concepts, etc. in the first place

The proposed Design Method intentionally does not help too much with coming up with own ideas and concepts. Here every designer or architect works differently to tap into their own creative sources. It is intended more of a design management and decision-making tool. Although, having explained Top Down and Bottom Up - Design Exploration elements via examples, views from other disciplines and descriptions, it might sometimes be difficult to clearly identify where one is located within a given design trajectory.

Adaptive Daylighting for large (span) roofs

Due to the nature of adaptive design dealing with daylight, a design parameter which is in constant change, sometimes within minutes rather than e.g. seasons a strong emphasis lies in the use of digital design tools such as parametric design to be able to cover those variations in all its details. At the same time daylight design in large (span) roofs intersects with a lot of other disciplines such as structural engineering or material sciences. Therefore, it is a requirement for a designer not only being apt in using those tools but to develop a profound understanding of the works of other disciplines too. With that, the proposed Design Method also promotes and stimulates a cross-disciplinary design approach.

Future of design tools - Simulation versus prototypes

With the current possibility to easily and cheaply manufacture functional prototypes and the ongoing tendency of more, relatively cheap, user friendly but none the less accurate 3-D printing technologies like FDM printers being released on the market and thus being applied by a larger group of users there is a great chance that we might face a renaissance of physical testing rather than simulation only approaches. It will be interesting to closely watch the coming years since manufacturing in form 3-D printing technology will become common property and if there is going to be a shift in design practices from simulating towards prototyping or even prototype becoming instantaneous the actual product even on a large scale and numbers. Another aspect regarding daylighting and simulation is that of material properties, where it is difficult without laboratory testing to determine exact material properties to be used in (day)lighting simulations. By using a physical daylight simulator and artificial sky not only can the material properties be tested and translated into digital material property parameters, but it would be possible to inverse the approach to come up with new specifications for material research and rather than assessing the performance of existing ones. Unfortunately, physical testing in lighting laboratories for architectural design purposes seems somewhat anachronistic, since those facilities if they are even still existing at universities are at least in the case of TU/e from a time where the operator is forced to use a DOS like user interface, not to mention the possibility for a digital loop of input, testing and result. The vision here would be to come up with a system of blending digital design, with manual and rapid prototyping, physical testing, where the measurements are fed back directly into the digital design environment.

8.2 Future of Adaptive Architecture

Architects are often concerned with conceptual, programmatic, cost and aesthetical aspects resulting in form giving rather than form finding through energy performance aspects. That also means that integration of technologies becomes an afterthought or even more so designs express sustainable aspects in form of green tokenism, rather than integrating technology. This became more apparent due to jury work on the FuturArc Green Leadership Award 2018, where basic passive design principles of building orientation or external sun shading where disregarded, but approval was thought via mounting photovoltaics on top of a high rises, powering merely fridges for 30 households for one year. In opposition to that, taking an old building, renovation project for instance: The building due to newly added insulation glazing, insulating walls, installing a more energy efficient heating system will perform thermally much better than in its original state. However, the appearance of the building will hardly change (if it is done well). That means due to the initial design intent of preserving the original look, the design never searches for technological expression but less evident integration of technology while having a similar performance to a newly built and designed building. Another example is the critically acclaimed BBC TV show Black Mirror. Here the benefits but also threats of current and future technology in form of social media, people interaction (technological enhanced), data manipulation, is often not displayed in front of futuristic architecture, or via expressive gadgets but in form of blending into the ordinary. Technology becomes an invisible, added layer of information and enhanced communication possibilities without altering necessarily the physical state of the environment by technological representation. In that sense, adaptive architecture with the aim to enhance performance, but also for the sake of wider acceptance and avoiding tokenism must move away from technological expression dominating the architecture itself, like Kinetic Architecture by adaptive Geometry towards Statically Dynamic Architecture by Smart Materials. By that architecture becomes freer in terms design variety and contemporary buildings do not have to display technology to emanate being state of the art. This integration of technology can be seen at the case study 2 Smart Glass in chapter 5.4.5.2, where windows can be (retro)fitted into any design. A similar conclusion was reached for the liquid lens in chapter 7 by moving away from mechanical and hydraulic elements towards changing material properties in form of Smart material coatings which can achieve similar optical effects. However, here lies the problem because architects and designers are not necessarily experts in Material Science and the subject is not easily accessible. To achieve further progress in terms of Adaptive Buildings, it is therefore recommended to investigate more in the field of Material Sciences, their application possibilities and outlining performance requirements for future materials by actively searching for collaborative research projects between Material Sciences and design disciplines.

9

Summary

Daylighting for buildings, meaning the supply of quantitative and qualitative adequate natural indoor light in combination with protection from overheating is a well-researched and applied design approach when it comes to vertical façades, especially regarding buildings with a high degree of façade standardisation. Here static as well as adaptive solutions like light shelves or reflective, retractable louvers are applied in the built environment and many different products are available. However, dealing with large roofs where the area of the roof and the horizontally laid out functions underneath cannot be sufficiently lit by vertical façades, the horizontal roof structure will become the main surface which has to transmit daylight. Since daylight is not static but its availability and direction over time changes, adaptive daylighting solutions are required. The different design requirements and the tendency that large roofed buildings are much more individually designed, ask for another design approach which needs to be formalized in form of a Design Method. This is relevant for buildings like stations, airports, sports facilities, museums, big atria, trade fair buildings and to a certain degree for industrial and storage buildings.

Another design (especially adaptive design) process related aspect which demands the formulation of a Design Method is the raise of digital design tools in form of parametric design and the integration of evaluation and simulation software in the recent years from being experimental towards being mainstream. That means, that formerly these tools were mainly used by a relative small crowd of architects and designers with a high computational design affinity and technical knowledge. Due to the seamless integration of various software packages with each other, while cumbersome file exchange, scripting for automation, etc. became obsolete, current software offer a much more integrated workflow. Therefore, the accessibility of tools for more general architectural practices became much better, which demands in conclusion that education from formerly self-taught needs to shift towards a more formalized Design Method.

In the design process of the afore mentioned larger scale projects due to budget, profit, importance and complexity a larger team of designers, architects and engineers is employed to solve all the building related questions. In addition, the recent years have seen an increase not only in high rise buildings but also in building types using large roofs like big infrastructural projects in form of train stations, or airports, but also shopping malls and museums, etc. In the Netherlands for example all major train stations are under redesign, or reconstruction, or recently have been finished, like Arnhem Central station by UNStudio with its main hall finished in 2016 and Rotterdam Central station by a cooperative between Benthem Crouwel Architekten, MVSA Meyer & Van Schooten Architects, and West 8 in 2014. The latter won the Velux Daylight Award 2014. Another milestone in terms of daylighting and large span roof for museums is the 2017 finished Louvre in Abu Dhabi by Jean Nouvel, a design where a common roof houses a “museum village” underneath. A further remarkable example in terms of daylighting combined with artificial lighting is the atrium installation at the Philips Lighting Headquaters in Eindhoven designed by LAVA and finished in 2016. The situation in the Asian region with China as powerhouse e.g. stadiums for their Olympic Games but also Japan with the plans for a new stadium in Tokyo but also upcoming countries like Indonesia is a rather promising field for daylight design for large roofs.

These types of buildings regarding daylight need to be treated differently in comparison to e.g. High-rise buildings because the part being most exposed towards the sun is the roof. In addition, the issue at hand is that daylight availability inside buildings due to location on the globe, axial rotation of planet earth, its orbit around the sun during one-year, various changing weather conditions, but also usage are not static design parameters but constantly changing and therefore highly dynamic and not only long term but also being responded to in a matter of minutes. Therefore, daylighting and solar energy gain related questions cannot be solved with static building envelopes, or openings but adaptive ones.

The aim of this dissertation is to gain an insight into these design issues and provide designers and architects with a Design Method especially in early design stages where the design team is smaller but most crucial design decisions are taken and to be able to come up with adaptive daylight system in large (span) roofs. The dissertation is organized in the following chapters:

Chapter 1 Introduction

Here the topic, research motivation and goal are introduced. It addresses the following research question:

How can architects, designers and engineers be supported with the use of a Design Method to be able to design adaptive daylight systems in large roofs under the consideration of daylight performance aspects?

To answer the main question several sub-questions need to be addressed: How can this particular Design Method:

- Integrate different time spans e.g. daily and seasonal changes of daylight and availability according to specific locations? Answered in Chapter 2
- Take functional aspects like the use of the building, the user and their needs into consideration? Answered in Chapter 2 & 3
- Make the designer understand the role of large roofs as mediator/interface between user/functional requirements and daylight availability? Answered in Chapter 3
- Enable the designer to evaluate the need for either a “static” or “adaptive” design? Answered in Chapter 4
- Clarify the role of the overall/global geometry of the roof in terms of design complexity but also potential influence on daylighting performance? Answered in Chapter 5 & 7
- Make the designer understand implications and outcomes of various materials of roof and openings in terms of daylight performance? Answered in Chapter 5 & 7
- Give advice about design and evaluation tools available, be it digital or physical and the principle use of them? Answered in Chapter 6 & 7
- Enable designers to assess their design outcomes and iterate and evaluate them further? Answered in Chapter 6 & 7

Chapter 2 Performance driven (Daylighting) Design

This chapter explains aspects of Performance Driven Design and specifically Performance Driven Daylighting design and gives an overview of tools at hand ranging from digital to physical modelling, simulation and evaluation possibilities. It further explains the physical principles of day and sunlight in terms of energy and visibility to the human eye, e.g. illuminance, luminance and wavelength as well as the interaction between light and surface material properties such as transmission, reflection, diffusion, roughness, albedo, etc.

Chapter 3 Large (Span) roofs

The third chapter describes the distinction between large span and large roof, their societal importance also in relation to daylighting design. It further introduces the issue of use individual versus collective use of people and the consequences in terms of approaching daylight design. A vital part is also to highlight the different functions under large (span) roofs such as infrastructural, commercial, cultural, recreational and sports. All these different functions have specific lighting requirements due to building regulation, safety, usability and user-user but also user-building interaction.

Chapter 4 Adaptive and Static

This chapter introduces adaptive and static architectural design. Here several definitions in terms of building components, reaction and Interface are looked at. Most importantly for this thesis a clear distinction is made in both static and adaptive architecture terms with respect to geometry and materiality or mix of both. The material properties always play a major role in daylighting in relation to incoming light and how light is "processed" by the material, however the geometrical component, the form often plays a major role. In addition, a new definition is worked out of Static Contextual Buildings, buildings which are designed via environmental design parameters however do not change. Here the two categories are Adapted Geometry (Smart Geometry) and Materials & High-Performance Materials. This equally is already defined for Adaptive Buildings, being Kinetic Architecture by Adaptive Geometry and Statically Dynamic Architecture by Smart Materials.

Chapter 5 Case studies

Chapter 5 analyses several designs in form of case studies being own design solutions or existing ones in terms of large (span) roofs and daylight performance. This is done according to the categories coming from chapter 4 Static Contextual Buildings – Adapted Geometry & High-Performance Materials and Adaptive Buildings – Kinetic Architecture by Adaptive Geometry and Statically Dynamic Architecture by Smart Materials. The case studies are:

5.1 Static Contextual Buildings – Adapted Geometry – Kimbell Art Museum
5.2 Static Contextual Buildings – Adapted Geometry – Origami Roof Structure
5.3 Static Contextual Buildings – High Performance Materials – Aerogel
5.4 Adaptive Buildings – Kinetic Architecture by Adaptive Geometry and Statically Dynamic Architecture by Smart Materials

All the case studies are researched, designed and evaluated according to the following categories:

- Context
- Function and Layout
- Lighting requirements
- Design process
- Geometrical & Material Aspects - Technical solutions & systems
- Lighting Analysis and Alternatives
- Conclusion

Chapter 6 Design Method

Based on the findings from chapter 5, this chapter derives with a Design Method which gets later applied in chapter 7. Initially Top Down and Bottom Up design trajectories get explained also with the use of several examples. The previous case studies get further classified what design trajectories where prevalent in the design process itself. As a next step boundary conditions relevant for daylighting are introduced. These are building's function, location & climate, quantitative aspects of daylight and qualitative aspects of daylight. Design tools are introduced, the way they operate, the physical principles which apply. Here Parametric Design, Simulation, Physical prototypes and ways of evaluation and feedback into the design system are explained. The final step of the fully fleshed out Design Method gives a step by step design guideline and a preview of the fully applied Design Method.

Chapter 7 Fully applied Design Method – Adaptive Liquid Lens

Here the final design result of this thesis is displayed in form of and Adaptive Liquid Lens being a daylight altering and redirection device. Like in the previous chapter explained it describes the Top Down and Bottom Up design elements and how the design came into being also with respect to design tools. It also shows the potentials and limitations of using simulations versus building prototypes and how such a daylighting system can be applied in 1:1 scale. The measured results get then evaluated and further design and research suggestions especially with respect to Smart Material applications are made.

Chapter 8 Conclusions

Offers conclusions, evaluations on the state of Adaptive Buildings and gives recommendations for future research. It also evaluates the proposed design Method, its applicability, etc.

10

Appendices

Appendix A - SI units and tables

Quantity	Symbol	Units
Thermal conductivity	λ	W/(m*K)
Thermal resistance	R	$(m^2K)/W$
Thermal transmittance	U	$W/(m^2K)$
Wavelength	λ	nm
Luminous flux	ϕ_v	lm
Illuminance	E_v	Lux
Luminance	L_l	$Lm/m^2/sr$
Luminous intensity	L_V	cd
Refractive index	n	
Reflection	R	

Table 29. SI units

Light Source	Efficacy (lumens/Watt)
Direct Sun (low altitude)	90 lm/w
Direct Sun (high altitude)	117 lm/w
Direct Sun (mean altitude)	100 lm/w
Diffuse Sky (clear)	150 lm/w
Diffuse Sky (average)	125 lm/w
Global (average of sky and sun)	115 lm/w
Incandescent (150 w)	16-40 lm/w
Fluorescent (40 w, CWX)	50-80 lm/w
High Pressure Sodium	40-140 lm/w

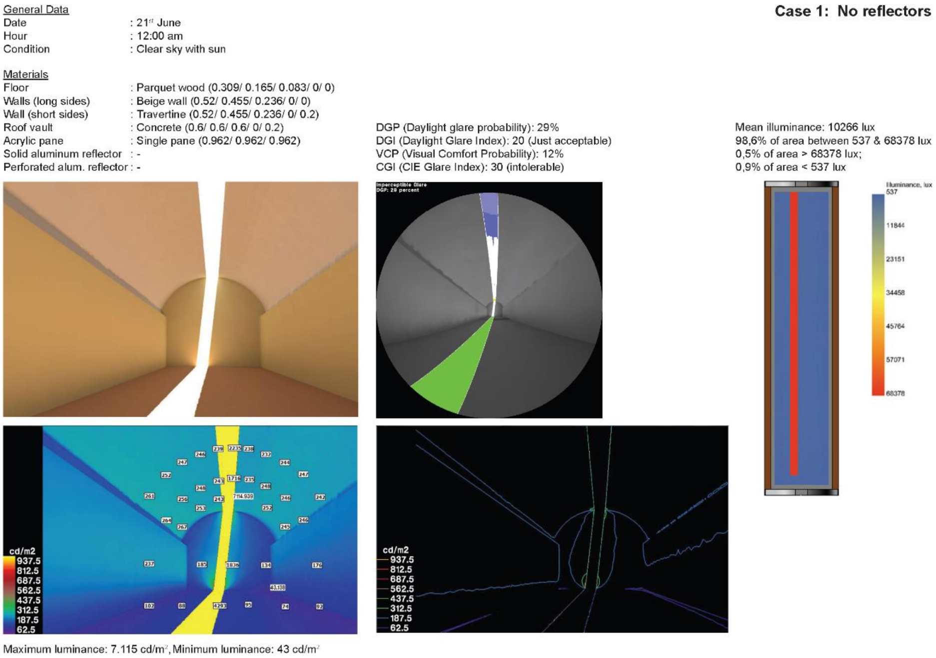
Table 30. luminous efficacy (Natural frequencies,2016)

Appendix B – Kimbell Art Museum

Results Test 1

Case 1 (no reflector)

As to be expected direct light enters the interior apart from the top glazing mostly unobstructed and leaves a clear distinct bright stripe on the floor and back wall. The mean illuminance is 10266 lux and looking at the various visual comfort indexes glare will be an issue.



Case 1: No reflectors

General Data
Date : 21st June
Hour : 12:00 am
Condition : Clear sky with sun

Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : -
Perforated alum. reflector : -

DGP (Daylight glare probability): 29%
DGI (Daylight Glare Index): 20 (Just acceptable)
VCP (Visual Comfort Probability): 12%
CGI (CIE Glare Index): 30 (intolerable)

Mean illuminance: 10266 lux
98,6% of area between 537 & 68378 lux
0,5% of area > 68378 lux;
0,9% of area < 537 lux

Maximum luminance: 7.115 cd/m^2, Minimum luminance: 43 cd/m^2

Figure 119. Simulation result case 1

Case 2 (Solid aluminum reflector specular reflection)

As the 2-dimensional file predicts and looking of the false color luminance image the left reflector reflects light on a larger surface, deeper into the vault. This is due to the specular (directed) reflective material properties. However, the effect is less strong as predicted. The false color image also shows a clear cut of luminance levels on form of a jump of around 2000cd/m². This is also shown in the visual comfort studies. Even though this configuration has no perforated reflectors, the visual comfort Index is high and glare probability is low. The luminance level on the wall, where paintings are located is around 84cd/m². The space appears to be homogenously lit. The mean illuminance is at 496 lux on the floor and the higher illuminated area is located on the left side.

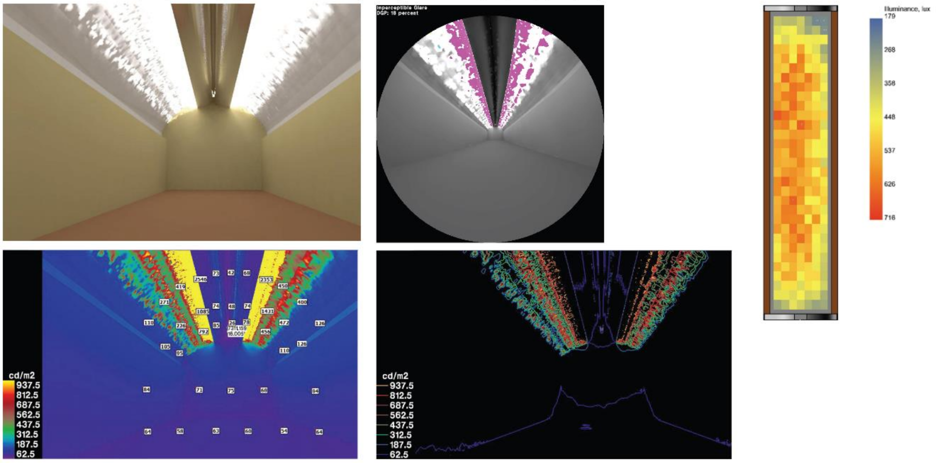
Case 2: Solid shiny aluminum reflectors

General Data
Date : 21st June
Hour : 12:00 am
Condition : Clear sky with sun

Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)

DGP (Daylight glare probability): 18%
DGI (Daylight Glare Index): 5 (Barely perceptible)
VCP (Visual Comfort Probability): 97%
CGI (CIE Glare Index): 12 (Barely perceptible)

Mean illuminance: 496 lux
100% of area between 179 & 716 lux

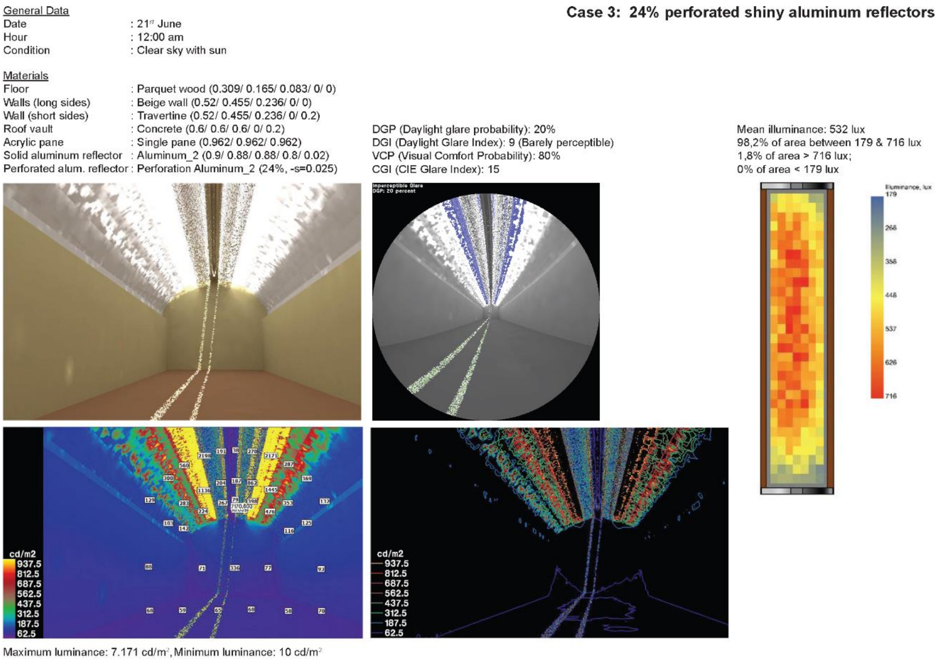


Maximum luminance: 7.311 cd/m², Minimum luminance: 16 cd/m²

Figure 120. Simulation result case 2

Case 3 (Perforated aluminum reflector specular reflection)

Like some photographs, direct light can enter the space. Currently, it happens to be two thin lines on the floor and wall but less intense in terms of luminance than in case 1 without reflectors. However, in contrary to the design intention to reduce glare due to contrast and increase visual comfort, the simulated results display worse performance in this respect in comparison to the solid reflectors of case 2 and 2’. The question remains why that is the case? The contrast ratio between directly and indirect lit area on the floor seems not that high to cause this result. The only possible explanation apart from imprecision of the radiance simulation is that the unlit, deep and narrower strip in the middle of the reflectors is the cause. The mean illuminance is at 532 lux on the floor which is 1.07 times higher than case 2 and the higher illuminated area is like case 2 located on the left side. Luminance levels on the walls with around 93 cd/m² is 1.1times higher than in case 2.



Case 3: 24% perforated shiny aluminum reflectors

General Data
Date : 21st June
Hour : 12:00 am
Condition : Clear sky with sun

Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : Perforation Aluminum_2 (24%, -s=0.025)

DGP (Daylight glare probability): 20%
DGI (Daylight Glare Index): 9 (Barely perceptible)
VCP (Visual Comfort Probability): 80%
CGI (CIE Glare Index): 15

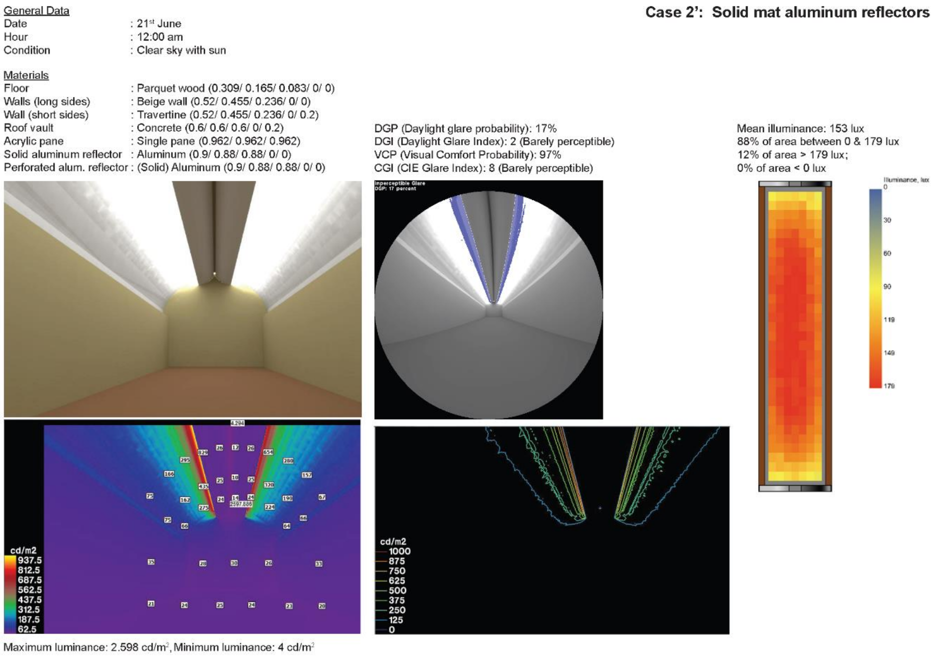
Mean illuminance: 532 lux
98,2% of area between 179 & 716 lux
1,8% of area > 716 lux;
0% of area < 179 lux

Maximum luminance: 7.171 cd/m², Minimum luminance: 10 cd/m²

Figure 121. Simulation result case 3

Case 2’ (Solid aluminum reflector diffuse reflection)

Due to the light scattering of the diffuse reflectors the enhanced light distribution on the left side is barely perceivable. Looking at the false color luminance image the luminance levels are more gradually distributed on the vault. The glare is slightly lower but like case 2 due to the darker underside of the reflectors. The mean illuminance on the floor is at 153 lux about 3.2 times lower than Case 2. The luminance level on the wall, where paintings are located is around 35cd/m². However, comparing luminance levels of case 2 and 2’ on the wall, case 2’ has 2.4 times lower luminance levels. It seems albeit lesser total amount of light gets inside, the diffuse reflector can reflect more of it on the wall. Also, the illuminance levels are more evenly distributed on the floor.



Case 2’: Solid mat aluminum reflectors

General Data
Date : 21st June
Hour : 12:00 am
Condition : Clear sky with sun

Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum (0.9/ 0.88/ 0.88/ 0/ 0)
Perforated alum. reflector : (Solid) Aluminum (0.9/ 0.88/ 0.88/ 0/ 0)

DGP (Daylight glare probability): 17%
DGI (Daylight Glare Index): 2 (Barely perceptible)
VCP (Visual Comfort Probability): 97%
CGI (CIE Glare Index): 8 (Barely perceptible)

Mean illuminance: 153 lux
88% of area between 0 & 179 lux
12% of area > 179 lux;
0% of area < 0 lux

Maximum luminance: 2.598 cd/m², Minimum luminance: 4 cd/m²

Figure 122. Simulation result case 2’

Case 3’ (Perforated aluminum reflector diffuse reflection)

Visual comfort is like case 3 lower than in case 2 and 2’. The luminance levels on the wall with around 46cd/m² are higher than case 2’ and mean illuminance on the floor with 241 lux is about 1.6 times higher than case 2’. It appears there is a shift in contribution of light transmittance into the interior within the various cases. In case 2 and 3 most comes due to the specular reflection of the reflectors and little is contributed by the perforation, while the ratio shifts when comparing 2’ in case 3’ where the perforation contributes a lot more. Also, the illuminance distribution on the floor is much less even than in the other cases.

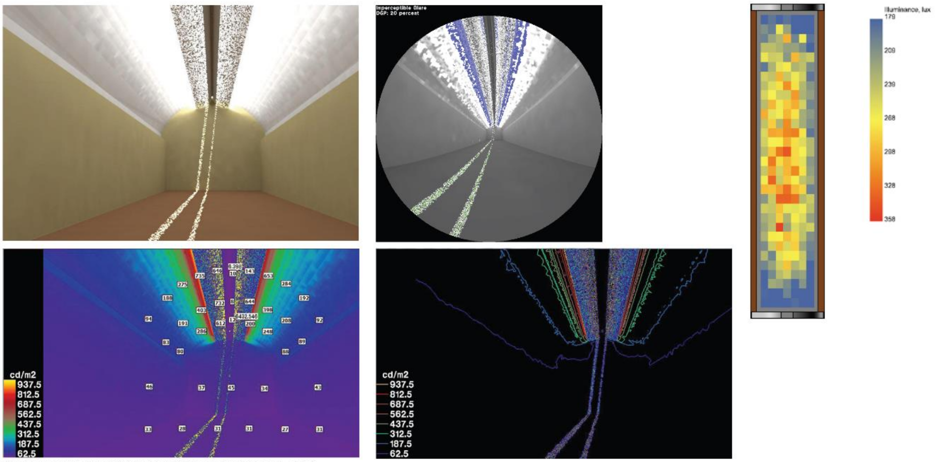
Case 3’: 24% perforated mat aluminum reflectors

General Data
Date : 21st June
Hour : 12:00 am
Condition : Clear sky with sun

Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum (0.9/ 0.88/ 0.88/ 0/ 0)
Perforated alum. reflector : Perforation Aluminum (24%, -s=0.025)

DGP (Daylight glare probability): 20%
DGI (Daylight Glare Index): 9 (Barely perceptible)
VCP (Visual Comfort Probability): 80%
CGI (CIE Glare Index): 15

Mean illuminance: 241 lux
88,5% of area between 179 & 358 lux
0% of area > 358 lux;
11,5% of area < 179 lux

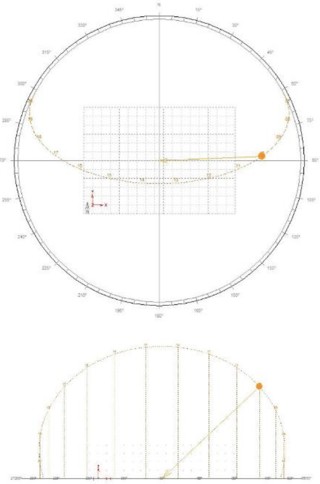


Maximum luminance: 6.433 cd/m², Minimum luminance: 6 cd/m²

Figure 123. Simulation result case 3’

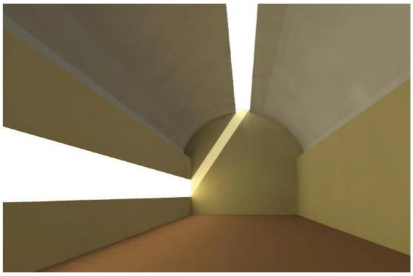
General Data

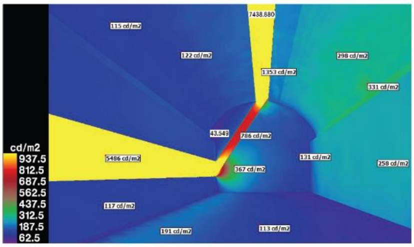
Location	: Fort Worth, Texas
Latitude	: 32,8
Longitude	: -97,1
Date	: 21st June
Hour	: 10:00 am
GMT	: -6
Daylight saving time	: Yes
Condition	: Clear sky with sun
Azimuth	: 87.48°
Altitude	: 43.21°
Altitude on xz plane	: 43.23°



Materials

Floor	: Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides)	: Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides)	: Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault	: Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane	: Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector	: None
Perforated alum. reflector	: None

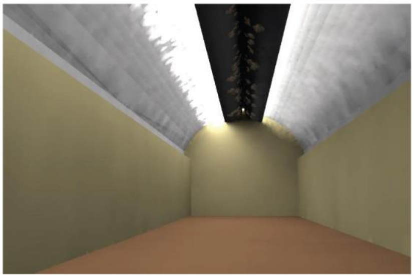


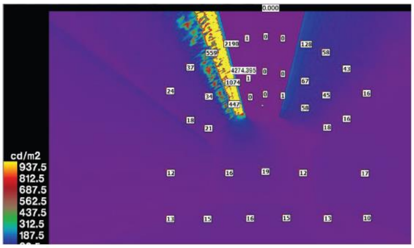


Maximum luminance: 7438 cd/m², Minimum luminance: 43,5 cd/m² **3.**

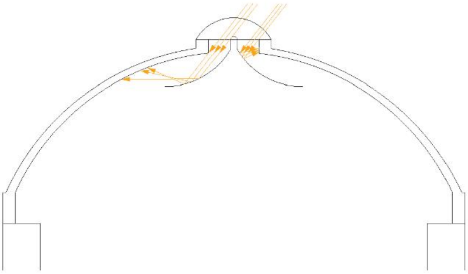
Materials

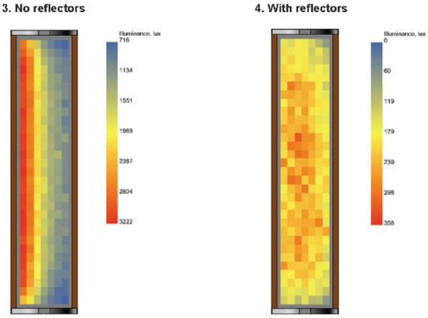
Floor	: Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides)	: Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides)	: Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault	: Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane	: Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector	: Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector	: (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)





Maximum luminance: 4274 cd/m², Minimum luminance: 0 cd/m² **4.**





3. No reflectors

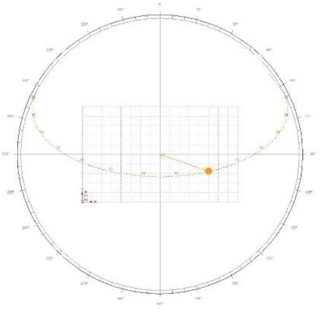
4. With reflectors

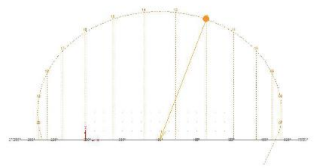
Mean illuminance: 1820 lux
97,7% of area between 716 & 3222 lux
1,8% of area > 3222 lux; 0,5% of area < 716 lux

Mean illuminance: 206 lux
100% of area between 0 & 358 lux

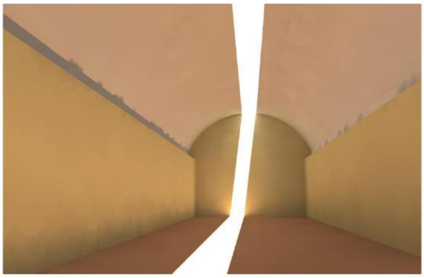
Figure 124. Daylight simulation 21.06., clear Sky with sun, 10:00, with and without reflectors

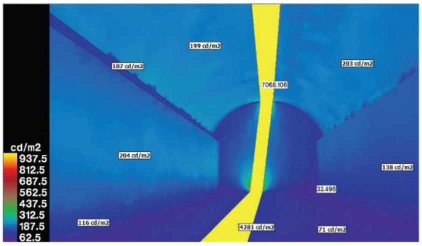
General Data
Location : Fort Worth, Texas
Latitude : 32,8
Longitude : -97,1
Date : 21st June
Hour : 12:00 am
GMT : -6
Daylight saving time : Yes
Condition : Clear sky with sun
Azimuth : 109,51°
Altitude : 68,08°
Altitude on xz plane : 69,2°





Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : None
Perforated alum. reflector : None

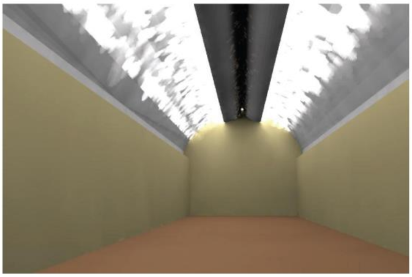


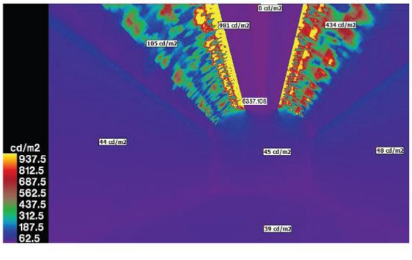


Maximum luminance: 7068 cd/m², Minimum luminance: 33 cd/m²

5.

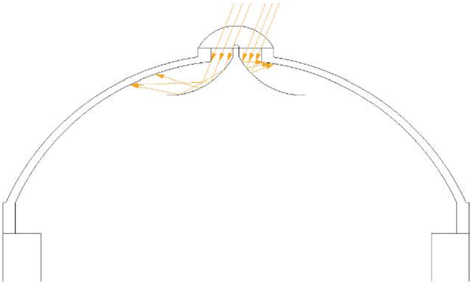
Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)

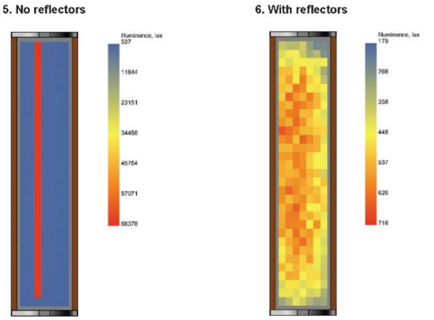




Maximum luminance: 6357 cd/m², Minimum luminance: 0 cd/m²

6.





5. No reflectors

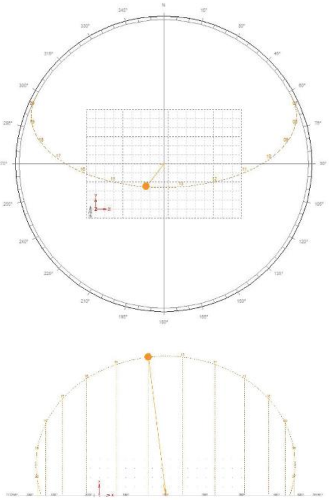
6. With reflectors

Mean illuminance: 10266 lux
98,6% of area between 537 & 68378 lux
0,5% of area > 68378 lux; 0,9% of area < 537 lux

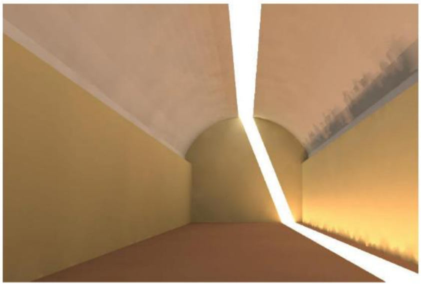
Mean illuminance: 496 lux
100% of area between 179 & 716 lux

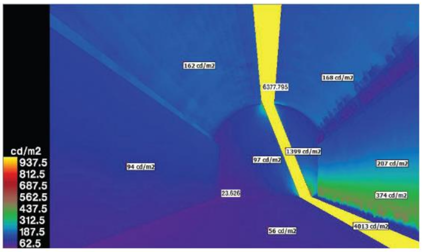
Figure 125. Daylight simulation 21.06., clear Sky with sun, 12:00, with and without reflectors

General Data
Location : Fort Worth, Texas
Latitude : 32,8
Longitude : -97,1
Date : 21st June
Hour : 14:00 am
GMT : -6
Daylight saving time : Yes
Condition : Clear sky with sun
Azimuth : 216.85°
Altitude : 78.58°
Altitude on xz plane : 83.1°



Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : None
Perforated alum. reflector : None

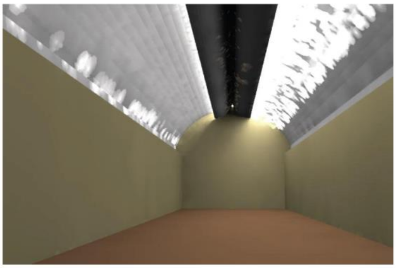


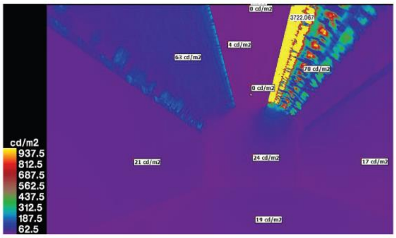


Maximum luminance: 6377 cd/m², Minimum luminance: 23,6 cd/m²

7.

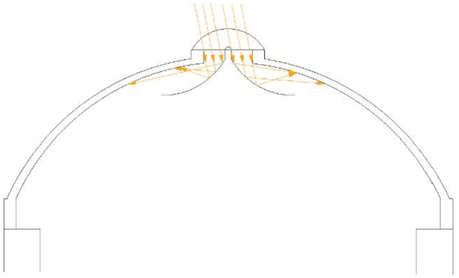
Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)

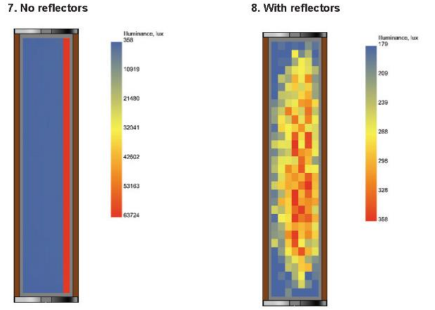




Maximum luminance: 3722 cd/m², Minimum luminance: 0 cd/m²

8.



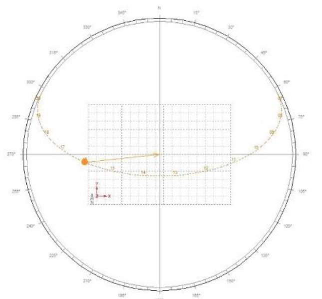

7. No reflectors
8. With reflectors

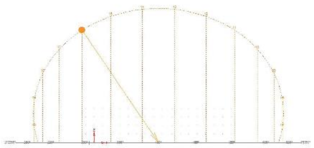
Mean illuminance: 9743 lux
99% of area between 358 & 63724 lux
0,5% of area > 63724 lux; 0,5% of area < 358 lux

Mean illuminance: 251 lux
85,8% of area between 179 & 358 lux
1,8% of area > 358 lux; 12,4% of area < 179 lux

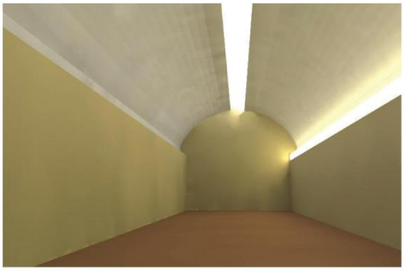
Figure 126. Daylight simulation 21.06., clear Sky with sun, 14:00, with and without reflectors

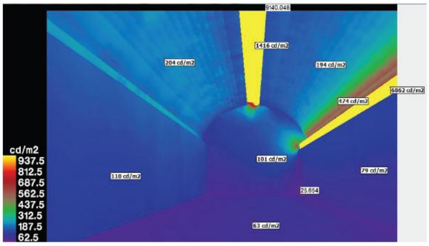
General Data
Location : Fort Worth, Texas
Latitude : 32,8
Longitude : -97,1
Date : 21st June
Hour : 16:00 am
GMT : -6
Daylight saving time : Yes
Condition : Clear sky with sun
Azimuth : 263.82°
Altitude : 55.89°
Altitude on xz plane : 56.05°





Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : None
Perforated alum. reflector : None

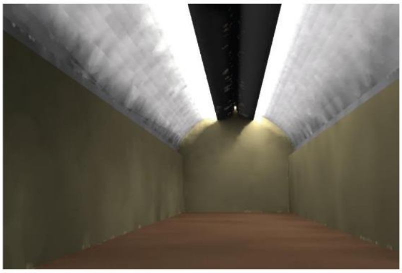


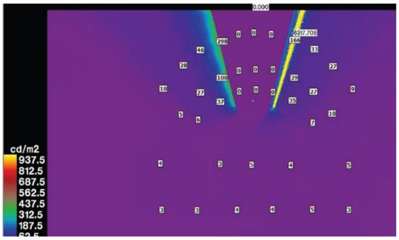


Maximum luminance: 9140 cd/m², Minimum luminance: 25,7 cd/m²

9.

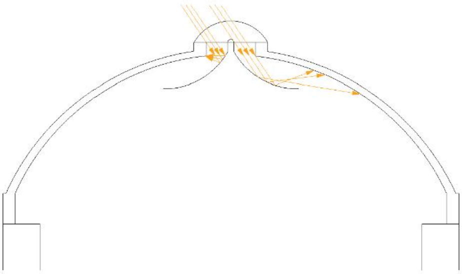
Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)

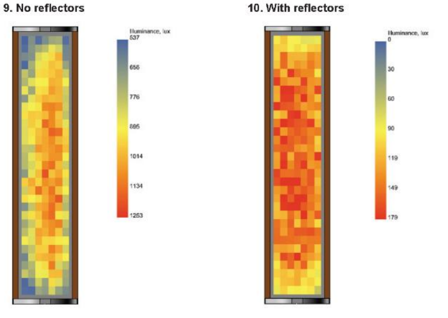




Maximum luminance: 6317 cd/m², Minimum luminance: 0 cd/m²

10.



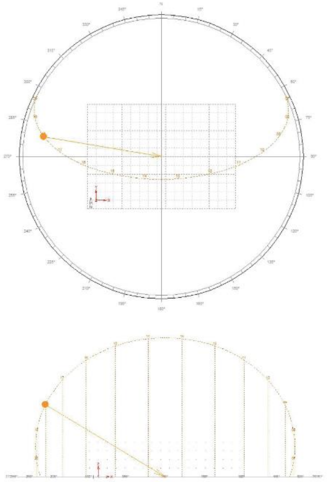


Mean illuminance: 894 lux
99,5% of area between 537 & 1253 lux
0% of area > 1253 lux; 0,5% of area < 537 lux

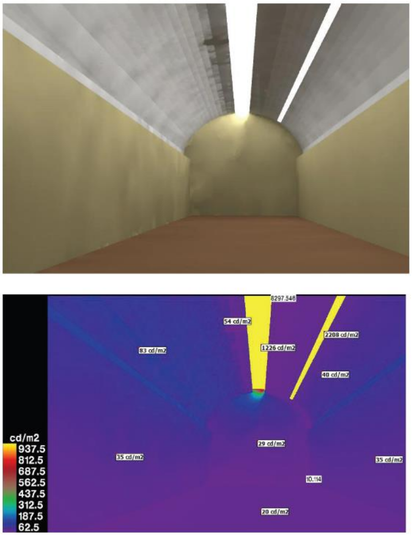
Mean illuminance: 138 lux
91,7% of area between 0 & 179 lux
8,3% of area > 179 lux; 0% of area < 0 lux

Figure 127. Daylight simulation 21.06., clear Sky with sun, 16:00, with and without reflectors

General Data
Location : Fort Worth, Texas
Latitude : 32,8
Longitude : -97,1
Date : 21st June
Hour : 18:00 am
GMT : -6
Daylight saving time : Yes
Condition : Clear sky with sun
Azimuth : 279.62°
Altitude : 30.79°
Altitude on xz plane : 31.17°



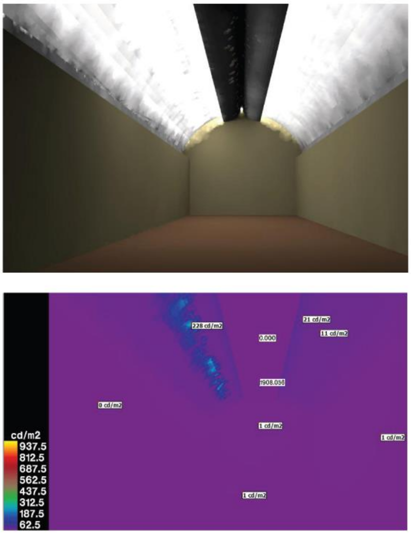
Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : None
Perforated alum. reflector : None



Maximum luminance: 8297 cd/m², Minimum luminance: 10 cd/m²

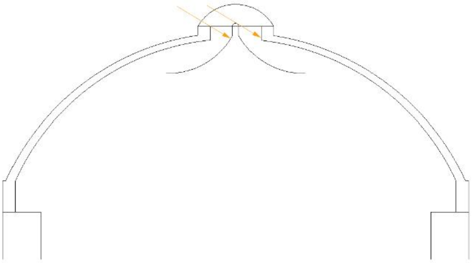
11.

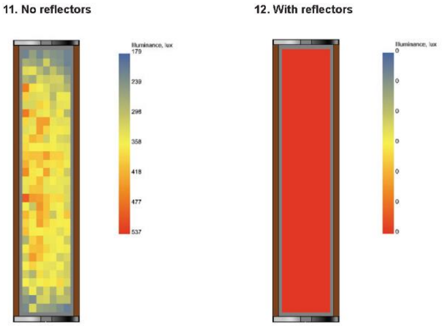
Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)



Maximum luminance: 1908 cd/m², Minimum luminance: 0 cd/m²

12.





11. No reflectors

12. With reflectors

Mean illuminance: 342 lux
98,6% of area between 179 & 537 lux

Mean illuminance: 34 lux
100% of area > 0 lux

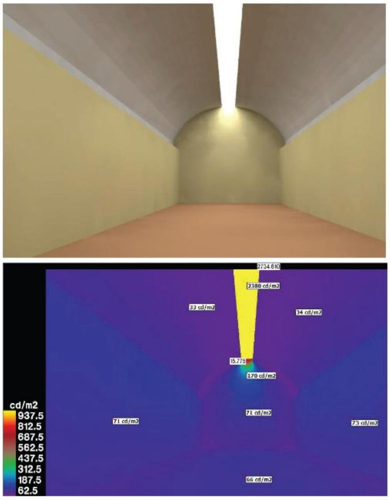
Figure 128. Daylight simulation 21.06., clear Sky with sun, 18:00, with and without reflectors

General Data

Date : 21st June
Hour : 10:00 am
Condition : Overcast sky

Materials

Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : None
Perforated alum. reflector : None

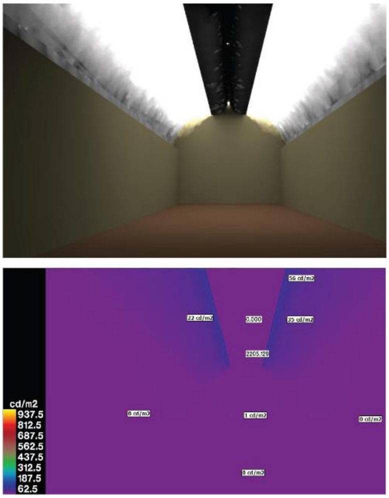


Maximum luminance: 2734 cd/m^2, Minimum luminance: 15 cd/m^2

19.

Materials

Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)



Maximum luminance: 2205 cd/m^2, Minimum luminance: 0 cd/m^2

Figure 129. Daylight simulation 21.06., overcast sky, 10:00, without and with reflectors

General Data

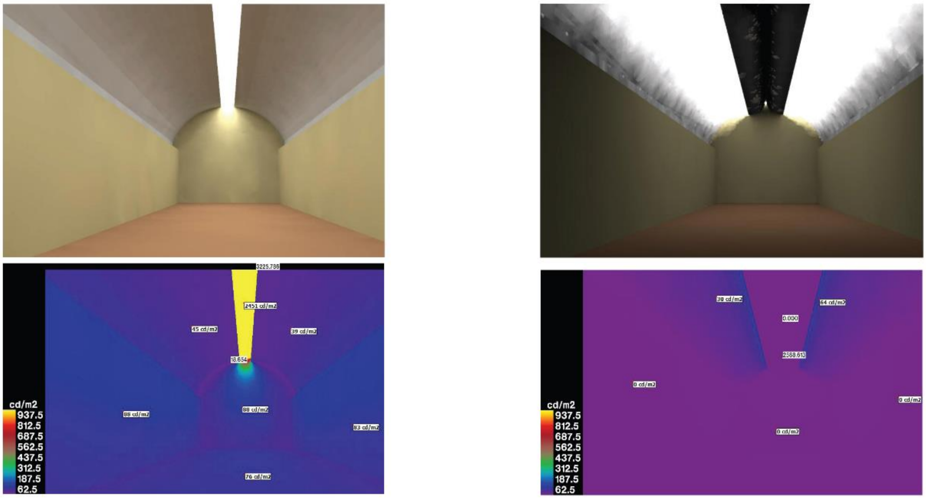
Date	: 21st June
Hour	: 12:00 am
Condition	: Overcast sky

Materials

Floor	: Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides)	: Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides)	: Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault	: Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane	: Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector	: None
Perforated alum. reflector	: None

Materials

Floor	: Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides)	: Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides)	: Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault	: Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane	: Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector	: Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector	: (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)



Maximum luminance: 3325 cd/m^2, Minimum luminance: 18 cd/m^2

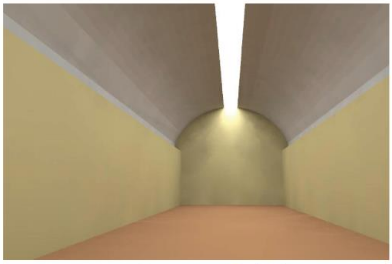
21.

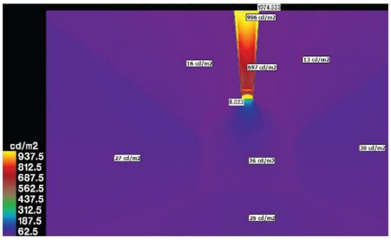
Maximum luminance: 2588 cd/m^2, Minimum luminance: 0 cd/m^2

Figure 130. Daylight simulation 21.06., overcast sky, 12:00, without and with reflectors

General Data
Date : 21st June
Hour : 18:00 am
Condition : Overcast sky

Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : None
Perforated alum. reflector : None

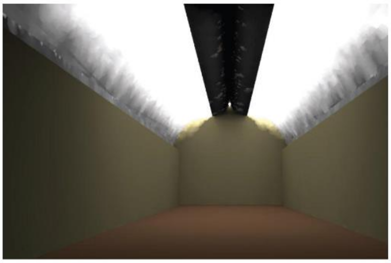


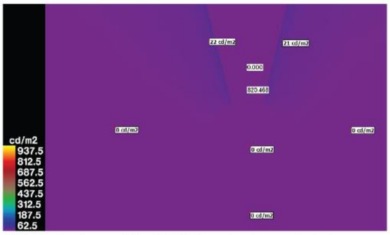


Maximum luminance: 1074 cd/m^2, Minimum luminance: 8 cd/m^2

23.

Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)

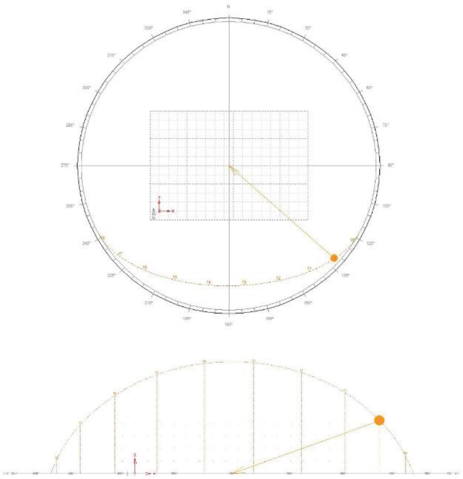




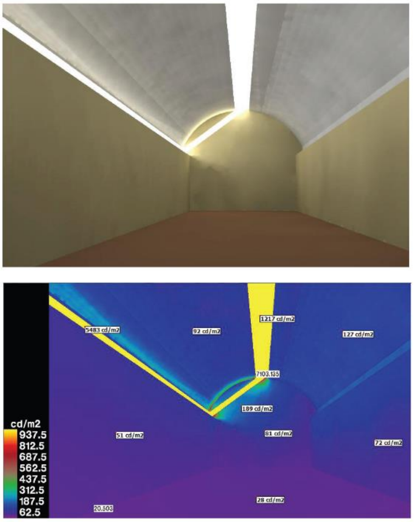
Maximum luminance: 820 cd/m^2, Minimum luminance: 0 cd/m^2

Figure 131. Daylight simulation 21.06., overcast sky, 18:00, without and with reflectors

General Data
Location : Fort Worth, Texas
Latitude : 32,8
Longitude : -97,1
Date : 21st December
Hour : 10:00 am
GMT : -6
Daylight saving time : Yes
Condition : Clear sky with sun
Azimuth : 131.78º
Altitude : 15.32º
Altitude on xz plane : 19.9º



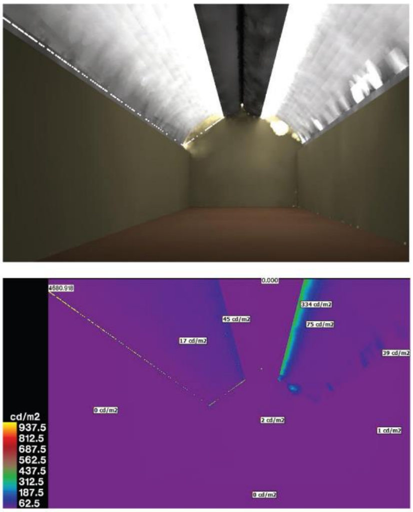
Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : None
Perforated alum. reflector : None



Maximum luminance: 7103 cd/m^2, Minimum luminance: 20 cd/m^2

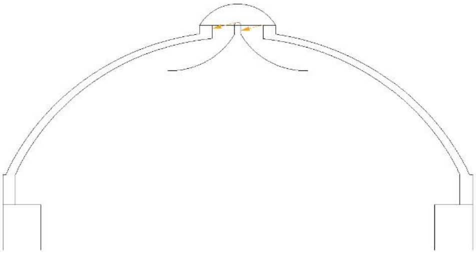
13.

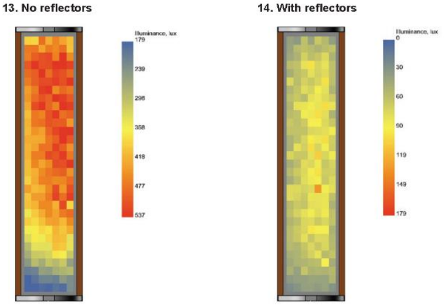
Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)



Maximum luminance: 4680 cd/m^2, Minimum luminance: 0 cd/m^2

14.




13. No reflectors

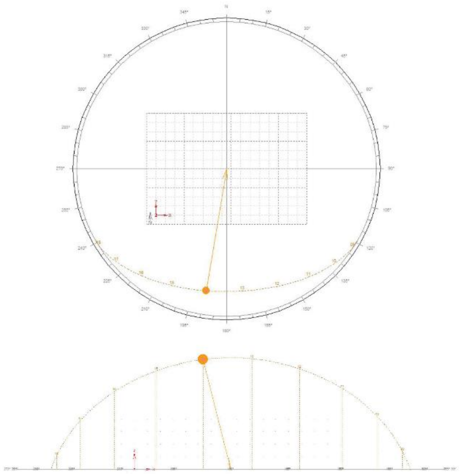
14. With reflectors

Mean illuminance: 426 lux
93,1% of area between 179 & 537 lux
5,5% of area > 537 lux; 1,4% of area < 179 lux

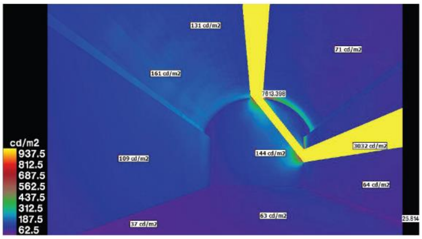
Mean illuminance: 66 lux
100% of area between 0 & 179 lux

Figure 132. Daylight simulation 21.12., clear Sky with sun, 10:00, with and without reflectors

General Data
Location : Fort Worth, Texas
Latitude : 32,8
Longitude : -97,1
Date : 21st December
Hour : 14:00 am
GMT : -6
Daylight saving time : Yes
Condition : Clear sky with sun
Azimuth : 189.16°
Altitude : 33.23°
Altitude on xz plane : 77°



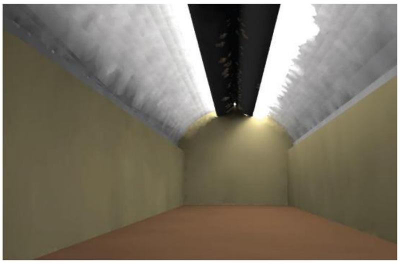
Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : None
Perforated alum. reflector : None

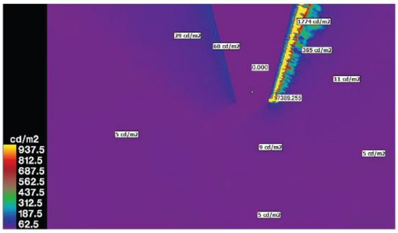


Maximum luminance: 7613 cd/m², Minimum luminance: 25 cd/m²

15.

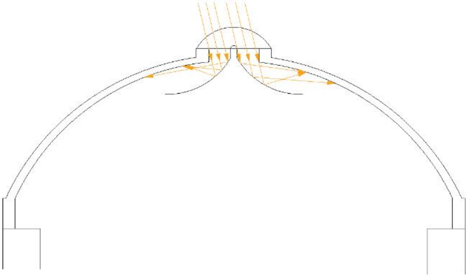
Materials
Floor : Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides) : Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides) : Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault : Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane : Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector : Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector : (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)

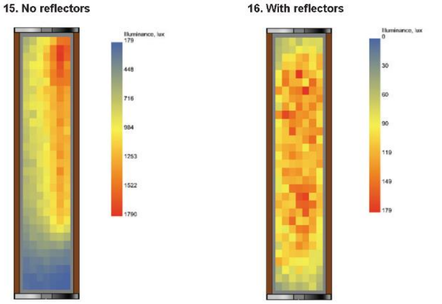




Maximum luminance: 7389 cd/m², Minimum luminance: 0 cd/m²

16.





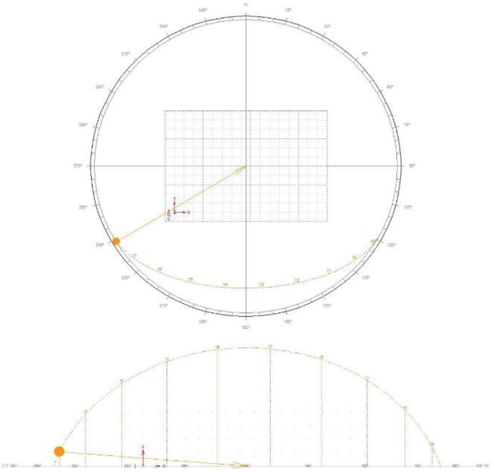
Mean illuminance: 876 lux
98,6% of area between 179 & 1790 lux
0% of area > 1790 lux; 1,4% of area < 179 lux

Mean illuminance: 108 lux
99,1% of area between 0 & 179 lux
0,9% of area > 179 lux; 0% of area < 0 lux

Figure 132. Daylight simulation 21.12., clear Sky with sun, 14:00, with and without reflectors

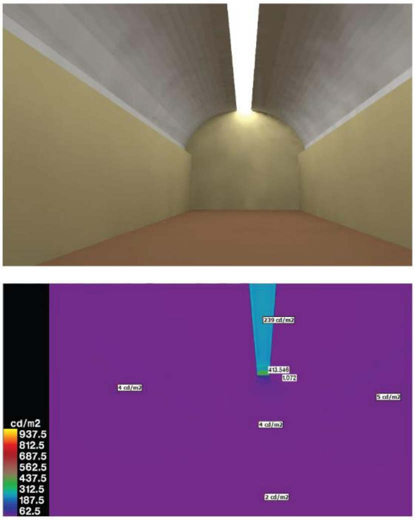
General Data

Location	: Fort Worth, Texas
Latitude	: 32,8
Longitude	: -97,1
Date	: 21st December
Hour	: 18:00 am
GMT	: -6
Daylight saving time	: Yes
Condition	: Clear sky with sun
Azimuth	: 238.73°
Altitude	: 4.17°
Altitude on xz plane	: 4.91°



Materials

Floor	: Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides)	: Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides)	: Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault	: Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane	: Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector	: None
Perforated alum. reflector	: None

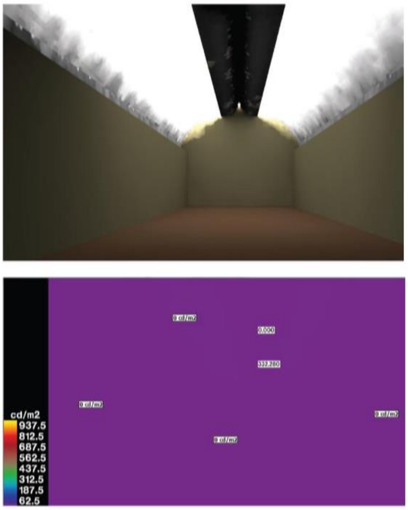


Maximum luminance: 413 cd/m², Minimum luminance: 1 cd/m²

17.

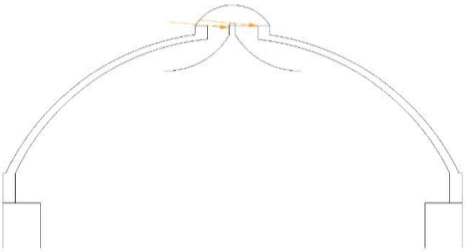
Materials

Floor	: Parquet wood (0.309/ 0.165/ 0.083/ 0/ 0)
Walls (long sides)	: Beige wall (0.52/ 0.455/ 0.236/ 0/ 0)
Wall (short sides)	: Travertine (0.52/ 0.455/ 0.236/ 0/ 0.2)
Roof vault	: Concrete (0.6/ 0.6/ 0.6/ 0/ 0.2)
Acrylic pane	: Single pane (0.962/ 0.962/ 0.962)
Solid aluminum reflector	: Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)
Perforated alum. reflector	: (Solid) Aluminum_2 (0.9/ 0.88/ 0.88/ 0.8/ 0.02)

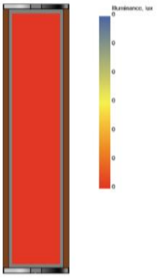


Maximum luminance: 332 cd/m², Minimum luminance: 0 cd/m²

18.

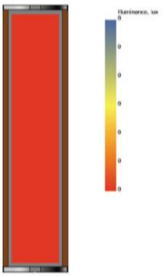


17. No reflectors



Mean illuminance: 32 lux
100% of area > 0 lux

18. With reflectors



Mean illuminance: 5 lux
100% of area between > 0 lux

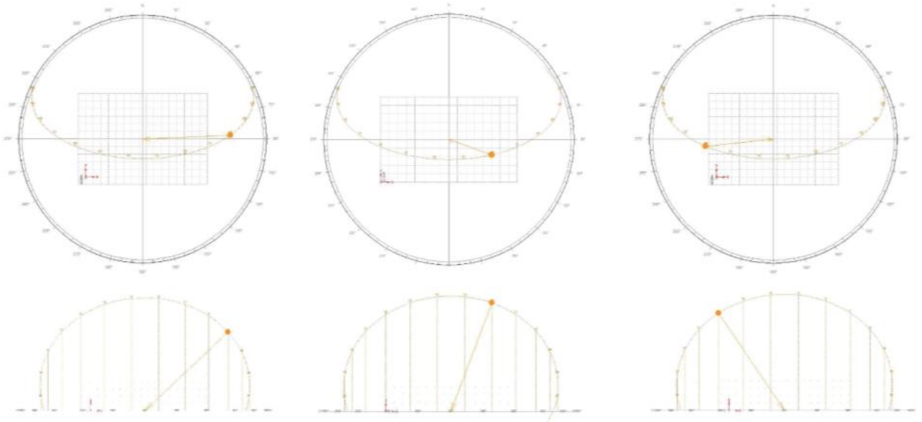
Figure 133. Daylight simulation 21.12., clear Sky with sun, 18:00, with and without reflectors

General data

Location : Fort Worth, Texas
Latitude : 32,8
Longitude : -97,1
Date : 21st June
Hour : 10:00 am
GMT : -6
Daylight saving time : Yes
Condition : Clear sky with sun
Azimuth : 87.48°
Altitude : 43.21°
Altitude on xz plane : 43.23°

Location : Fort Worth, Texas
Latitude : 32,8
Longitude : -97,1
Date : 21st June
Hour : 12:00 am
GMT : -6
Daylight saving time : Yes
Condition : Clear sky with sun
Azimuth : 109,51°
Altitude : 68,08°
Altitude on xz plane : 69,2°

Location : Fort Worth, Texas
Latitude : 32,8
Longitude : -97,1
Date : 21st June
Hour : 16:00 am
GMT : -6
Daylight saving time : Yes
Condition : Clear sky with sun
Azimuth : 263.82°
Altitude : 55.89°
Altitude on xz plane : 56.05°



Sun angle, 21/06 10:00,
Plan and W-E elevation

Sun angle, 21/06 12:00,
Plan and W-E elevation

Sun angle, 21/06 16:00,
Plan and W-E elevation

Figure 134. Fort Worth, sun position 21.06. 10:00, 12:00, 16:00

Appendix C – Origami Roof Structure

Shading and shadow pattern
Barrel vault like, single curved, monoclastic

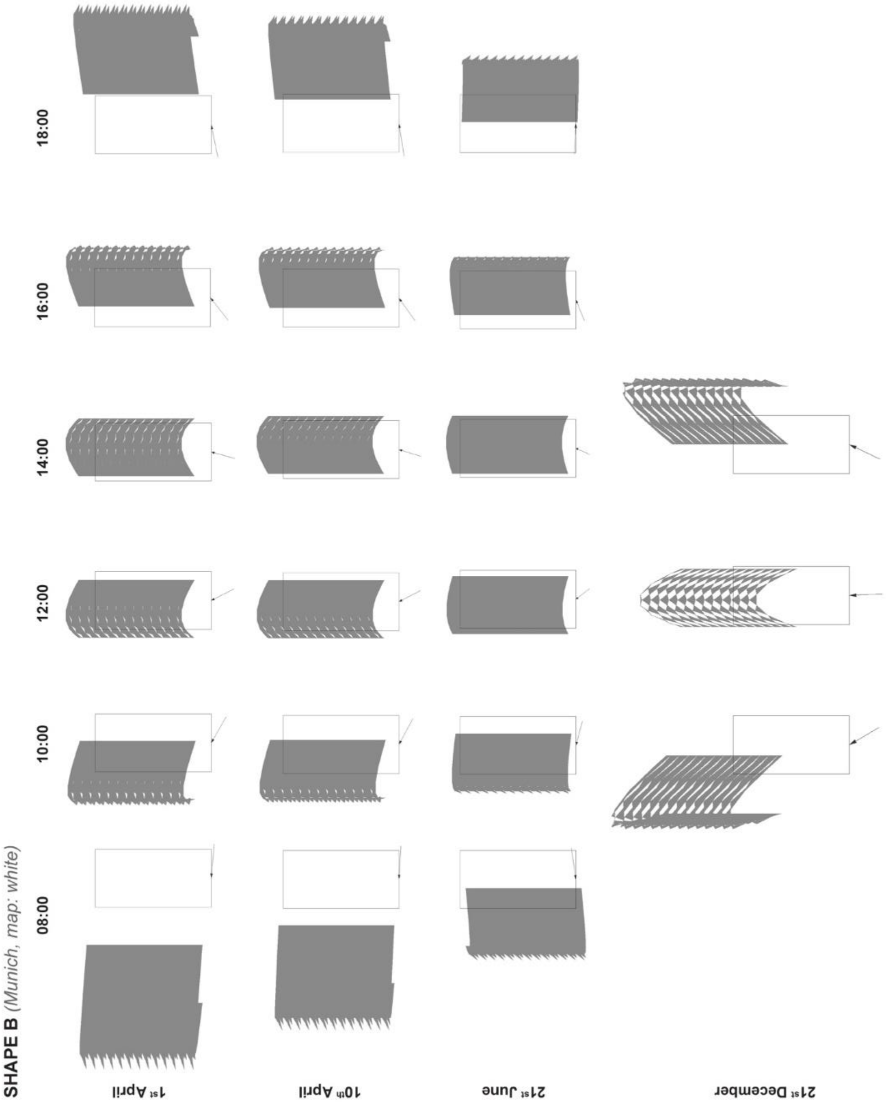


Figure 135. Barrel vault like, single curved, monoclastic shadowpattern

Shell like, double curved, synclastic, slightly anticlastic at the edges

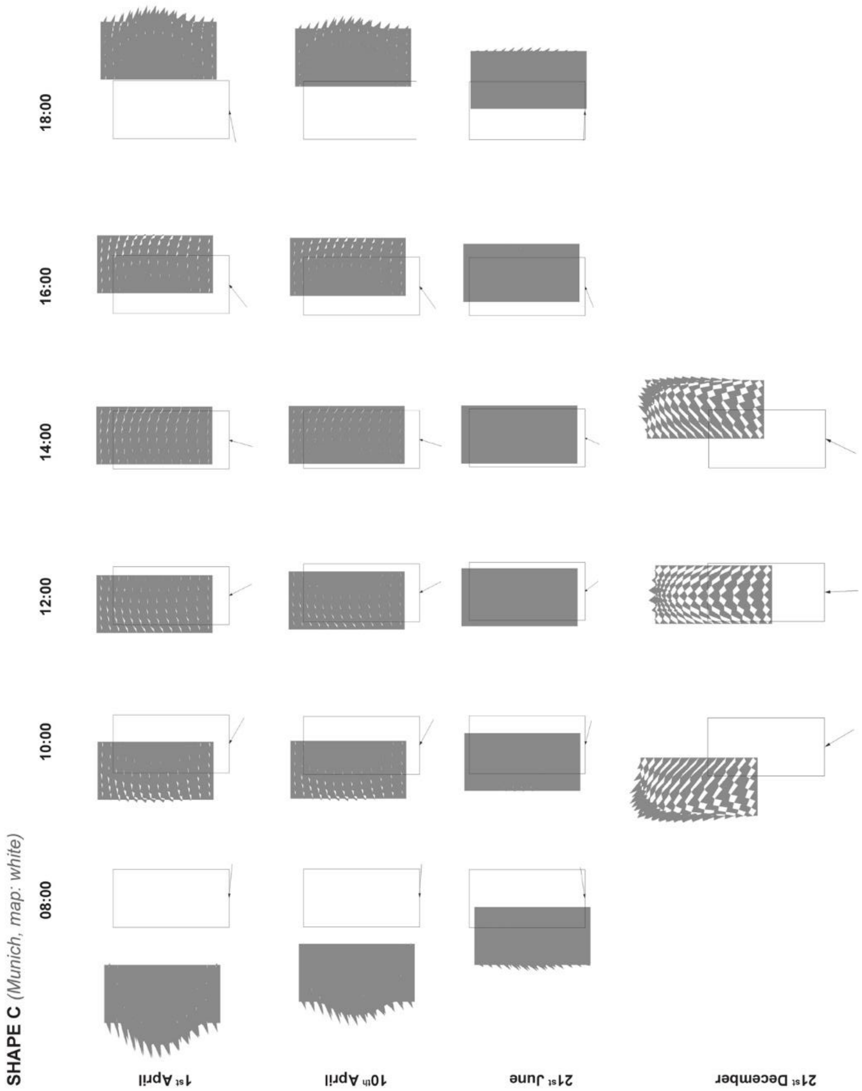


Figure 136. Shell like, double curved, synclastic, slightly anticlastic at the edges shadowpattern

Free-form, double curved, synclastic and anticlastic

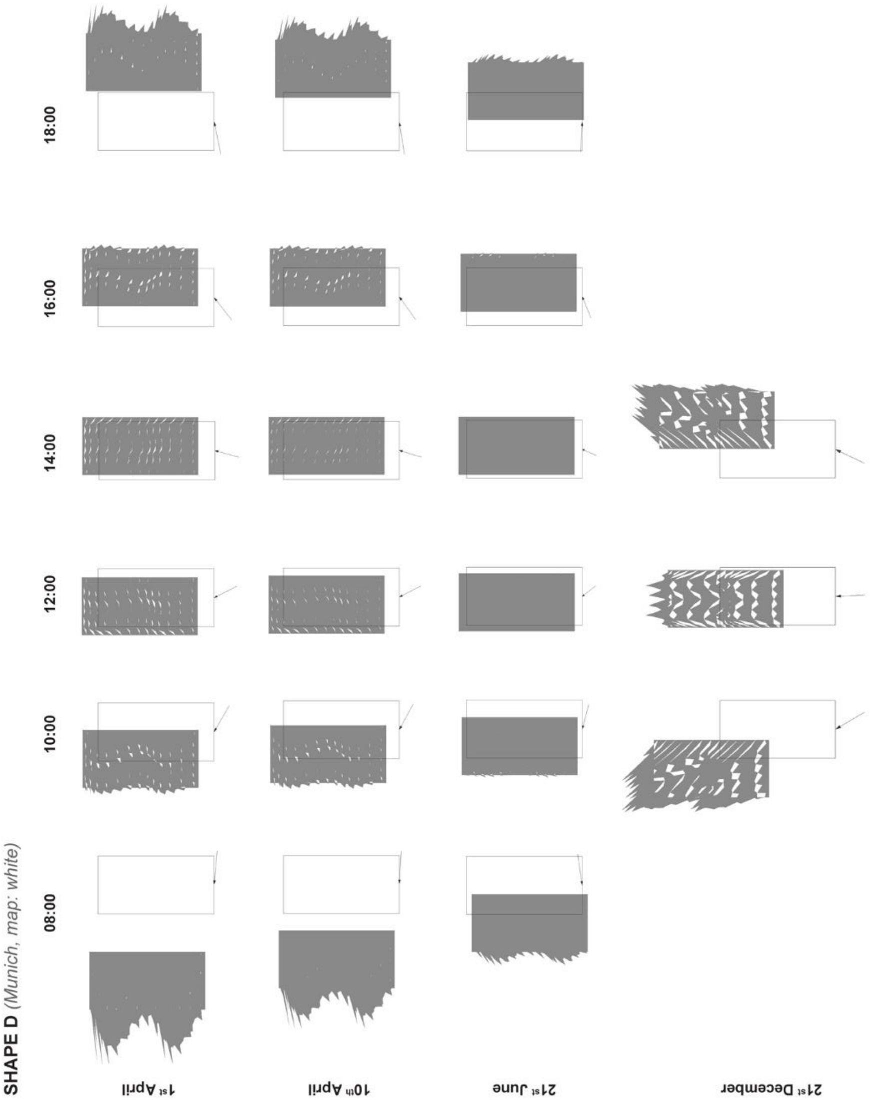


Figure 137. Free-form, double curved, synclastic and anticlastic shadowpattern

Initial comparison – white map

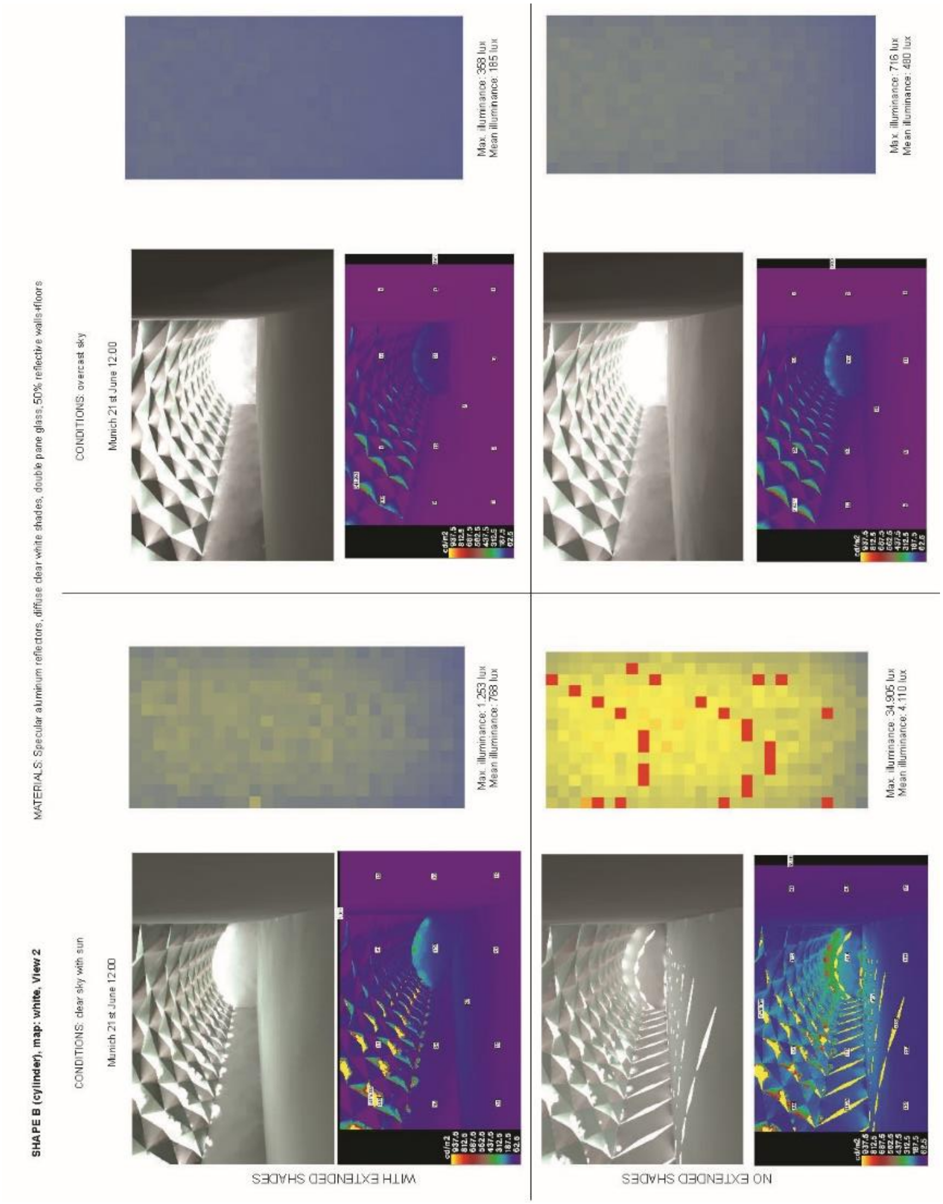


Figure 138. Daylight simulation, 21.06, 12:00, Barrel Vault, White map

Shell Like

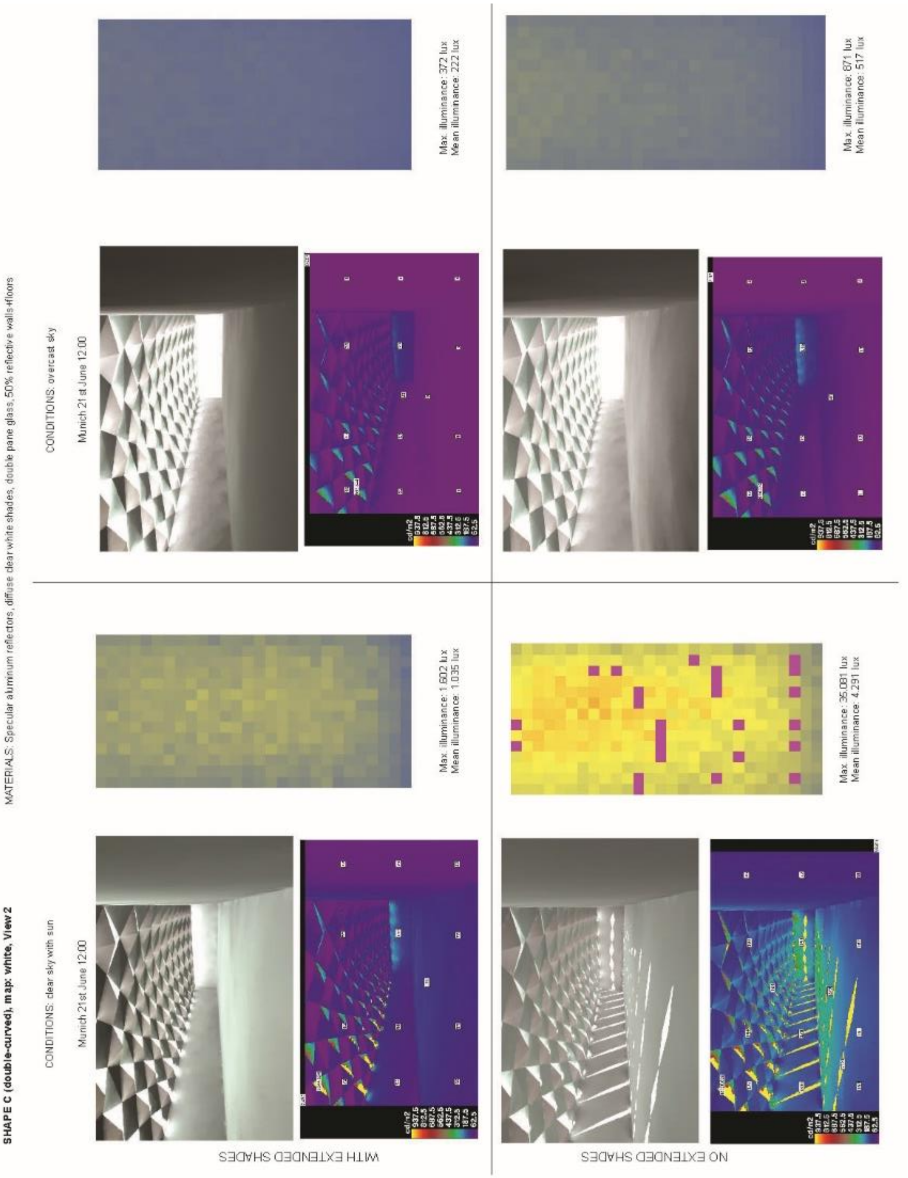


Figure 139. Daylight simulation, 21.06, 12:00, Shell Like, White map

Free-form

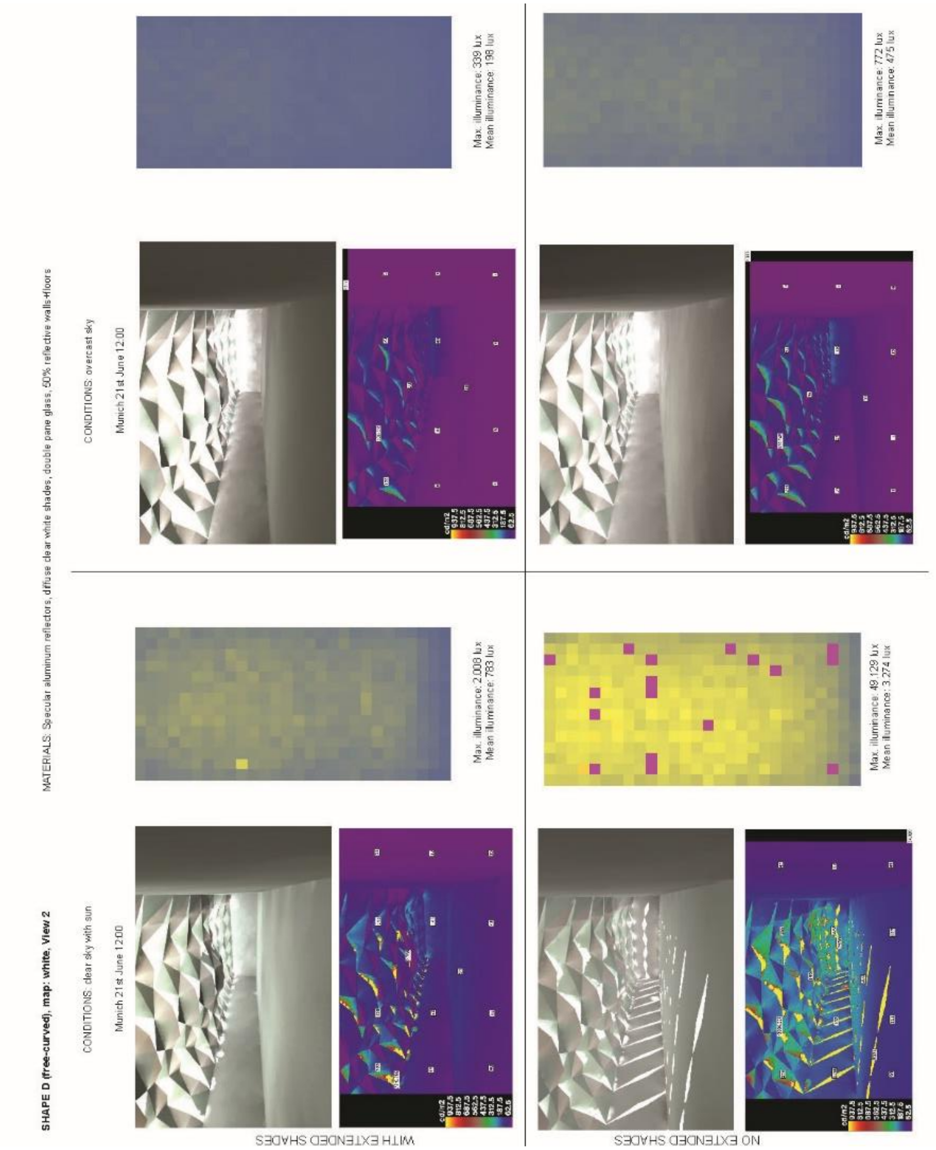


Figure 140. Daylight simulation, 21.06, 12:00, Free-form, White map

Barrel vault

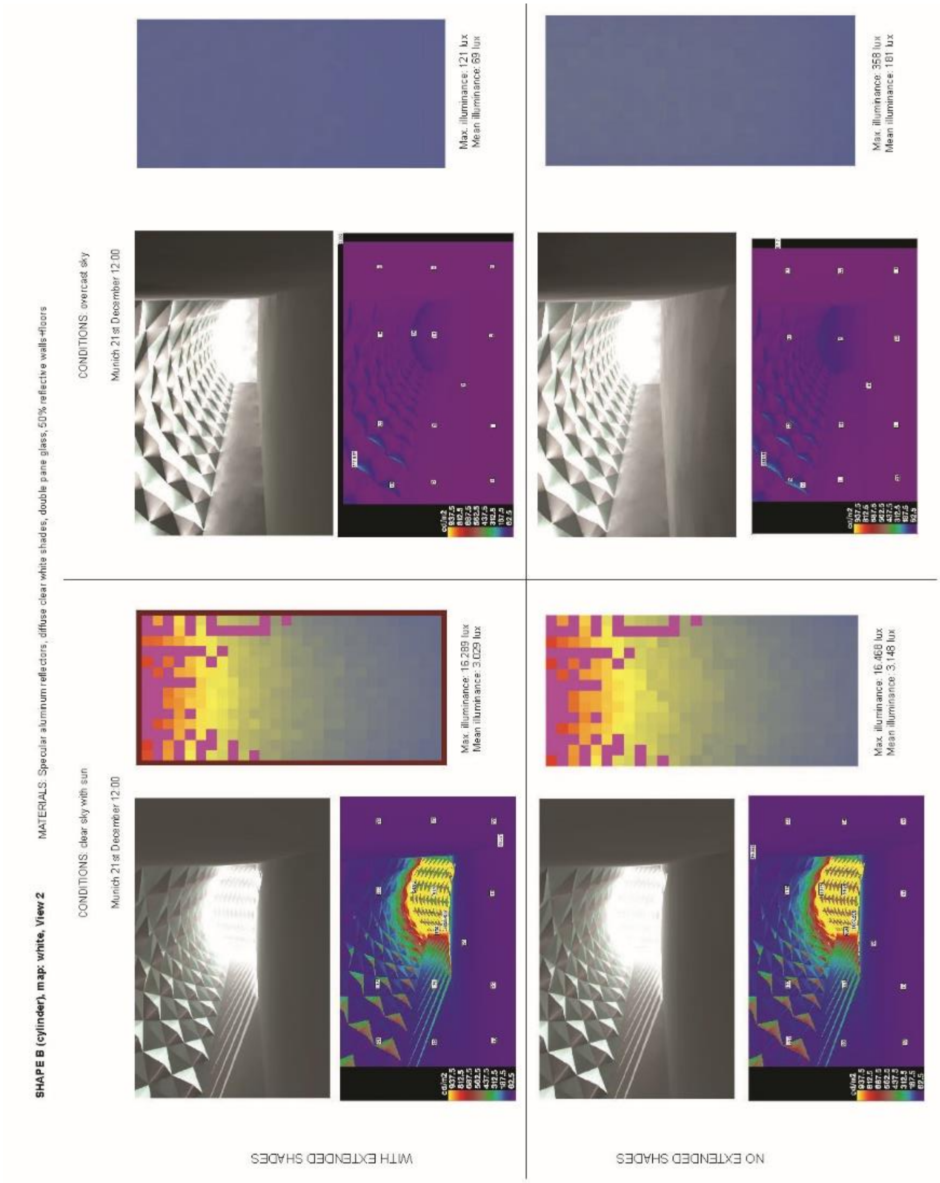


Figure 141. Daylight simulation, 21.12, 12:00, Barrel Vault, White map

Shell like

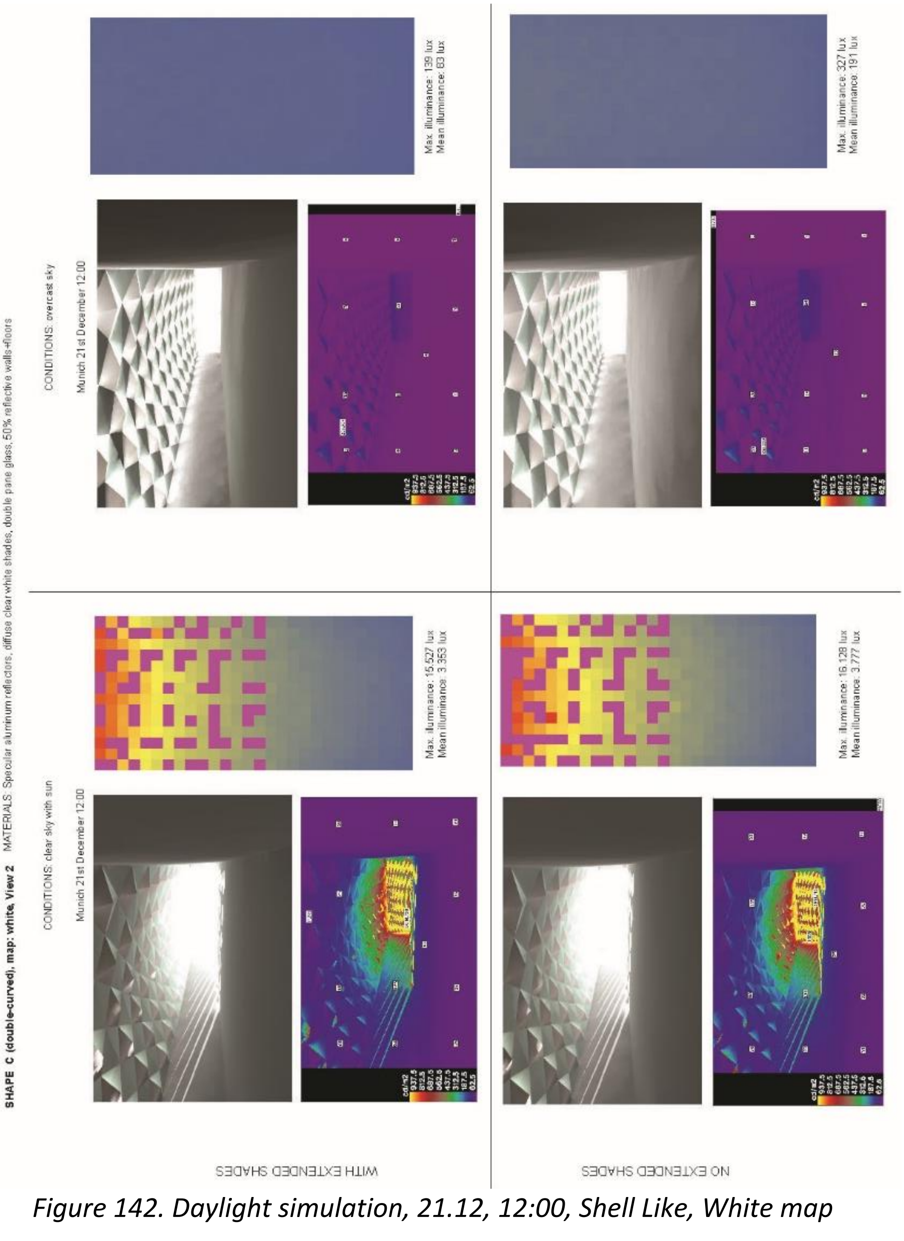


Figure 142. Daylight simulation, 21.12, 12:00, Shell Like, White map

Free-form

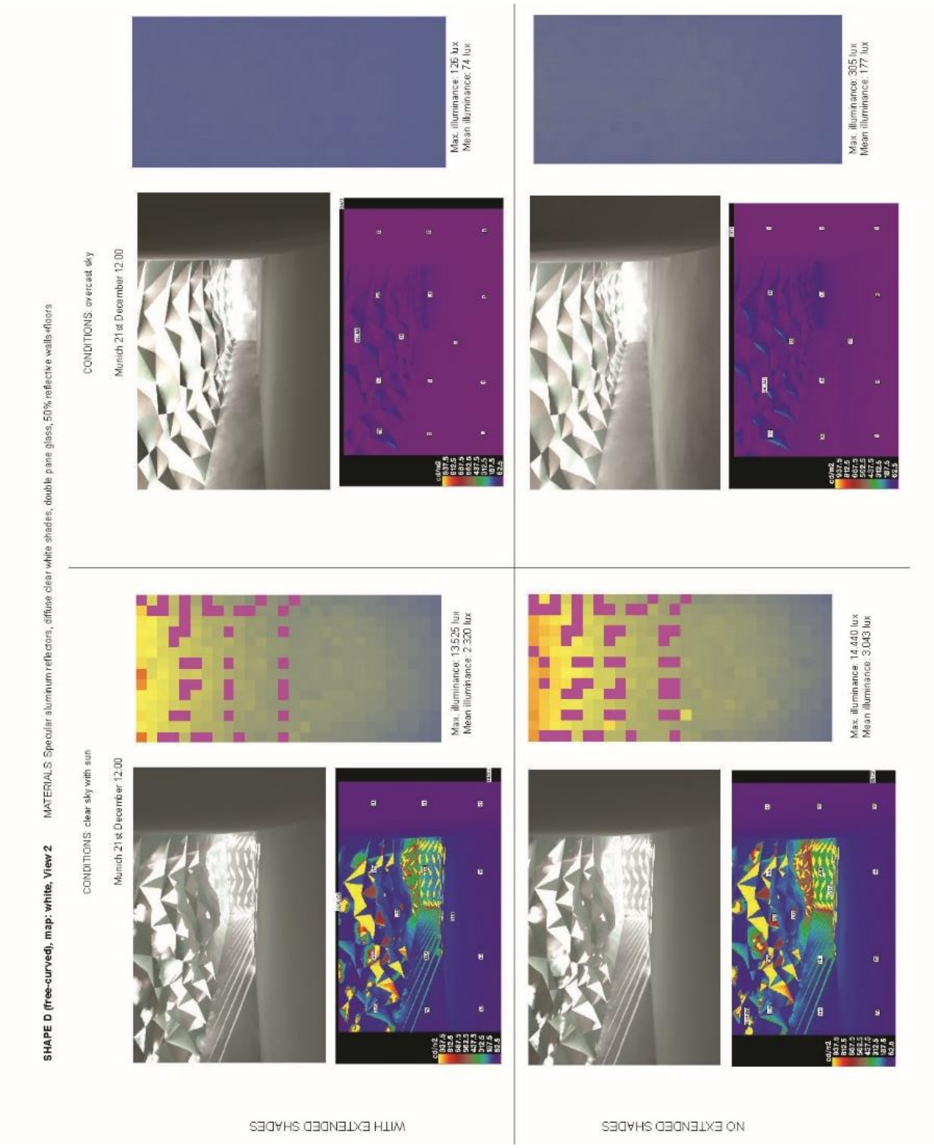


Figure 143. Daylight simulation, 21.12, 12:00, Free-Form, White map

Curriculum Vitae

Florian Heinzelmann was born on 28th of March 1976 in Munich, Germany. After graduating from his vocational training as draftsman in 1997 he received his high school degree in 1998 at the FOS/BOS Technik München, Germany.

He received his Diplom Ingenieur (FH) degree in Architecture from Munich University of Applied sciences in 2003. At that time, he got a scholarship by the Carl Duisberg Gesellschaft for conducting an internship in Tokyo, Japan at Sato Mitsuhiko Architect. Together with Tobias Hoffman, he got honorable mention for their Diploma work “mise en scene” at the International Archiprix award in 2003.

Florian was working as freelance architect for several German architecture firms e.g. KSP Jürgen Engel Architekten, before he continued his study at the Berlage Institute in Rotterdam, the Netherlands. For the latter, he received a two-year scholarship by the German Academic Exchange Service (DAAD) and graduated receiving the Berlage Diploma in 2006. His research and studio work were exhibited amongst others at the International Architecture Biennale in Venice in 2006.

After that, Florian was working for UNStudio van Berkel and Bos, an architecture firm renowned for the Mercedes Benz Museum in Stuttgart where was project leader for the Fraunhofer Institute - Center of Virtual Engineering (ZVE) also located in Stuttgart. The building received a Gold certificate of the German Sustainable Building Council DGNB.

In 2009, he started to work as researcher for TU Delft and in 2010 started his PhD research with Prof.Dr.-Ing. Patrick Teuffel at TU Delft, Faculty of Architecture, Department of Architectural Engineering and Technology, Chair of Architectural Engineering. During that time, he was also Project Manager/Leader of the TU Delft Solar Decathlon 2012 team as well as tutoring master students.

By the end of 2012, he joined Patrick Teuffel at TU Eindhoven, Department of the Built Environment, section Structural Design, Chair of Innovative Structural Design continuing his PhD research till end of 2014 of which the results are presented in this dissertation.In 2014 together with a team from TU Delft and TU Eindhoven, they were selected for the 4TU.Bouw Lighthouse initiative for their Double Face research.

In 2009 together with Tobias Hofmann and Daliana Suryawinata, he set up their office SHAU, with current locations in Passau - Germany, Rotterdam – The Netherlands and Bandung – Indonesia where he is currently residing.

In 2017 SHAU received an Architizer +A Award for their Microlibrary Bima both by public vote and by the Jury, a Frim of the Year award by the American Institute of Architects, a World Architecture Festival X Smart Cities Award for the Jakarta Jaya project and Silver Award by Lafarge Holcim in the Asia-Pacific Region for their Fibonacci Microlibrary.

Florian is currently lecturing mostly in the South-East Asian region at various Universities and conferences and further is regularly invited as jury member for architectural competitions most notably the FutureArc Prize and FuturArc Green Leadership award 2018. Since 2018 Florian together with Daliana Suryawinata are coordinators for Archiprix Indonesia.

Relevant publications of the author

Heinzelmann, F., Bristogianni, T., Teuffel P., (2015), Functional-layered textile in architecture. In: Fabric Structures in Architecture, Elsevier/Woodhead, pp. 159-186

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Heinzelmann, F., Bristogianni, T., Teuffel, P., (2013), Adaptive Fluid Lens and Sunlight Redirection System. In: *Proceedings of eCAADe Conference 2013*, Delft, Then Netherlands, 18-20 September 2013

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Wang, Y., Heinzelmann, F., Teuffel, P., Holzbach, M., (2012) Kinetic mirror facade – conveying messages with daylight. In: *Proceedings of the Intercad, International Conference on Architecture and Design*, Vienna, Austria, 17-18 October 2012

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Daylighting for buildings, meaning the supply of quantitative and qualitative adequate natural indoor light in combination with protection from overheating is a well-researched and applied design approach when it comes to vertical façades, especially regarding buildings with a high degree of façade standardisation. Here static as well as adaptive solutions like light shelves or reflective, retractable louvers are applied in the built environment and many different products are available. However, dealing with large roofs where the area of the roof and the horizontally laid out functions underneath cannot be sufficiently lit by vertical façades, the horizontal roof structure will become the main surface which has to transmit daylight. Since daylight is not static but its availability and direction over time changes, adaptive daylighting solutions are required. The different design requirements and the tendency that large roofed buildings are much more individually designed, ask for another design approach which needs to be formalized in form of a Design Method. This is relevant for buildings like stations, airports, sports facilities, museums, big atria, trade fair buildings and to a certain degree for industrial and storage buildings.

This dissertation explores the afore mentioned design challenges among others by means of case studies and results in a Design Method for Adaptive Daylight Systems for buildings covered by large (span) roofs.

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