Design of an adaptive facade

with reflective properties for UHI mitigation and indoor daylight performance improvement

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Prof. Dipl.-Ing. Peter Bauer

Technischen Universität Wien
Institut für Architekturwissenschaften
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eingereicht an der Technischen Universität Wien
Fakultät für Architektur und Raumplanung

o. Prof. Dr.-Ing. Dr.-Ing. E.h. Dr. h.c. Werner Sobek

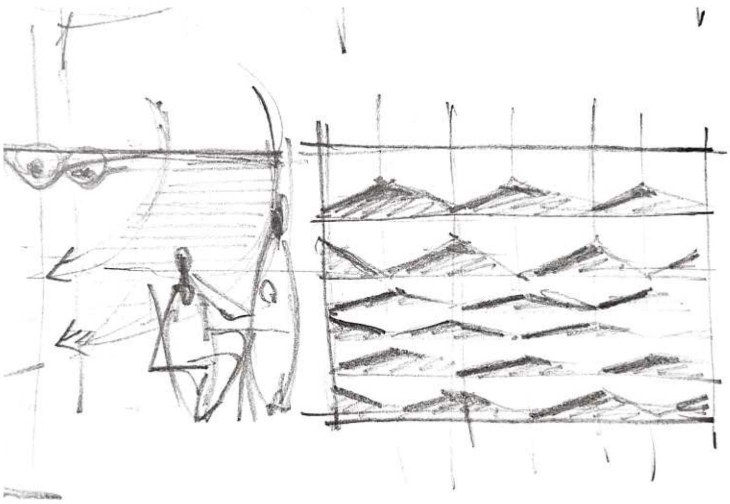
Jun.-Prof.Dr.-Ing. Maria Matheou

Universität Stuttgart

Institut für Leichtbau Entwerfen und Konstruieren

von Miruna Vecerdi
01427666

Wien am



*"Technology is the answer,
but what is the question?"*

Cedric Price

Acknowledgments

I want to thank my family for the unconditional support throughout my studies. I would have not been here if it weren't for all the love and encouragements and advice I got from them.

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Contents

List of Figures

all unannotated figures are produced by the author

List of Abbreviations

CS	= ClimateStudio
DA	= Daylight Analysis
DOF	= degree of freedom
EPW	= EnergyPlus weather data
GH	= Grasshopper
HOY	= hour of the year
HS	= heat stress
IR	= Infrared
LB	= Ladybug Tools Plug-in for Grasshopper
PV	= photovoltaic
Rhino	= Rhinoceros3D
UHI	= Urban Heat Island
UTCI	= Universal Thermal Climate Index

List of Symbols

a_{max} = max. distance from center [m]
g = dead load [N/m]
I_a = area moment of inertia [cm^4]
l = length [m]
M = material performance [%]
M_b = bending moment [kNm]
M_i = insolated area of the material
M_t = total area of the material
q = total load [N/m]
r = angle between the the reflected ray and its horizontal projection [°]
R = reflection performance [%]
R_p = nr. of relevant reflected rays
R_t = total nr. of rays hitting the object
t_{air} = dry bulb temperature [°C]
t_{UTCI} = temperature measured with UTCI [°C]
W = section modulus [cm^3]
w = wind load [N/m]
α_{solar} = solar altitude angle [°]
σ_{max} = maximum stress
$\Delta_{azimuth}$ = South azimuth angle [°]

Abstract

DE

In Anbetracht der steigenden Temperaturunterschiede zwischen städtischen und ländlichen Gebieten - ein Phänomen, das als urbane Wärmeinsel bekannt ist - ist die Suche nach Lösungen zur Verbesserung des Mikroklimas und des menschlichen Komforts etwas, woran Stadtplaner, Architekten und Ingenieure arbeiten sollten.

Das Ziel dieses Projekts ist es, eine adaptive sekundäre Fassadenhaut als Lösung zur Abschwächung von Wärmeinseln zu entwerfen. Das Design besteht aus textilen Elementen, die zwischen drehenden Lamellen, die an Wellenstäben befestigt sind, spannen. Zwei separate Servomotoren treiben das System an und drehen zwei Gruppen von abwechselnden Lamellen. Bei der alternativen Rotation werden die Textilien zur Sonne hin ausgerichtet. Auf diese Weise wird eine sonnennachgeführte Bewegung mit einachsiger Rotation erreicht. Die solar reagierenden Elemente verändern ihre Geometrie, um die Reflexion der Strahlung zu erhöhen und das städtische Mikroklima und die Tageslichtleistung im Innenraum zu verbessern. Wärmeabweisende Materialien werden berücksichtigt, um die Reflexion auch im Infrarotspektrum zu gewährleisten.

Dieses Fassadenkonzept soll für zukünftige Entwürfe geeignet sein, aber auch in der bereits bestehenden städtischen Struktur als mögliche Nachrüstungsmaßnahme eingesetzt werden können. Die Gesamtstruktur sollte leicht demontierbar sein, wenn sie ihren Bedarf und ihre Nutzung beendet haben sollte. Alle Komponenten des Systems müssen wiederverwertbar sein und die Verbindungen und Befestigungen sollten größtenteils mechanisch sein, ohne Verwendung von Verklebungen.

Ein parametrisches Modell wurde mit Rhinoceros3D und Grasshopper erstellt. Wetter- und Solardaten wurden mit LadybugTools für Grasshopper extrahiert und die Tageslichtanalyse wurde mit ClimateStudio simuliert. Auf diese Weise konnte das kinetische Verhalten der Geometrie leicht modifiziert und unter Berücksichtigung aller Parameter mit einer relativ schnellen Reaktion auf die untersuchte Leistung bewertet werden, was eine konsekvente Feedback-Schleife für Design Iterationen ermöglichte.

Das spezifische Design, das in diesem Projekt vorgestellt wird, berücksichtigt die klimatischen Bedingungen in Stuttgart und kann auf den adaptiven Demonstratorturm in Campus Vaihingen montiert werden. Für den Entwurf einer sonnenempfindlichen Fassadenhaut ist ein spezifisches Standort notwendig, um das korrekte kinetische Verhalten unter dem Einfluss des spezifischen lokalen Klimas zu gewährleisten. Dennoch kann dieser Systemansatz an jeden Standort angepasst werden.

EN

Considering the ever-increasing temperature differences between urban and rural areas - a phenomenon known as Urban Heat Island (UHI) - finding solutions to improve micro-climate and the comfort of citizens is something city planners, architects and engineers should work towards.

The aim of this project is to design an adaptive second skin for facades as a solution for UHI mitigation. The design consists of textile elements spanning between rotating fins that are attached to horizontal shaft bars. Two separate servomotors actuate the system, rotating two groups of alternating fins. The alternative rotation is orienting the textile panels towards the sun. This way a sun-tracking similar motion is achieved using mono-axial rotation. The solar-responsive elements modify their geometry to increase solar radiation reflection and improve urban micro-climate and indoor daylight performance. Heat repellent materials are considered to ensure reflection also in the infra-red spectrum.

This second facade skin is envisioned to be suited for future designs, but also to be applicable in the already existing urban fabric, as a possible retrofitting measure.

The overall structure should be easily demountable if it should have ended its need and use. All components of the system have to be recyclable and the joints and mounting should be mostly mechanical with no use of lamination.

A parametric model was made using Rhinoceros3D and Grasshopper. Weather and solar data was extracted using LadybugTools for Grasshopper and the daylight analysis was simulated with ClimateStudio. In this way, the kinetic behavior of the geometry could easily be modified and evaluated considering all parameters with a relatively quick response for the investigated performance, making it possible to have a consequent feedback loop for design iterations.

The specific design presented in this project is made to respect the climatic conditions of Stuttgart and to be fitted onto the adaptive demonstrator tower in Campus Vaihingen. It is important to mention that designing a solar responsive façade skin requires a specific site location, to ensure the correct kinetic behavior influenced by the specific local climate. Nevertheless, this system approach can be adapted to any location and facade geometry.

So, what is the problem?

The Urban Heat Island Effect

The temperature difference between urban and rural areas is a phenomenon known as urban heat island effect. (UHI)

Urban landscapes are dominated by horizontal dark surfaces, mostly roofs and pavements, that absorb solar radiation and release it in form of longer wavelengths (IR) as heat.

Sealed surfaces cover more than 60% of the urban areas, trapping heat and causing temperature to increase. This is mostly the case during summer periods and leads to overheating, which in turn asks for more cooling energy. The lack of porous areas and vegetation decrease evaporation, also contributing to the accumulation of heat loads in cities. The temperature increase caused by the ongoing climate change amplifies the overheating within urban landscapes.

Due to the different manifestation and intensities two types of atmospheric UHI can be differentiated: the urban canopy layer (UCL), that stretches from the ground to the average roof height and the urban boundary layer (UBL) above it. The UCL is highly influenced by urban geometry. Heat is trapped in the street canyon and accumulated due to multi-reflectivity of the canyons horizontal and vertical surfaces.[1,2]

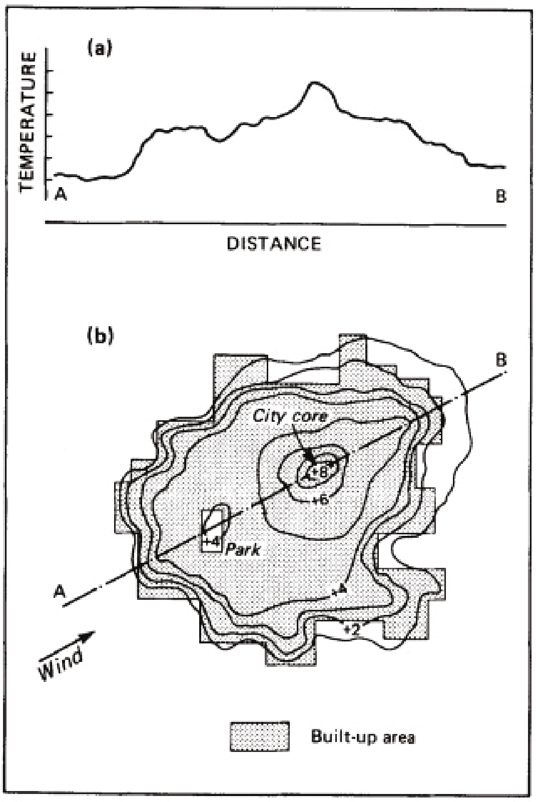


Fig.01. Hypothetical representation of UHI, by Ref. 1

Causes

Following factors causing UHI have been identified[3]:

- Shortwave radiation is absorbed by the poorly reflective materials and gets trapped in the urban canyon
- Long wave radiation gets absorbed and re-emitted into the urban fabric by air pollution
- Long wave heat gets trapped within street canyons due to obstructing surfaces and is radiated back into the environment
- Anthropogenic heat (traffic, industry etc.) increases the heat load and amplifies the UHI effect
- Low permeability of urban surfaces decrease water evaporation reducing the cooling potential
- Urban geometry reduces wind speed, which in turn decreases cooling

Effects

The impact of the UHI on a city is influenced by various factors. The topography of the area, the heat produced by anthropogenic activities, the thermal and optical characteristics of the materials of the urban environment, the urban geometry and density can determine the intensity of the UHI. Moreover, the rural reference for determining the impact also influences its quantification[4].

The heat loads caused by the urban heat island have a major impact on the energy performance of the buildings. Urban heating results in more cooling energy consumption and an increase in peak and total electricity consumption. The increase in ambient temperatures is correlated with the increase of the peak electricity demand, that results in more energy consumption, more heat release and implicitly more costs.[4,5]

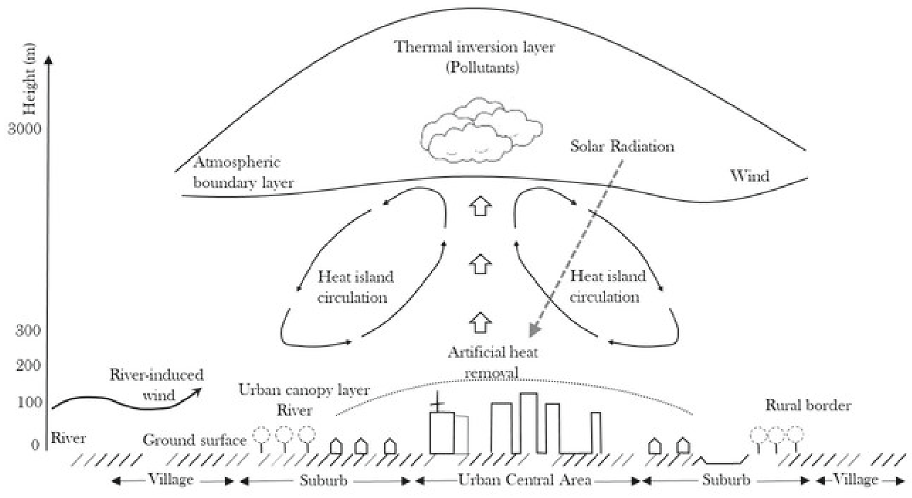


Fig.02. Diagram of UHI layers, by Ref. 6

Some studies show that there is a trend showing demand for more cooling energy during the summer period than for heating during the winter time. The lack of natural ventilation and increased use of air conditioning also aids the heat stress in the urban fabric, having a negative impact on the micro-climate.

Thermal pollution increases air pollution and poses health risk factors for humans. Extended heat periods have more damaging effect on the young and elderly.

This phenomenon has been witnessed on a global scale, ranging from temperate regions to subtropical ones. The impact is varying depending on region, with the highest values registered in areas with more cooling degree days.

UHI in Stuttgart is a result of the urban density, the high mount of sealed surfaces and inadequate air exchange due to the orographic conditions of the environment. Due to the different altitudes of the city regions, it is difficult to quantify UHI in Stuttgart. Nevertheless, measurements show that compared to the outer city regions, differences of up to 5K can be determined within the city center, resulting in high heat stresses, especially over the summer period.[7]

Mitigation

The visible and large-scale impact of UHI has determined cities to come up with mitigation solutions. The following solutions are found to be common amongst European cities[3]:

- Increase of vegetation results in passive cooling due to passive cooling and evapo-transpiration. In this way green facades and roofs are encouraged.
- Increase of water surfaces for cooling effects
- Planning of urban geometry that allows for more air flow
- Use of permeable materials and coatings with high albedo on exposed urban surfaces, roofs pavements and facades, to reduce the amount of short-wave heat that gets accumulated.

A look at the state of the art

In this chapter a range of selected existing solutions and projects are presented. While the solutions are directly concerning UHI mitigation, the projects showcase different adaptive approaches, to improve the energy performance and indoor comfort of the building.

Increasing albedo

The albedo value, or whiteness, indicates the amount of diffusely reflected solar radiation of a surface and it is defined by the ratio between the radiosity and irradiance received. More reflected sunlight results in less heat absorbance. Increasing albedo on facades and roofs is not a new strategy. It has been used in vernacular Mediterranean and Subtropical architecture. High albedo materials (HAM) are being investigated and developed. Today this method is used for buildings and pavements to mitigate UHI also in moderate climate environments[9].

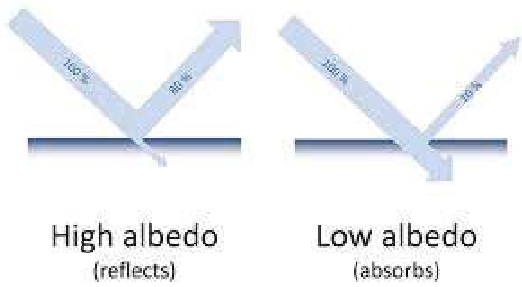


Fig.03 Albedo principle, by © KMKG-MRAH

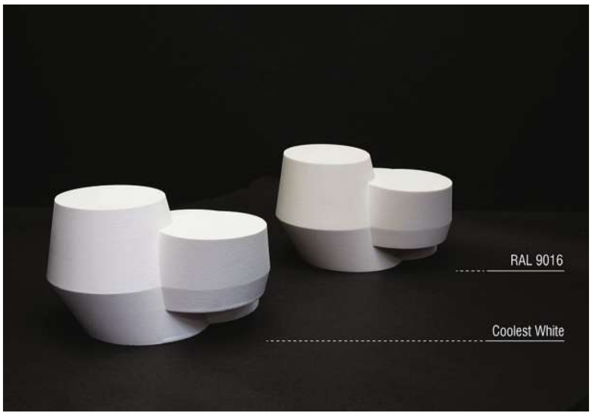
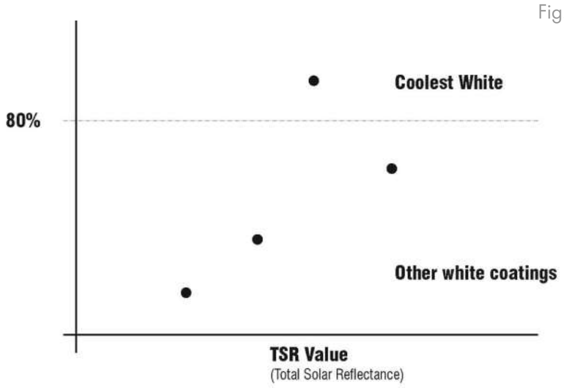


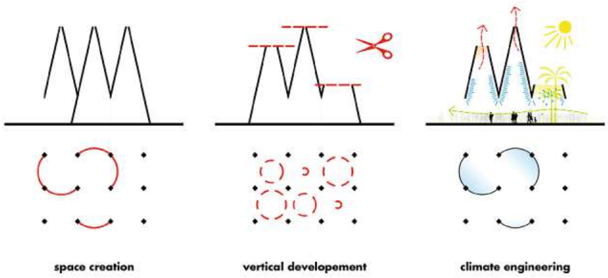
Fig.04

Fig.05

Fig.06

Fig.07





product: coating

UN Studio + Monopol Colors, The Coolest White

This ultra durable coating for buildings is made to enhance the albedo value of facades, increasing reflectivity and reducing heat loads.

building type: pavillion

querkraft architekten, Austrian Pavilion EXPO Dubai 2020

Using white concrete instead of the usual one, is meant to improve thermal performance of the pavilion, reducing energy requirement by 70%

Tilted surfaces

Tilting a surface towards the sun results in increased reflection of solar radiation. Due to their geometrical juxtaposition, angled components or glazing modules are generating self shading, improving indoor thermal comfort. Their sunlight reflectance is dependent on the reflective coating and on the tilt angle, but overall they do reduce heat gain.

Not involving actuation or laborious fabrication processes, this is a rather simple and efficient method to reflect solar radiation. The performance can be further improved if the tilt angles are optimized to parameters such as sun path at certain periods and indoor daylight performance.

Fig.08

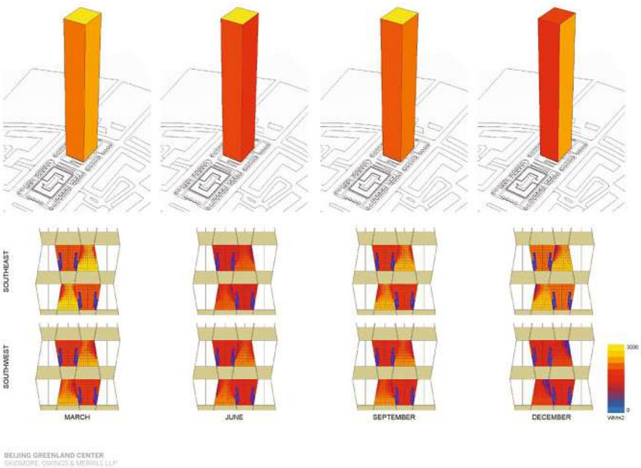
building type: office

SOM,
Beijing Greenland Center

By alternatively mirroring the glazing modules, self shading is generated. Although the facade elements are not differing based on facade orientation, this method improves the indoor thermal comfort and reduces the energy consumption of the building.

The tilted windows are not only chosen for aesthetic purpose, but also to reflect the sunlight into the surrounding area, reducing the heat load inside the building. Nevertheless, this can disturb the micro-climate of the surrounding urban area.

Fig.09



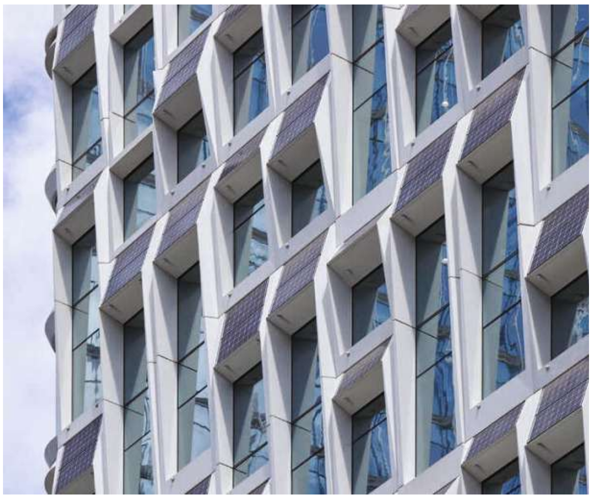


Fig.10

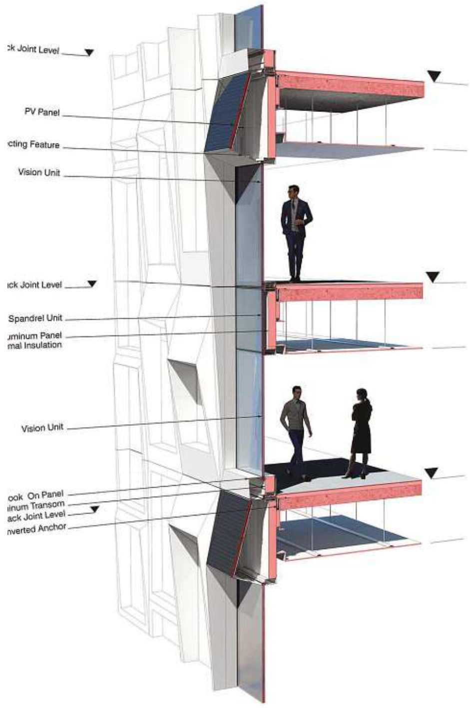


Fig.11

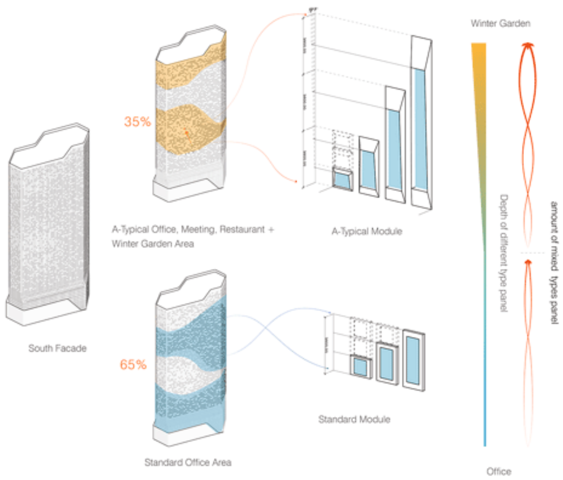
building type: office

UN Studio,
Hanwha HQ

The design of this facade is made considering facade orientation, proportion of unobstructed and obstructed views and user program.

A thorough parametric and energy model was made for the implementation and variation of the facade modules. In accordance to the sun-path and required indoor daylight performance, different heights, depths and angles for the shading components were modeled. The tilted surfaces create depth, providing shading and contain PV panels for solar gains.

Fig.12



Static shading elements

A typical approach for overheating mitigation is to use shades/blinds. Static shading elements show better performance when they also increase sunlight reflection, reducing glare and improving daylight performance of the buildings.

Using computational design methods, the geometry and overall placement of static components can be optimized in respect to the contextual sun path and annual solar radiation.

Fig.13

building type: office

Gerber Architekten,
King Fahad National Library

This project was refurbished to become more energy efficient. It employs a light weight structure made from tensile fabric elements arrayed as a second layer on the outside, that provide shading and improve indoor daylight performance.

"...Given exterior temperatures of up to 50º Celsius, the membrane facade, which was optimized in relation to the local sun path by means of complex, three-dimensional light refraction, combines the required protection from the sun with maximum light penetration and transparency."[10]

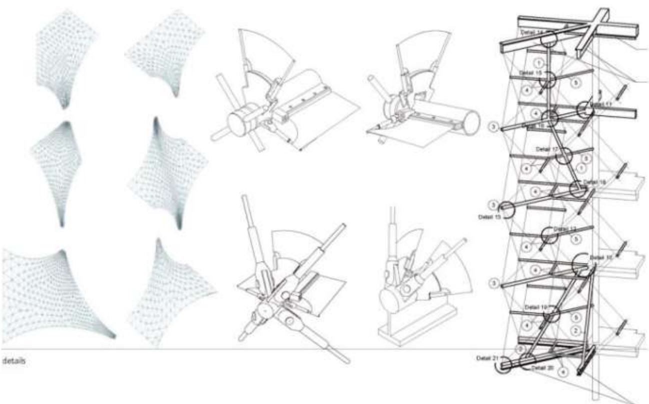


Fig.14

Fig.15

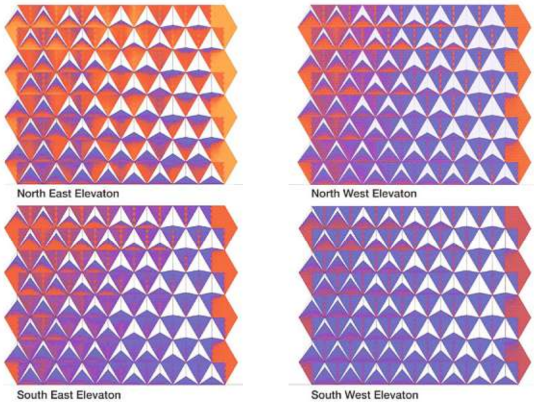


Fig.16

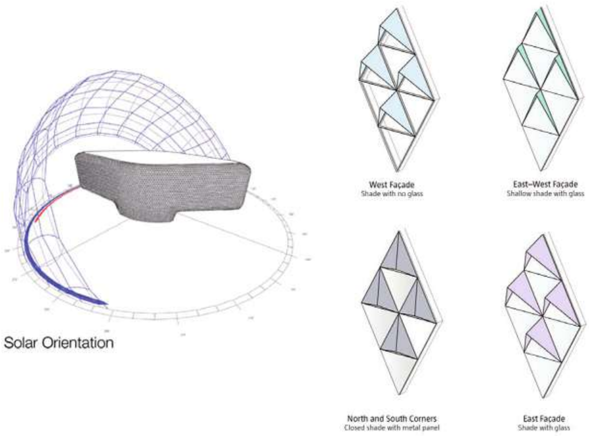


Fig.17, 18

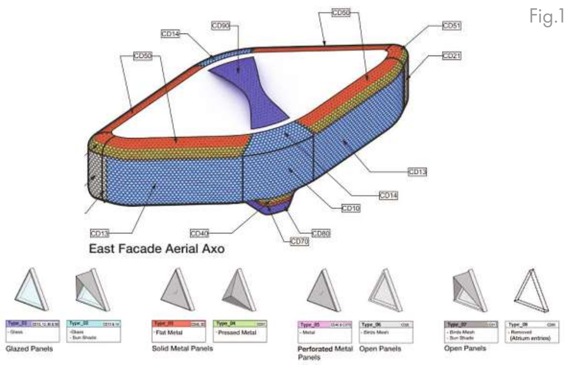


Fig.19

building type: research facility

Woods Bagot,
SAHMRI

Inspired by the pine cone skin, this facade is optimized for daylight performance and heat load reduction. According to orientation and indoor lighting requirement 4 different derivations of the initial shader are generated. The panelization is optimizes as a feedback of the insolation performance. This integrative design made possible by a workflow between Grasshopper and Revit that also included fabrication constraints.[11]

Responsive facade

Adaptive dynamic facades with 1 degree of freedom (DOF) showcase movement, usually folding or rotation along one axis. This kinematic behavior is usually electrically controlled, but can be overwritten for manual control and occurs in response to the external climatic influence. These systems are easier to regulate than those which move with more DOFs, but can improve the energy performance of the building only to some extent.

Actuating rotation around one axis can also be seen as folding. This can achieve more complexity if a more complex pattern is involved.

Simple origami patterns can be folded using linear actuators along just only one of the creases or vertices.

Fig.20, 21

building type: showroom

Ernst Gieselbrecht + Partners, Kiefer Showroom

The folding panels react to weather conditions, regulating the amount of sunlight for the indoor. This reduces the need for air conditioning during summer.

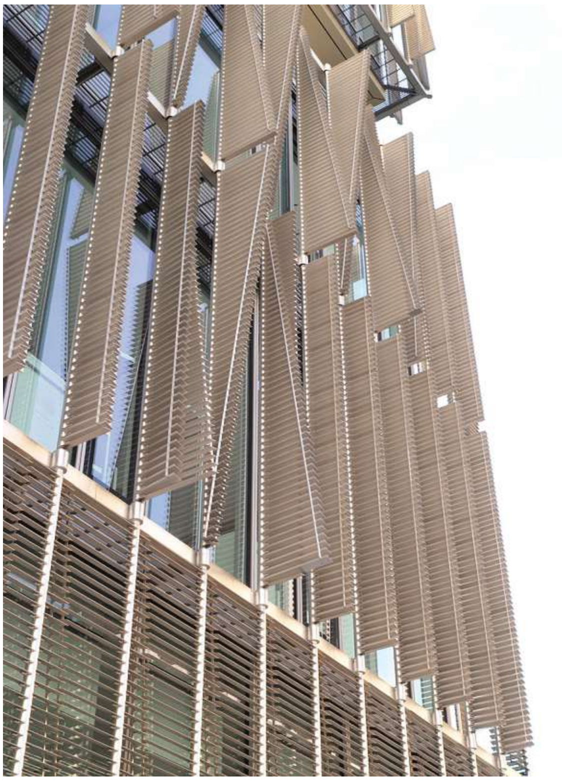


Fig.22

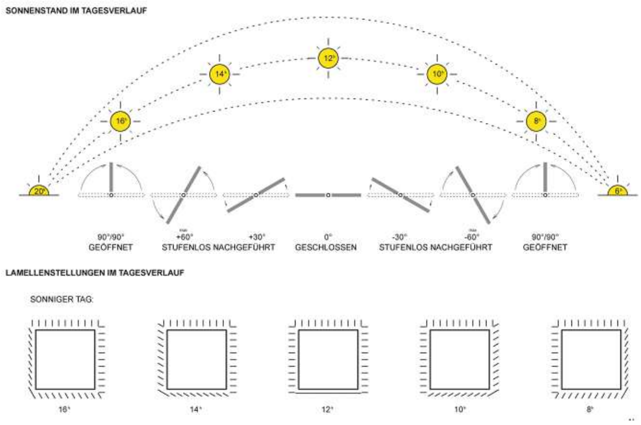
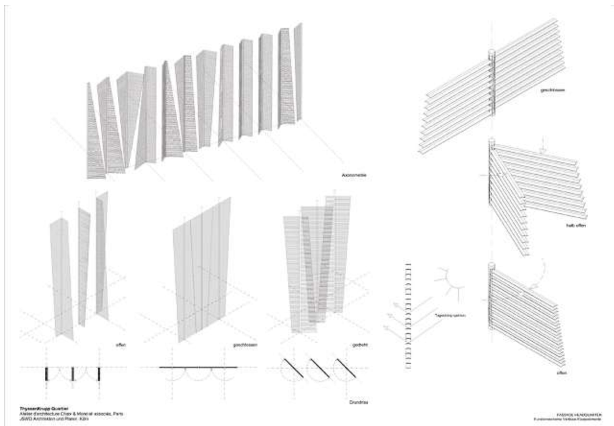


Fig.23

Fig.24



building type: office

JSWD Architekten + Chaix & Morel et Associés, Thyssenkrupp Q1

Comprised of stainless steel vertical twisting fins, this facade reduces heat gain being controlled according to measurements by a weather station on the roof of the building.

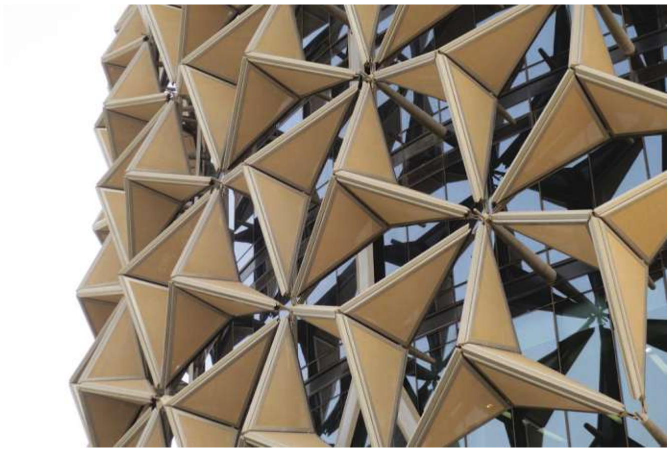


Fig.25

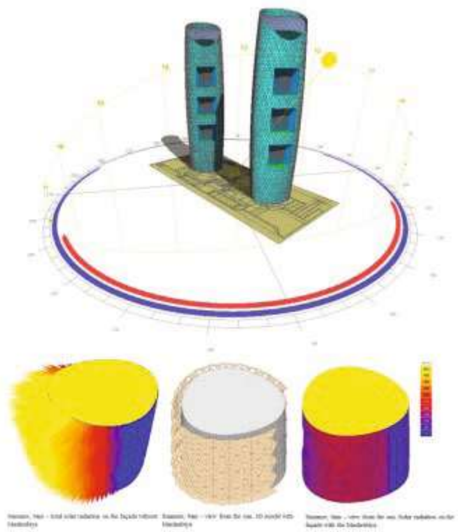


Fig.26

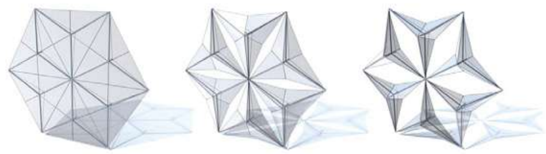


Fig.27

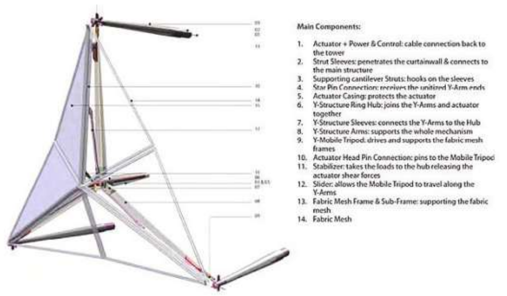


Fig.28

builting type: office

Aedas Architects + Arup, Al Bahar Towers

The system makes use of a simplified kinetic principle of an umbrella. Pushing and pulling the middle of each triangle results in the folding of the subdivided faves. Areas of the facade open and close in response to sun movement. This significantly reduces the cooling energy required.[12]

Fig.29

prototype

ETH Zurich, Nagy Z., et al, Adaptive Solar Facade

This prototype features a sun tracking lightweight shading system with integrated thin film PV. The actuation is performed by a soft actuator with pneumatic chambers that allows for bi-axial movement. The system can also be overwritten by voice control to adapt to specific user needs.[13]

Accurate sun tracking requires bi-axial movement with respect to azimuth and solar altitude angles. More DOFs allow for better adaptation to sun position, which in turn comes with greater construction and regulation difficulties.

This usually implies a complex hierarchy of subsystems, more components and more complex actuation. Reasonable trade-offs have to be made between all these requirements and the overall performance of the system.

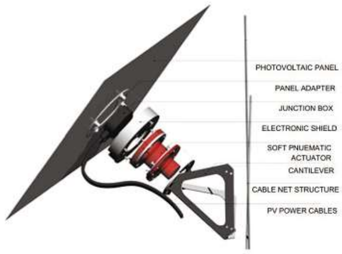


Fig.30

Fig.31

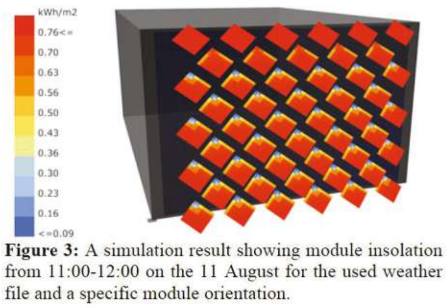


Fig.33

Fig.34

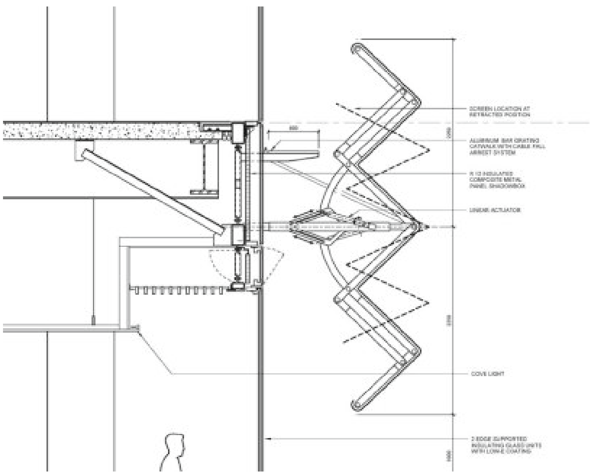


Fig.32

building type: office

Yazdani Studio, CJ R&D Center

An umbrella like system responsible for the actuation of the shading membrane mesh, that would enfold in both direction increasing its surface.

Due to the complex nature of the design, as well as time and budget constraints, the building was completed with a static shader consisting of perforated aluminum panels.

Recap

The presented examples show different approaches for improving energy and daylight performance of buildings. They represent to some extent benchmarks that set the trend of adaptive façades.

Coatings that increase albedo can reduce the overheating indoors, but in turn, the heat is reflected back into the urban environment.[14] Moreover, albedo increase should be considered for the entire spectrum of solar light, which is not the case with most of the coatings.

Geometrical approaches for façades are promising for indoor thermal comfort, but if done without proper consideration of façade orientation and sun position can they increase the heat loads of the surroundings. Customized shading elements can be adapted to solar parameters, and show great potential in improving daylighting and energy performance of the buildings. Nevertheless, they can be optimized just for specific cases and do not react to possible changes of the environmental conditions.

Responsive shading makes use of kinetic systems to react to climatic conditions but require thorough testing and investigation before actual implementation.[15]

Even though these projects are well-known, there is scarce or no quantifiable information about the actual improvement they bring to the building's energetic performance. The lack of documentation of such projects, mostly after their completion, makes it hard for the industry to draw conclusions and evolve.[16,17]

Nevertheless, they have set some benchmarks in the trend for adaptive architecture. As UHI and Climate Change influence each other, increasing heat loads in the urban environment, disrupting the thermal comfort of the citizens and leading to more energy consumption for cooling, there is a obvious need for adaptive systems in the construction industry. [18,19]

Design Workflow

The following design aims to address the thermal discomfort caused by UHI and propose an adaptive second skin that reflects solar radiation away from the surrounding environment back to the atmosphere. It can be applicable to existing buildings and also integrated into new designs. This façade takes into account solar data to reflect most of the incoming radiation and provide shading for the inside of the building, when placed in front of a glazing. It features a kinetic system that allows the facade elements to changes their geometry to improve the reflective performance. This way, heat loads should be reduced during heat stress periods.

The design aims to minimize the amount of necessary actuators, using only a single axis motion, while also orienting the elements towards the sun to increase reflectivity towards the outside of the urban environment. Being a solution for a temporary problem, that manifests mostly during summer time, the design also aims to be temporary, showcasing a lightweight structure, made of recyclable materials.

The specific design presented in this project was made to fit the climatic conditions of Stuttgart and to be fitted onto the adaptive demonstrator tower in Campus Vaihingen. It is important to mention that designing a solar responsive façade skin requires a specific site location, since the kinetic behavior is determined by the specific local climate. Nevertheless, the presented design approach is adaptable to other climatic regions as well.

At first an analysis investigating the specular reflectivity performance of different surface typologies is conducted. The performance **R**[%] is defined by the percentage of reflected rays **Rp**, that feature a reflectance angle **r** ∈ **[45,90°]**, measured between the reflected rays and their horizontal projection, in relation the total incoming rays **Rt**. This interval ensures that the reflected radiation is not directed towards the surrounding urban fabric and also not reflected back towards the building. For this evaluation the heat stress period for Stuttgart is calculated using the Universal Thermal Climate Index (UTCI) and a set of relevant dates are determined. The rays were generated using solar data and the 3d reflection on the surface geometries was computed using the ForwardRaytracing component by Ladybug Tools (LB)[20] for Grasshopper (GH). Based on this investigation, the motion for the development of the kinetic system and the shape for the facade elements is decided.

An Incident Radiation analysis for the heat stress (HS) period in Stuttgart is performed on the tower to determine the placement of the adaptive facade elements.

Based on these decisions, the preliminary design of the kinetic system and facade elements is made. The design is then refined by optimizing the morphology of the elements, based on reflection performance (as described above), material performance as a result of self cast shading and daylight performance. The goal is maximize the insolated area of the facade and achieve a median illuminance of 800 lux indoors[21].

The Daylight Analysis (DA) is made with ClimateStudio (CS) the Point in Time Workflow. The day is set on to 21. June at 12:00 o'clock, with a Perez Sky computed from the weather data of Stuttgart. Materials are assigned to the digital model of the tower in accordance to its real materiality correspondence. Different materials are tested for the facade skin.

The final result is then evaluated for DA for the initially determined evaluation dates.

The described design workflow is documented below.

Reflection performance

The first step is to investigate how surfaces with different curvature reflect sunlight. This was done using the ForwardRaytracing component provided by LB. For this step no materiality is assigned to the geometry and only specular reflection is considered. The surfaces are facing South in their initial non-adjusted position.

The performance **R[%]** is determined as the ratio between the total number of hitting rays **R_t** and the reflected rays **R_p** that feature an angle **r ϵ [45°;90°]**, defined as the angle between the reflected ray and its horizontal projection. This is to ensure that the reflection is not directed towards the inside of the building, the pavement or the neighboring constructions.

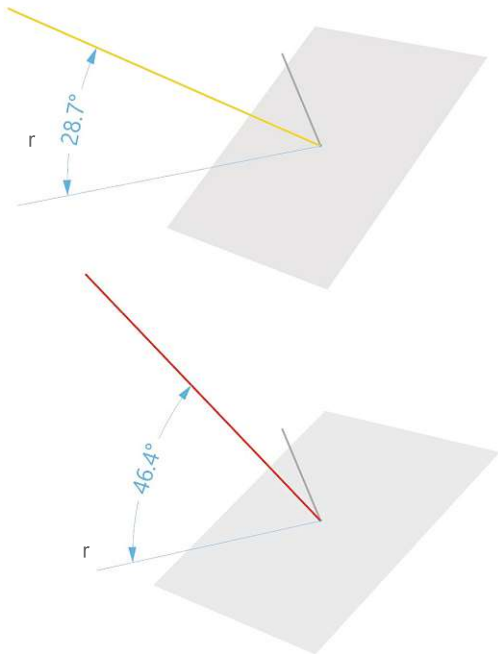


Fig. 35: *Diagram showing the reflection performance definition. The rays that feature an angle between them and their horizontal projection that falls within the interval r[45,90]*

A set of motion case studies is put together for performance evaluation:

$$R = \frac{R_p}{R_t}\ [\%]$$

Case 0 - initial non-adjusted state

Case 1 - rotation around X-axis - inclination in respect to solar altitude

Case 2 - rotation around Z-axis - rotation in respect to azimuth

Case 3 - (1+2) biaxial movement - sun tracking

The aim is to identify if and how surface curvature influences reflection and what kinetic behavior yields better performance.

Evaluation Period | UTCI

For the reflection investigation an evaluation period is needed. Considering UHI having the most relevant impact during the summer period in European cities, the heat period for Stuttgart is derived from available climate data. To determine the heat stress period, calculation of temperature using the Universal Thermal Climate Index (UTCI) was applied.

UCTI was reinforced by the COST Action 730. It is the equivalent temperature for the environment derived from the reference environment.[22]

This presents a more adequate way of measuring temperature, that takes into consideration local climate factors. This renders a more accurate way of climate driven design, compared to only taking into consideration air temperatures or regional mean values.

UTCI is used as a standard value to asses heat and cold stress and for thermal hazard evaluation. It is divided into 10 categories ranging from -5 to 5, with the negative and positive values indicating cold and heat stress respectively. Heat stress is indicated by a temperature offset of the environment from the reference environment that is higher than 26°C. The dark areas in the chart indicate thermal stress. (red for heat and blue for cold stress)

It takes into account the dry air temperature, wind velocity, mean radiation temperature, relative humidity and compared to the majority of the other available thermal indices, it also includes a complex multi-nodal thermo-regulation human model developed by Fiala et. al.[23]

For this project, the UTCI was calculated using Ladybug Tools for Grasshopper. The necessary input parameters for the calculation of UTCI were extracted from an EPW file for Stuttgart. An annual chart indicating the measured temperatures was evaluated and the heat stress HOYs were extracted. This indicated a heat stress period for Stuttgart that begins on 4. April and ends on 5. October with some gaps in the late spring and early autumn days. The heat stress peak was identified on 16. August, with major heat stress from mid-July to mid-August.

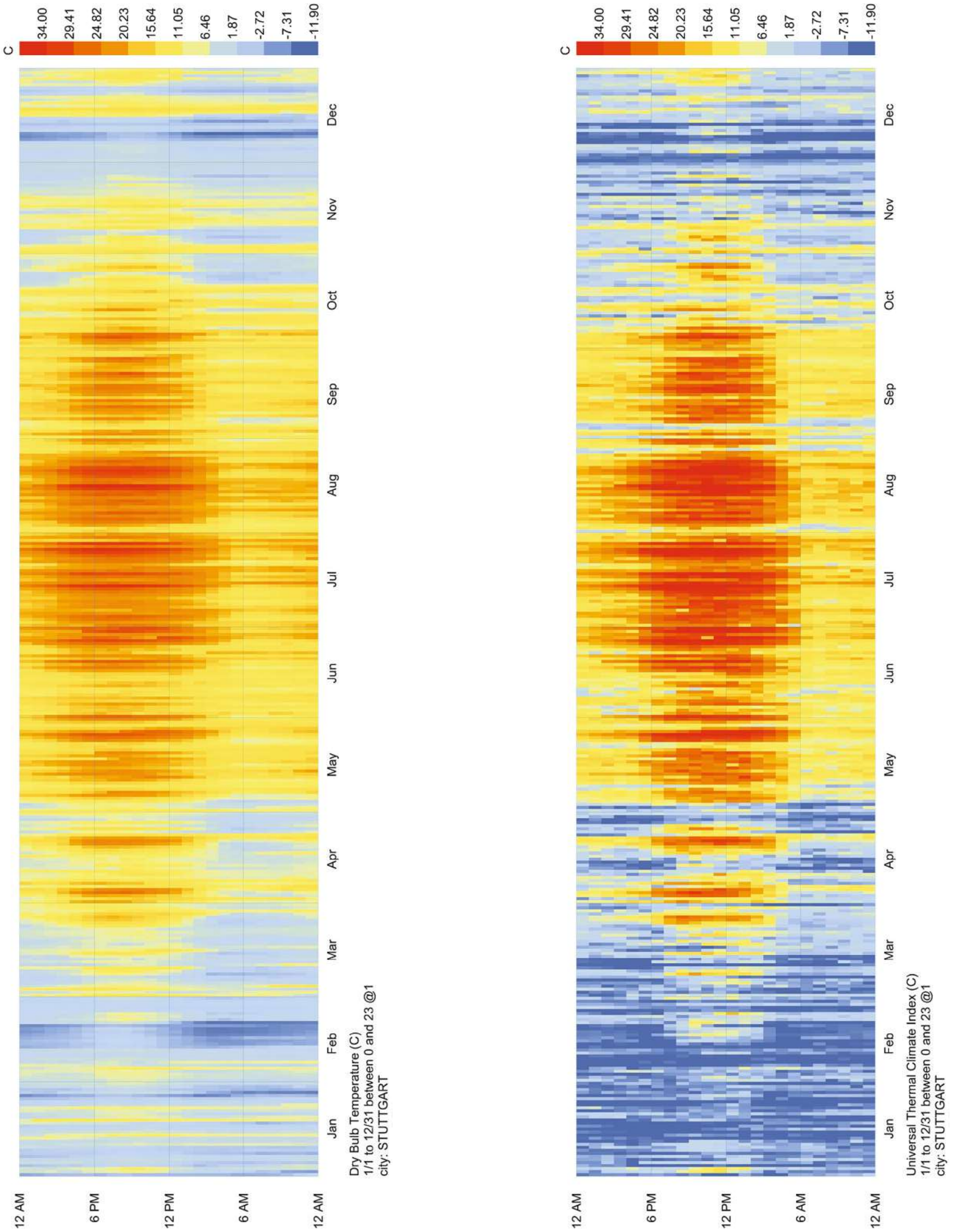


Fig. 36: *Comparison between annual air temperature (left) and UTCI (right)*

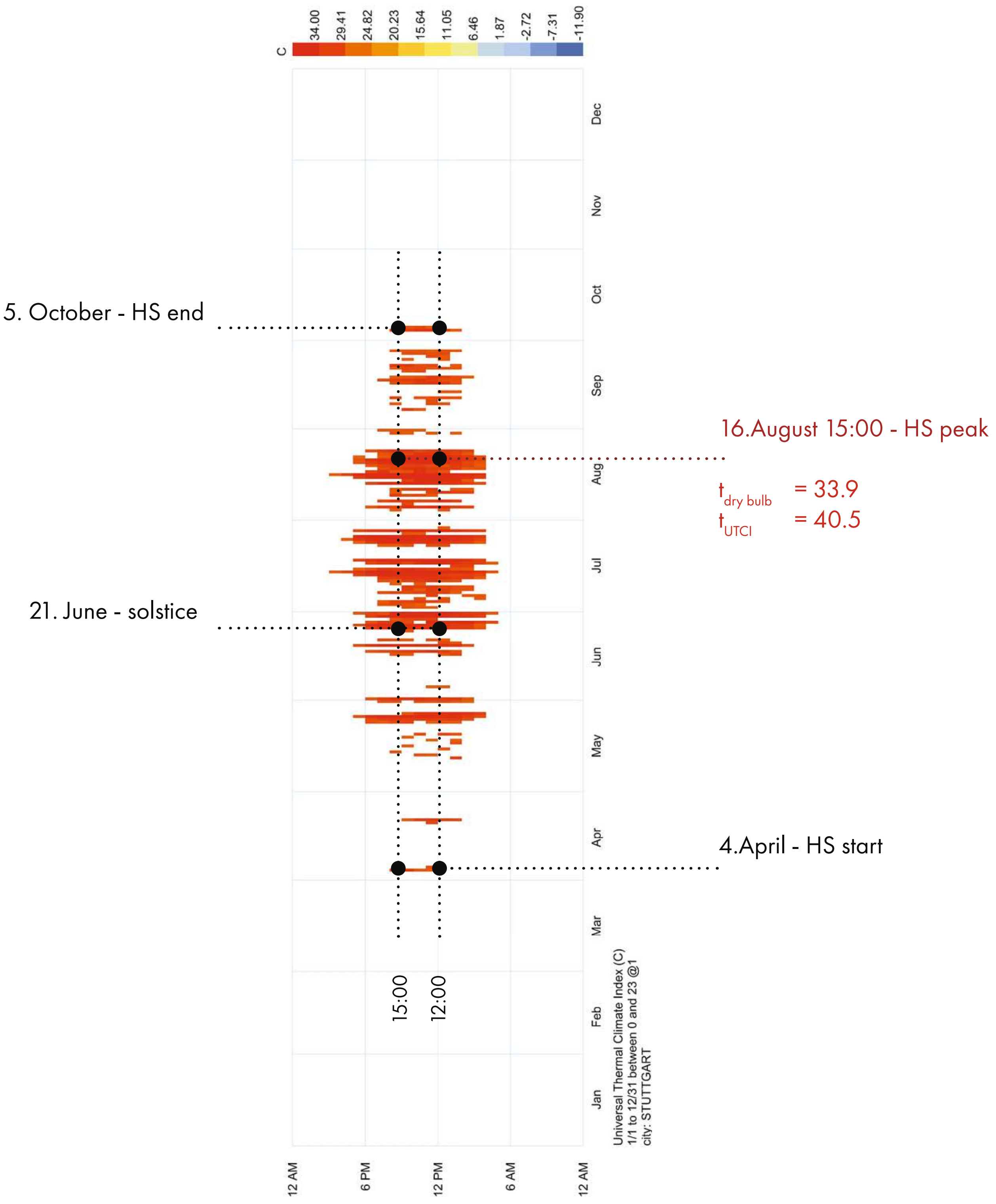
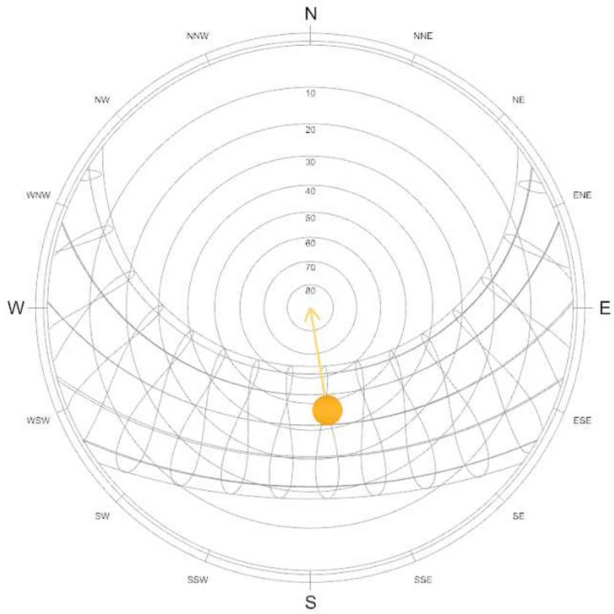


Fig. 37: *Annual chart with HS period for Stuttgart and chosen evaluation dates*

4. April 12:00

Stuttgart



t_{air} = 20.50°C
t_{UTCI} = 26.15°C

α_{solar} = 46.83°
$\Delta_{azimuth}$ = 9.48°

surface
typology

planar
no curvature

cylinder
single crv

revolved
double crv

loft
double crv

saddle
double crv

Case 0	Case 1	Case 2	Case 3
no adjustment	rotation around x-axis solar altitude α	rotation around z-axis sun azimuth Δ	biaxial rotation sun tracking α +Δ

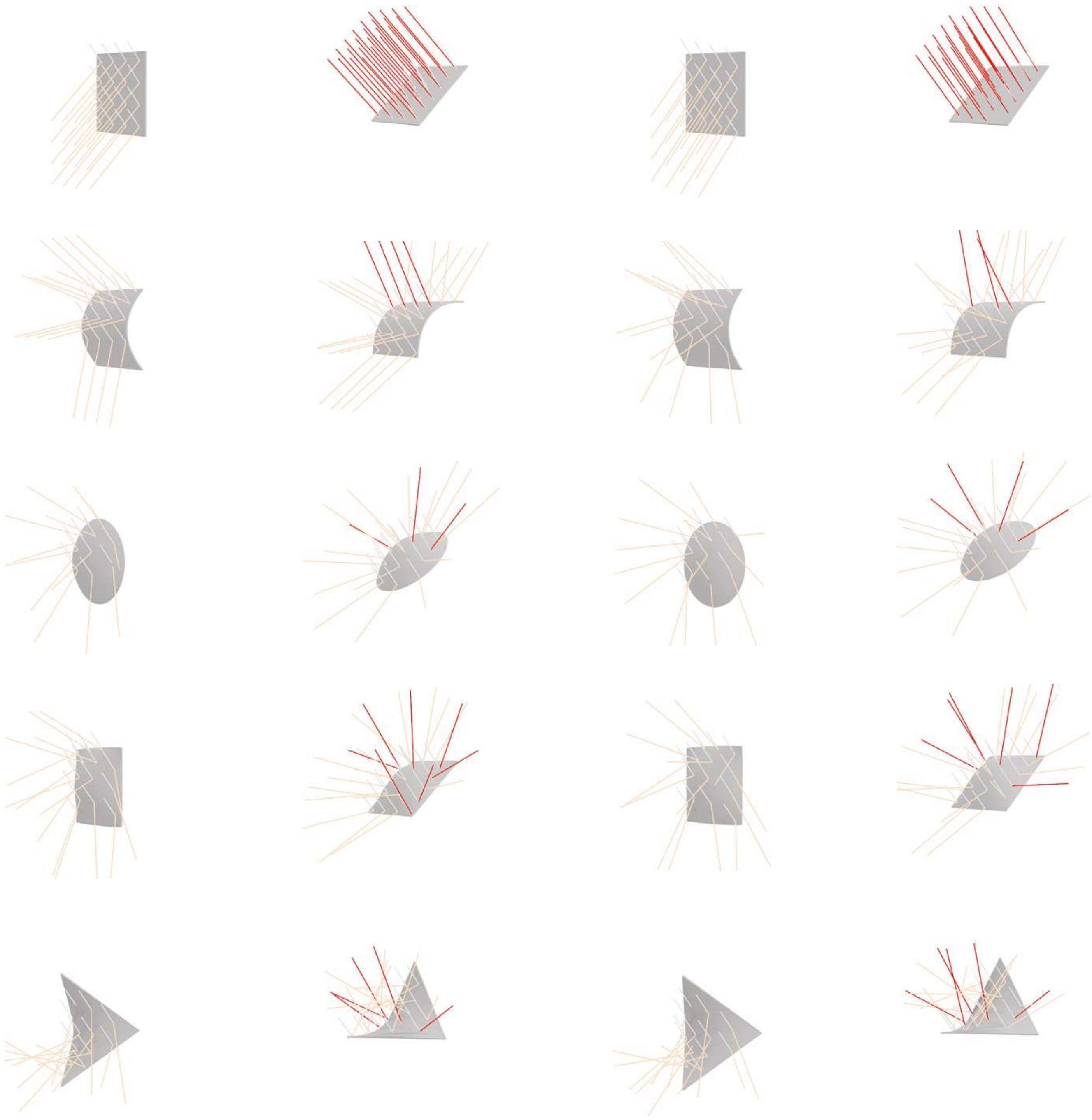
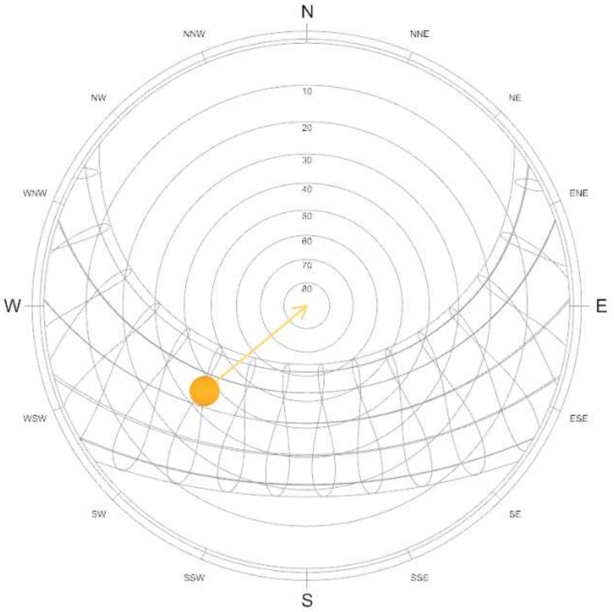


Fig. 38 *reflection study at HS beginn - 4.4 12:00*

surface
typology

4. April 15:00

Stuttgart



t_{air} = 24.70°C
t_{UTCI} = 28.66°C

α_{solar} = 36.83°
$\Delta_{azimuth}$ = -50.15°

planar
no curvature

cylinder
single crv

revolved
double crv

loft
double crv

saddle
double crv

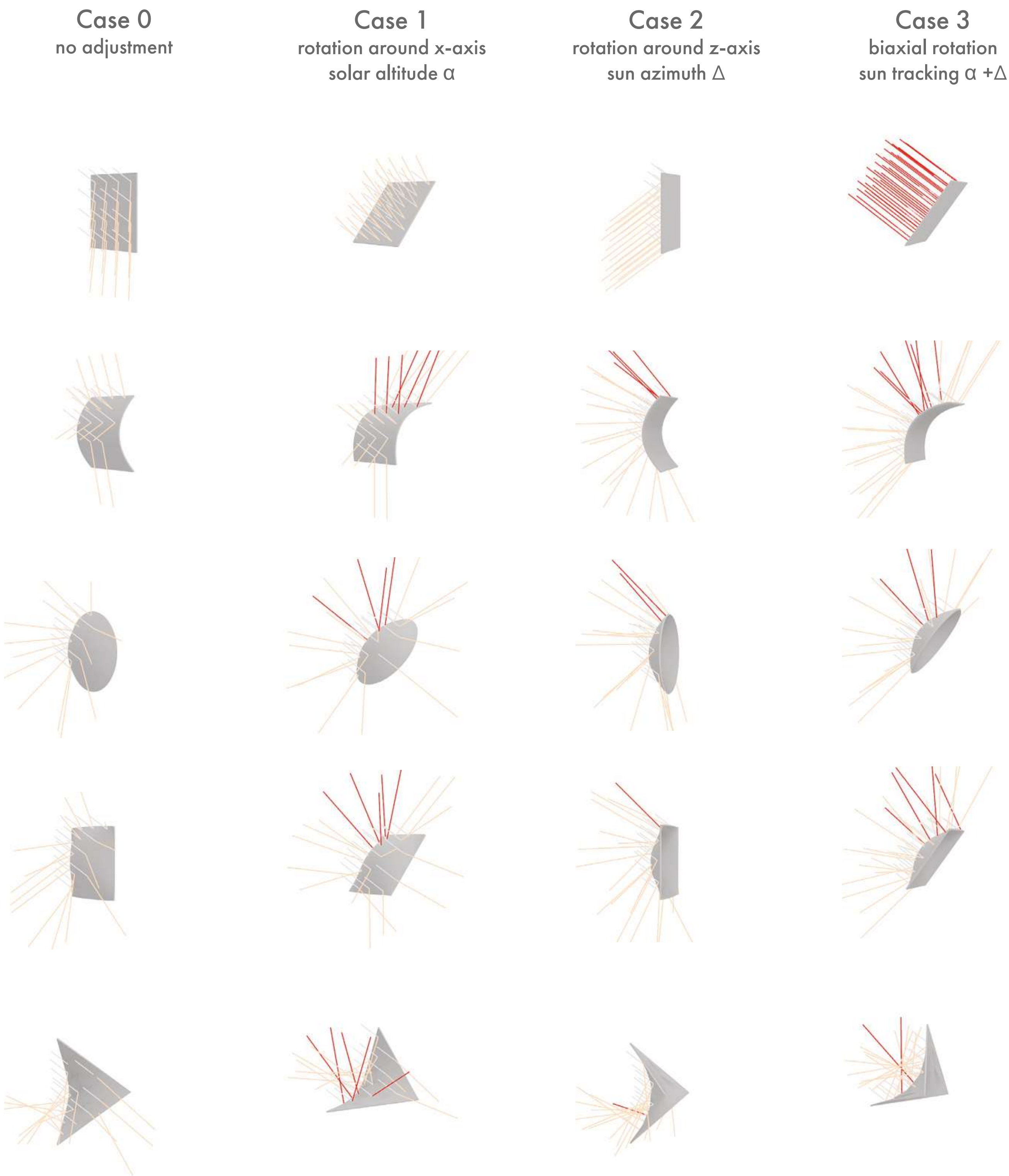
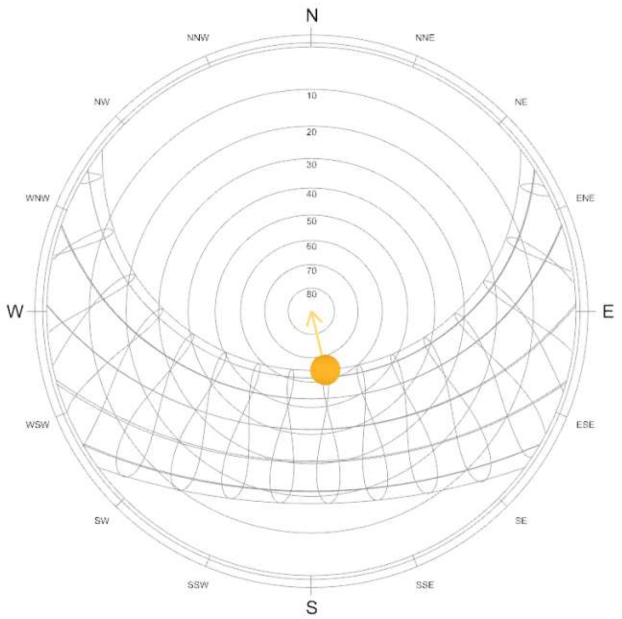


Fig. 39. *reflection study at HS beginn - 4.4 15:00*

21. June 12:00

Stuttgart



t_{air} = 18.70°C
t_{UTCI} = 27.66°C

α_{solar} = 64.28°
$\Delta_{azimuth}$ = 13.28°

surface typology

planar
no curvature

cylinder
single crv

revolved
double crv

loft
double crv

saddle
double crv

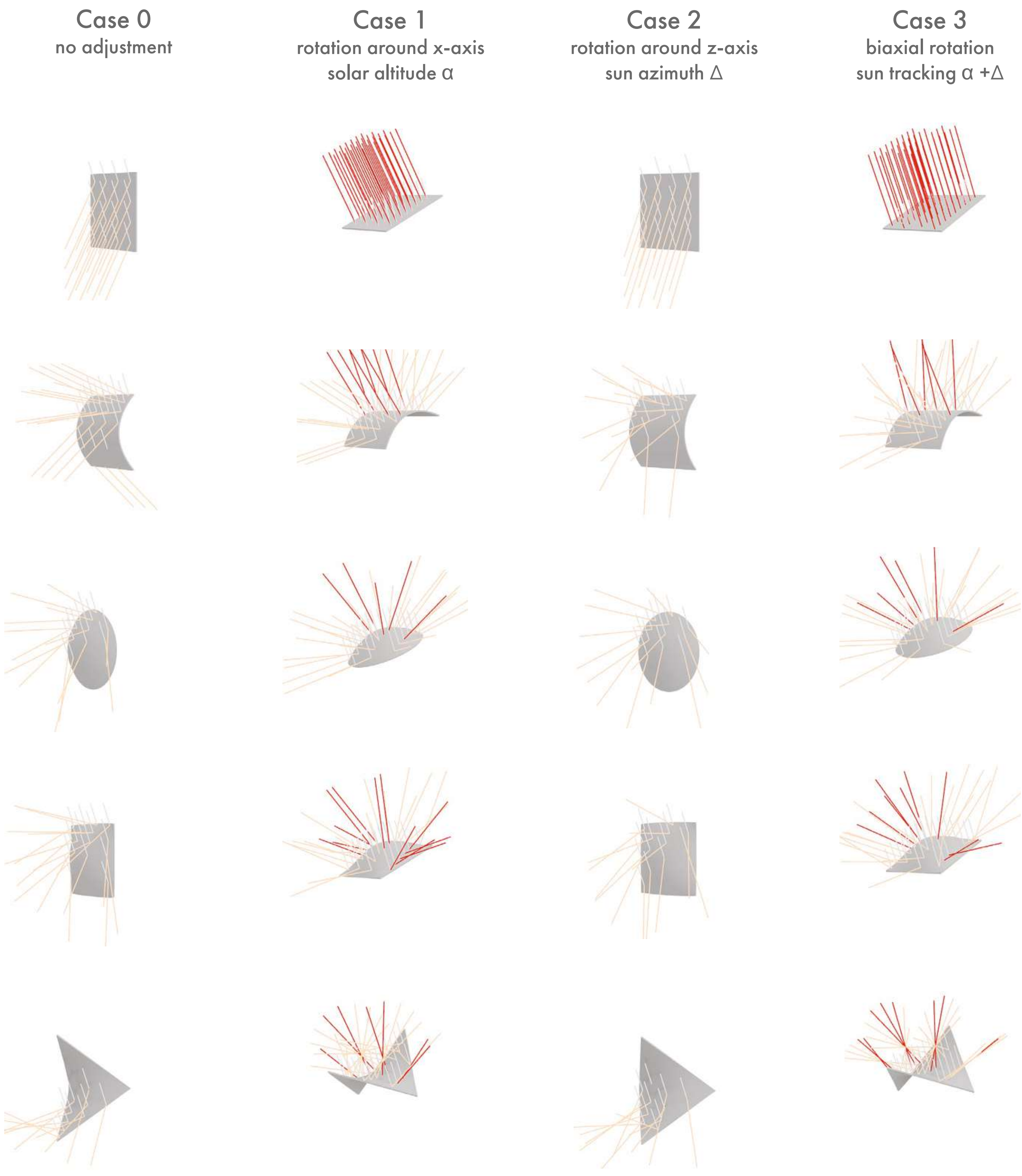
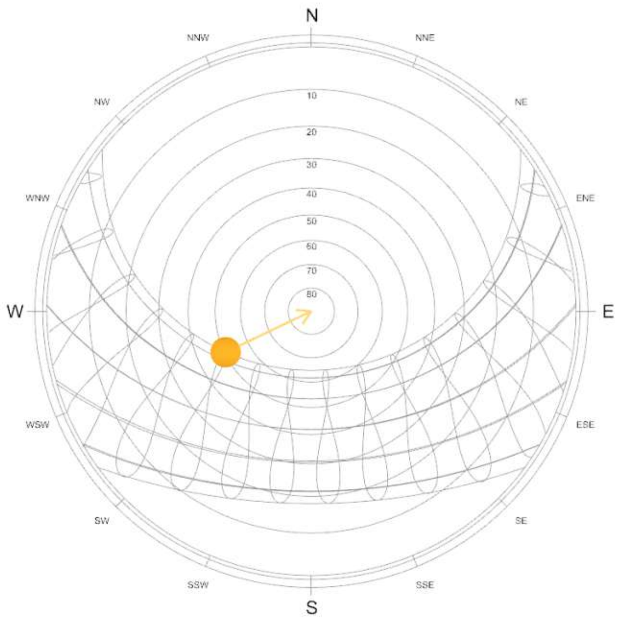


Fig. 40. *reflection study at solstice - 21.6 12:00*

surface
typology

21. June 15:00

Stuttgart



planar
no curvature

cylinder
single crv

revolved
double crv

t_{air} = 19.40°C
t_{UTCI} = 24.45°C

loft
double crv

α_{solar} = 50.46°
$\Delta_{azimuth}$ = -64.43°

saddle
double crv

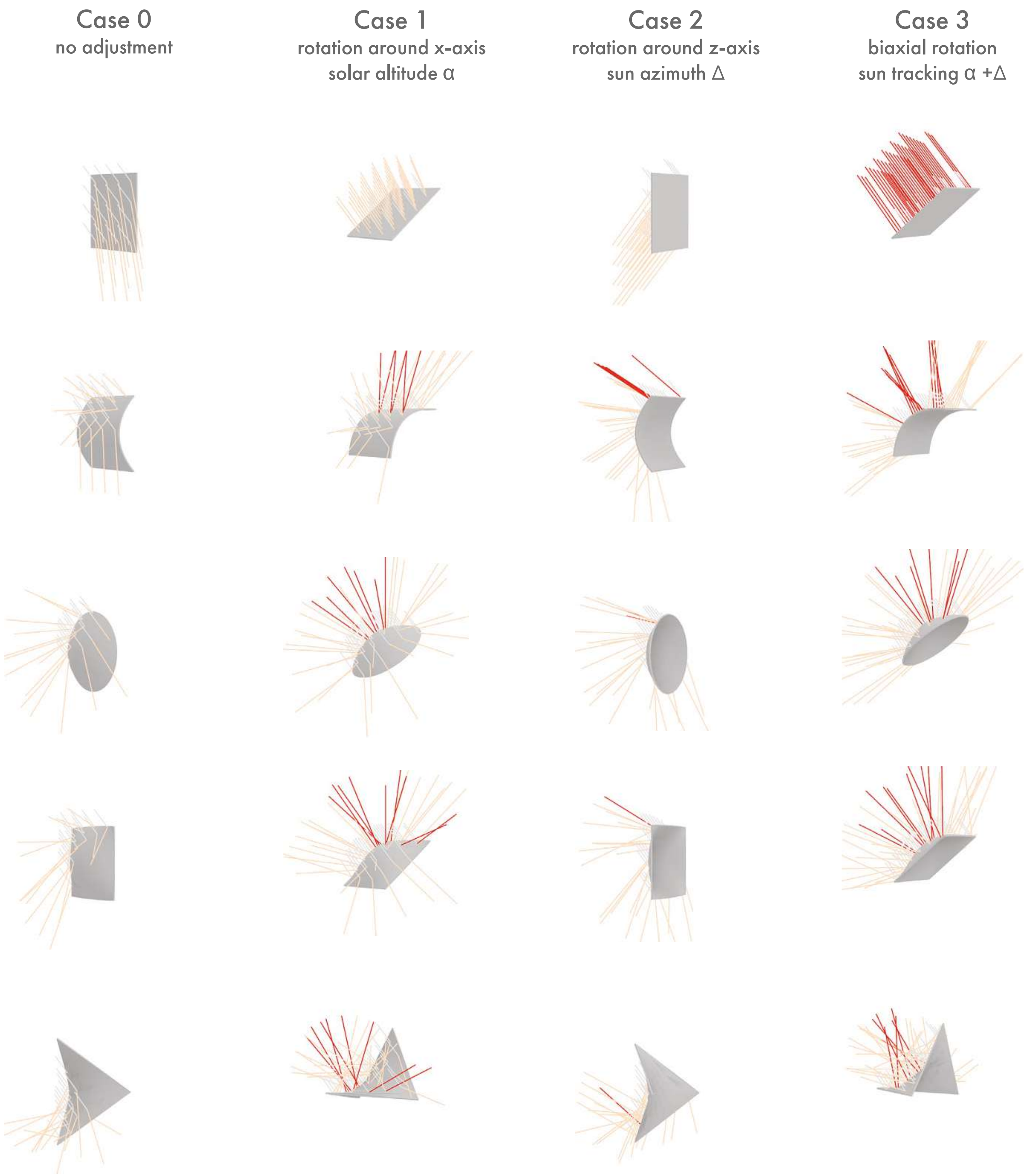
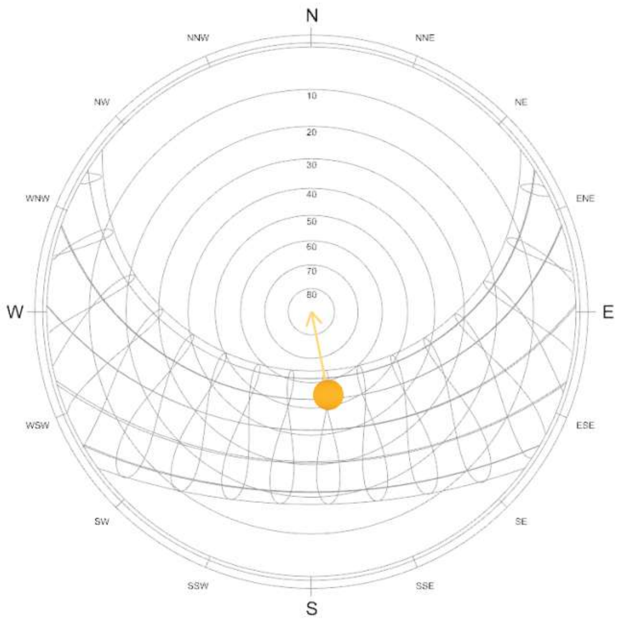


Fig. 41. *reflection study at solstice - 21.6 15:00*

16. August 12:00

Stuttgart



t_{air} = 30.30°C
t_{UTCI} = 38.72°C

α_{solar} = 54.46°
$\Delta_{azimuth}$ = 11.49°

surface
typology

planar
no curvature

cylinder
single crv

revolved
double crv

loft
double crv

saddle
double crv

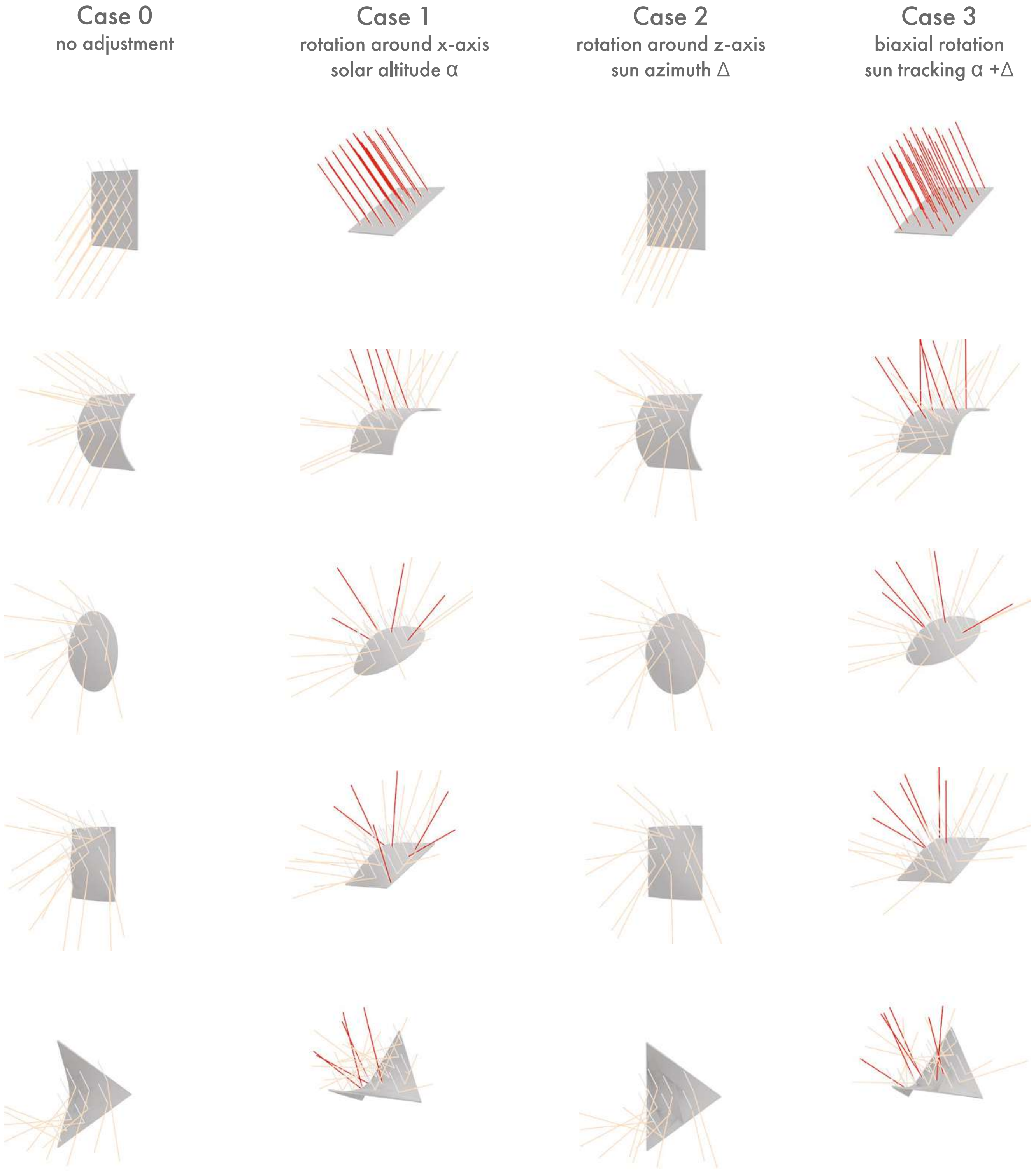
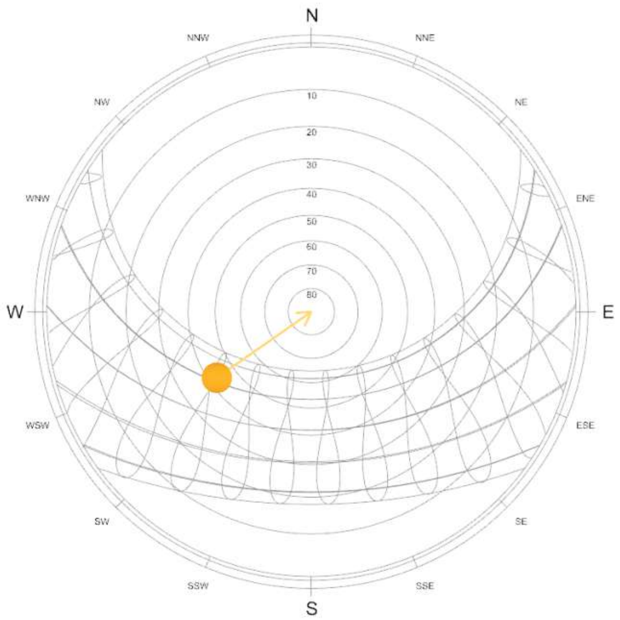


Fig. 42. *reflection study at HS peak - 16.8 12:00*

16. August 15:00

Stuttgart



t_{air} = 33.90°C
t_{UTCI} = 40.52°C

α_{solar} = 42.91°
$\Delta_{azimuth}$ = -55.08°

surface typology

planar
no curvature

cylinder
single crv

revolved
double crv

loft
double crv

saddle
double crv

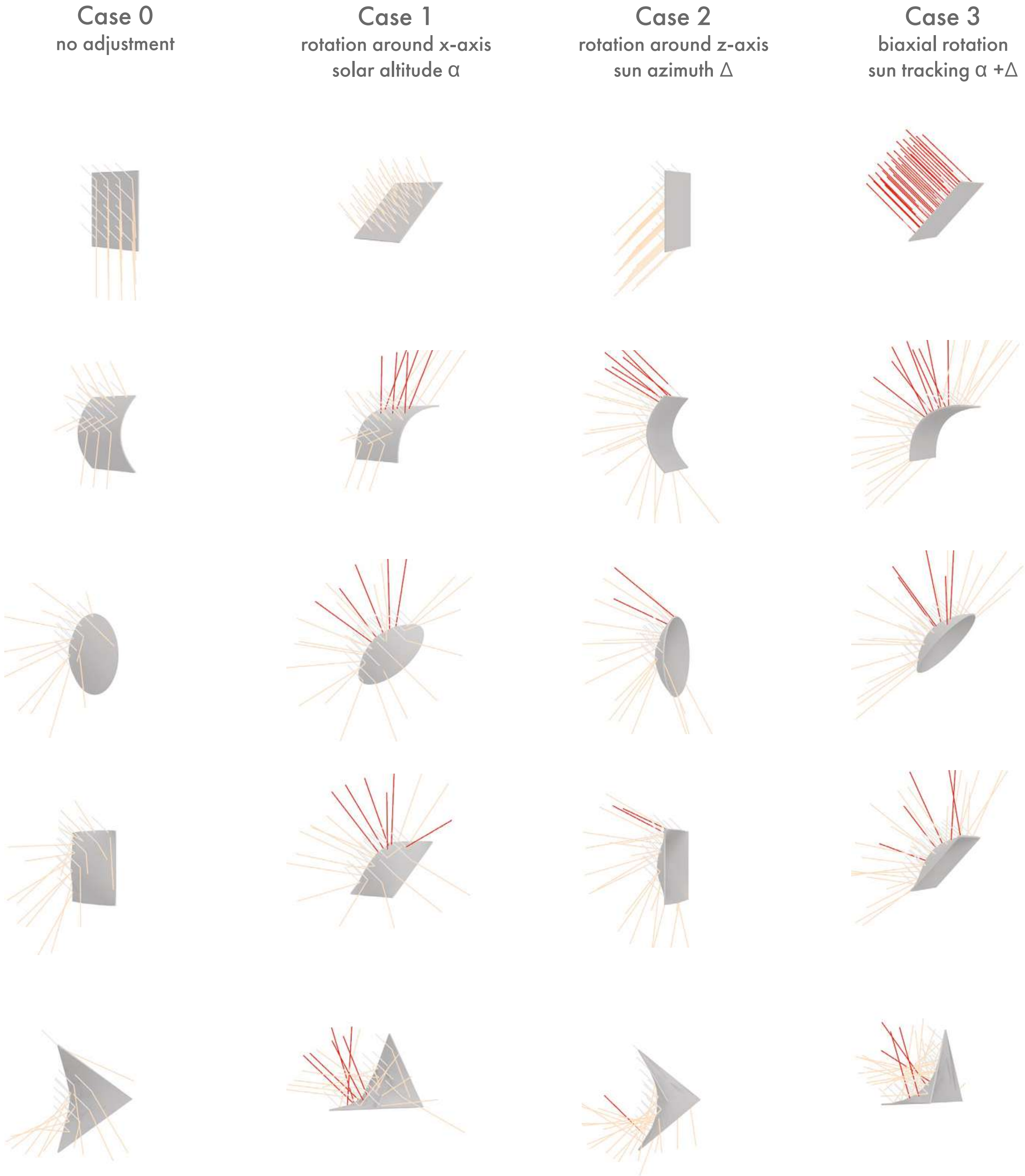
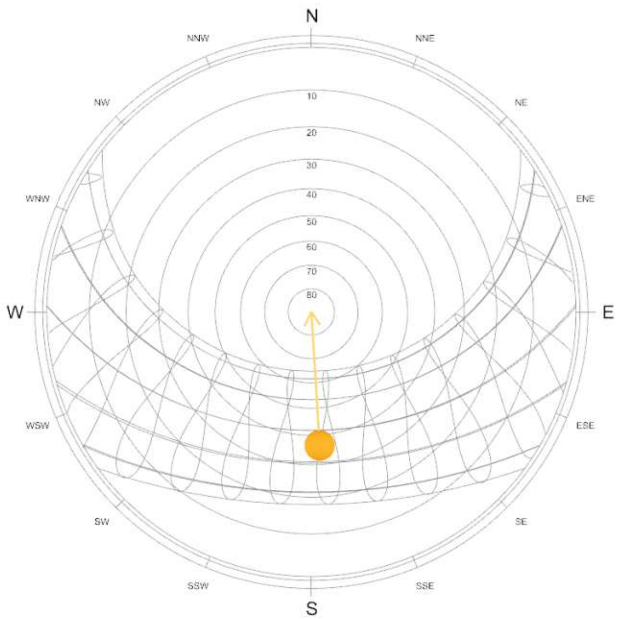


Fig. 43. *reflection study at HS peak - 16.8 15:00*

surface
typology

05. October 12:00

Stuttgart



planar
no curvature

cylinder
single crv

revolved
double crv

t_{air} = 23.10°C
t_{UTCI} = 26.08°C

loft
double crv

α_{solar} = 36.38°
$\Delta_{azimuth}$ = 3.55°

saddle
double crv

Case 0
no adjustment

Case 1
rotation around x-axis
solar altitude α

Case 2
rotation around z-axis
sun azimuth Δ

Case 3
biaxial rotation
sun tracking α +Δ

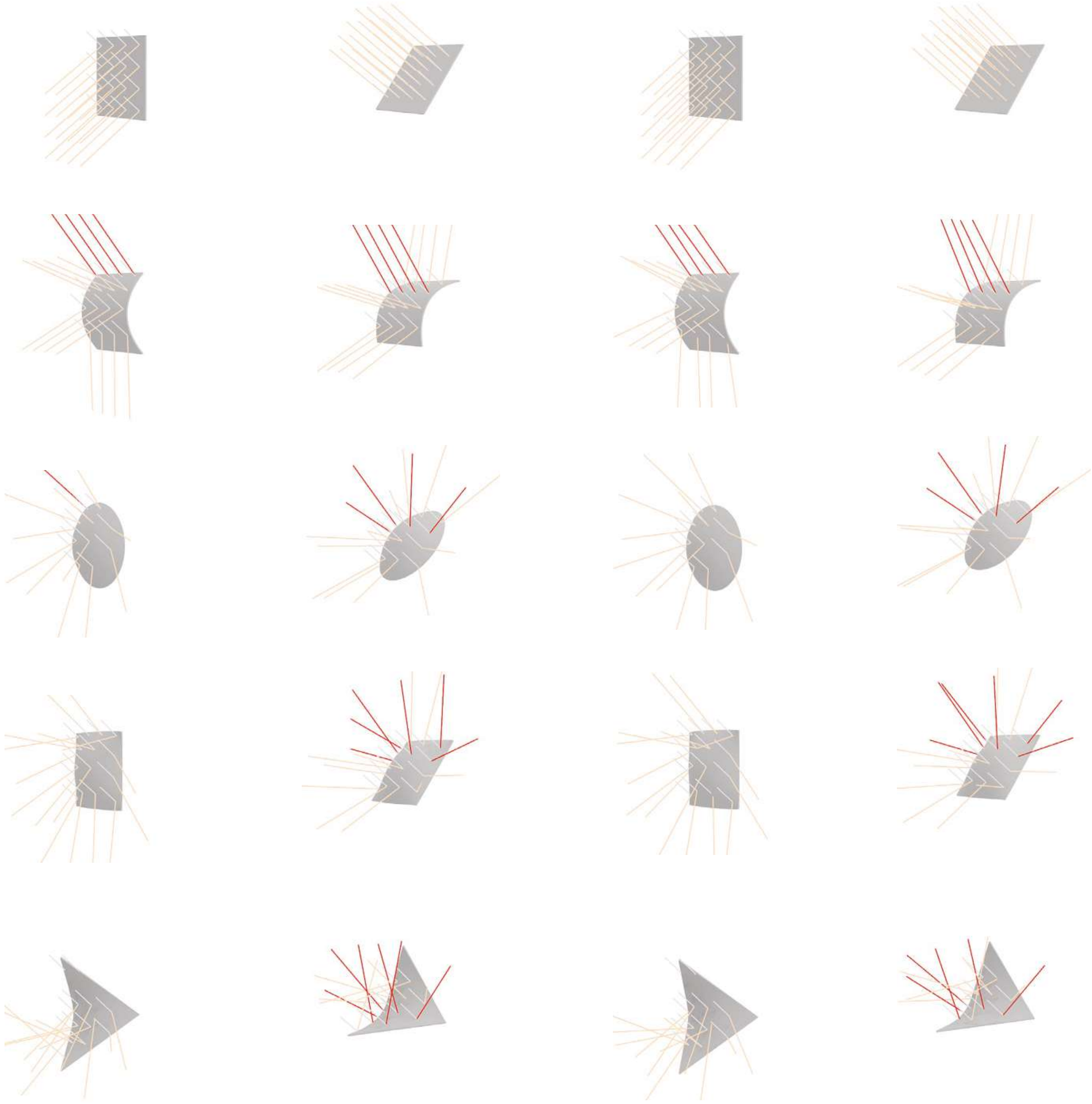
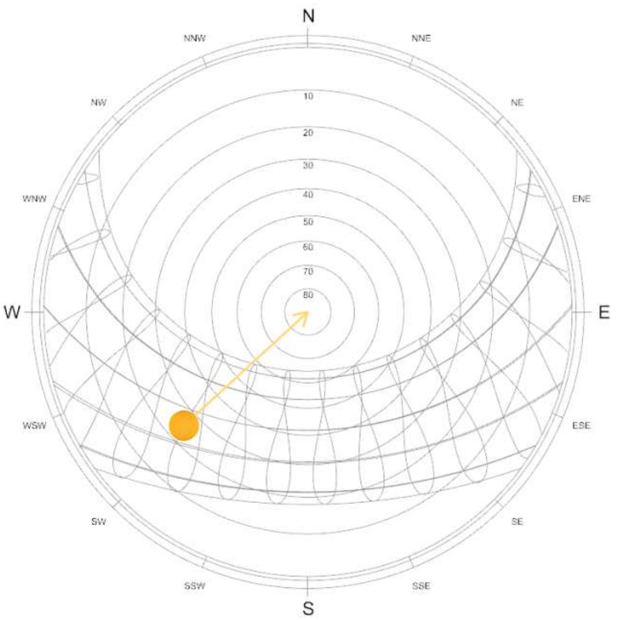


Fig. 44. *reflection study at HS end - 05.10 12:00*

surface typology

05. October 15:00

Stuttgart



t_{air} = 24.80°C
t_{UTCI} = 25.16°C

α_{solar} = 25.05°
$\Delta_{azimuth}$ = -47.53°

planar
no curvature

cylinder
single crv

revolved
double crv

loft
double crv

saddle
double crv

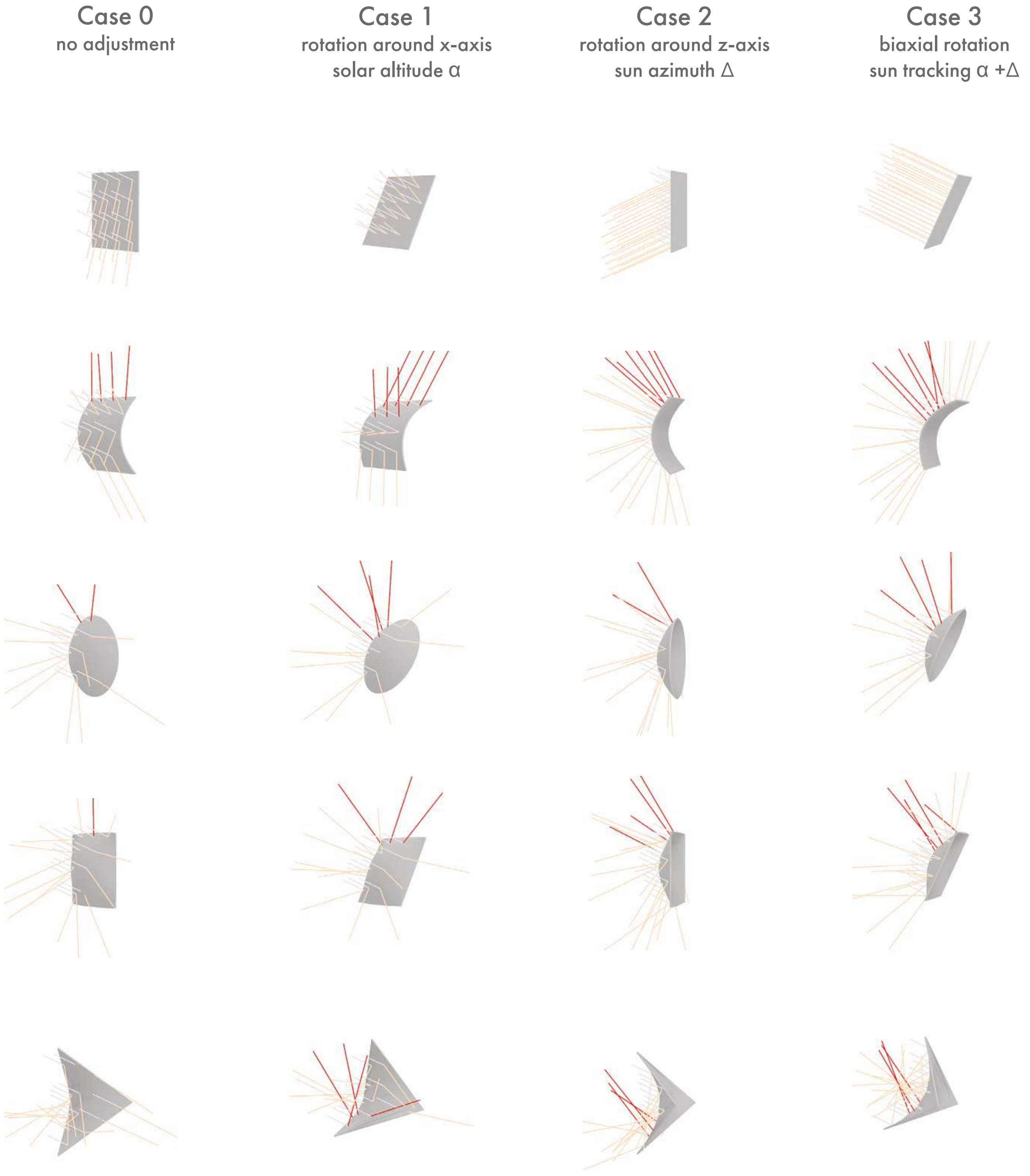


Fig. 45 *reflection study at HS end - 05.10 15:00*

Results | Interpretation

The areas covered on the charts reveal the performance R[%] for each shape in every case and chosen HOY.

Reflection performance is strongly influenced by the initial orientation of the analyzed surface.

Conclusion:
For Case 0 the all reflected rays for all surface typologies do not fall between the previously defined range, thus no performance is registered for Case 0.

No significant performance is investigated for Case 2.

No significant difference is registered between single and double curved surfaces.

The least performance is registered with the revolved surface. This typology would also most of the incoming rays into the interior of the building.

The planar surface is the only one that renders R = 100%. Even though it is retro-reflective in Case 3, full performance is not noted when solar altitude is below 45°C.

surface
typology

planar
no curvature

cylinder
single crv

revolved
double crv

loft
double crv

saddle
double crv

Case 0	Case 1	Case 2	Case 3
no adjustment	rotation around x-axis solar altitude α	rotation around z-axis sun azimuth Δ	biaxial rotation sun tracking α +Δ

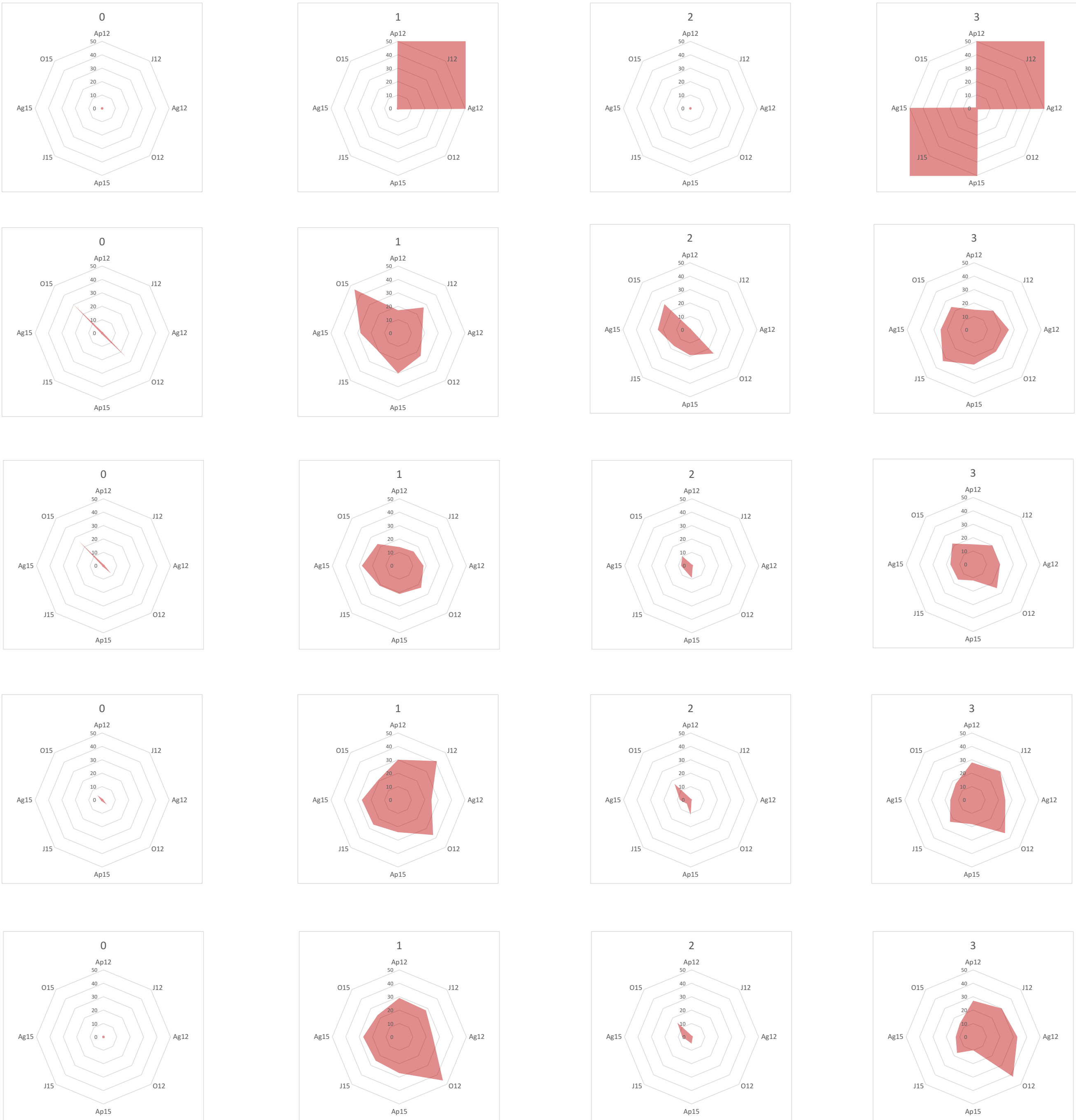


Fig. 46. *result charts for reflection performance R(%)*

Decision

Based on the previous conclusion, the following surface variation is taken into consideration for further development: the planar surface, single and double curved surfaces with linear edges and a rather low curvature.

Since biaxial movement requires more energy and a more complex system, usually resulting in more mass, with apparently no significant improvement in performance, only the inclination in respect to sun altitude will be further implemented for the kinetic system.

surface
typology

planar
no curvature

cylinder
single crv

revolved
double crv

loft
double crv

saddle
double crv

Case 0
no adjustment

Case 1
rotation around x-axis
solar altitude α

Case 2
rotation around z-axis
sun azimuth Δ

Case 3
biaxial rotation
sun tracking α +Δ

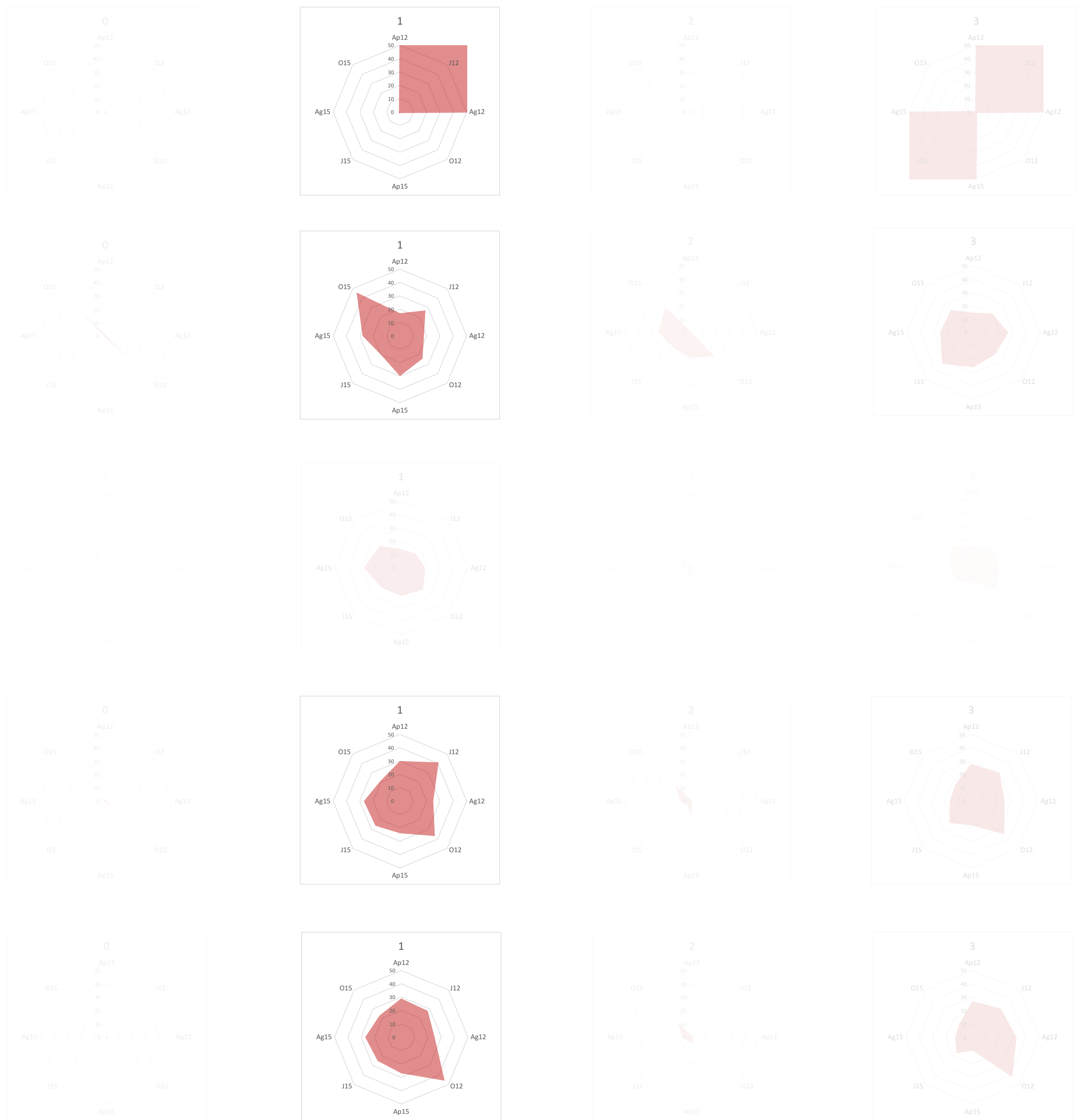


Fig. 47. *emphasis of relevant results for R(%)*

Location | Test Building

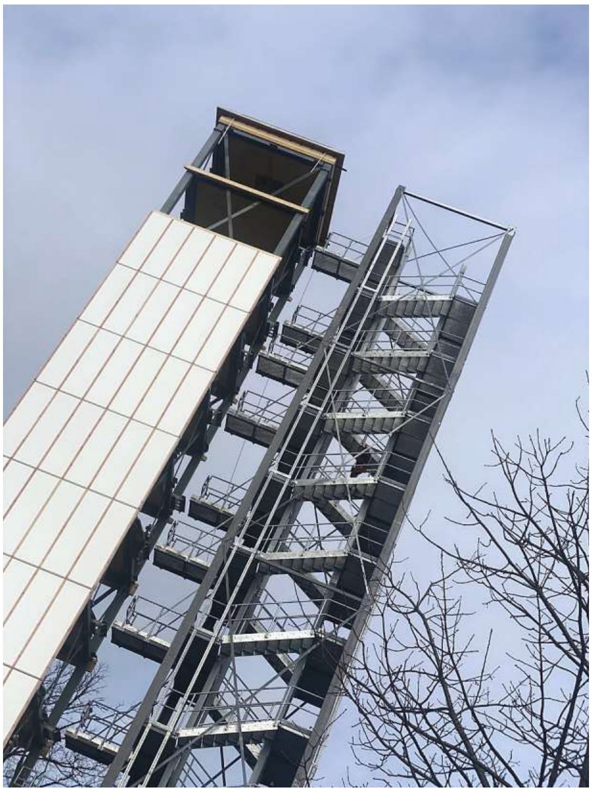
For the design of the solar responsive facade system specific location and facade orientation are required. For this project the design is made to fit onto the adaptive tower demonstrator in Campus Vaihingen, Stuttgart.

Rising 36 m above ground, the newly finished construction represents the highest adaptive structure in the world.

It has a modular build, with a 3 m story height and a quadratic floor plan measuring 5 x 5 m.

Strain gauges measure the deformations occurring under wind loads. These sensors transfer the measurements to the actuation system. Linear actuators are placed in the reinforcing elements and in the lower parts of the pillars. They can dampen the oscillation that occurs under external loads but also actively move the structure to simulate them.

Currently, preparations are being made to mount different adaptive facade systems onto the structure and to test their behavior and efficiency.



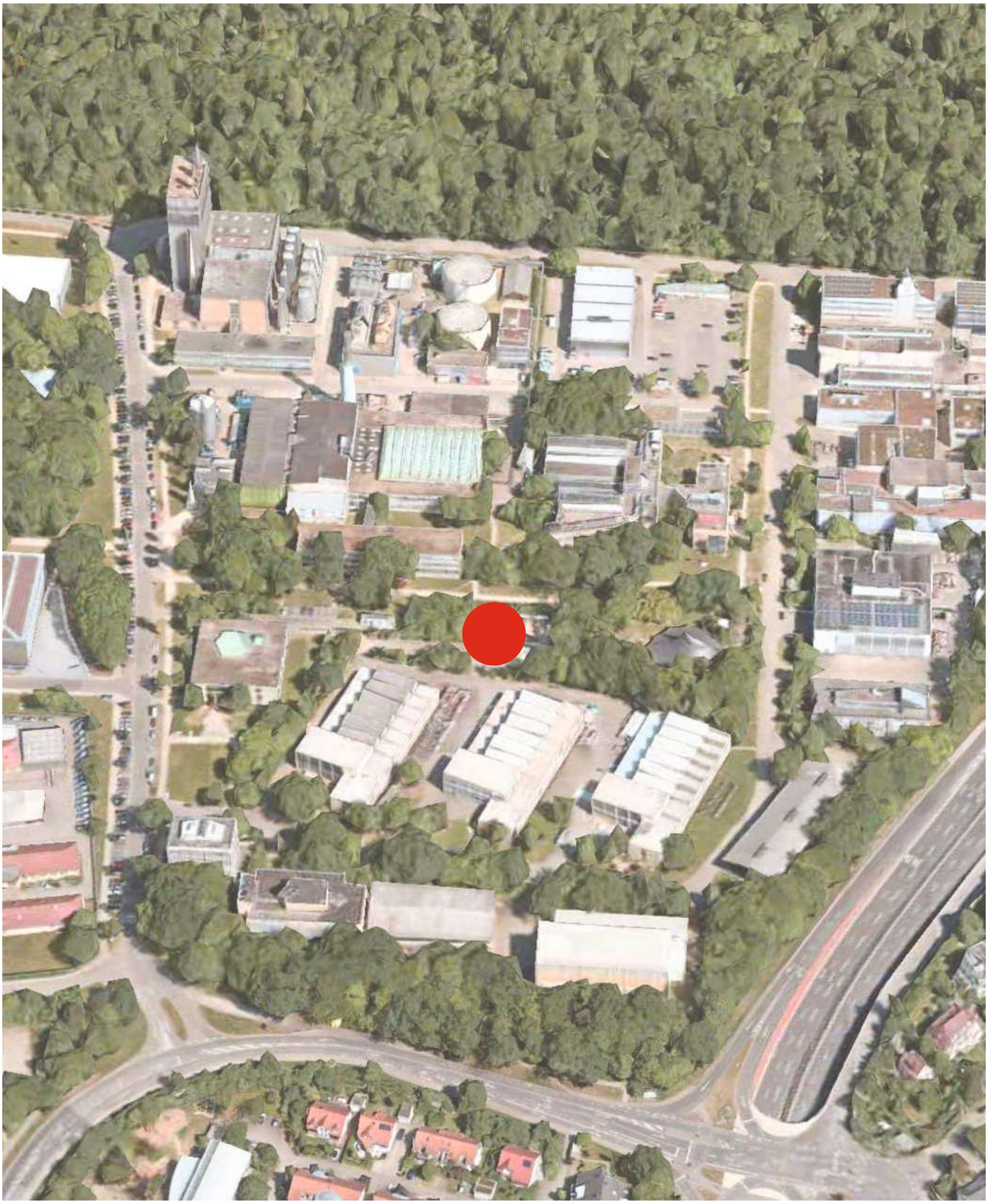


Fig. 48. site map

Incident Radiation in HS period

To determine where the adaptive second skin should be placed on the tower facade, an incident radiation analysis for the heat stress period was made using Ladybug.

This has shown that the South oriented faces display significantly more irradiation than the ones facing North. The NE and NW facades will not be considered for the facade design and will be kept opaque for daylight analysis, SW and SE facades will be glazed.

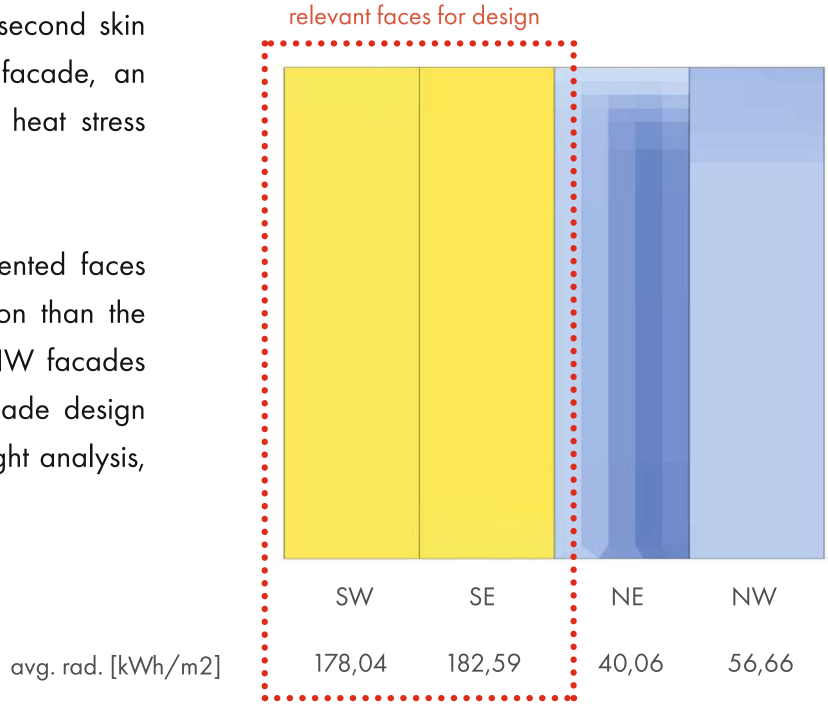
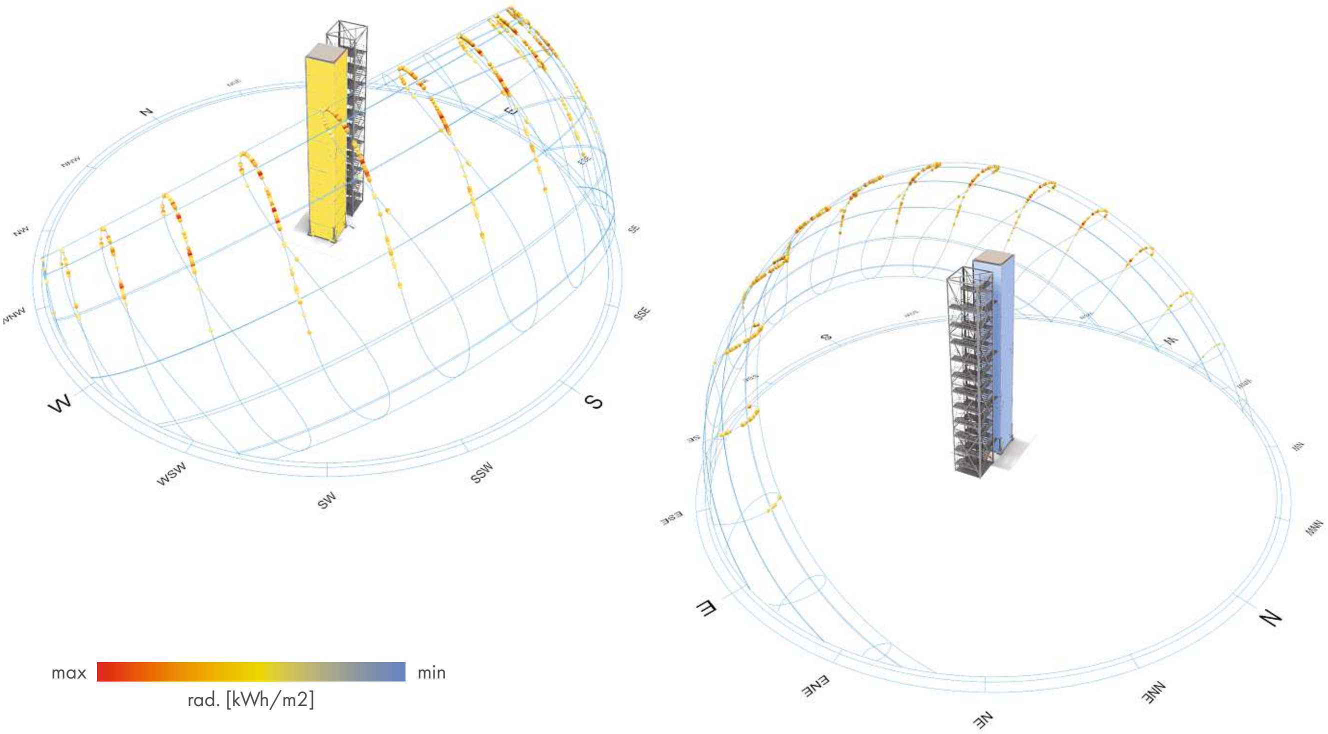


Fig. 49: *Incident radiation on tower faces and sun path showing sun position for the HS period.*

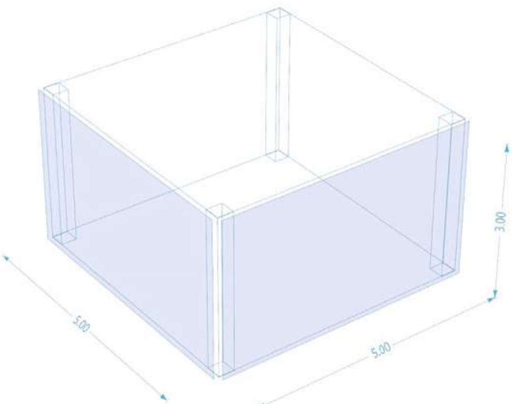
Fig. 50: *Incident radiation on simplified tower geometry shows that only the South facing surfces are insolated durring the HS period of Stuttgart with averege irradiation values for each face*



Preliminary design | Module definition

Fig. 51: *CAD model of the tower with applied materials*

Fig. 52: *Storey module 5 x 5 x 3 m with highlighted faces for design*



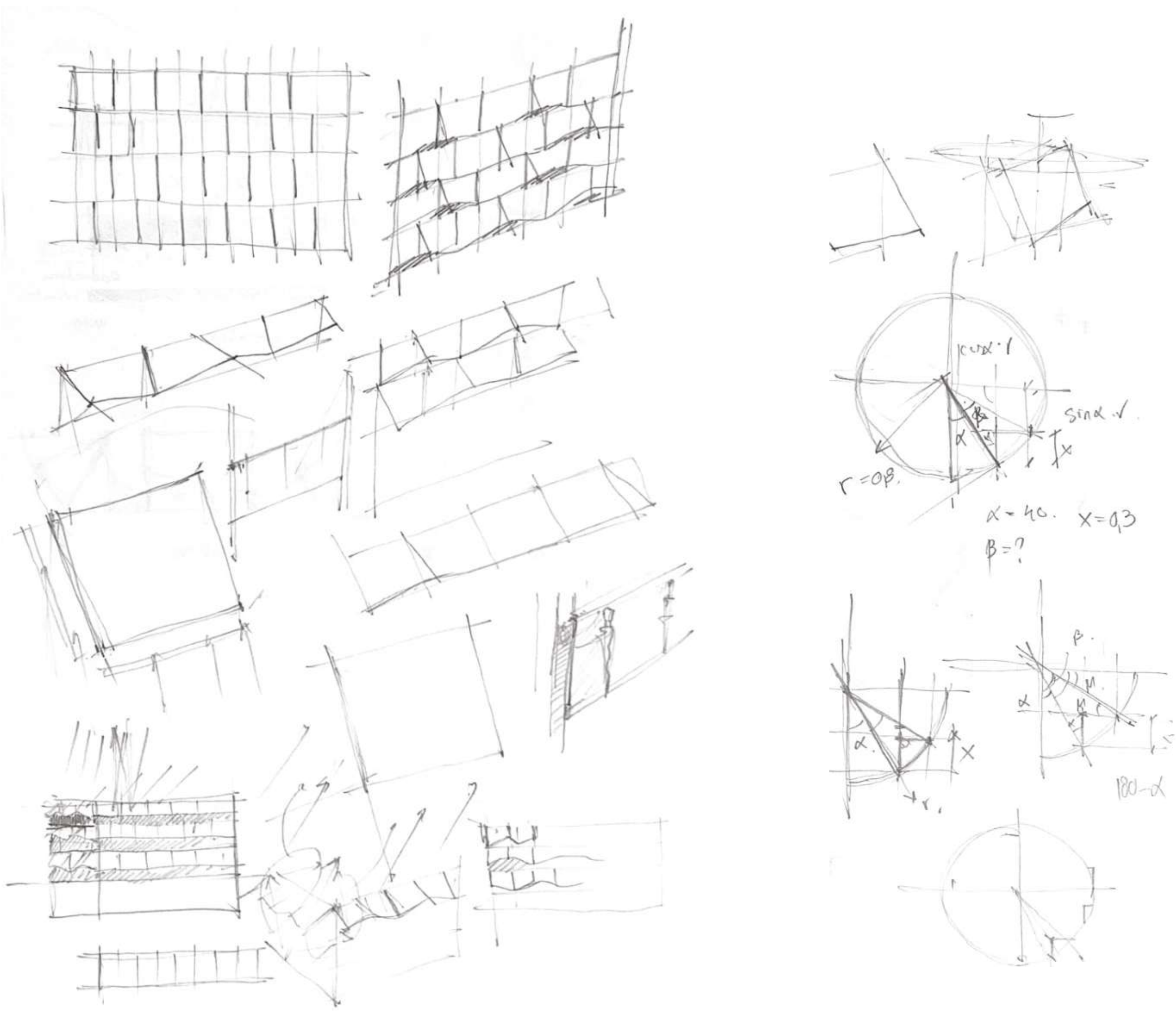
Based on the irradiation analysis, the South facing sides are covered with glazed panels, in front of which the adaptive facade skin will be placed. The North facing sides remain covered with the initial PTFE membrane. This configuration should imitate an indoor space for the DA.

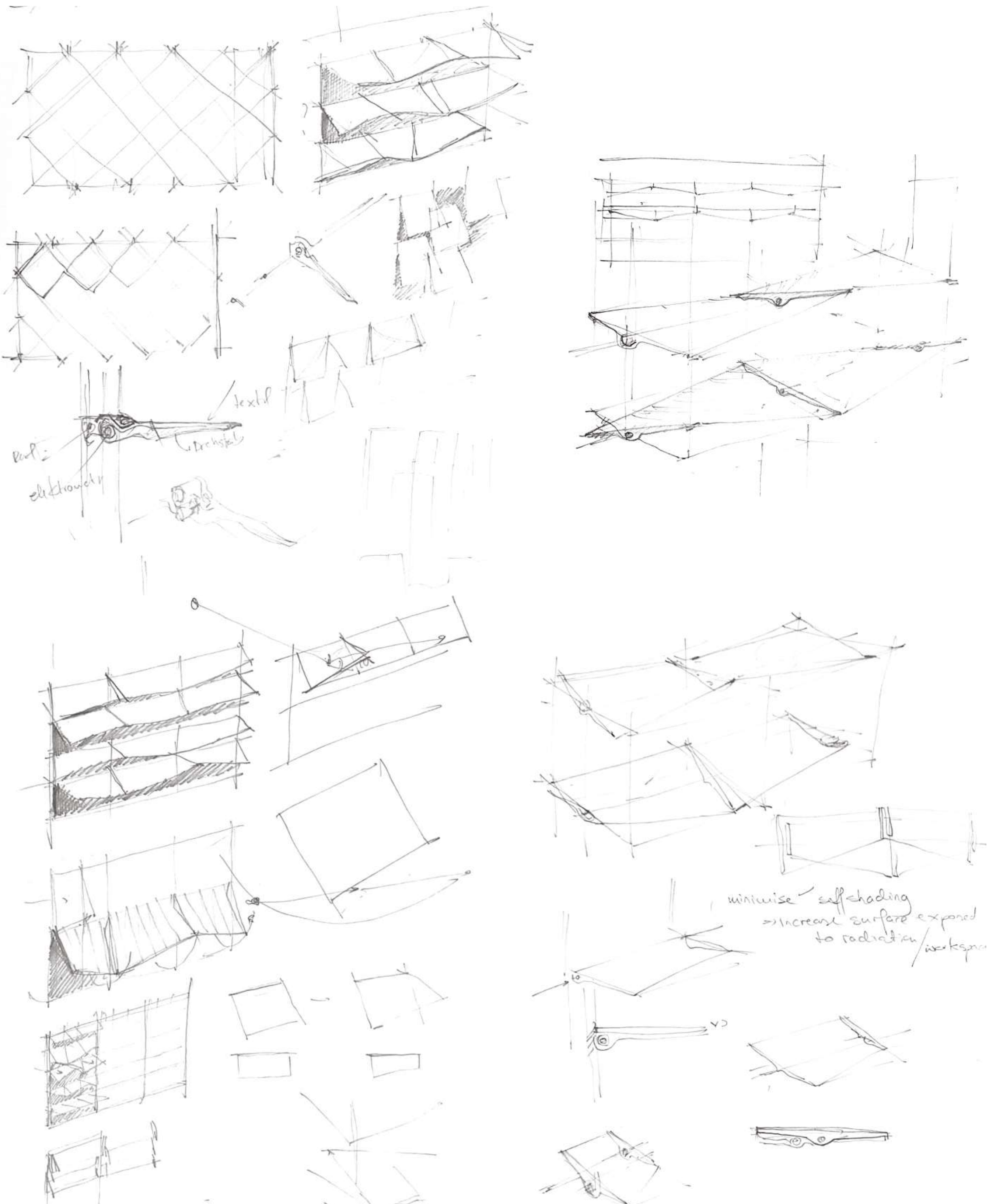
Due to the modular construction of the tower, the design is executed for one level module on the SE and SW faces. The boundary dimensions are set at 3m height and 5m length for each face.

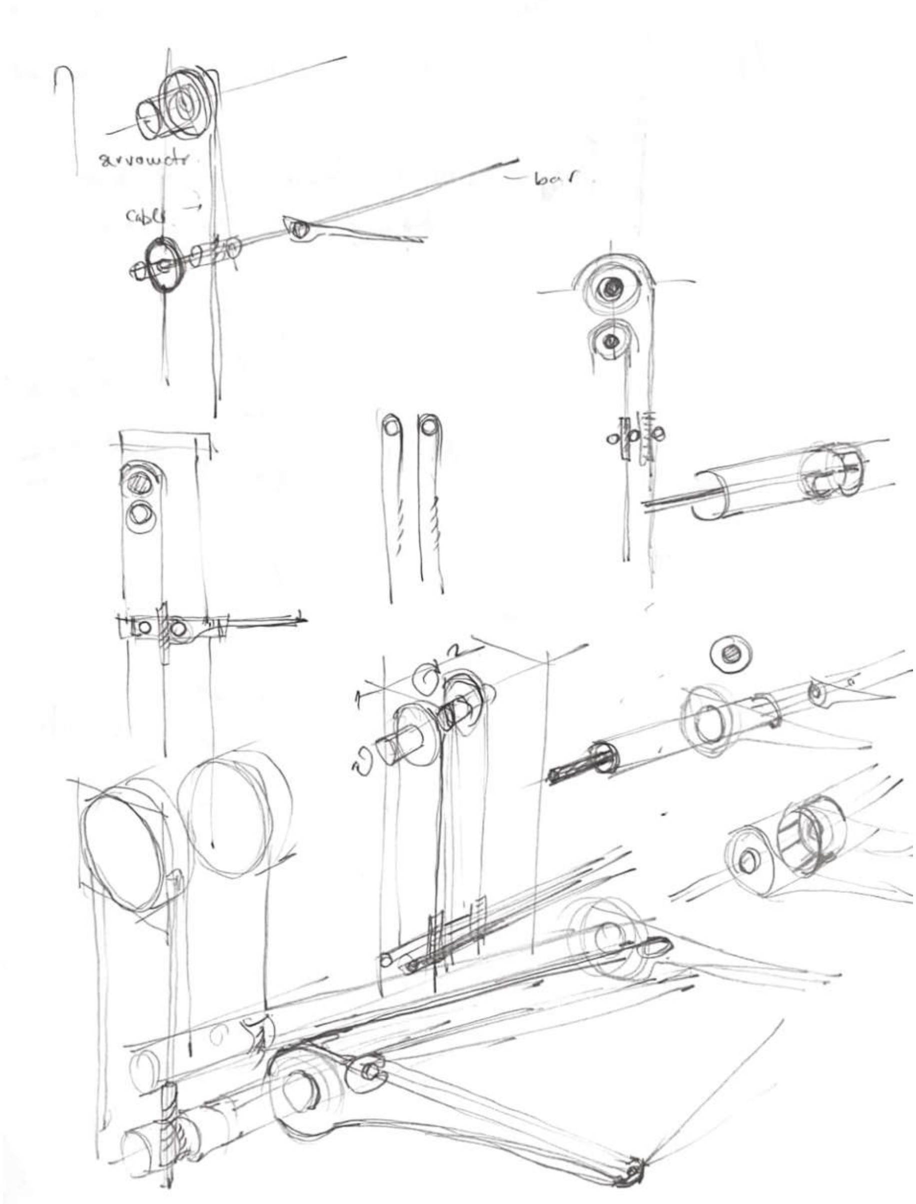
Preliminary design | Sketches

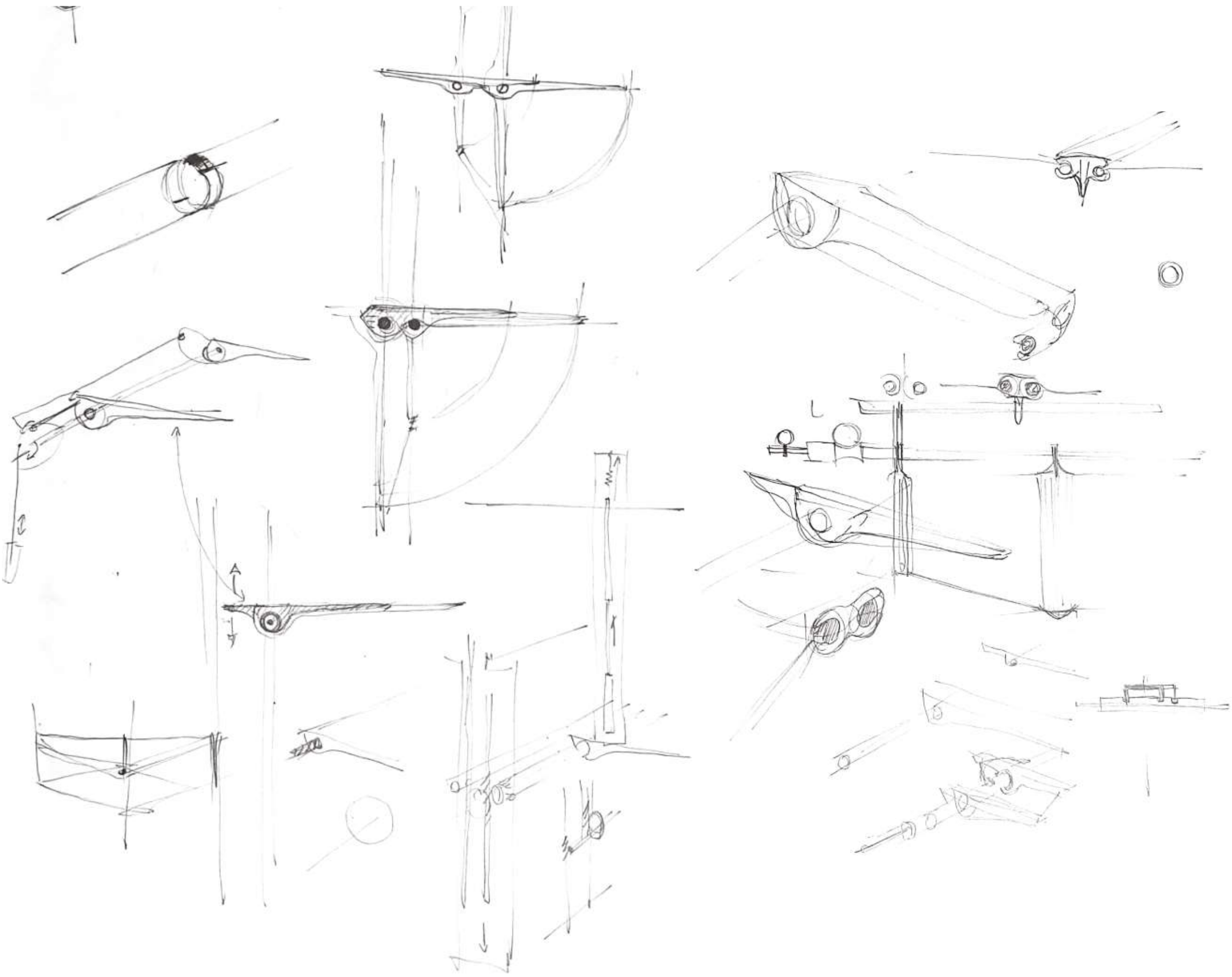
With the boundary dimensions set, the patterning of the facade surfaces is investigated. The geometry and kinematic of the adaptive system cannot be designed independently. When determining the shapes, the kinetic behavior and mechanism has to be considered as well. This way, the patterning of the facade determines the way it can behave and vice versa.

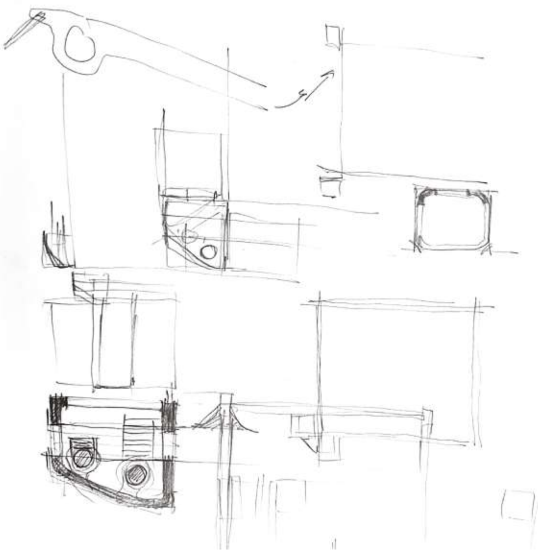
The concept is influenced by the understanding gained from the previously shown references, as well as from the decisions made based on the reflection analysis.

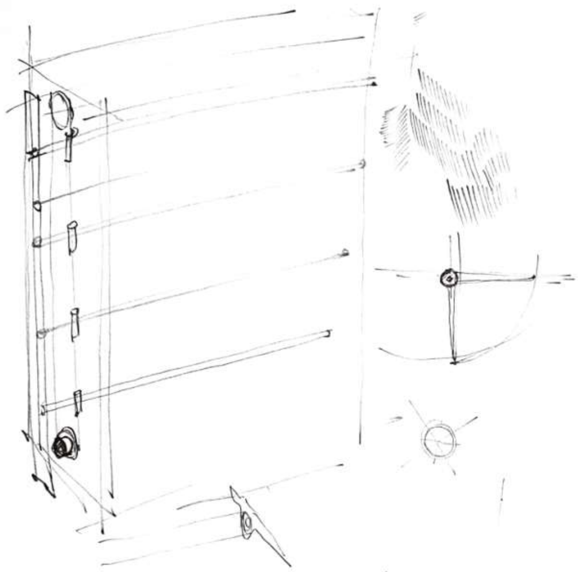



textil
minimise self-shading
=> increase surface exposed
to radiation/workspace


cable
bar
1
2







Concept

The concept derives from the well known venetian blinds, a vertical array of horizontal elements placed in front of windows for shading. These elements can rotate to increase the shading area, but only in respect to sun inclination. This motion is relevant for proper reflection while the facade is facing the sun directly and reflects the solar radiation into the urban fabric in every other case.

The presented approach mimics the sun-tracking motion by only using rotation along the horizontal axis of the elements. Mounting the facade elements on rotating fins that alternate rotation at different angles can orient the facade elements also in respect to the sun position.

Having two groups of alternating rotating elements can improve the reflection performance of the horizontal elements. One group will rotate in respect to solar altitude, while the other will rotate to mimic the orientation towards the solar azimuth.

This way, the elements can reflect solar radiation even when not facing the sun directly.

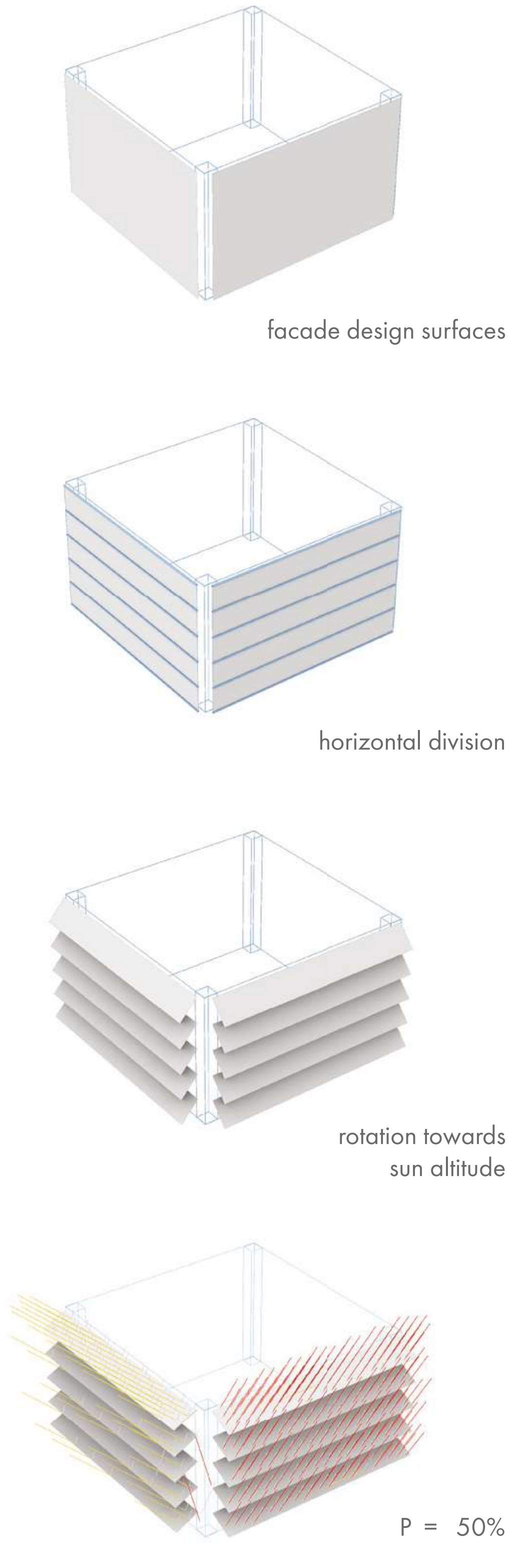
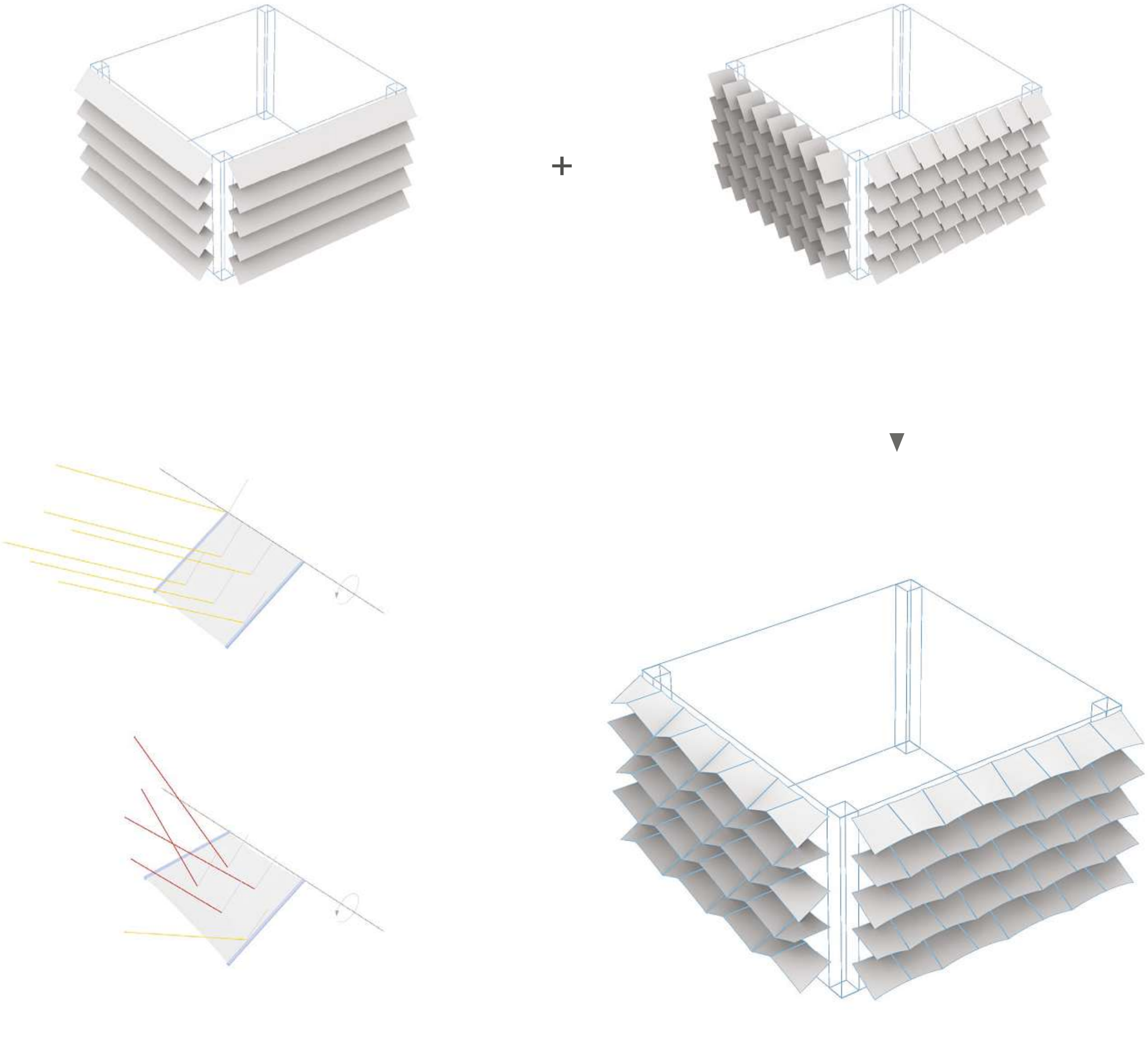
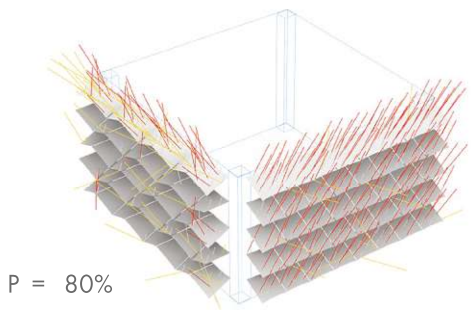


Fig. 53: *Diagram of conceptual development*





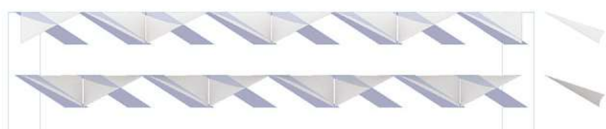
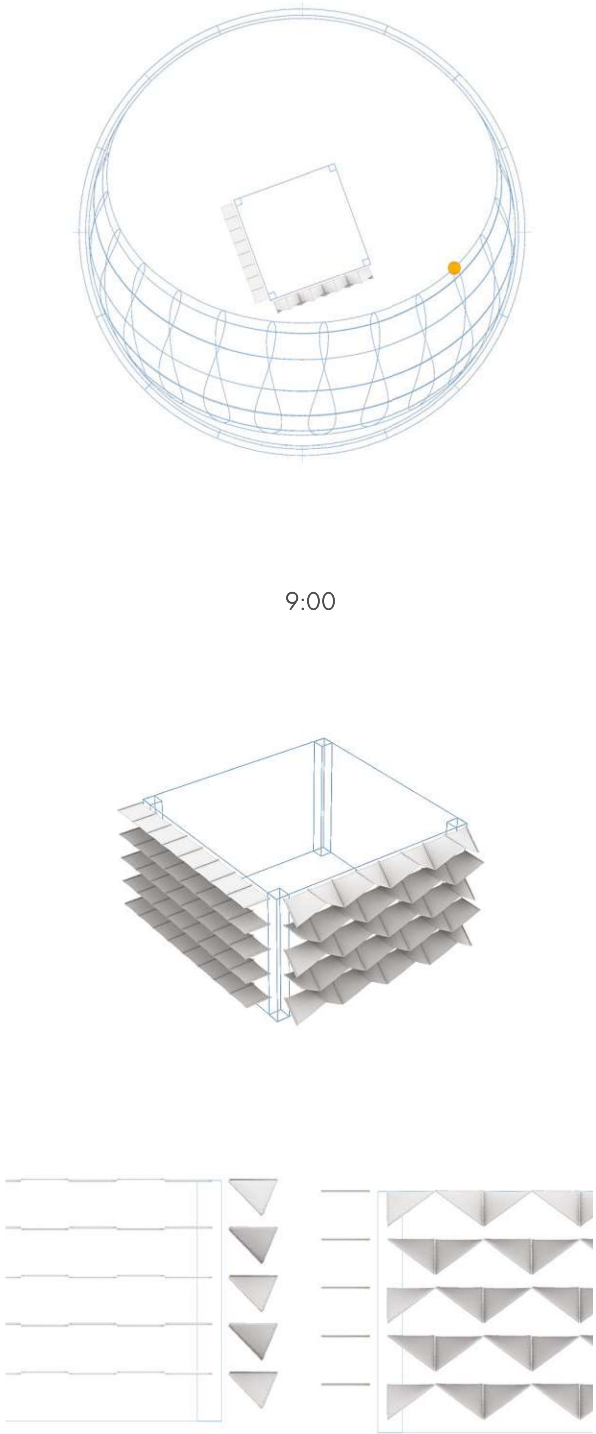


Fig. 54: *Side view: Alternating the rotation of the fins can mimic the sun-tracking behavior of individual panels and improves solar reflection towards the atmosphere*

Motion

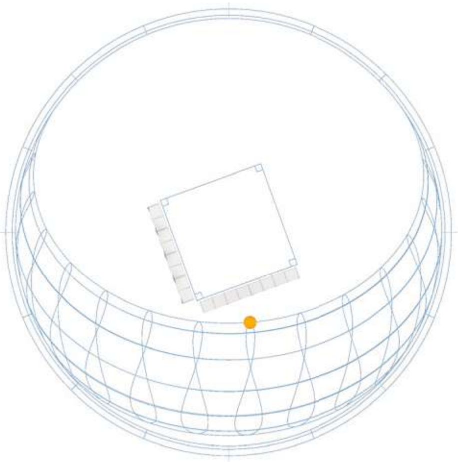
The actuation and implicit motion of the adaptive elemnts is determined by the sun position and the cardinal orientation of the facade. As the sun changes position during the day, the facade adapts and orient the textile elements towards it.

The elements will mantain their horizontal position when they are in shade from the tower. This is the case for the SW facade in the morning and for the SE facade in the evening. wh

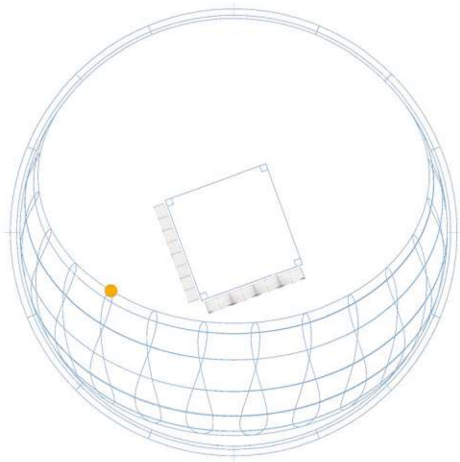


SW SE

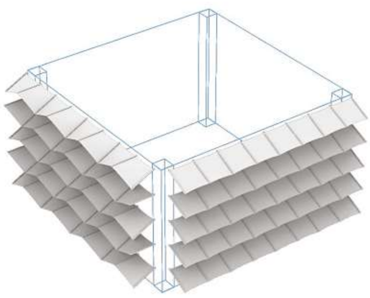
Fig. 55: *Diagram showing motion of the facade elements at different hours*

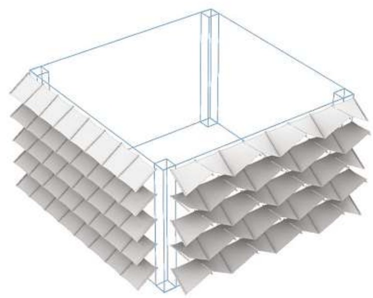


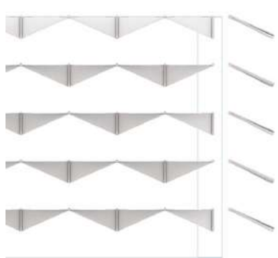
12:00



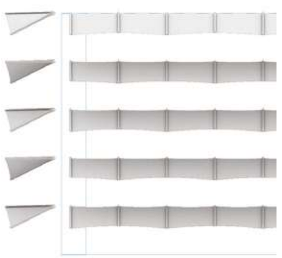
15:00



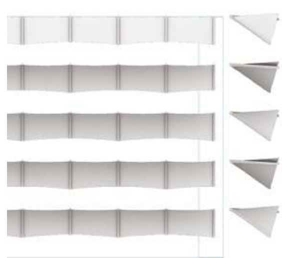




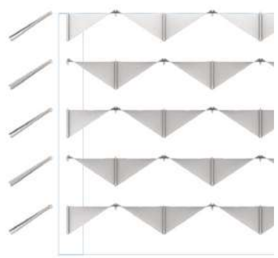
SW



SE



SW



SE

Structure| Details

The system is actuated by two servomotors (1 a,b) within the frame profile(2). These motors rotate two vertical bars (3 1,b) attatched to the inside of the frame profile. The bars have threaded rods (4 a,b) that allow the horizontal rotation of the bearing shaft bars (5 a,b). Two groups of caltilever fins (6 a,b) are each attatched to a bearing bar. To maintain the same rotation axis for the two groups, one bearing bar is placed within the other, and gaps (in red) are considered so that no collisions occur. The bars are mounted in sleave bearings (7)in the profile.

The two cantilever groups alternate along their linear array on the shaft bar. Textile elements span between these elements. The first group (in white) rotates in respect to solar altitude, while the second one (in dark grey) will incline the textile tords the sun position in respect to its azimuth. The fins placed at the edge of each bar have a bracing element to compensate the tension caused by the stretching of the textile elements during actuation.

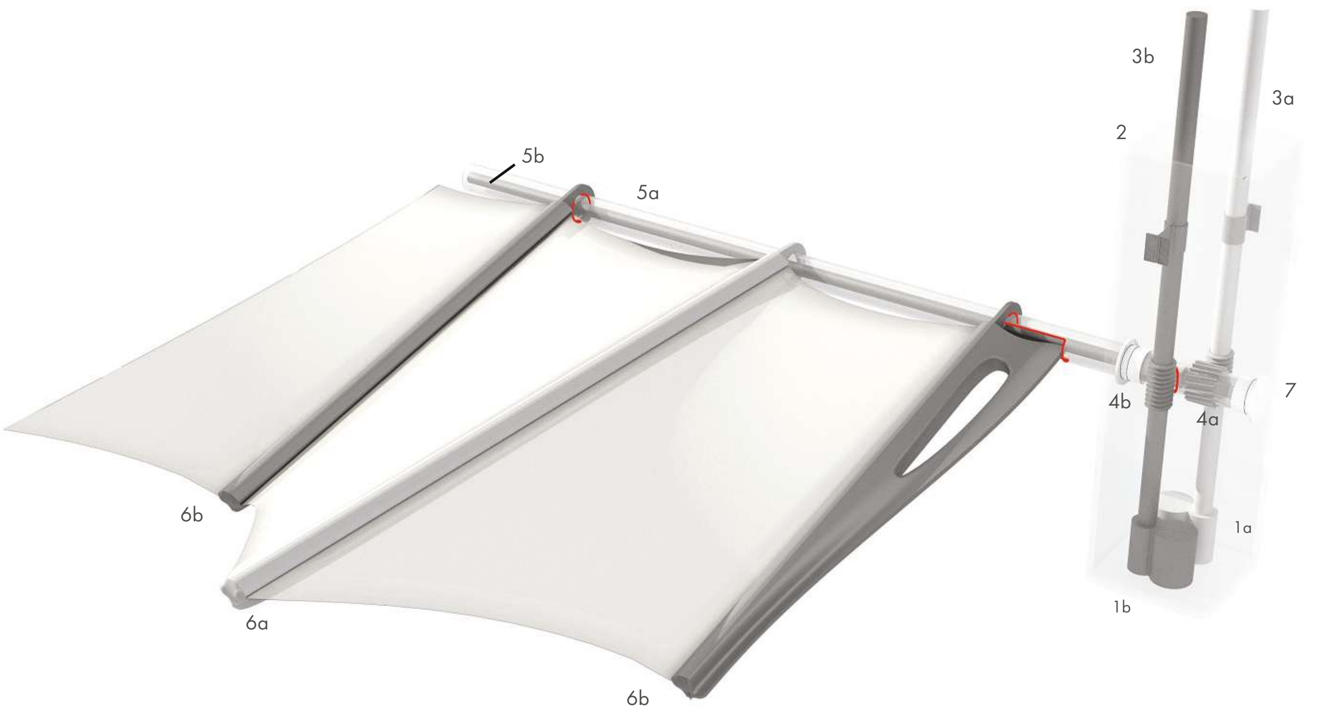
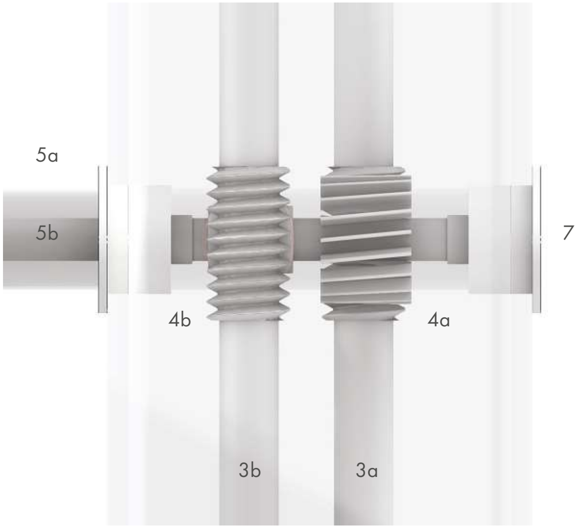
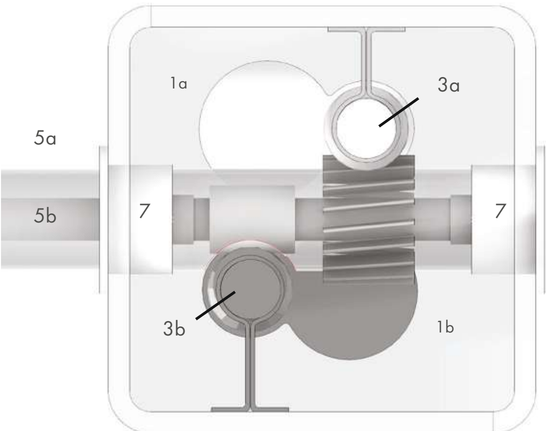


Fig. 56: *Perspective of mechanism components. The dlength of the textile elements is reduced for vizialization purposes. Mechanism for the first actuator a (in white) and second b (in dark grey)*

Fig. 57: *Profile front view*

Fig. 58: *Profile left view*





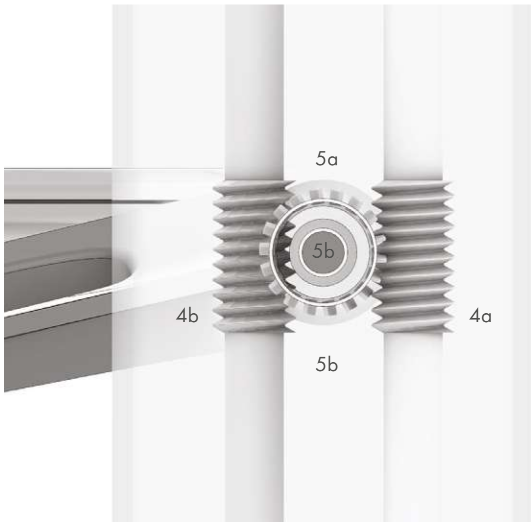


Fig. 59: *Profile top view.*

Fig. 60: *Profile right view*

Fig. 61: *System front view*

Fig. 62: *System top view*

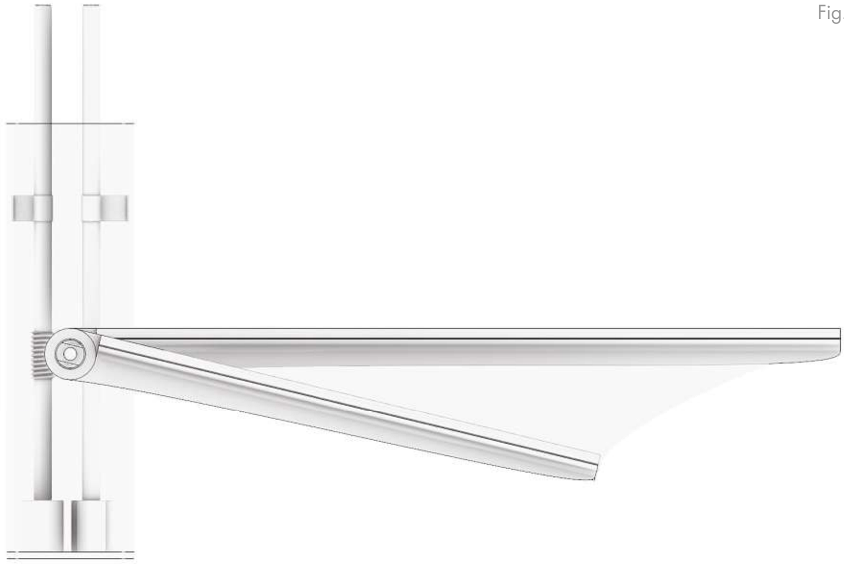


Fig. 63: *System left view*

Fig. 64: *System right view*

Structural Analysis

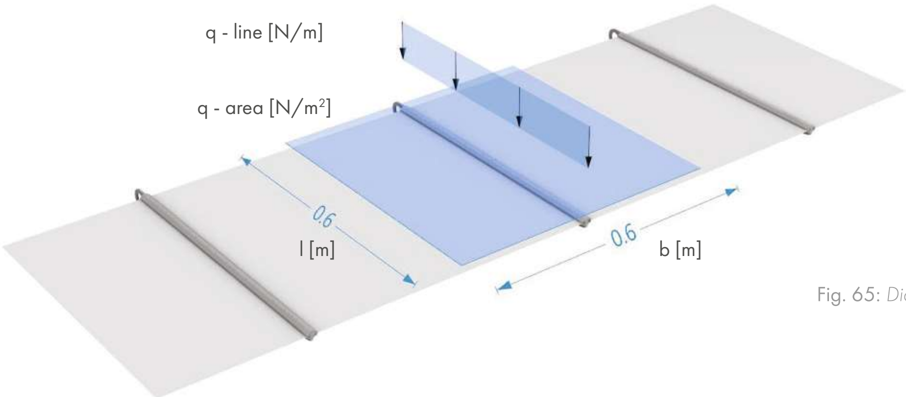


Fig. 65: *Diagram for load calculation*

$$q = (w + g_{membran})/0{,}6$$
$$\gamma_{membran} = 60g/m^2$$
$$g_{membran} = \gamma_{membran} * a_{membran} * g$$
$$g_{membran} = 60 * 10^{-3} * 0{,}6 * 0{,}6 * 10$$
$$g_{membran} = 0{,}216\ N$$

$$\gamma_{aluminium} = 27kN/m^3$$
$$g_{profil} = V_{profil} * \gamma_{aluminium}$$
$$g_{profil} = 176{,}7 * \ 10^{-6} * 27$$
$$g_{profil} = 4{,}771\ N$$

$$w = P * a_{membran} * C_d$$
$$P = 0{,}613 * v^2 \qquad v^2 = 35km/h = 9{,}72m/s$$
$$C_d = 2\ (for\ plane\ surface)$$
$$w = 0{,}613 * 9{,}27^2 * 0{,}36 * 2$$
$$w = 41{,}7N$$

$$q = 69{,}86\ N/m$$

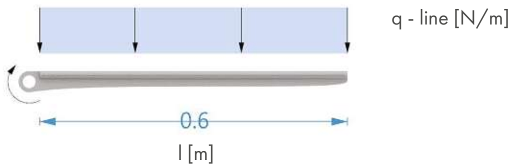


Fig. 66: *Diagram for load calculation on cantilever*

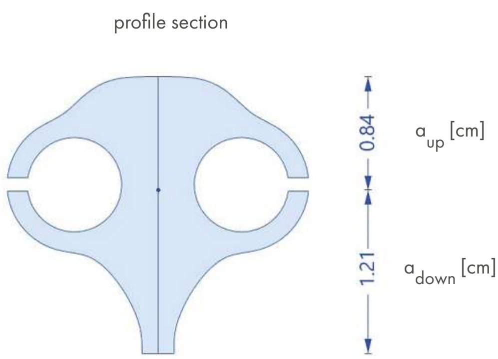


Fig. 67: *Cantilever profile section*

The structure is made of aluminium, with a tensile strength of 100MPa. The textile is Tyvek Alu, with a characteristic mass of 60g/m^2. For the showcased design, with the facde subdivision of 5/8, a textile module of 0,6 x 0,6 m used.

The area moment of inertia I for the specific profile of the cantilever fins is calculated with GH.

$$\sigma_t = \frac{M_b}{W} \qquad M_b = q * \frac{l^2}{2} + g_{profil} * \frac{l}{2} \qquad W = \frac{I}{a_{max}}$$

$$I = 0{,}417\ cm^4$$

$$\sigma_{aluminium} = 100\ MPa$$

$$M_b = 69{,}86 * \frac{0{,}36}{2} + 4{,}771 * \frac{0{,}6}{2}$$

$$M_b = 14\ Nm$$

$$W_{down} = \frac{I}{a_{down}} = 0{,}35 * 10^{-6} \qquad W_{up} = \frac{I}{a_{up}} = 0{,}5 * 10^{-6}$$

$$W = \frac{W_{down} + W_{up}}{2} = 0{,}425 * 10^{-6}\ m^3$$

$$\sigma_t = 14 * \frac{10^6}{0{,}425} = 32{,}94 * \frac{10^6 N}{m^2} = 32{,}94 MPa$$

$$\sigma_t * 1{,}5 \leq \sigma_{aluminium}$$

$$\mathbf{49,41\ MPa \leq\ 100\ MPa}$$

Optimization| Self shading

To reduce mass and improve the performance of the adaptive facade, the geonetry is investigated for self-shading.

It is assumed that only insolated parts of the material reflect solar radiation. By reducing self cast shadow, the insolated material area is increased, which should result in better reflection performance.

Using LB an insolation analysis is made for different subdivisions of the facade, to investigate if the dimension of the textile elements influence the overall insolated area. This analysis is made for 21.06 at 9:00, 12:00 and 15:00.

The material performance **M[%]** is defined by the ration between the insolated material area **Mi** to the total area of the material **Mt.**

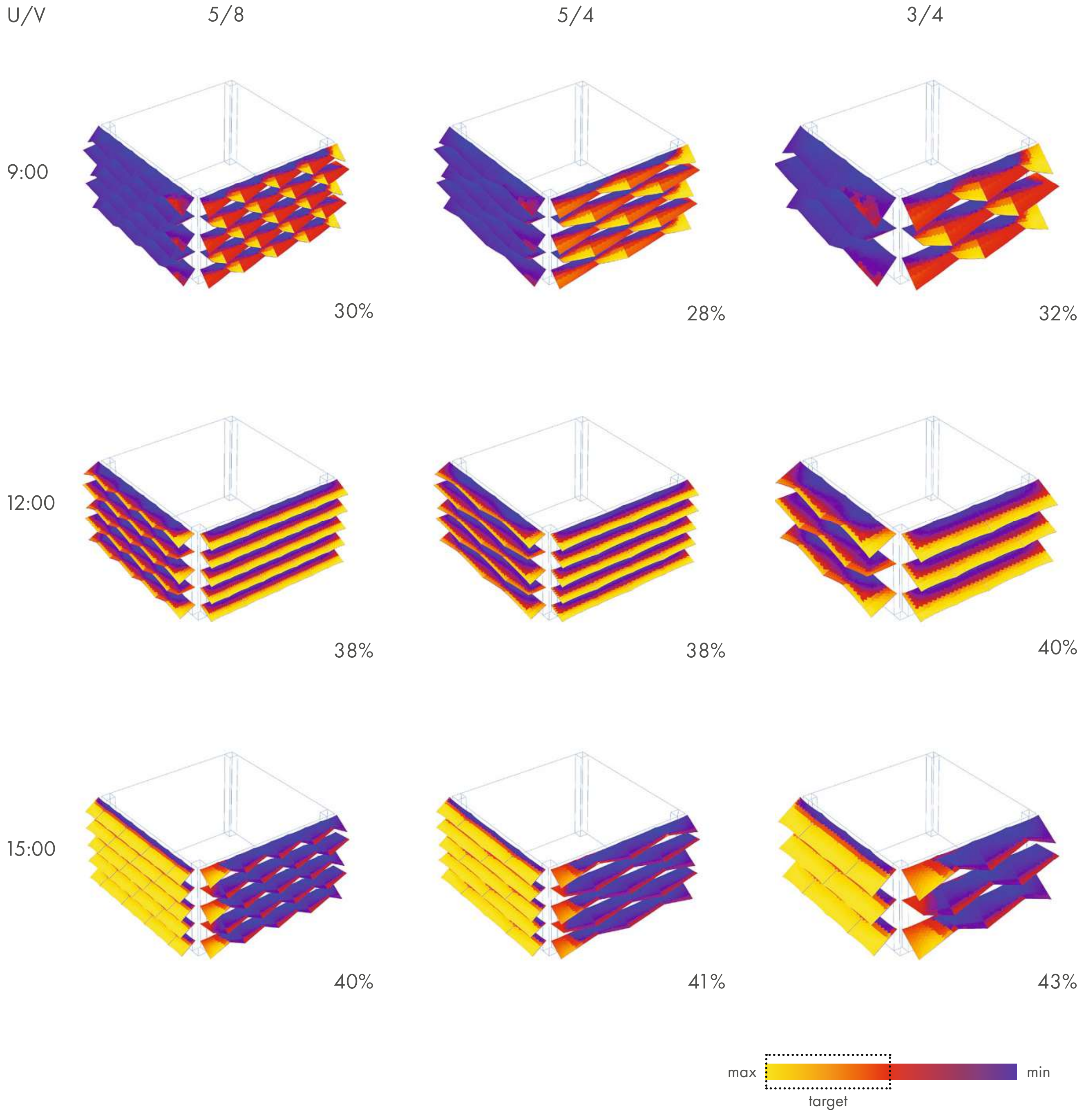
$$M = \frac{M_i}{M_t}\ [\%]$$

For the shape optimization of the textile elements, the parts that are not insolated at all throughout the day are left out. The new shape is then tested for dailighting peformance with CS, for a target of 800 lux. If the target is not met, the shape is adjusted. The resulting shape is then tested again for material and reflection performance for the comparison with the initial results.

Fig. 68: *Diagram showing insolation analysis for different facade subdivisions at different hours*

The influence of the element subdivision on the self shade generation is investigated below, with the resulting **M[%]** for each case.

As it shows, the same amount of geometry is affected by radiation regardless of subdivision parameters.

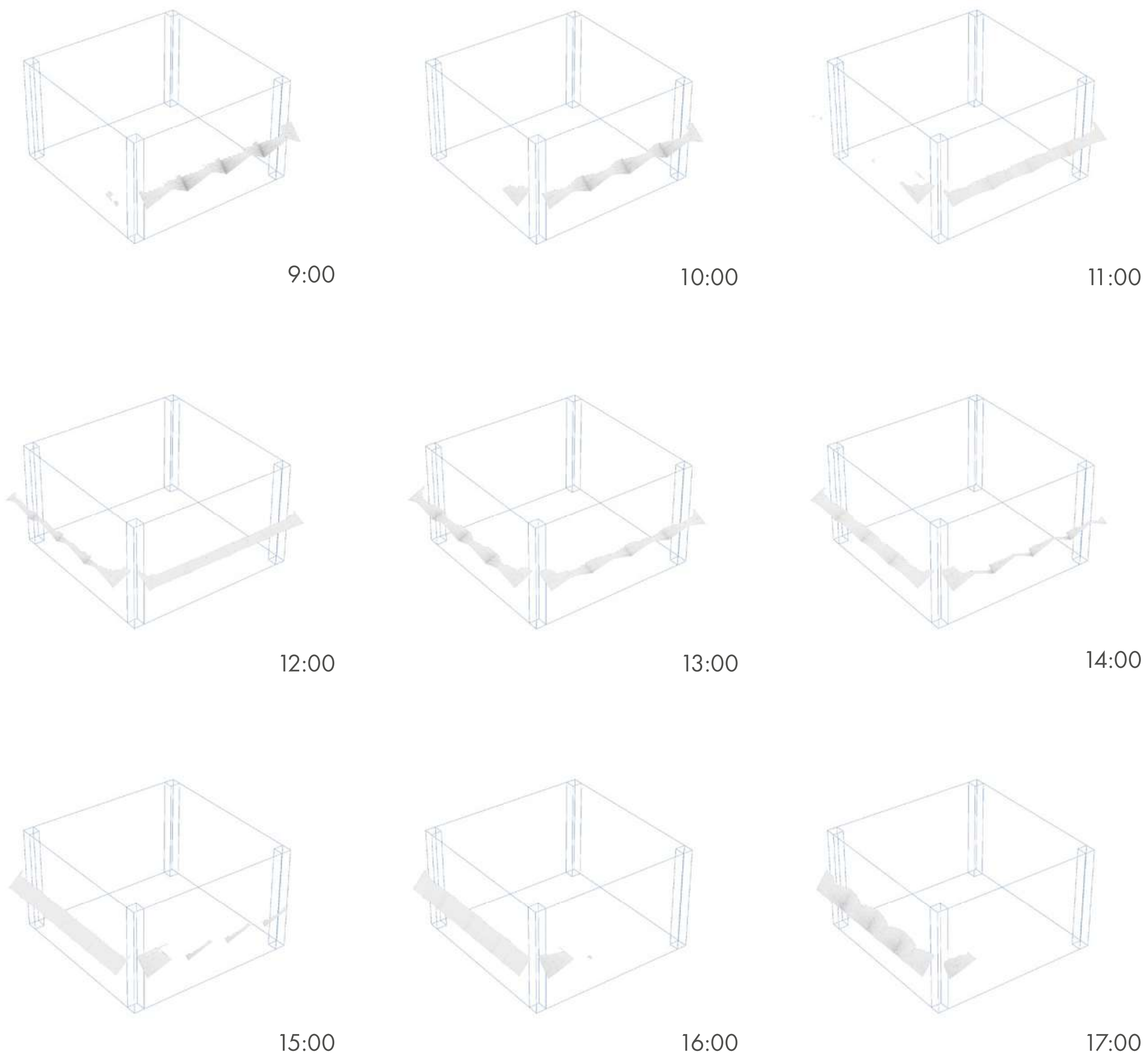


Optimization| Shape

To improve the shape and material use of the facade elements, parts that are in shade throughout the entire day are left out.

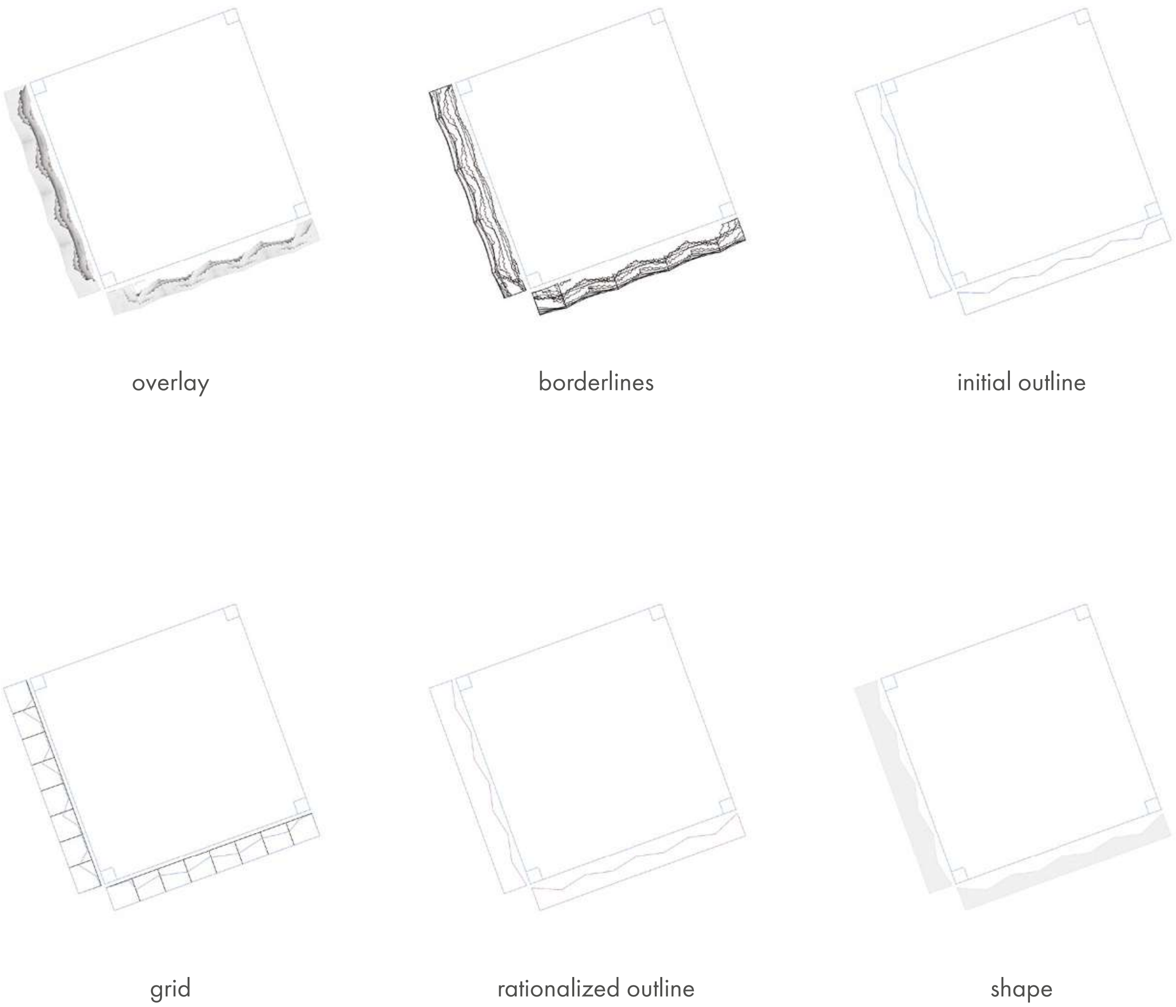
The motion is looked at throughout the day from 9:00 to 17:00. At each hour, the amount of insolated material is extracted, while shaded parts are left out.

Fig. 69: *Diagram showing extracted insolated material for each hour of the day*



Overlaying the resulting parts and outlining the projection reveals that material near the facade is always in shade. The resulting outline is fitted to the subdivision grid. The new shape is evaluated for daylighting performance.

Fig. 70. *Diagram of shape optimization process*



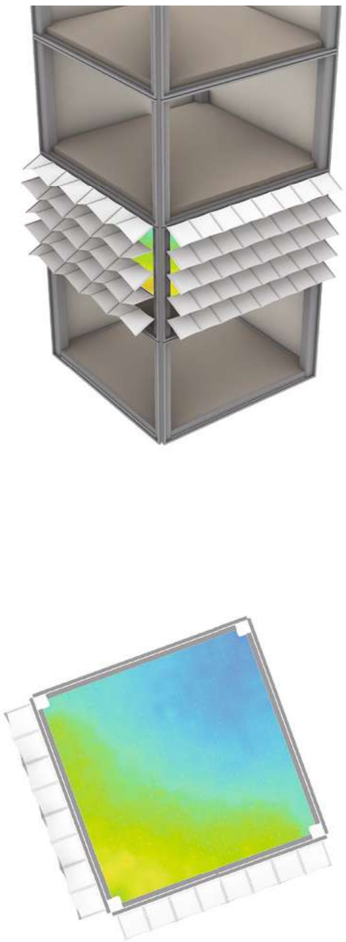
Daylight Analysis

For the DA materials are assigned to the model as mentioned previously. The day is set at 21 June 12:00 o'clock. A simulation without the second skin is run to determine the default median illumination value.

The baseline value is determined for the chosen subdivision U/V = 5/8 as comparison value for the optimization. Different materials are chosen

default
2597 lux

Fig. 71. *DA default with bare structure*

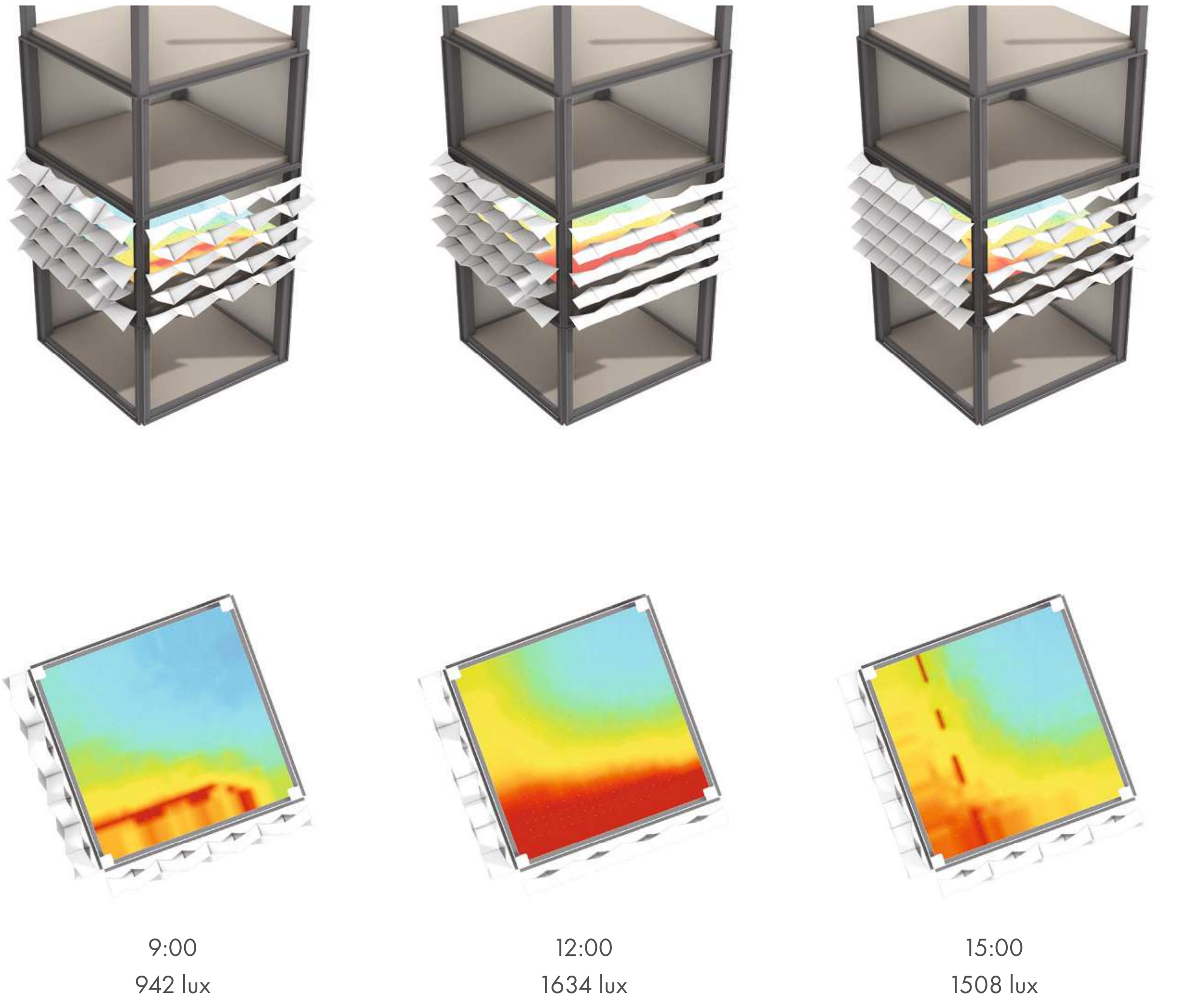


baseline
951 lux

Fig. 72. *DA baseline with 5/8 subdivision*

To evaluate the new shape a daylight analysis is conducted using Point in Time Illuminance with Climate Studio, with the day set to 21.06 at 9:00, 12:00 and 18:00 o'clock

The target illuminance is max 800 lux which is by far exceeded in the two latter cases. The gap on the facade edge lets too much light in resulting in undesirable illumination and glare. Leaving gaps at edge along the facade lets too much light to pass through.



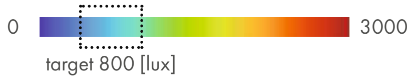


Fig. 73. *DA for optimized shape*

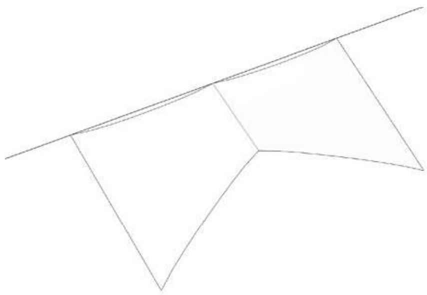


Fig. 74. *Final shape morphology*

Having different lengths for the rotating fins results in a shape that doesn't leave gaps along the facade edge. Reducing the length of the second actuation fins to half results in 25% material reduction. This renders satisfying daylighting performance compared to the previous optimization.

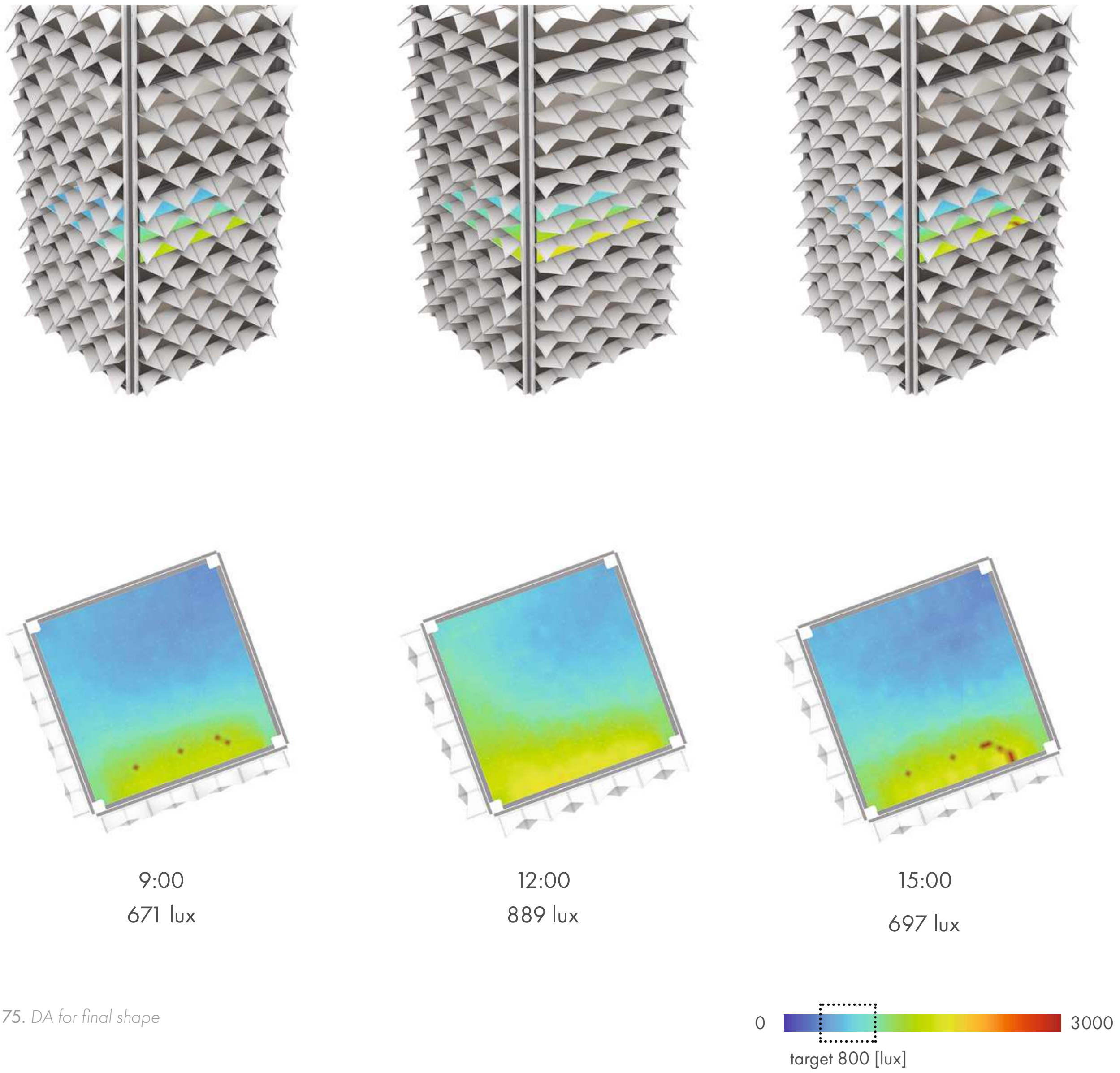
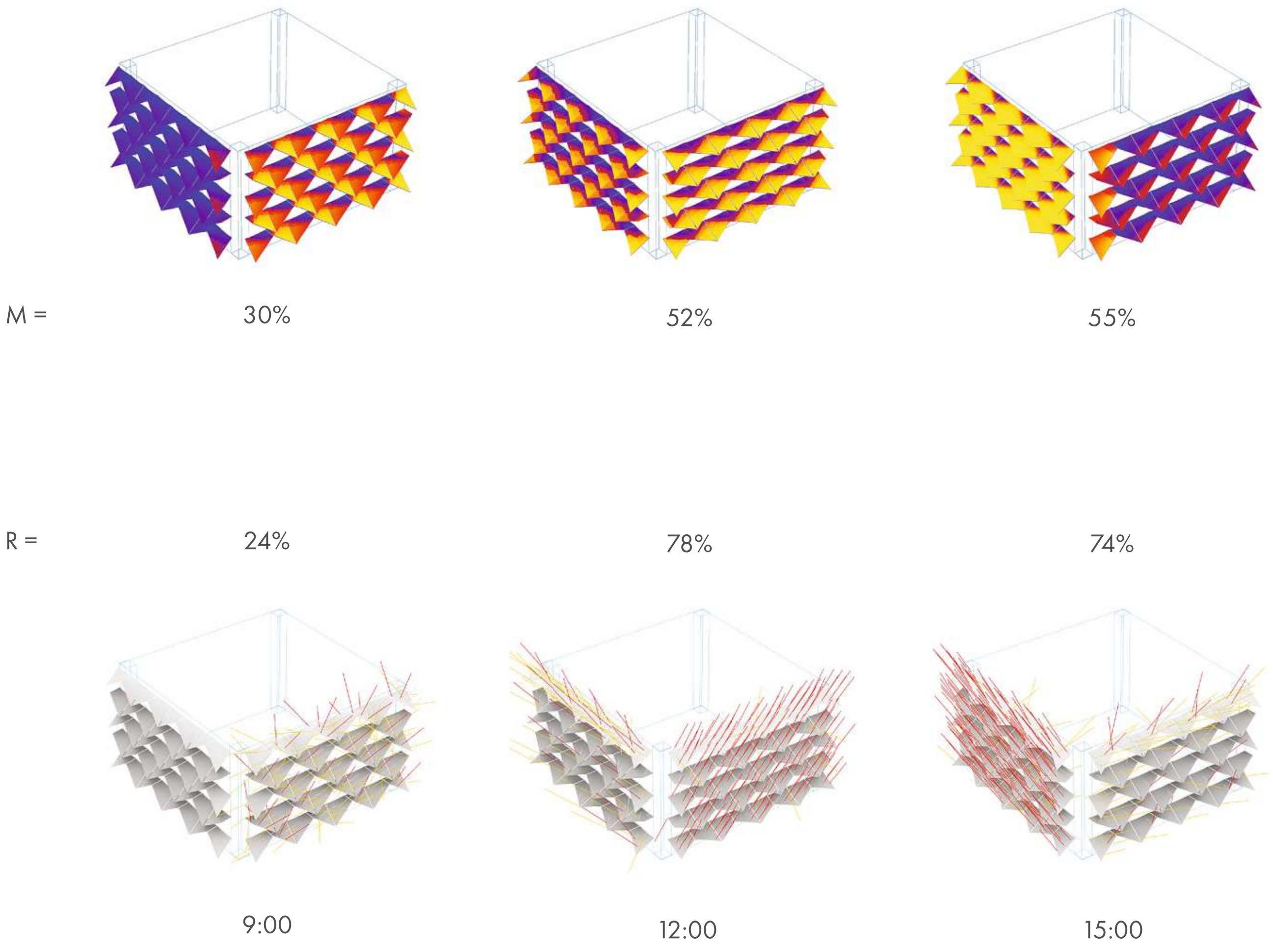


Fig. 75. *DA for final shape*

Comparing the new results to the baseline, an increase of approx. 20% in insolated material can be observed, which would mean that the reflection performance increases aswell.



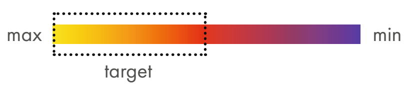
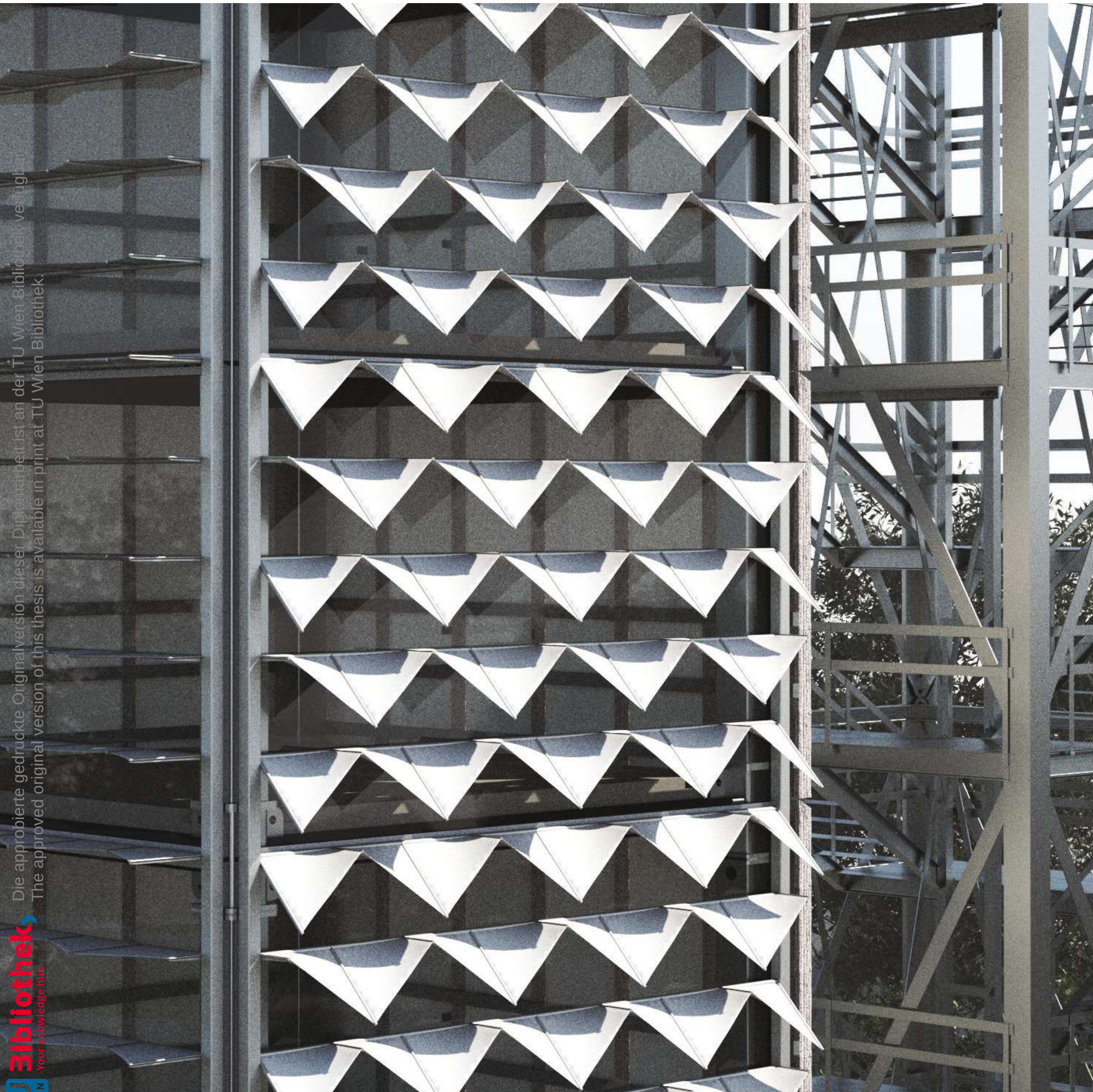
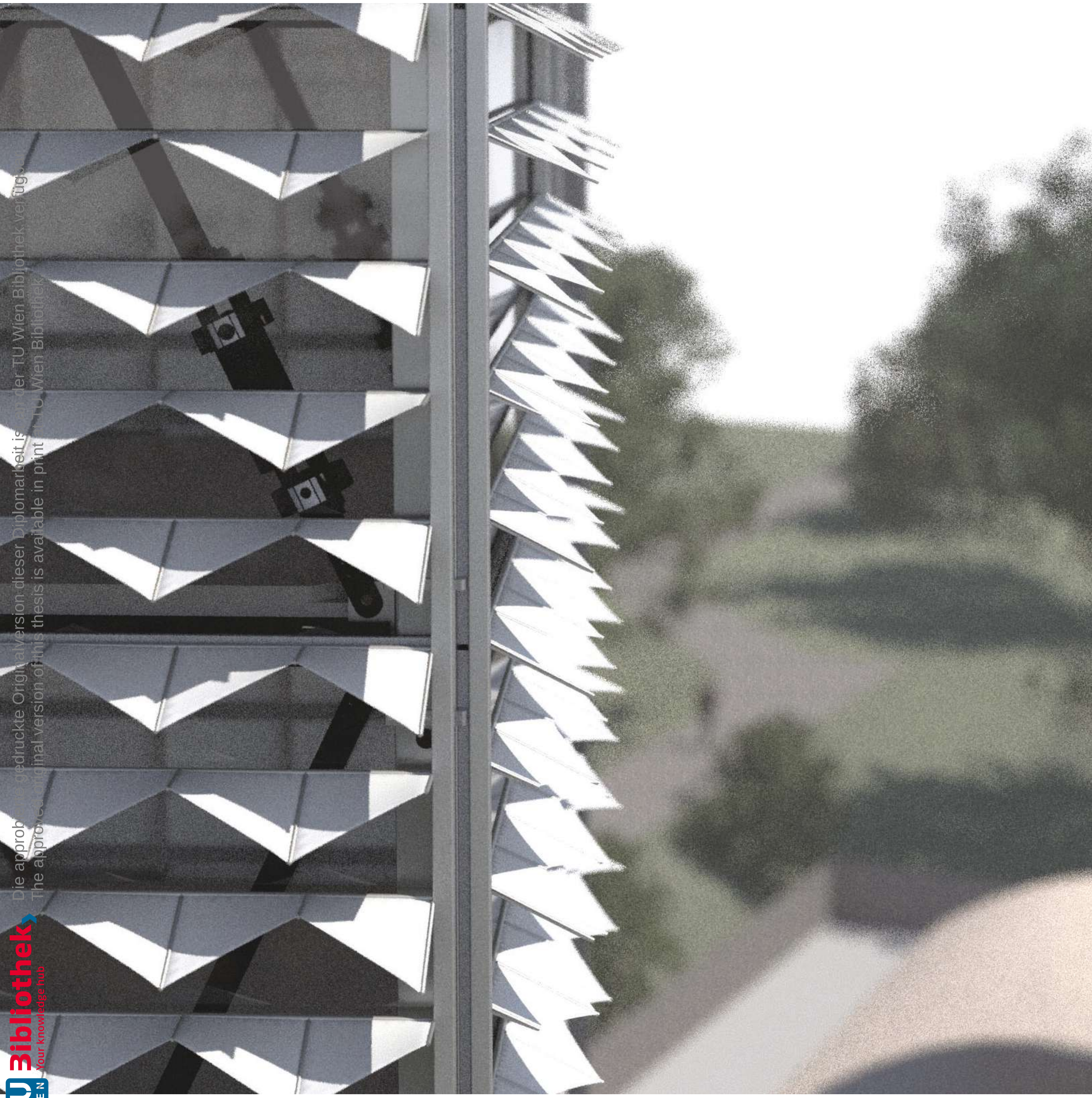
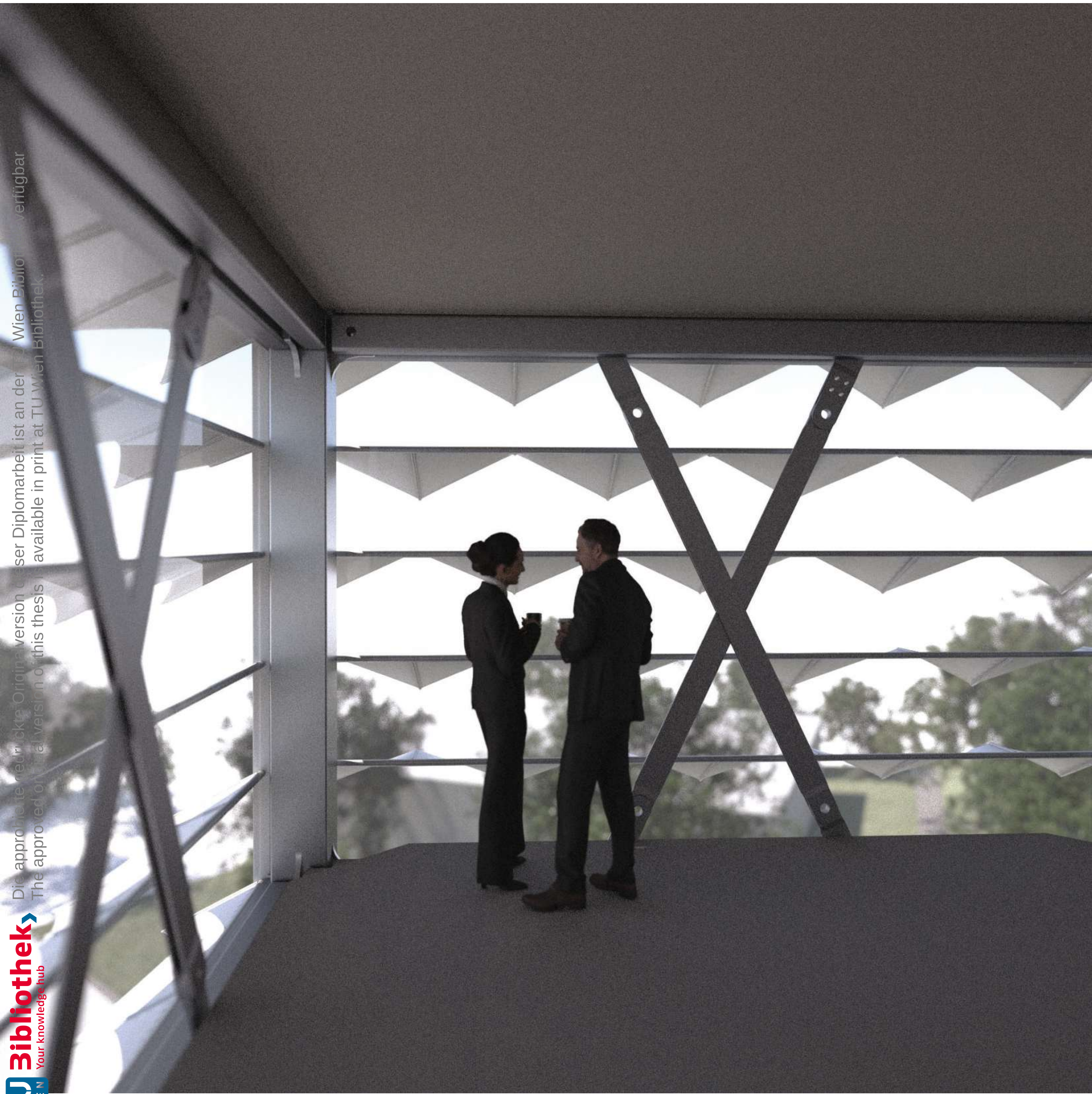


Fig. 76. *Reflection and material performance of final shape*

Visualization







References

1.Oke, T. R. The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteirilogical Society 108 (1982).

2.Oke, T. R. The Heat Island of the Urban Boundary Layer: Characteristics, Causes and Effects. In Wind Climate in Cities, edited by J. E. Cermak, A. G. Davenport, E. J. Plate & D. X. Viegas (Springer Netherlands, Dordrecht, 1995), pp. 81–107.

3.Kleerekoper, L., van Esch, M. & Salcedo, T. B. How to make a city climate-proof, addressing the urban heat island effect. Resources, Conservation and Recycling 64, 30–38; 10.1016/j.resconrec.2011.06.004 (2012).

4.Santamouris, M. On the energy impact of urban heat island and global warming on buildings. Energy and Buildings 82, 100–113; 10.1016/j.enbuild.2014.07.022 (2014).

5.Santamouris, M., Cartalis, C., Synnefa, A. & Kolokotsa, D. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. Energy and Buildings 98, 119–124; 10.1016/j.enbuild.2014.09.052 (2015).

6.Yang, L., Qian, F., Song, D.-X. & Zheng, K.-J. Research on Urban Heat-Island Effect. Procedia Engineering 169, 11–18; 10.1016/j.proeng.2016.10.002 (2016).

7.Rinke, R. et al. Pilot Actions in European Cities – Stuttgart. In Counteracting Urban Heat Island Effects in a Global Climate Change Scenario, edited by F. Musco (Springer International Publishing, Cham, 2016), pp. 281–303.

8.Chokhachian, A., Perini, K., Dong, M. S. & Auer, T. How Material Performance of Building Facade Affect Urban Microclimate. In Powerskin Conference Proceedings (2017), pp. 83–95.

9.Morini, E., Touchaei, A., Castellani, B., Rossi, F. & Cotana, F. The Impact of Albedo Increase to Mitigate the Urban Heat Island in Terni (Italy) Using the WRF Model. Sustainability 8, 999; 10.3390/su8100999 (2016).

10.Gerber Architekten. King Fahad National Library. Refurbishment and extension of the National Library in Riyadh, Saudi Arabia (Dortmund, 2014).

11.Burger, S. South Australian Health and Medical Research Institute (Sahmri. In ACADIA 2014 design agency. Projects of the 34th annual conference of the Association for Computer Aided Design in Architecture, October 23 25, 2014, Los Angeles, California, edited by D. Gerber, A. Huang & J. Sanchez (Riverside Architectural Press, Cambridge, Ontario, 2014), Vol. pp. 201-204.

12.Xuereb, K. The Al Bahar Towers - Enhancing sustainability through innovation. In The ISE Annual Conference. Sustainable Energy 2014 (2014).

13.Nagy, Z. et al. The Adaptive Solar Facade: From concept to prototypes. Frontiers of Architectural Research 5, 143–156; 10.1016/j.foar.2016.03.002 (2016).

14.Doya, M., Bozonnet, E. & Allard, F. Experimental measurement of cool facades' performance in a dense urban environment. Energy and Buildings 55, 42–50; 10.1016/j.enbuild.2011.11.001 (2012).

15.Karanouh, A. & Kerber, E. Innovations in dynamic architecture. FDE 3, 185–221; 10.3233/FDE-150040 (2015).

16.Alotaibi, F. The Role of Kinetic Envelopes to Improve Energy Performance in Buildings. J Archit Eng Tech 04; 10.4172/2168-9717.1000149 (2015).

17.Fox, M. Interactive architecture. Adaptive world / Michael Fox, editor (Princeton Architectural Press, New York, 2016).

18.Attia, S. Evaluation of adaptive facades: The case study of Al Bahr Towers in the UAE. QScience Proceedings 2016, 8; 10.5339/qproc.2016.qgbc.8 (2016).

19.Attia, S. et al. Current trends and future challenges in the performance assessment of adaptive façade systems. Energy and Buildings 179, 165–182; 10.1016/j.enbuild.2018.09.017 (2018).

20.Roudsari, M. S. & Pak, Michelle, Adrian Smith + Gordon Gill Architecture. Ladybug - a Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conciuous Design. In 13th Conference of International Building Performance Simulation Association (2013).

21.Reinhart, C. Daylighting Handbook I. Fundamentals. Designing with the Sun (Ria Stein, USA, 2014).

22.Zare, S. et al. Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year. Weather and Climate Extremes 19, 49–57; 10.1016/j.wace.2018.01.004 (2018).

23.Fiala, D. et al. Physiological modeling for technical, clinical and research applications. Frontiers in bioscience (Scholar edition) 2, 939–968; 10.2741/s112 (2010).