Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Semester Project
Spring Semester 2014

Visualizing the control strategies of the adaptive solar façade

Architecture & Sustainable Building Technologies (SUAT)
Institute of Technology in Architecture
Swiss Federal Institute of Technology Zurich (ETHZ)

Giovanni Bianchi

Supervisor: Dr. Zoltan Nagy
Prof. Dr. Arno Schlüter

May 2014

Acknowledgements

I would like to sincerely thank:

- Dr. Zoltan Nagy, supervisor of this thesis, for his help and great support during this project
- Prof. Dr. Arno Schlüter for his essential help
- Andreas Thoma and Abel Groenewolt for their valuable knowledge and help
- Gearoid P. Lydon for reviewing this report

Contents

Chapter 1

Introduction

The adaptive solar façade project explores novel integration of photovoltaics technology into building façades combined with occupant centered control.[1] The aim of the research is to develop architectural systems that are energetically productive, but also respond to the desires of building occupants thereby providing improved comfort.
Multiple prototypes where built. The prototype in Figure 1.1 is characterized by square and triangular solar panels controlled by two servomotors.
At this point one question arises: which orientation control lawis required to automate the solar panels?
Since the orientation of the solar panels affects both the electricity production and the energy required for the room behind, its control law will derive from multi-objective optimization.
This project aims to find the module orientation able to save or even produce the maximal amount of energy. The energy saving potential is given by the shading effects of the adaptive solar facade, the electricity production instead is generated from the photovoltaics cells.
Another goal of this project is to visualize and compare the results obtained by minimizing the heating, cooling and electricity consumption of the building or maximizing the electricity production of the photovoltaics cells. The only way to obtain a valid result in reasonable period of time is to simulate a portion of the facade. We have chosen to simulate a single room equipped with fifty-four panels because a complete façade model would require too much computational effort. This report describes the simulation software used for the simulations as well as the modality in which has been used and the obtained results.

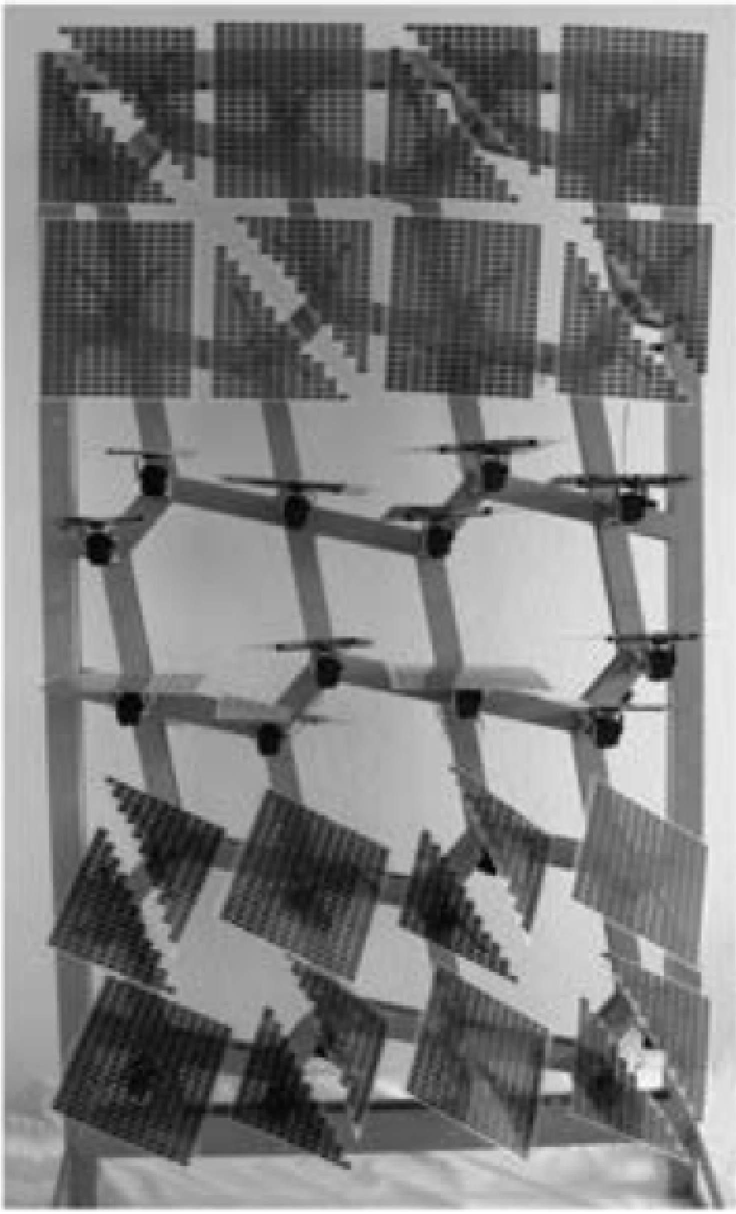

Figure 1.1: Full scale prototyp for the shading of one window [2]

Chapter 2

Experimental Setup

This chapter explains the experimental setup built to run the simulations. First of all, the involved software are presented, then the specific files are described.

- **Rhinoceros 3D**
  Rhino 3D is a stand-alone NURBS(Non Uniform Rational Basis-Splines)-based 3D modeling software. The software is commonly used for architecture, reverse engineering and graphic design.[3]

- **Grasshopper**
  Grasshopper 3D is a visual programming language running within Rhino. The principal advantage of this software is to parametrize the geometrics elements. It is an indispensable tool for modelling moving parts.

- **EnergyPlus**
  EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up and associated mechanical and other systems, EnergyPlus calculates heating and cooling loads necessary to maintain thermal control set-points, conditions throughout a secondary HVAC (Heating, Ventilation and Air Conditioning) system and coil loads, and the energy consumption of primary plant equipment. Simultaneous integration of these -and many other- details verify that the EnergyPlus simulation performs as would the real building.[4]

- **DIVA-Daylight Simulation**
  DIVA-for-Rhino is a highly optimized daylighting and energy modelling plug-in for the Rhinoceros - NURBS modeller. The plug-in was developed at the Graduate School of Design at Harvard University. DIVA-for-Rhino allows users to carry out a series of environmental performance evaluations of individual buildings including Climate-Based Daylighting Metrics, Annual and Individual Time Step Glare Analysis, and Single Thermal Zone Energy and Load Calculations.

This softwares interacts to obtain a thermal simulation of our Adaptive Solar Facade equipped building. All static elements were designed in Rhinoceros (Section 2.1). Inside this model the moving parts, in our case the solar panels are added from Grasshopper.
DIVA is the connection between EnergyPlus and Rhinoceros, it extracts the input parameters from the Rhino model and inserts them in EnergyPlus. The user does not need to know EnergyPlus, because the Interface of DIVA provides all the necessary necessaries information. The following sections describes the files designed to simulate the room which is equipped with the adaptive solar façade.

2.1 Room Description

The analyzed room (Figure 2.1) has an internal size of: 7 meters of length, 4.9 meters wide and 3.1 meters of height. The window has a 5 cm thick frame and a glass panel of 4.5 by 3 meters. The walls have a thickness of 15 cm.
The room has been drawn in Rhino as show in Figure 2.1.

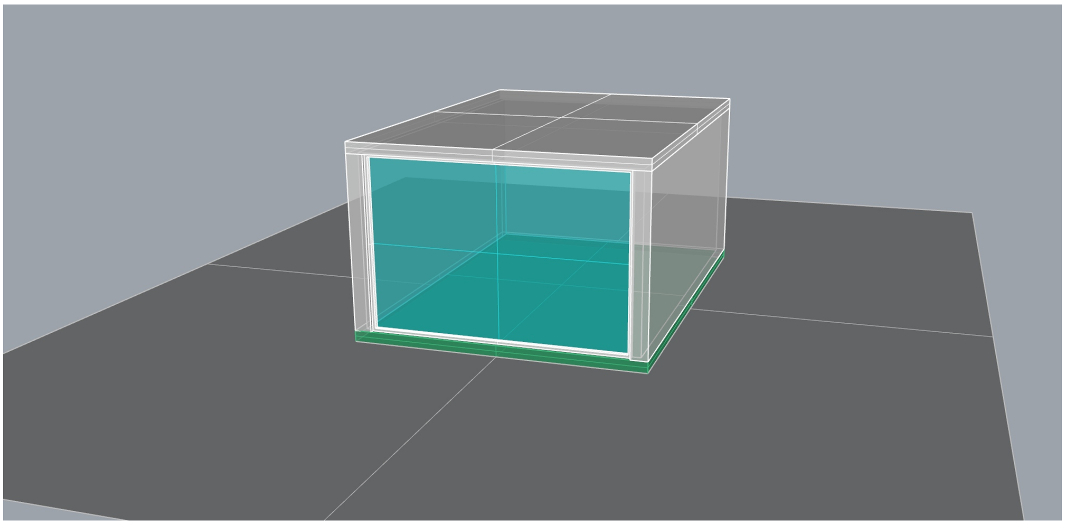

Figure 2.1: Room

2.2 Thermal Model

The Rhino model (Section 2.1) doesn't have an influence in the simulations, but from this geometry the thermal model was build in Grasshopper (Figure 2.2).

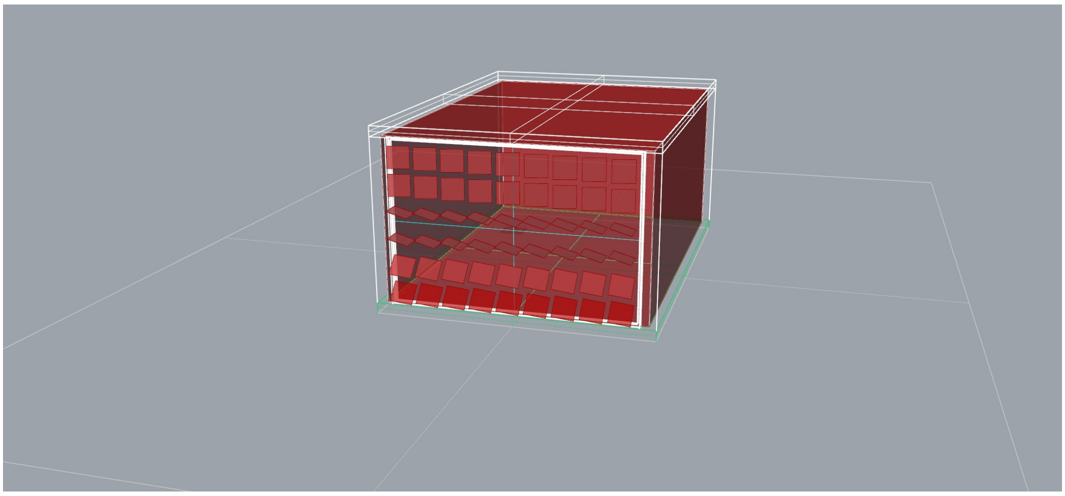

Figure 2.2: Thermal model

2.3 Grasshopper program

The Grasshopper program (Figure 2.5) is structured with 3 groups of objects: the six bands in the middle corresponding to the six rows of solar panels, in the bubble frame on the left side all geometric elements common to all the solar panels have been grouped. These geometries have been adapted starting from a previous work of Andreas Thoma. The right side of the Grasshopper program is responsable for the simulations. These three groups are described below.

2.3.1 Parametric design of a solar panel row

The square solar panels have a side length of 400 mm and are extruded for 10 mm. The panels are rotated and displaced repeatedly to reach the desired position and orientation.

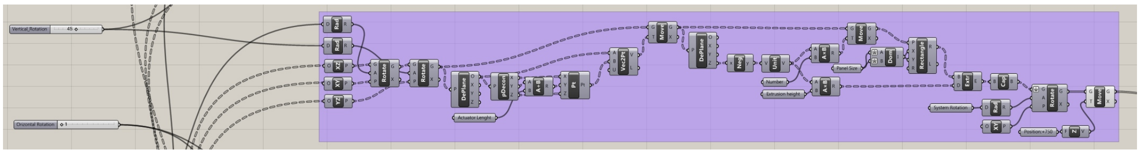

Figure 2.3: Single row of panels

The six groups differs only for the inputs and for the position height on the facade. The top band is placed 1250 mm above the center. The center of the bands are spaced of 500 mm so that the bottom band -1250 mm shifted.
A single slider controls the vertical rotation of all panels (upper left side in Figure 2.3). The horizontal rotation is controlled in groups of two rows of solar panels.

2.3.2 Common geometrics elements

The geometrical parameters common to all the rows of solar bands are have been grouped, these are: the grid angle (set to 0), the panel spacing (set to 500mm), and the frame size (set to 4500 mm in x-direction and 500 mm in y-direction).

2.3.3 Thermal analysis

The Thermal Analysis is performed by the Viper Component (Figure 2.4). This element runs the DIVA environmental analysis program. The required inputs are:

- **Project Name:** connected to the vertical rotation slider to name the simulation file automatically
- **Lighting Control:** threshold of 300 lux
- **Zone:** the three internal walls, the ceiling and the floor are set as adiabatic. The external wall has an R-value of 13-7.5 W/m^2K
- **Window:** Double glazing, glass 3mm/13mm capity fill with air
- **Shade:** all the solar panels, with a Visible and a Solar Reflectance of 0.5
- **Run:** connected to a toggle button

The chosen settings are:

- **Weather Location:** Geneva (the only available weather data for Switzerland)
- **Occupancy:** Office (from 8 am to 6 pm)
- **Simulation Parameters:** from 1 January to 31 December, 1 step per Hour.

And the chosen simulations output are:

- **IndoorTemp** Zone Mean Air Temperature [C]
- **Heating E** Heating Energy Consumption (load divided by efficiency) [kWh]
- **Cooling E** Cooling Energy Consumption (load divided by efficiency) [kWh]
- **Elec: Light** Interior Lights: Electricity [kWh]

This is the setup for the programs used for the simulations of the next chapter.

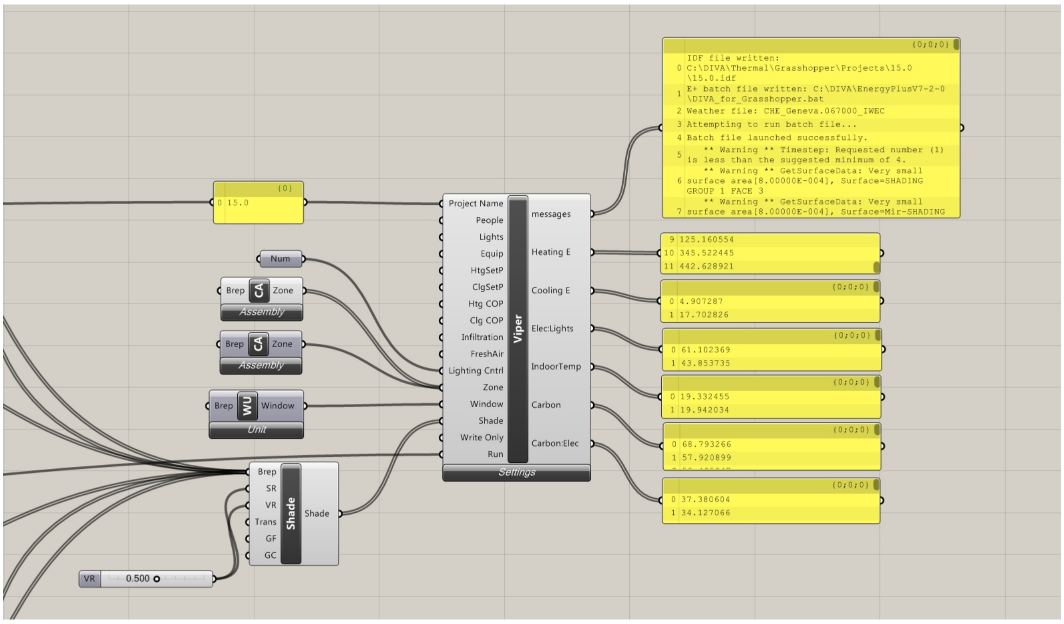

Figure 2.4: Viper Component

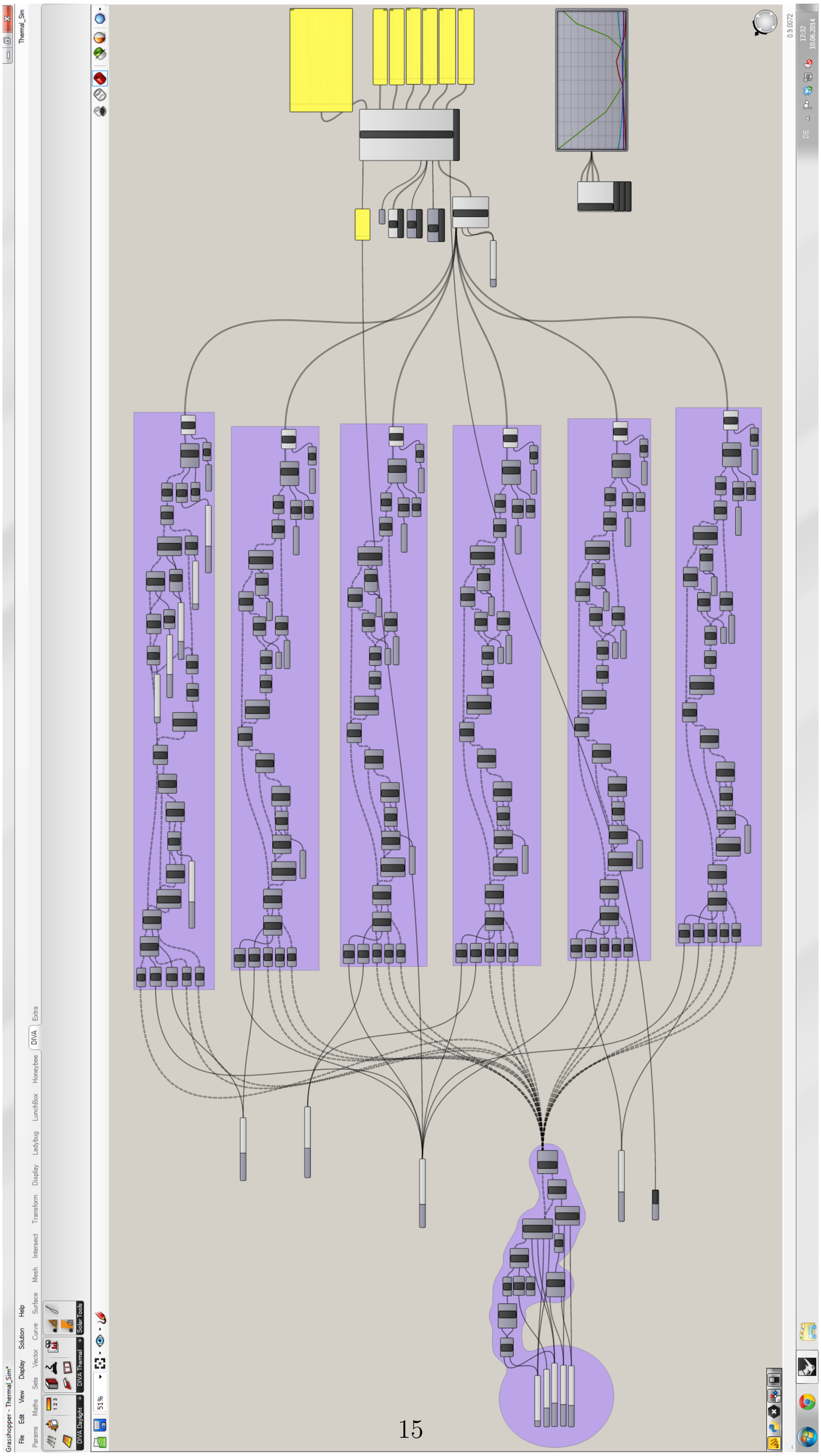

Figure 2.5: Grasshopper complete program

Chapter 3

Simulations

3.1 Control strategies evaluation

The previous chapters described the Grasshopper program simulating the behavior of the the room equipped with static panels, but our goal is to investigate the control strategies [1] for the movement of the panels.
Therefore a quasi-static approach has been chosen. The idea is to simulate the behavior of the room in all reachable positions, analyze the obtained data, and finally find (backward) the corresponding optimal panels orientation.
The chosen parameters to be minimized, and therefore to be generated as result of the simulation are:

- heating consumption
- cooling consumption
- electricity consumption

at each of the 8760 hours of a year. The limiting factor in this approach is the time required for a simulation. Assuming the simulation for a single position has a duration of about 3 minutes, a limited choice of positions has to be used.
Another investigation option is simulation automation. The recommended way to automate the DIVA for grasshopper simulation is to use the animate function of the numeric slider [5]. This is an integrated function of Grasshopper (by right clicing in the slider).

[1]The term control strategies is not interpreted as in the field of control system theory, it indicate the way to control the orientation of the panels so as reach a certain objective.

The two main advantages of this method are: simplicity and automatic adaptation to the time required for the simulation.
An automation made by a script, how vary the panel position is instead not possible because the time required to simulate each position is different.

3.2 Panel position selection

A slider was automated to move between -90 and 90 degrees in 12 steps to control the rotation on the vertical axis. All panels move together since there is no particular benefit in combining different vertical rotations in the same façade.
Previous researches has shown that the optimal horizontal rotation of the panels is not uniform in the entire façade, especially for comfort optimization. [6]
The horizontal rotation affects the profoundness with which the light penetrate inside the room. Therefore three groups, of two lines of panels, were set.
The three chosen degrees of rotation are: 0°, 45° and 90°. This positions were called 1,2 and 3 respectively. These three numbers are assigned to identify the combination in which the simulation is made, and are used to identify the combinations in the results (see Figure 3.1).
The total number of evaluated positions and accordingly of simulations is:

$$\mathbf{3^3 \times 12 = 324} \tag{3.1}$$

This amount of positions is a satisfactory starting point to indicate the direction in which a more precise analysis can continue.

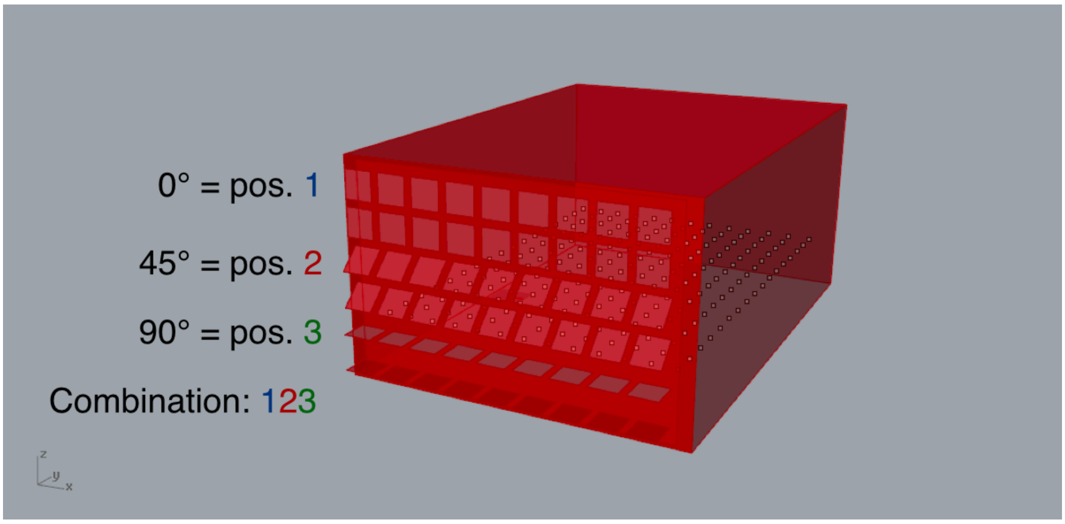

Figure 3.1: Horizontal Combinations

Chapter 4

Results and Discussion

Our Setup described in Chapter 2 was completed as described in Chapter 3, to collect the building energy requirement in dependence of 324 different panels orientations.
The data manipulation is described and then the obtained results are explained.
Each simulation provides a .cvs table with the following structure: each row corresponds to an hour of the year and in the five columns the corresponding time, heating, cooling, electricity consumption and room temperature are saved. This large amount of data is analyzed in MATLAB in the following way:
Each parameter (Heating E, Cooling E, Electricity E) is analyzed separately but with the same strategy. All the file-tables are imported as matrixes in MATLAB. The minimization occurs in two steps: first for each combination the vertical rotation with minimal energy is found (see also the *combination Analysis* file in the appendix), then the obtained data are inserted in a new matrix and minimized to find the horizontal combination with minimal energy (see *Overall minimization* in appendix). The obtained data are visualized (using the file *Minimal plot* in appendix) in the figure display in the following sections.

4.1 Heating minimization

The rotations minimizing the heat required by the room are displayed in Figure 4.1. Especially in the cold season and in the morning there is a configuration involving many orientations each day, almost each hour required a different orientation from the previous. We remark that the background is blue, corresponding to an orientation of $-75°$, not because it required less energy, but because it required the same energy as all other orientations. Two reasons explain this situation: the building requires no additional heat (specially in summer) or the panel orientation doesn't influence the heat required from the building (during the night).
The panels follows the sun, but to allow much solar radiation as possible to penetrate inside the building.

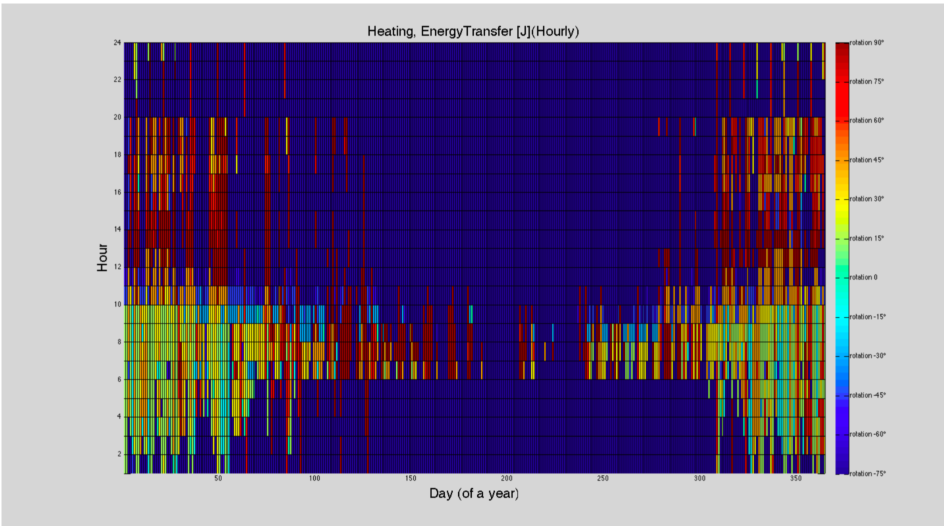

Figure 4.1: Rotations minimizing the heat required by the room

The configurations minimizing the heat required by the room (see Figure 4.2) can be divided in two groups. During the morning the configuration obtained from the minimization is the '222' (green) indicating alls panels are oriented at 45°. During the afternoon, the panels turn to combination '323' (Red) indicating a plain orientation of two rows.

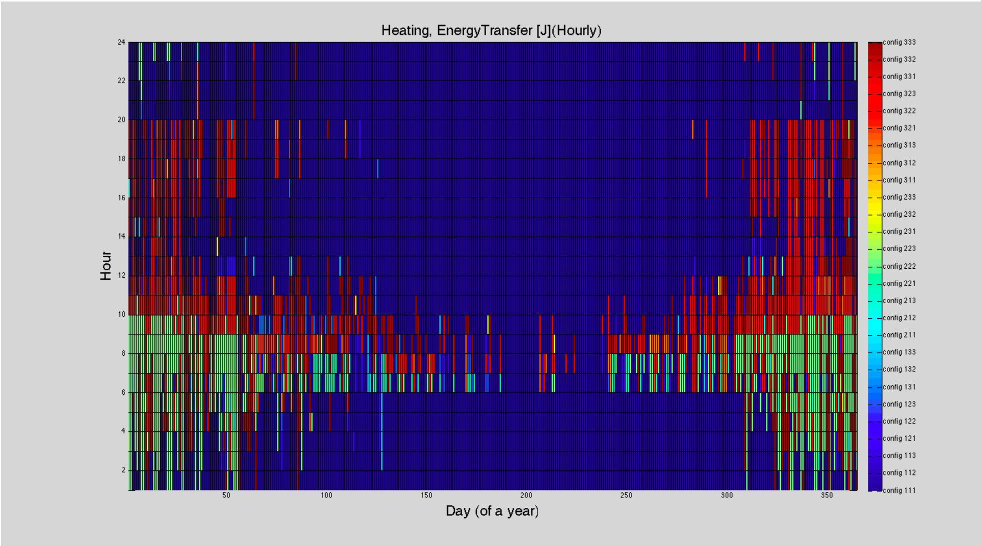

Figure 4.2: Configurations minimizing the heat required by the room

4.2 Cooling minimization

Chiefly in the summer afternoon, the panel configuration affect the energy required to cool the building. The configuration '222' is dominating the Figure 4.3, this configuration is able to maximize the shading effect.

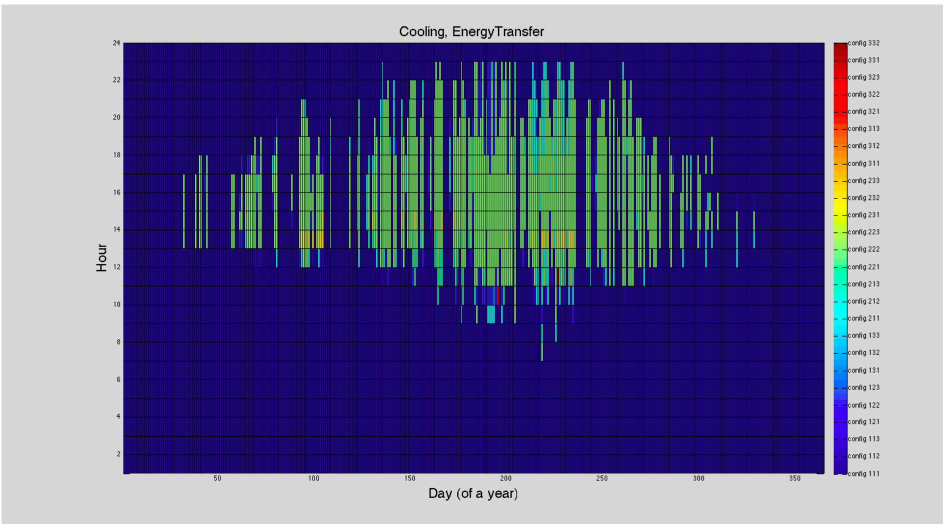

Figure 4.3: Configurations minimizing the cooling energy required by the room

4.3 Electricity minimization

The configurations minimizing the electric light (Figure 4.4) are only three. In the middle of the night and day the electric light are off (no occupancy during the night, no electrical light requirement in the middle of the day).
Only in the morning and in the evening configurations '333' (red) and '133' (azure) are exploited. This configurations maximize the light crossing the solar adaptive façade.

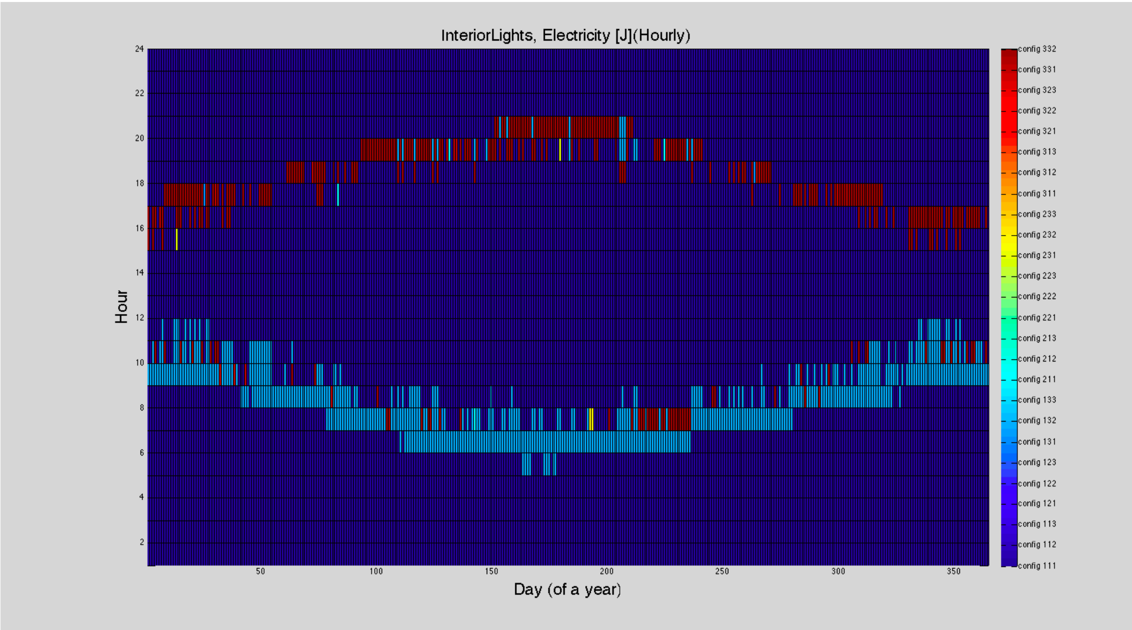

Figure 4.4: Configurations minimizing the electric light required by the room

4.4 Visualization

In order to visualize the results the pictures in Figure 4.5 have been created using the 'DIVA Daylight Visualization tool'. They compare the results obtained by minimizing the heating (left column), the cooling (middle) and the electricity (right column). These images are all related to the first of February, this day was chose because it describe a typical day with several different combinations inside (the shadows have the same place at each hour to enphasize the pannels).

This visualization highlights non homogeneous solutions: the three bands of panels presents often different orientation from each other. We deduce that the lower panels band has a limited impact on the daylight penetration in the room.

The resulting visualization are not easily predictable due to the complexity and the high number of factors which are influenced by. But some common characteristics can be drawn: an open solution provides a reduction in heat and electric light consumption due to increased passive solar irradiation gain, a close solution instead limited the cooling requirement due to reduced passive solar irradiation gain.

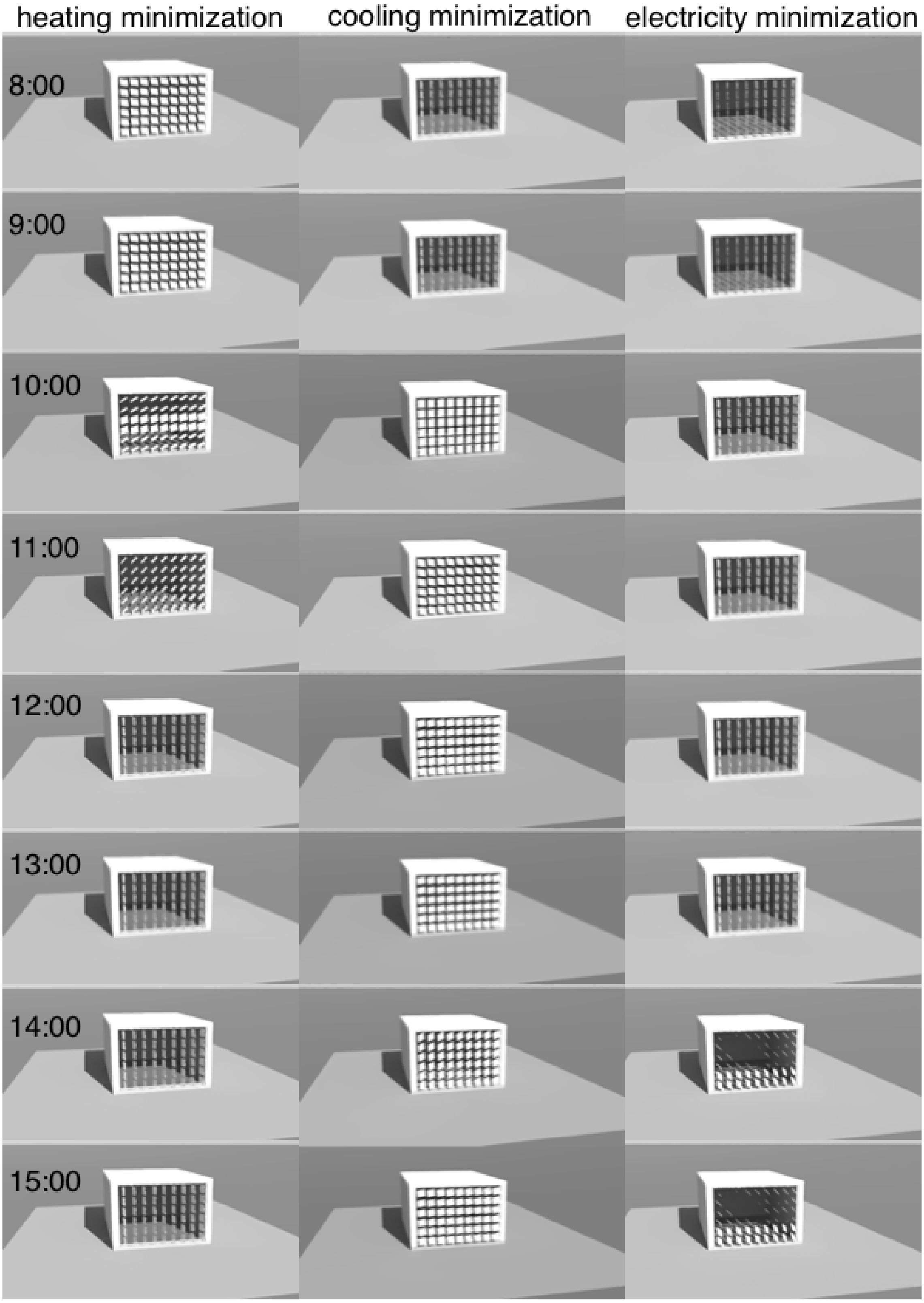

Figure 4.5: Comparison of the solutions obtained by minimizing the heating, cooling and electricity consumption at the first of February.

Chapter 5

Conclusion and Outlook

The software setup was created to investigate the energy behavior of the zone. Everything is build in the Rhino environment. This allows changes the geometry and observation of the resulting effects. With little manual effort it is possible to investigate many orientations of the facade.
The completed simulations created a reliable setup. The chosen strategy to minimize the consumption hours by hours doesn't take into account the thermal inertia of the building, this aspect can reduce the precision of the obtained results. Our results highlight that the optimal panels orientation will be a tradeoff between the three solutions we obtained. Inside this tradeoff solution a fourth parameter will play a fundamental role: the electricity production of the photovoltaics cells. It was not possible to integrate the calculation of this parameter in our setup because it is not yet implemented in DIVA for Grasshopper.
Figure 5.1 has been obtained with ladybug (Rhinoceros3D additional tool) and suggest a promising way to calculate the solar irradiation.

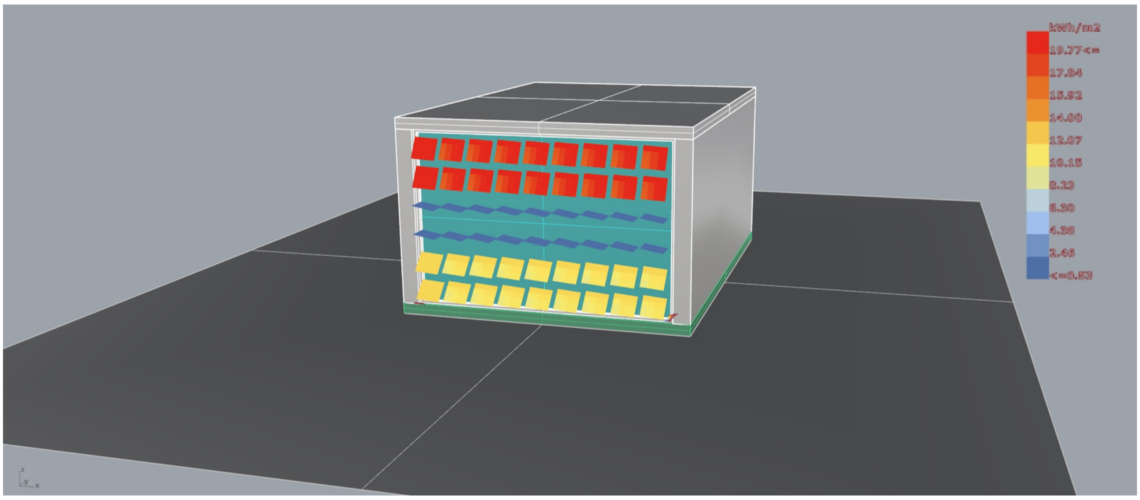

Figure 5.1: Solar irradiation

Bibliography

[1] http://www.suat.arch.ethz.ch/en/research/adaptive-solar-facade, May 2014

[2] Rossi, D., Nagy, Z., Schlueter, A., Adaptive Distributed Robotics for Environmental Performance, Occupant Comfort and Architectural Expression. International Journal of Architectural Computing, 2012, pp. 341-360.

[3] http://en.wikipedia.org/wiki/Rhinoceros-3D, May 2014

[4] Diva for Rhino. User Guide. http://diva4rhino.com/user-guide. May 2014

[5] http://www.grasshopper3d.com/group/diva4rhino/forum/topics/automate-multiple-simulations, May 2014

[6] Brotas, L., Rusovan, D., Parametric Daylight Envelope, London Metropolitan University, 2013.

Appendix

```
% Combination Analysis
% Semester Project
% Author: G.Bianchi
% Email: gibianch@student.ethz.ch
clear all, clc, close all
Minimal_value=zeros(8760,28);
Index_with_minimal_value=zeros(8760,28);

% Chose the parameter to plot (2-5)
%Coulum i=2 for: Heating, EnergyTransfer [J](Hourly)
%Coulum i=3 for: Cooling, EnergyTransfer [J](Hourly)
%Coulum i=4 for: InteriorLights, Electricity [J](Hourly)
i=4
% Chose the comb to import: e.g. '232'
orizontal_comb = ['332'];
load(['/Users/giovanni/Documents/MATLAB/Workspace_' orizontal_comb '.mat'])

orizontal_comb=str2num(orizontal_comb);

eval(sprintf('vm7 = Matrix_%d_m75(:,i)', orizontal_comb));
eval(sprintf('vm6 = Matrix_%d_m60(:,i)', orizontal_comb));
eval(sprintf('vm4 = Matrix_%d_m45(:,i)', orizontal_comb));
eval(sprintf('vm3 = Matrix_%d_m30(:,i)', orizontal_comb));
eval(sprintf('vm1 = Matrix_%d_m15(:,i)', orizontal_comb));
eval(sprintf('v0 = Matrix_%d_00(:,i)', orizontal_comb));
eval(sprintf('v1 = Matrix_%d_15(:,i)', orizontal_comb));
eval(sprintf('v3 = Matrix_%d_30(:,i)', orizontal_comb));
eval(sprintf('v4 = Matrix_%d_45(:,i)', orizontal_comb));
eval(sprintf('v6 = Matrix_%d_60(:,i)', orizontal_comb));
eval(sprintf('v7 = Matrix_%d_75(:,i)', orizontal_comb));
eval(sprintf('v9 = Matrix_%d_90(:,i)', orizontal_comb));

A=[vm7 vm6 vm4 vm3 vm1 v0 v1 v3 v4 v6 v7 v9];
[Y,I] = min(A, [], 2);
Minimal_value=Y;
Index_with_minimal_value=I;
save('Index_with_minimal_value_332','Index_with_minimal_value_332')
```

```
% Overall minimization
% Semester Project
% Author: G.Bianchi
% Email: gibianch@student.ethz.ch

clear all, clc, close all

load(['Users/giovannibianchi/Documents/MATLAB/Comparison_matrix.mat'])

Minimal_value=Minimal_value(:,1:27);

[Y,I] = min(Minimal_value, [], 2);

combination_with_minimal_value=I;

absolute_minimal_value=Y;

save('combination_with_minimal_value','combination_with_minimal_value')
```

```matlab
% Minimal plot
% Semester Project
% Author: G.Bianchi
% Email: gibianch@student.ethz.ch

clc, close all
M=zeros(24,365);

M(:,1)=Index_with_minimal_value(1:24,1);

for j =1:364;
    n=j*24;
    M(:,j+1)=Index_with_minimal_value(n+1:n+24,1);
end

plot_title='Cooling:EnergyTransfer [J](Hourly) ';

figure
pcolor(M)
title(plot_title,'FontSize',20)
ylabel('Hour','FontSize',20);
xlabel('Day (of a year)','FontSize',20);
labels = {'Position -75°','Position -60°','Position -45°','Position -30°', ...
    'Position -15°','Position 0°','Position 15°','Position 30','Position 45°', ...
    'Position 60°','Position 75°','Position 90°'};
colorbar('YTickLabel',labels,'FontSize',20);
```