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# Numerical Energy Analysis of PV Modules as Adaptive Building Shading Systems

Master Thesis

ITA – Architecture and Building Systems  
Swiss Federal Institute of Technology (ETH) Zurich

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Zurich, May 4, 2016

# Abstract

Numerical optimization of the adaptive solar facade (ASF)

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# Chapter 1

## Introduction

### 1.1 Motivation and Literature Review

Buildings are at the heart of society and currently account for 32% of global final energy consumption and 19% of energy related greenhouse gas emissions [1]. Nevertheless, the building sector has a 50-90% emission reduction potential using existing technologies [1]. Within this strategy, building integrated photovoltaics (BIPV) have the potential of providing a substantial segment of a building's energy needs [2]. Even the photovoltaic (PV) industry has identified BIPV as one of the four key factors for the future success of PV [3].

Dynamic building envelopes have gained interest in recent years because they can save energy by controlling direct and indirect radiation into the building, while still responding to the desires of the user [4]. This mediation of solar insolation offers a reduction in heating / cooling loads and an improvement of daylight distribution [5]. Interestingly, the mechanics that actuate dynamic envelopes couples seamlessly with the mechanics required for facade integrated PV solar tracking. [6] reviews current building performance simulations of adaptive facades and points out the lack of adaptability in building simulation tools. Single axis dynamic shading has been evaluated in [7], emphasizing the importance of numerical evaluations in facade design decisions.

Previous BIPV research analyses electricity production and building energy demand for static BIPV shading systems [8–15]. The performance of fixed PV shading devices in dependence of different angles is analysed for cooling and electrical performance in [8] with a simplified PV electricity model. That work is extended in [9] to include different building orientations. In [10] the efficiency of fixed PV-shading devices is analysed, suggesting indices for comparison. [11] concludes that fixed surrounding PV shading devices are most efficient. The same authors assess different PV simulation models in [12] and are able to show that extended electrical modelling is

needed for complex PV geometry. [13] also includes visual comfort and finds brise-soleil systems to perform best. A first approach on assessing building energy demand with dynamic shading in combination with estimated PV electricity production is given in [15].

PV electricity production of shading devices has been evaluated for fixed angles in [16], where different BIPV facade geometries are analysed, finding horizontal louvers to perform best. In [17] a in-depth analysis of dynamic shading modules was evaluated for various design parameters with solar tracking.

This thesis expands on the work in [15] and [17] by analysing dynamic PV shading systems, while also taking into account mutual shading amongst modules and its effect on PV electricity generation. The approach allows us to reduce efficiency degradation due to partial shading of PV modules [17].

The work presented in this thesis is applied in the context of the Adaptive Solar Facade (ASF) project [18]. The ASF is a lightweight PV shading system composed of CIGS panels, that can be easily installed on any surface of new or existing buildings. This thesis will present a methodology of simulating an ASF while simultaneously calculating the energy demand of the office space behind the facade.

## 1.2 Problem Statement

The optimization problem has to be solved for pv modules as adaptive building shading systems:

$$\text{minimize}(C + H + L - PV) \quad (1.1)$$

## 1.3 Objectives of Research

Based on the problem statement, the objectives are to

- Develop a framework for modelling an adaptive solar facade
- Find the best configurations to minimize the building energy demand

## 1.4 Thesis Outline

## Chapter 2

# Methodology

This chapter describes the methodology used to find the optimum configurations of the ASF. To study the electricity generation and building energy consumption, a 3D geometry of the room and solar facade is built using the Rhinoceros software [19], and its parametric modelling plugin Grasshopper [20]. The acquired data is then post-processed in Python [21] to extract the configurations that minimise building energy consumption and maximise PV electricity production.

### 2.1 Building Energy Analysis

The building energy simulation is conducted using EnergyPlus [22] through the DIVA [23] interface. In EnergyPlus, the geometric solar facade is interpreted as an external shading system. Simulations are performed for a whole year at fixed angle positions, outputting hourly values of energy use for heating, cooling and lighting. Optimum positions can then be found by comparing the electricity demand during every hour for all combinations.

### 2.2 Radiation and PV Analysis

A solar radiance simulation is run using Ladybug [24], which uses Radiance [25] to determine the incident insolation on the solar facade. The approach enables to calculate solar irradiance on the modules with high spatial resolution including the effect of module mutual shading as seen in Figure 2.1. The radiation is analysed for cumulative monthly hours for the whole year. The results are afterwards coupled to an electrical circuit simulation of thin-film PV modules with sub-cell level representation [17]. PV electricity production is calculated based on a reference module. The model includes temperature dependency and irradiation dependency. The temperature is estimated as suggested in [26] with the following equation:

$$T_{cell} = T_{air} + \left( \frac{T_{cell}^0 - T_{air}^0}{S^0} \right) S_{cell} \quad (2.1)$$

where  $T_{cell}$  is the temperature of each grid point on the module,  $T_{air}$  is the ambient temperature,  $T_{cell}^0$  is the temperature of the cell at reference insolation  $S^0 = 800 \frac{W}{m^2}$  and reference air temperature  $T_{air}^0 = 20^\circ C$ , and  $S_{cell}$  is the insolation of each gridpoint in  $\frac{W}{m^2}$ . The value of  $T_{cell}^0$  was estimated using a thermal images of the solar facade and typical values given in [26].

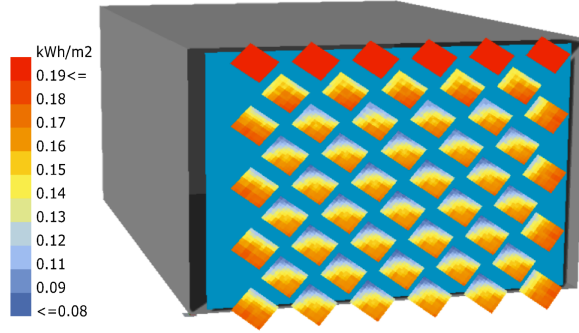


Figure 2.1: A simulation result showing module insolation from 11:00-12:00 on the 16 June for the used weather file and a specific module orientation.

The electrical model of the PV cells builds up on the methodology presented in [17] which is using the standard equivalent circuit model to calculate sub-cell I-V curves with a single diode, one series and one shunt resistance [27].

## 2.3 Combined Evaluation

To combine the results of the building energy and the pv analysis, the building energy results were cumulatively combined to correspond to the pv analysis format. With this, the net energy useage of the room including the PV electricity production of the ASF can be given for monthly hours as described in equation 1.1.

## 2.4 Simulation Framework

A corresponding workflow can be seen in Figure 2.2.

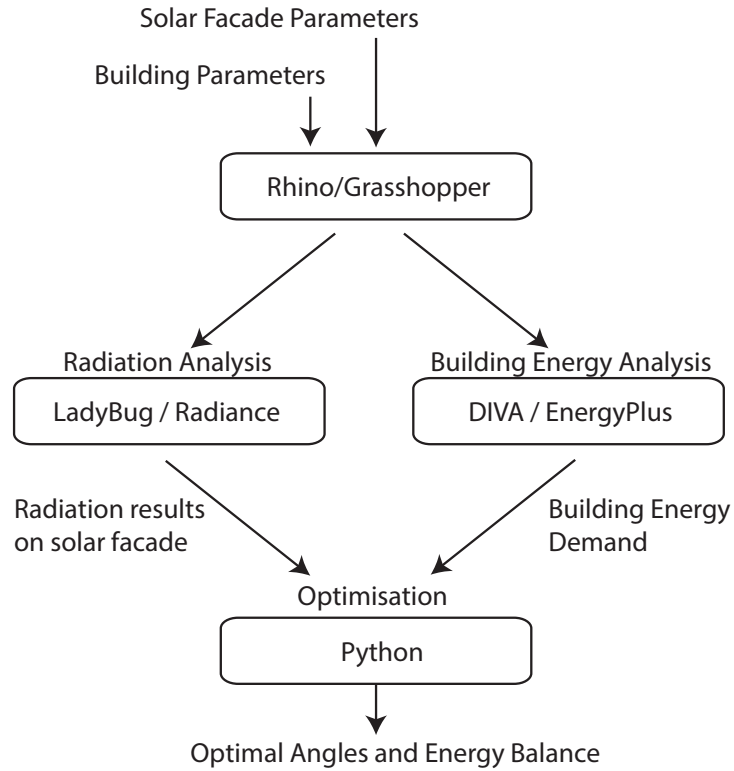


Figure 2.2: Work flow of the simulation framework

## 2.5 Case Study

The solar facade consists of 400mm CIGS square panels that can rotate in two degrees of freedom. On the horizontal axis, the panels can move from  $0^\circ$  (closed) to  $90^\circ$  (open) position in steps of  $22.5^\circ$ . In the vertical axis, it can move from  $45^\circ$  to  $-45^\circ$  in  $22.5^\circ$  steps. Existing ASF systems [18] have independently actuated panels and a continuous range of actuation, however for simplicity, we group all panels into one cluster that moves in unison. This leaves us with 25 possible dynamic configurations of the facade system.

The office environment is heated with a heatpump with an average COP of 5 and cooled with an average COP of 3. When required, the electric lighting consumption is  $11.7 \text{ W/m}^2$ .

A simulation of each possible dynamic configuration of the facade is run for each hourly timestep of the year using a weather file for Kloten, Switzerland.



## Chapter 3

# Results

Results could be achieved for the building energy analysis, the PV analysis and the combined analysis, as described in this chapter.

### 3.1 Building Energy Analysis

The optimal configurations of the ASF can be visualised using carpet-plots. For a classical building analysis this was done for every hour of the year. Figures 3.1 and 3.2 show the optimizing altitude and azimuth angles for heating, cooling, lighting and total building energy demand, respectively. Carpet plots detailing the optimal altitude angles to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) total building energy demand. In figure darker colors represent closed positions, whereas brighter colors correspond to open positions. To optimize heating and lighting, open positions (corresponding to large altitude angles) are favorable, cooling is optimized by using closed positions (corresponding to small altitude angles). The overall optimized solutions follow the corresponding patterns at the hours of importance.

### 3.2 Radiation and PV Analysis

The detailed radiation pattern on the PV panels was analysed and a detailed estimation of the PV electricity production was performed.

#### 3.2.1 Grid Convergence

With a larger gridsize, results are less accurate. In order to study this effect, a grid convergence study was conducted. Figure 3.4 shows the grid size dependency of the total radiation on the asf. It can be seen that a smaller gridsize leads to larger deviations. The normalization is done by dividing the total radiation of each gridsize by the total radiation with gridsize 12.5 mm.

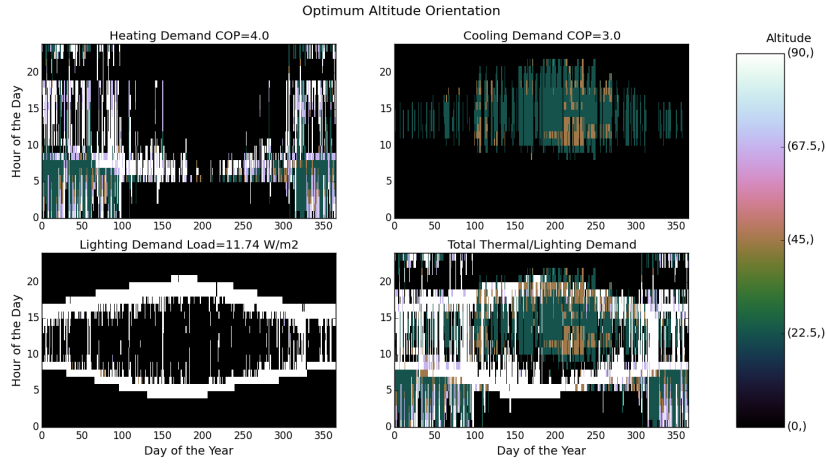


Figure 3.1: Carpet plots detailing the optimal altitude angles to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) total building energy demand. Darker colors represent closed positions, whereas brighter colors correspond to open positions. To optimize heating and lighting, open positions are favorable, cooling is optimized by using closed positions.

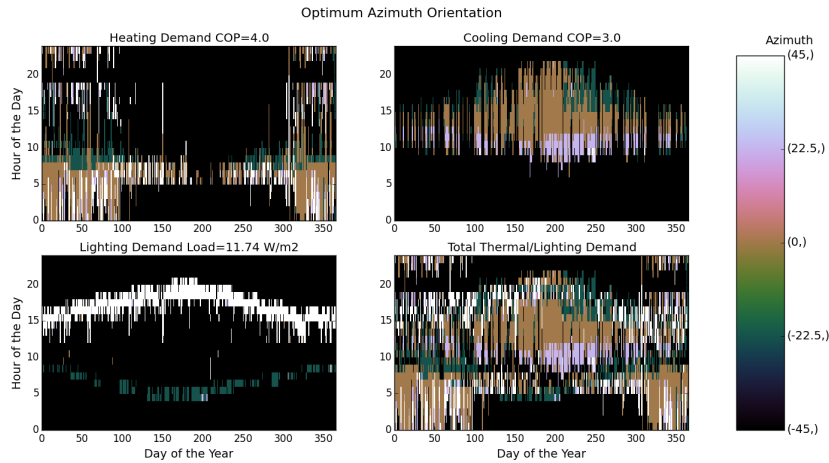


Figure 3.2: Carpet plots detailing the optimal azimuth angles to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) total building energy demand. Cooling is minimized by blocking the sun, whereas lighting and heating is minimized by opening the facade to let the insolation in.

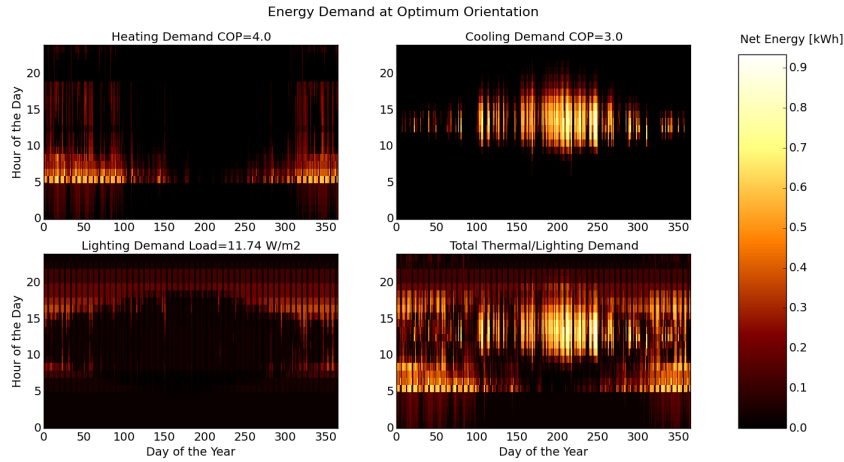


Figure 3.3: Carpet plots detailing the net energy consumption. Each square represents the total energy consumption for that specific hour of the entire month. Red colours detail the energy demand, while blue colours detail the energy supply.

While for a gridsize of 400 mm the average deviation is over 10%, the deviation goes down to below 1% for a grid size of 25 mm. 25 mm was therefore taken as the gridsize of all simulations, as it gives accurate results, while still being computationally feasible.

### 3.2.2 Comparison of Sun Tracking to Optimized Solution

In order to evaluate the optimum configuration for PV production, simulations using sun-tracking were compared to simulations evaluating the basecase of 49 different combinations (i.e. 7 different azimuth and altitude angles). In figure 3.5 it can be seen that while the radiation on the panels is pretty similar for both sun tracking and the optimized solution, the PV electricity production of the optimized solution is significantly higher than the sun-tracking solution in the afternoon hours. This is caused by the layout of the PV panels, longitudinal shading causes high power losses [17], thus the optimized solution decreases the longitudinal shading compared to sun-tracking.

## 3.3 Combined Evaluation

By combining results for building energy simulations and PV electricity production, the overall optimum configurations can be found. Figure 3.6 details carpet-plots of the facade optimised to maximise PV generation, and

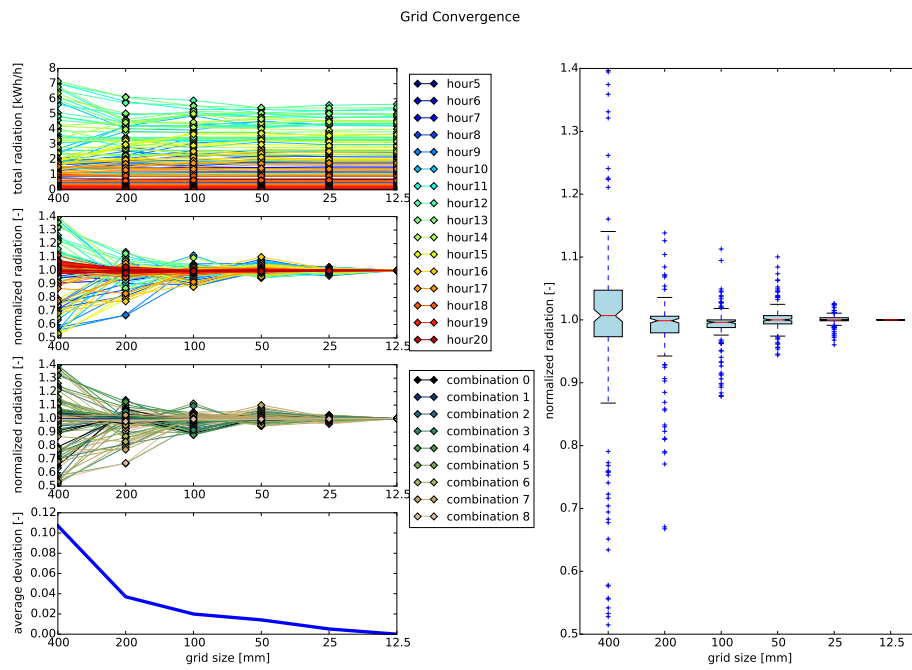


Figure 3.4: Grid convergence evaluation

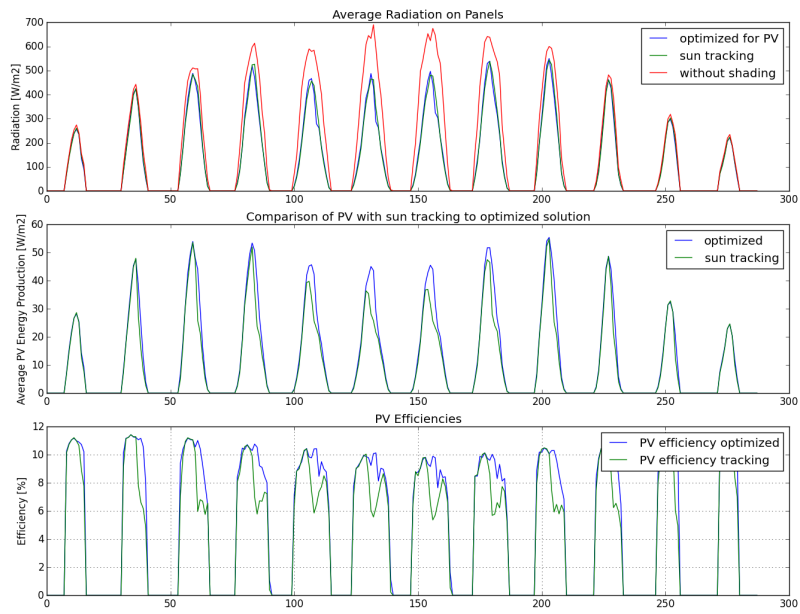


Figure 3.5: Comparison of optimized solution to sun-tracking. a) average radiation on panels compared to radiation without shading b) PV electricity production comparison c) efficiency comparison

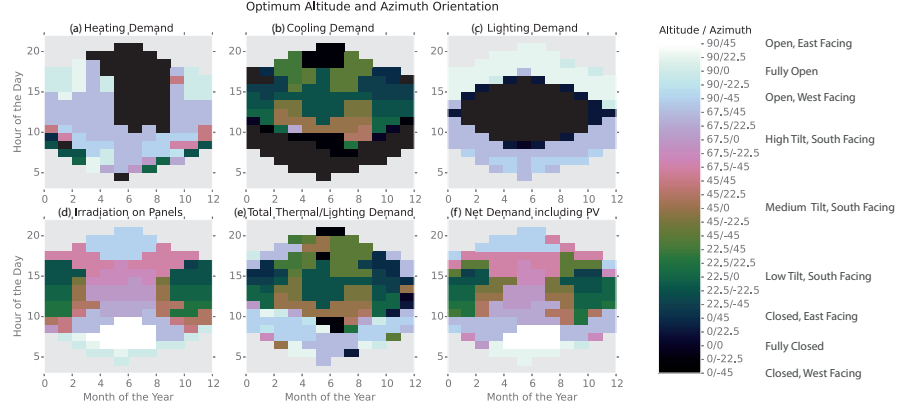


Figure 3.6: Carpet plots detailing the optimal configuration to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) maximise irradiance on PV panels. Each configuration is represented by an angle of orientation around the x-axis (Altitude) and y-axis (Azimuth) as seen in the legend. Figure (e) details the combinations for optimum building thermal management without PV production. (f) also includes the PV production

minimise heating, cooling and lighting demands independently. It can be seen that open configurations (light coloured) are chosen to minimise the building heating demands during the winter months and early mornings of spring and autumn. Likewise closed configurations (dark colours) are the preferred solutions to minimise the cooling demand during the summer months. Lighting control is only apparent during the twilight hours where the facade prefers an open position to avoid the use of artificial lighting. The PV optimisation follows a solar tracking model for most hours and as far as the limited range of angles allows. This causes some issues during twilight summer hours as the actuator cannot physically align itself normal to the sunlight.

When the four optimisation cases are combined to achieve the configurations for total energy minimisation we get some interesting results. There is a conflict in the summer evenings between minimising lighting and cooling demands. Likewise, we also see a conflict between heating and PV production during the winter months. The overall energy optimization including PV electricity production shows a strong tendency to follow the optimal PV production pattern. This, however changes if the building system becomes more inefficient. Less efficient heating for example, would result in configurations optimised for heating overpowering those of PV electricity generation.

Figure 3.7 shows the net energy use at these optimum angles. It is

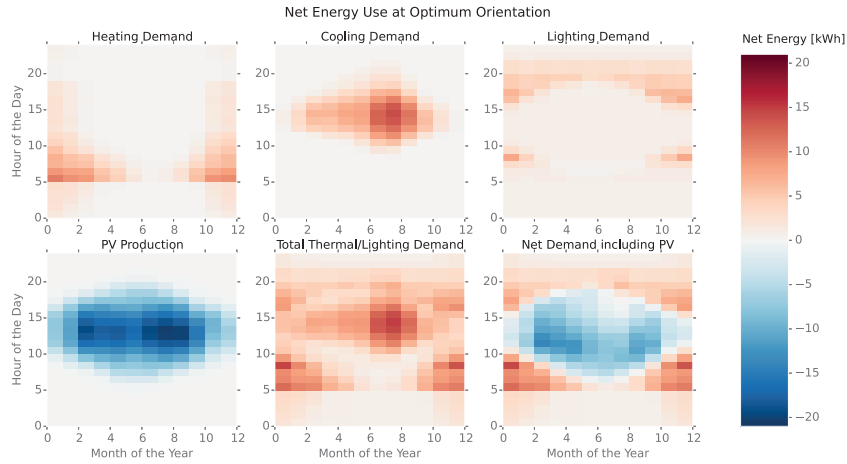


Figure 3.7: Carpet plots detailing the net energy consumption. Each square represents the total energy consumption for that specific hour of the entire month. Red colours detail the energy demand, while blue colours detail the energy supply.

interesting to see how the combination of electricity generation and adaptive shading can compensate for the entire energy use during sunlit hours.

### 3.3.1 Orientation Analysis

It was found that the PV apertures should be oriented from middle left to top for facades that are west or south-west oriented, whereas they should be laid out from middle left to bottom for east or south-east oriented facades.

## Chapter 4

# Discussion

here are some cool results



## Chapter 5

# Conclusion

In this paper, we present a simulation methodology to evaluate a dynamic photovoltaic shading system, combining both electricity generation, and the energy demand of the building. It is then coupled with a post processing python script to determine the optimum system configuration for control. The methodology can be applied to evaluate different PV system geometries, building systems, building typologies and climates.

The dynamic PV integrated shading system has clear advantages to a static system as it can adapt itself to the external environmental conditions. This enables it to orientate itself to the most energy efficient position. The optimum orientation however, strongly depends on the general efficiency of the building. Decreasing the efficiency of the heating, cooling or lighting systems will give higher preference for configurations optimised for building thermal management through adaptive shading, than for PV electricity production.

This work ultimately presents a methodology for the planning and optimisation of sophisticated adaptive BIPV systems. We are currently working on integrating the effects of module shading on PV efficiency, and the energy demand for the dynamic actuation. Future work will use this methodology to determine the environments and building typologies that could benefit from adaptive BIPV systems.

## Chapter 6

# Outlook

More research is necessary

## Appendix A

# Appendix A

This is appendix A

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