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Numerical Energy Analysis of PV Modules as Adaptive Building Shading Systems

Master Thesis

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Abstract

Numerical optimization of the adaptive solar facade (ASF)

Contents

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.

Previous BIPV research analyses electricity production and building energy demand for static BIPV shading systems [6] [7] [8] [9]. This paper expands on this work 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 [10].

The work presented in this thesis is applied in the context of the Adaptive Solar Facade (ASF) project [11]. 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:

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

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

Literature Review

General Introduction/ methods topics

- Photovoltaic - Energy Balance (U-Value, g-Value...) - User Comfort - Self Shading of panels (if evaluated)

The Adaptive Solar Facade: From Concept to Prototypes (Nagy15)

Control

- two axis solar tracking (experiment corresponds to forecast) - interaction with environment (user needs and interaction as well as energy savings must be taken into account) - voice recognition (robustness needs to be improved, redundant system is wished for by users)

Numerical Analysis

Energy Demand Savings - Single room - Three bands - hourly time steps over one year with 324 possible configurations analyzed in Energy Plus - Energy savings mainly through decreased cooling demand but also less heating and lighting than with regular blinds

PV System Design - Takes into account: building geometry, horizon contour line, module geometry - determine: shadow shape, orientation towards the sun, sky view factor, visibility of reflecting elements - Cells should be connected in strings with similar shading to minimize electrical mismatch losses

Prototypes - ETH House of Natural Resources: monitor temperature, humidity and illuminance inside ASF office as well as adjacent one - HiLo will have two facades, user interaction in residential building will be studied

Numerical Simulation of Energy Performance, and Construction of the Adaptive Solar Facade

Numerical Simulations

- ETH House of Natural Resources - net energy demand for heating, cooling and lighting - heating with heatpump, cooling with district water, LED lighting - convert energy demand to the end electricity demand of the HoNR office - cooling energy predominant in summer afternoons, heating in winter during days and lighting in the evenings and mornings - largest absolute savings compared to no facade and standard louvers system at 45 degrees caused by decrease of cooling demand - 25% savings compared to louvers and 56 % compared to no shading (energy demand) - ASF saves electricity compared to louvers but probably building needs more electricity than without shading (as heating uses the most electricity and cooling is very efficient in the chosen configuration, where electricity is only needed to pump the fresh water into the cooling system). - ASF produces more electricity than needed by building

Climate adaptive building shells: State-of-the-art and future challenges [12]

- active and passive building technology (active means utilizing modern technology (such as PV), whereas passive directly uses wind and sun to optimize the building) -> combine them - climate adaptive building shells (CABS) can take advantage of variable outdoor conditions - definition of CABS: "A climate adaptive building shell has the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance." - building integrated PV (BIPV) and static daylighting systems are not included in CABS (not adaptive) - Robustness is the ability to reduce negative influences caused by external changes, it should be defined together with flexibility which describes the ability of the system to change according to the external conditions (adaptability, multi-ability and evolvability) - adabtable building shells can react to external changes - multi-ability means that one technology can perform different tasks, depending on the user or the external conditions (e.g. foldable balcony) - evolvability is the ability to react to changes in the long run - CABS are characterized by four physical categories: (Thermal, Optical, Air-flow, and Electrical) - time scales can range from seconds (wind changes) to seasonal changes - adaption can take place on a macro or a micro scale. Macro scale stands for visible, mostly mechanical changes, whereas on the micro scale mostly optical properties change - Control can be extrinsic (feedback loops, needs sensors, processors and actuators, either distributed or centralized) or intrinsic (direct reaction to changes e.g. by smart materials). Extrinsic control provides the opportunity of centralized control and evolvability, wheras intrinsic control utilizes less parts and a more direct feedback. - all reviewed projects take into account the thermal domain, most consider wind-flows, some consider optical domain or electrical domain (mostly by PV) - tendency towards extrinsic control on macro scale (conservative solution with sensors and servomotors, pumps or fans as actuators) - CABS are still in the development phase, high risk projects. The demand for building performance simulations is increasing. - Tradeoffs for CABS control: “daylight vs. glare, views vs. privacy, fresh air vs. draught risk, solar shading vs. artificial lighting, passive solar gains vs. potential overheating”. - advanced supervisory control strategies are needed such as optimal control and model based predictive control with weather forecast. - users should be able to override control - cost is still a major issue, large scale production is needed for CABS to have an impact

Energy efficiency of a dynamic glazing system [13]

- triple glazing, shading component in outer gap and ventilation in inner gap - independent variables: specific fan power, venetian blind position, kind of glazing system, difference between the air gap and the indoor air temperature - dependent variables: U-value, g-value, energy consumption, predicted percentage of dissatisfied (PPD)(, air change, daylighting factor)

Parametric analysis and systems design of dynamic photovoltaic shading modules (hofer15)

- utilization of 3D geometrical modeling to calculate mutual shading - parameters varied: facade orientation, distance between modules, electrical design parameters, one or two axis-tracking - Solar radiation calculated by use of three-component model (direct, diffuse sky and diffuse reflected radiation):

$$G_{tot,m,p}(t) = G_{dir,m,p}(t) + G_{dif,m,p}(t) + G_{ref,m,p}(t) \tag{2.1}$$

- Solar position generated by use of DIVA plugin - Shading on panels calculated as vector graphics - Solar insolation is averaged for every hour of the month and only one day per month is evaluated. - Power loss increases linearly with shaded area for 100% lateral shading, but increases faster for smaller lateral shading. - Solar altitude tracking leads to high mutual shading in summer and low mutual shading in winter, therefore seasonal variations in PV production are relatively small. - Overall, two axis tracking with small spacing results in highest insolation per facade area, though modules become less efficient caused by the mutual shading. –> What spacing results in highest energy production?

Chapter 3

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 [14], and its parametric modelling plugin Grasshopper [15]. The aquired data is then post-processed in Python [16] to extract the configurations that minimise building energy consumption and maximise PV electricity production.

3.1 Building Energy Analysis

The building energy simulation is conducted using EnergyPlus [17] through the DIVA [18] 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, outputing hourly values of energy use for heating, cooling and lighting. Optimum positions can then be found by comparing the electricity deman during every hour for all combinations.

3.2 Radiation and PV Analysis

A solar radiance simulation is run using Ladybug [19], which uses Radiance [20] 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 3.1. 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 [10]. 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 [21] with the following equation:

$$T_{cell} = T_{air} + \left(\frac{T^0_{cell} - T^0_{air}}{S^0} \right) S_{cell} \tag{3.1}$$

where T_{cell} is the temperature of each grid point on the module, T_{air} is the ambient temperature, T^0_{cell} is the temperature of the cell at reference insolation $S^0 = 800\frac{W}{m^2}$ and reference air temperature $T^0_{air} = 20°C$, and S_{cell} is the insolation of each gridpoint in $\frac{W}{m^2}$. The value of T^0_{cell} was estimated using a thermal image of the solar facade and typical values given in [21].

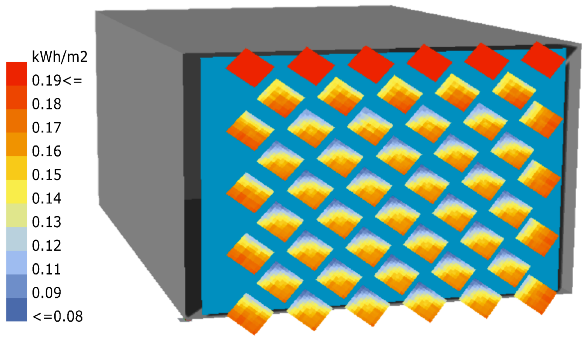

Figure 3.1: A simulation result showing module insolation from 11:00-12:00 on the 16 June for the used weather file and a specific module orientation.

3.3 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 analyis 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.

3.4 Simulation Framework

A corresponding workflow can be seen in Figure 3.2.

3.5 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° (closed) to 90° (open) position in steps of 22.5°. In the vertical axis, it can move from 45° to -45° in 22.5° steps. Existing ASF systems [11] have independently actuated panels and a continuous range of actuation, however

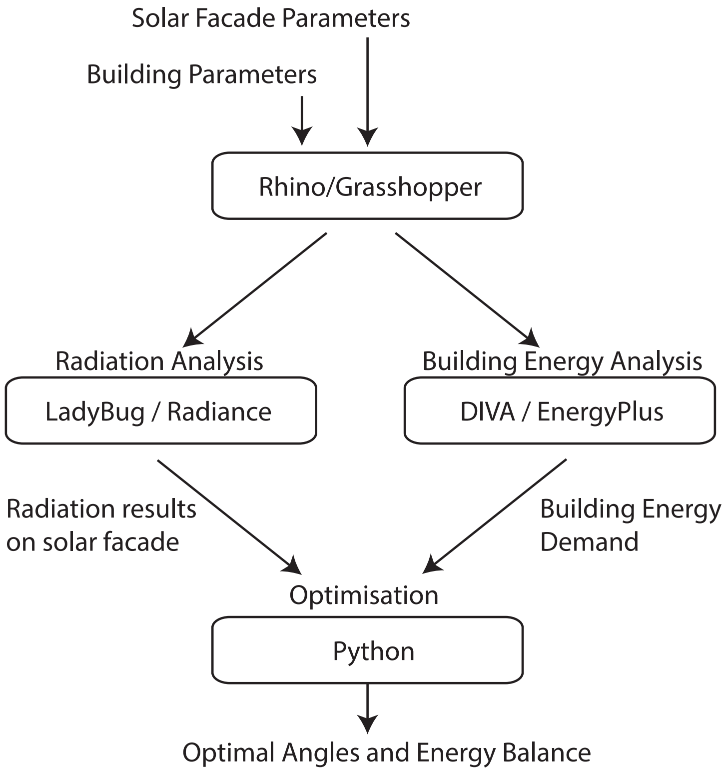

Figure 3.2: Work flow of the simulation framework

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 W/m^2.

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

Chapter 4

Results

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

4.1 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 4.1 and 4.2 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 arker 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.

4.2 Radiation and PV Analysis

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

4.2.1 Grid Convergence

With a larger gridsize, results are less accurate. In order to study this effect, a grid convergence study was conducted. Figure 4.4 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.

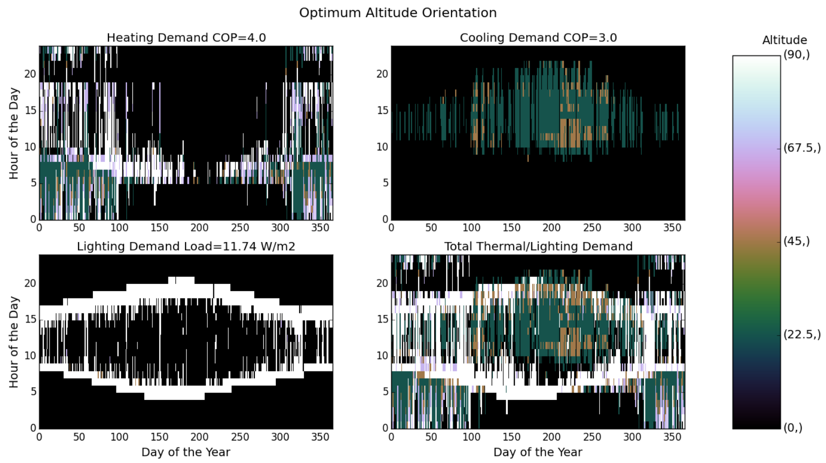

Figure 4.1: Carpet plots detailing the optimal altitude angles to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) total building energy demand. Darker colors represent closed positions, whereas brighter colors correspond to open positions. To optimize heating and lighting, open positions are favorable, cooling is optimized by using closed positions.

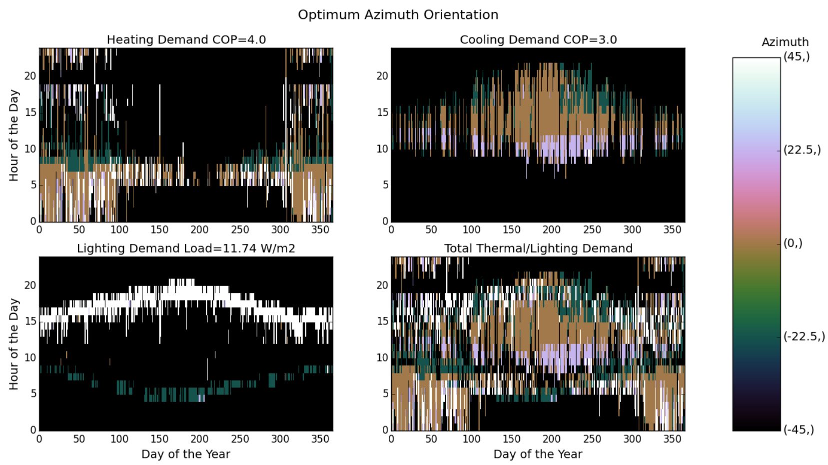

Figure 4.2: Carpet plots detailing the optimal azimuth angles to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) total building energy demand. Cooling is minimized by bocking the sun, wheras lighting and heating is minimized by opening the facade to let the insolation in.

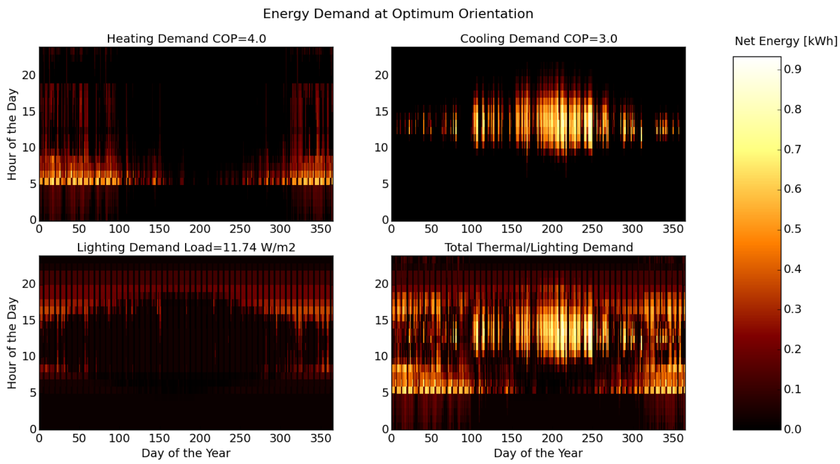

Figure 4.3: Carpet plots detailing the net energy consumption. Each square represents the total energy consumption for that specific hour of the entire month. Red colours detail the energy demand, while blue colours detail the energy supply.

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 computationaly feasible.

4.2.2 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 4.5 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 [10], thus the optimized solution decreases the longitudinal shading compared to sun-tracking.

4.3 Combined Evaluation

By combining results for building energy simulations and PV electricity production, the overall optimum configurations can be found. Figure 4.6 details carpet-plots of the facade optimised to maximise PV generation,

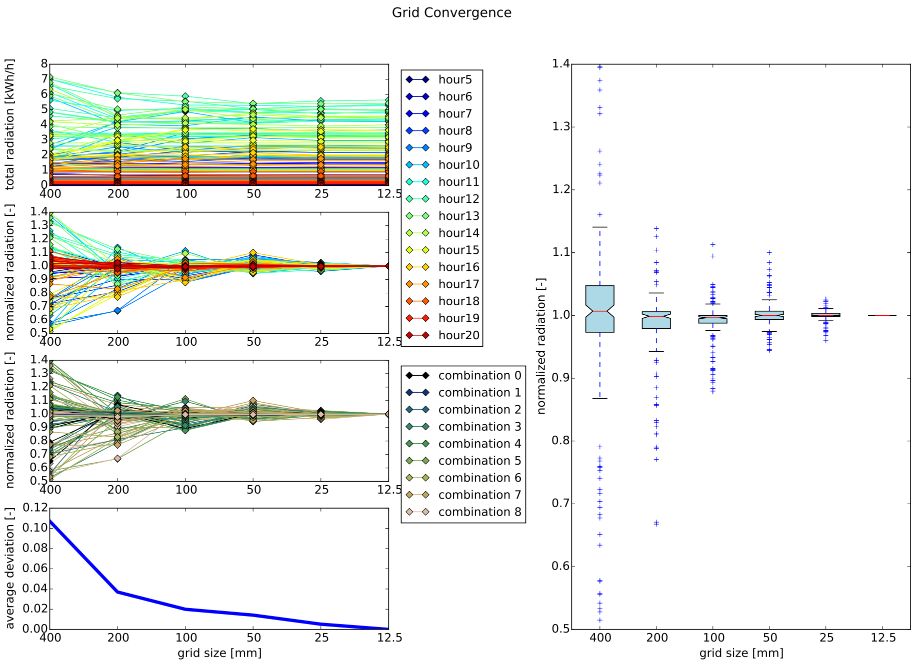

Figure 4.4: Grid convergence evaluation

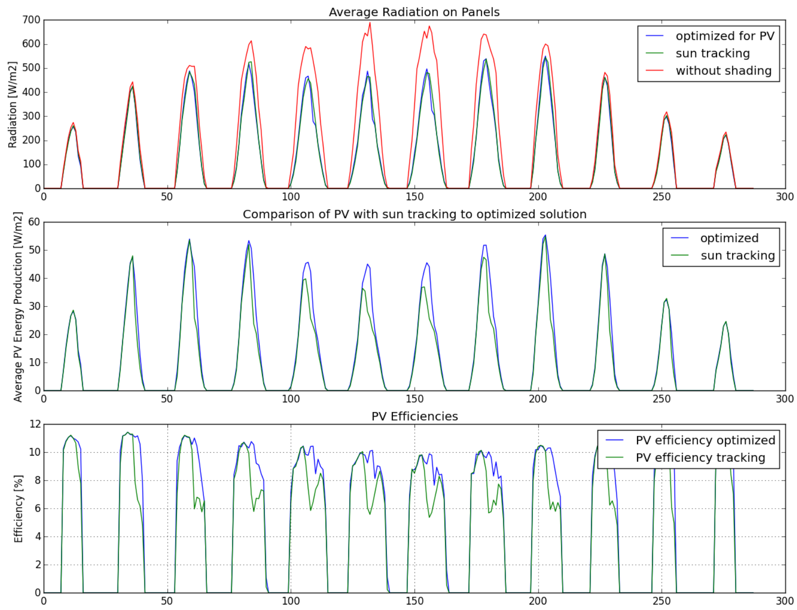

Figure 4.5: Comparison of optimized solution to sun-tracking. a) average radiation on panels compared to radiation without shading b) PV electricity production comparison c) efficiency comparison

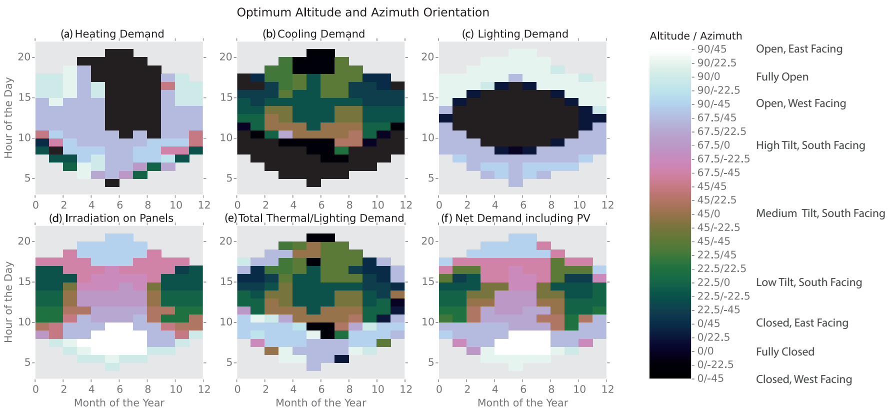

Figure 4.6: Carpet plots detailing the optimal configuration to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) maximise irradiance on PV panels. Each configuration is represented by an angle of orientation around the x-axis (Altitude) and y-axis (Azimuth) as seen in the legend. Figure (e) details the combinations for optimum building thermal management without PV production. (f) also includes the PV production

and minimise heating, cooling and lighting demands independently. We can see how 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 4.7 shows the net energy use at these optimum angles. It is

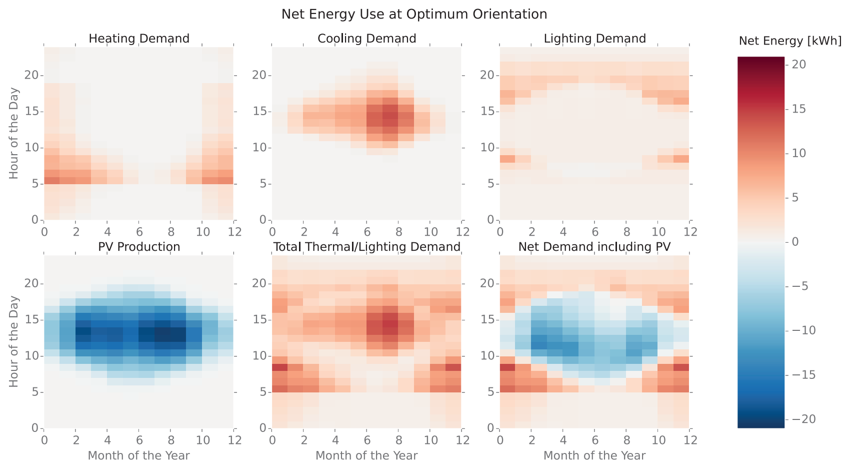

Figure 4.7: Carpet plots detailing the net energy consumption. Each square represents the total energy consumption for that specific hour of the entire month. Red colours detail the energy demand, while blue colours detail the energy supply.

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

Chapter 5

Discussion

here are some cool results

Chapter 6

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 7

Outlook

More research is necessary

Appendix A

Appendix A

This is appendix A

Bibliography

[1] Fifth assessment report, mitigation of cliamte change. *Intergovernmental Panel on Climate Change*, pages 674–738, 2014.

[2] PR Defaix, WGJHM van Sark, E Worrell, and Erika de Visser. Technical potential for photovoltaics on buildings in the eu-27. *Solar Energy*, 86(9):2644–2653, 2012.

[3] Marco Raugei and Paolo Frankl. Life cycle impacts and costs of photovoltaic systems: current state of the art and future outlooks. *Energy*, 34(3):392–399, 2009.

[4] RCGM Loonen, M Trčka, Daniel Cóstola, and JLM Hensen. Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, 25:483–493, 2013.

[5] Dino Rossi, Zoltán Nagy, and Arno Schlueter. Adaptive distributed robotics for environmental performance, occupant comfort and architectural expression. *International Journal of Architectural Computing*, 10(3):341–360, 2012.

[6] M Mandalaki, K Zervas, T Tsoutsos, and A Vazakas. Assessment of fixed shading devices with integrated pv for efficient energy use. *Solar Energy*, 86(9):2561–2575, 2012.

[7] Seung-Ho Yoo and Heinrich Manz. Available remodeling simulation for a bipv as a shading device. *Solar Energy Materials and Solar Cells*, 95(1):394–397, 2011.

[8] Freitas Sara and et al. Maximizing the solar photovoltaic yield in different building facade layouts. *EU PVSEC (2015)*, 2015.

[9] Prageeth Jayathissa, Zoltan Nagy, Nicola Offedu, and Arno Schlueter. Numerical simulation of energy performance and construction of the adaptive solar facade. *Proceedings of the Advanced Building Skins*, 2:52–62, 2015.

[10] Johannes Hofer, Abel Groenewolt, Prageeth Jayathissa, Zoltan Nagy, and Arno Schlueter. Parametric analysis and systems design of dynamic photovoltaic shading modules. *EU PVSEC 2015 conference, Hamburg, Germany (paper in review).*

[11] Zoltan Nagy, Svetozarevic Bratislav, Prageeth Jayathissa, Moritz Begle, Johannes Hofer, Gearoid Lydon, Anja Willmann, and Arno Schlueter. The adaptive solar facade: From concept to prototypes. *under review.*

[12] R.C.G.M. Loonen, M. Trčka, D. Cóstola, and J.L.M. Hensen. Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, 25:483 – 493, 2013.

[13] R. Lollini, L. Danza, and I. Meroni. Energy efficiency of a dynamic glazing system. *Solar Energy*, 84(4):526 – 537, 2010. International Conference {CISBAT} 2007.

[14] Rhinoceros v5, 2015.

[15] Grasshopper - algorithmic modeling for rhino, 2015.

[16] Python.

[17] Drury B Crawley, Linda K Lawrie, Curtis O Pedersen, and Frederick C Winkelmann. Energy plus: energy simulation program. *ASHRAE journal*, 42(4):49–56, 2000.

[18] Diva for rhino.

[19] M Roudsari, Michelle Pak, and Adrian Smith. Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. 2014.

[20] Gregory J Ward. The radiance lighting simulation and rendering system. In *Proceedings of the 21st annual conference on Computer graphics and interactive techniques*, pages 459–472. ACM, 1994.

[21] R.G. Jr. Ross and M.I. Smokler. *Flat-Plate Solar Array Project: Final report: Volume 6, Engineering sciences and reliability.* Oct 1986.