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

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# Abstract

With building integrated photovoltaic (BIPV), dynamic shading systems and adaptive envelopes becoming increasingly important in new buildings, the adaptive solar facade (ASF) project, which combines a dynamic shading system with photovoltaic (PV) cells, provides a promising technology for the future energy efficient buildings. This work presents a methodology to simultaneously calculate the building energy demand and the PV electricity production of a building with PV modules as adaptive building shading system. A parametric model was built for dynamic evaluations and optimisations of such a system. A case study was then performed on a model representing the prototype of the ASF at the house of natural resources at the campus of ETH Zurich. It was possible to find the optimizing configurations of such a system as well as the corresponding building energy demand. Furthermore, various influences were evaluated including sensitivities on the orientation, the location, the control strategy, and the building system parameters. For the chosen base case evaluation, energy benefits of 9% compared to a fixed solar facade at the most beneficial angle, could be achieved through the optimization of the angle actuation. The corresponding PV electricity output is able to compensate for 41% of the total building energy. The benefits are even larger for warmer regions than Zurich, as well as for buildings that have less efficient heating and cooling.

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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. Further literature on dynamic building envelopes includes [6], where current building performance simulations of adaptive facades are reviewed and the lack of adaptability in building simulation tools is addressed. 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 asses 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. With this approach it is possible 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

Previous research has evaluated adaptive shading systems and building integrated photovoltaics. Combined evaluations - however - could not be found in existing literature. Even though there already are prototypes of the adaptive solar facade - with new ones to be built soon - a comprehensive way to numerically analyse the energy demand combined with the electricity production is missing. A parametric model to analyse PV modules as adaptive solar shading systems needs to be developed in order to optimise the control strategy of said prototypes. Optimum configurations are yet to be found and the corresponding energy benefits must be evaluated. Furthermore, the potential of PV modules as adaptive building shading systems needs to be quantized in more detail, in order to asses the hypothesis of the energy benefits from the general concept. Finally, different parameters must be evaluated to assess the effects of building orientation, possibilities and limits of current simulation tools, as well as various control strategy approaches.

### 1.3 Objectives of Research

Based on the problem statement, the objectives are to

- Develop a modelling framework to simulate the energetic performance of adaptive photovoltaic envelopes
- Find the best configurations to minimise the net building energy demand
- Assess effects of the building orientation, system parameters, location and simulation strategies
- Suggest factors that must be taken into account to find the optimum control strategy

### 1.4 Thesis Outline

Chapter 2 introduces the methodology used within this thesis and describes the approaches taken for building simulation, radiation and PV analysis as well as the combination of the two separate simulations. In chapter 3, the results for the building simulation and the electricity production are presented and different influences are shown and discussed. The work is summarized and concludes in chapter 4 and an outlook for further research is given in chapter 5.

## Chapter 2

# Methodology

This chapter describes the methodology used to find the optimum configurations of the ASF. In general terms, the optimum configuration must correspond to the following optimisation problem that has to be solved for PV modules as adaptive building shading systems:

$$\text{minimise}(C + H + L - PV) \quad (2.1)$$

Where  $C$  is the electricity needed for cooling,  $H$  is the electricity used for heating,  $L$  is the lighting power demand and  $PV$  represents the electricity production.

An evaluation of the tools that were selected and how they are combined to create a modelling framework is given, and details of the simulation methodology are described.

### 2.1 Simulation Tool Selection

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]. Rhinoceros is a state of the art computer-aided design (CAD) software, which can be used to generate complex geometries, such as the ASF. Combined with Grasshopper, which provides a visual programming language with a wide range of add-ons, it is particularly suited for simulations that are evaluating geometric structures. The simulation part can then be split up into three parts, namely *building energy simulations*, *radiation simulations* and *photovoltaic simulations*, which will be described in the following subsections. While Grasshopper is well suited for the simulation part, it is not very suited for post-processing the data. The post-processing was therefore done in Python, a programming language with powerful scientific packages, a simple syntax, extended documentation, and a very active community.

### 2.1.1 Building Energy Simulation

There are various building energy analysis engines, such as EnergyPlus [21] or TRNSYS [22]. As EnergyPlus is open source, widely used, and well documented, it was chosen as the building simulation engine for all simulations within this thesis. There are multiple ways of connecting to EnergyPlus. Within this work, mainly DIVA [23] and Honeybee [24] were evaluated. While Honeybee provides a large range of settings and adaptability, DIVA is kept very basic. However, the EnergyPlus analysis with honeybee is running significantly slower than with DIVA. Therefore, and for its simplicity, DIVA was chosen to connect Grasshopper with EnergyPlus. 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.

### 2.1.2 Radiation Simulation

A solar radiance simulation is run using Ladybug [24], which is another grasshopper plugin by the same developers as Honeybee. It includes various components to process weather data and calculate radiation on surfaces based on an automatically generated or a predefined mesh. Ladybug uses Radiance [25] to determine the incident insolation on the solar facade. This approach enables the calculation of 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.

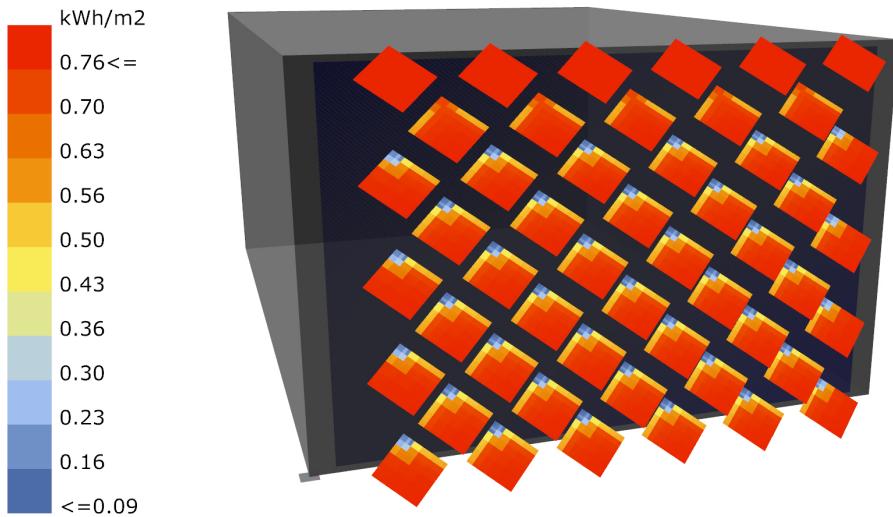


Figure 2.1: A simulation result showing module insolation from 12:00-13:00 on the 11th of August for a weather file of Kloten-Zurich and a specific module orientation.

### Grid Convergence

With a larger grid-size, radiation results are less accurate. In order to account for this effect, a grid convergence study was conducted. Figure 2.2 shows the grid size dependency of the total radiation on the ASF. The colours in the first two plots on the upper left ((a) and (b)) represent the hours of the day. One can see in the second plot (b) - where the radiation is normalized by a division with the radiation for a grid-size of 12.5 mm - that the results are significantly more accurate for morning and evening hours. This is caused by increased self-shading at midday hours. The colours in the third plot on the left (c) show the dependency on different combinations. No clear pattern could be found here. Finally, the average deviation is depicted in the fourth plot on the left (d) and a box-plot with all deviations is shown on the right (e). It can be seen that a smaller grid-size leads to larger deviations. While for a grid-size 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 grid-size of all simulations, as it gives accurate results, while still being computationally feasible.

#### 2.1.3 Photovoltaic Simulation

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 [26].

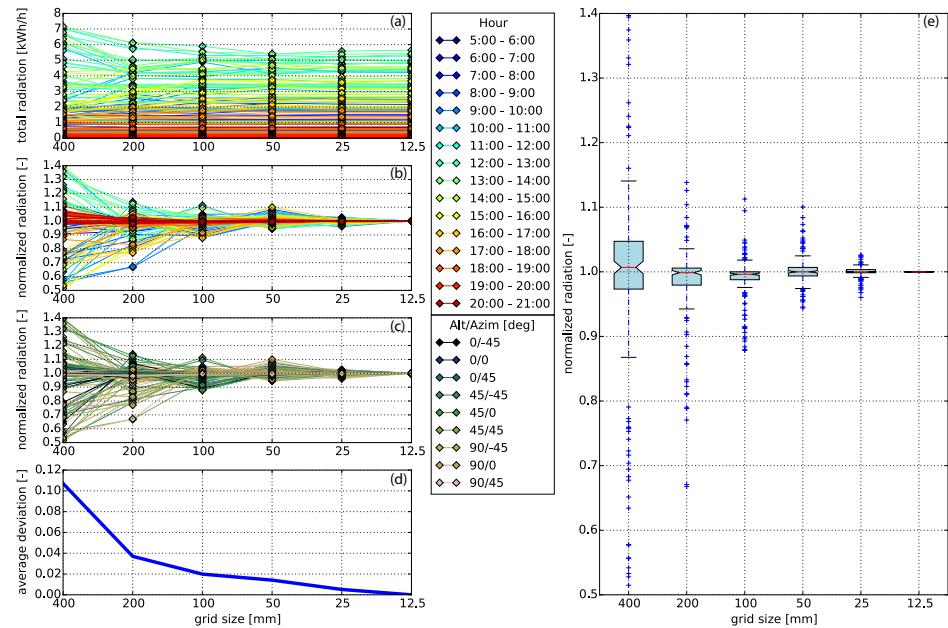


Figure 2.2: Grid convergence evaluation, showing the deviations of the radiation in dependence of the grid size, time of the day and panel orientation. (a) shows the total radiation on the panels in dependence of the hour of the day, (b) depicts the same results, but normalized with a division of the results with the smallest grid-size, (c) presents the influence of the panel orientation, (d) plots the average deviation from the smallest grid-size and (e) visualises all deviations with the usage of box-plots.

For the work in [17], the PV simulation was implemented with MATLAB. For this work, the MATLAB code was adjusted to match the new radiation simulations and then translated to python, in which the rest of the framework is written (details in section 2.2). PV electricity production is calculated based on a reference module. In addition to the irradiation dependency, the PV simulation includes temperature dependency. The temperature is estimated as suggested in [27] with the following equation:

$$T_{cell} = T_{air} + \left( \frac{T_{cell}^0 - T_{air}^0}{S^0} \right) S_{cell} \quad (2.2)$$

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 thermal images of the solar facade and typical values given in [27] to be  $38^\circ C$ .

## 2.2 Simulation Framework

In order to combine the single simulations, an evaluation framework was built with the use of Grasshopper and Python. In the following, details on how the combination was done and on the resulting parametric simulation model are given.

### 2.2.1 Combined Evaluation

As the building energy and the radiation simulations are done within Grasshopper, whereas the PV simulation is done within Python, a framework is necessary to easily combine the simulations. For this end, a folder structure was created to manage the files that are written both within Grasshopper and Python. There are two main files for the combined evaluation, one Grasshopper and one Python file. In the Grasshopper file, all the parameters can be set and the simulations can be started. After the building energy and the radiation simulations are finished, the corresponding results are read by Python, where the PV electricity production is calculated and the results are combined. The combination of the building energy analysis with the PV electricity results is done by cumulatively combining the building energy results to correspond to the PV analysis format. With this, the net energy usage of the room including the PV electricity production of the ASF can be given for monthly hours as described in equation 2.1. An overview of the corresponding work-flow can be seen in Figure 2.3.

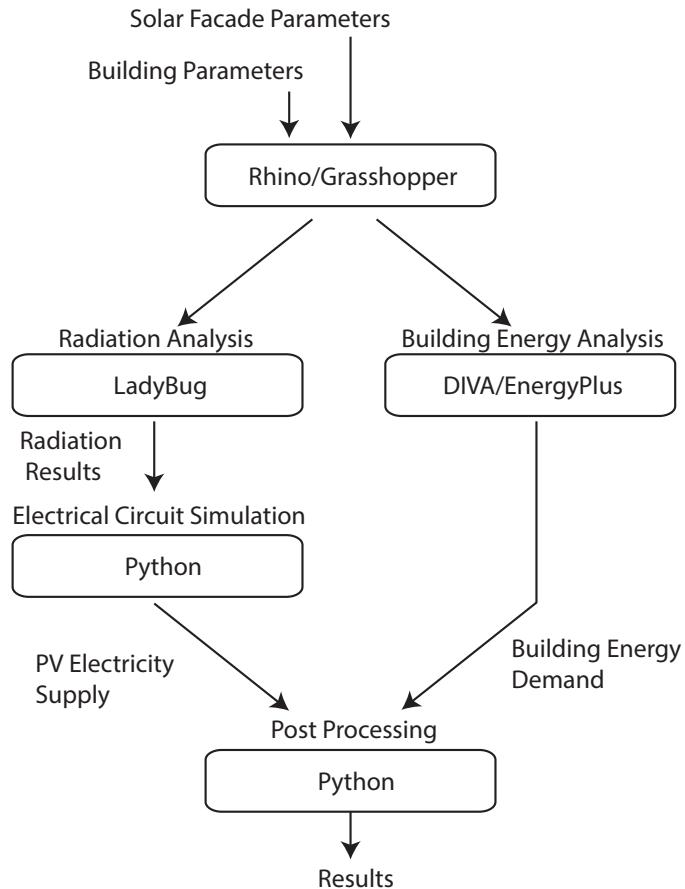


Figure 2.3: Work flow of the simulation framework

### 2.2.2 Parametric Simulation Model

Because of the many influences on simulations, the evaluation environment was built as a parametric simulation model. The parameters that can be set and the outputs of the simulation model are shown in figure 2.4. The Location of the simulation is given by an epw weather file, out of which all relevant informations are automatically extracted. The building system can be varied according to the DIVA parameter inputs, that is heating and cooling COP, infiltration rate, lighting power, fresh air, material type and occupancy. The direction which the building and the facade are facing, can be set with a single number representing the deviation from south. Geometry settings are available for the ASF as well as for the building, enabling to easily evaluate every room size and facade layout. The actuation range is set by defining the azimuth and altitude angles, that will be evaluated. An additional input provides the possibility to split up the facade into multiple

panel clusters, thus providing the possibility to account for the independent actuation of the panels. Finally, the radiation grid-size can be set, which influences accuracy of the radiation results and computational speed at the same time, as described in section 2.1.2.

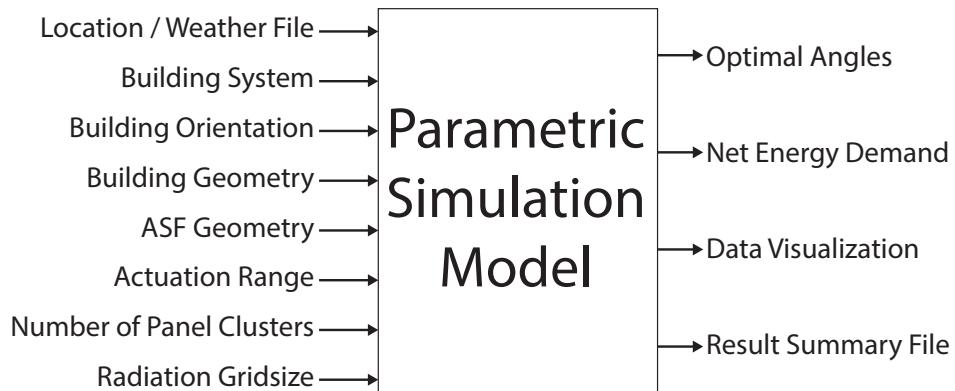


Figure 2.4: Blackbox visualization of the parametric simulation model

### 2.3 Case Study

The case study is done for a room and facade representing the prototype of the ASF at the house of natural resources (HONR) [18]. 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), whereas in the vertical axis, they can move from -45° to 45°.

The office environment is heated with a heatpump with an average COP of 4 and cooled with an average COP of 3. When required, the electric lighting consumption is  $11.7 \text{ W/m}^2$ .

Simulations are run for different angle combinations, with a weather file for Kloten-Zurich, Switzerland. There are two base-cases for the simulations. The first one consists of 49 different angle combinations (i.e. seven azimuth and seven altitude angles, with a stepsize of 15°), which is used for detailed evaluations of the angle positions. The second base-case consists of 25 angle combinations (five azimuth and five altitude angles), this case is used for the comparison of different system parameters. Simulations are done for average days of every month of the year, and the results are then compared to control strategies where the angles are fixed or follow sun tracking. Furthermore, the sensitivity of various parameters, such as building orientation, location, and COP is evaluated. A corresponding picture of the prototype installed at the HONR, can be seen in figure 2.5.



Figure 2.5: Prototype of the adaptive solar facade on the house of natural resources

## Chapter 3

# Results and Discussion

By combining results for building energy simulations and PV electricity production, the overall optimum configurations can be found. Figures 3.1 and 3.2 detail carpet-plots of the facade optimised to maximise PV generation, and minimise heating, cooling and lighting demands independently. The simulation was done for a total of 49 angle combinations with seven different states for the altitude and the azimuth angles, i.e. a step size of  $15^\circ$ . While the altitude angles are shown in figure 3.1, the corresponding azimuth angles of the same optimisation are shown in figure 3.2.

In the altitude angle visualization it can be seen that open configurations (light coloured) are chosen to minimise the building heating (a) and lighting (c) demand. Likewise, closed configurations (dark colours) are the preferred solutions to minimise the cooling demand (b). The PV optimisation tends to choose more open angles, corresponding to the minimisation of longitudinal shading as will be described in section 3.2. In (e), the angles that optimise the overall building demand are shown. The optimisation chooses open positions at hours where heating and lighting are important, whereas closed positions are used for hours where cooling is dominant. The configurations for total energy minimisation - including the PV electricity production - are depicted in (f). It can be seen that there is a conflict in the summer evenings between minimising lighting and cooling demands. Likewise, there is a conflict between heating and PV production during the winter months. The overall energy optimisation 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.

Similar patterns can be seen for the azimuth variations. The azimuth angles correspond to the deviation from the building facade normal. Since the simulation was done for a south-facing facade, this means an angle with a positive sign represents the panels facing towards south-east (bright colours),

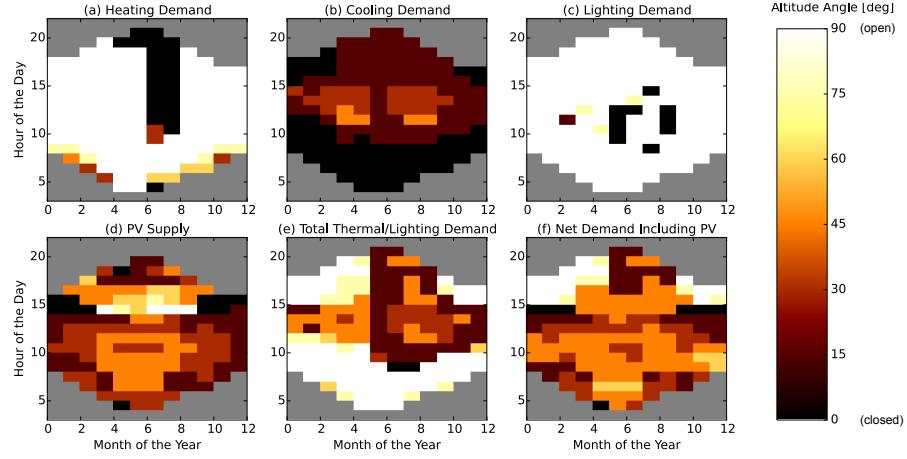


Figure 3.1: Carpet plots detailing the optimal altitude angles to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) maximise PV electricity production. Figure (e) details the combinations for optimum building thermal management without PV production, (f) also includes the PV production. Small angles correspond to closed positions, whereas large angles represent open positions. The corresponding azimuth angles for each hour can be seen in the following figure (3.2).

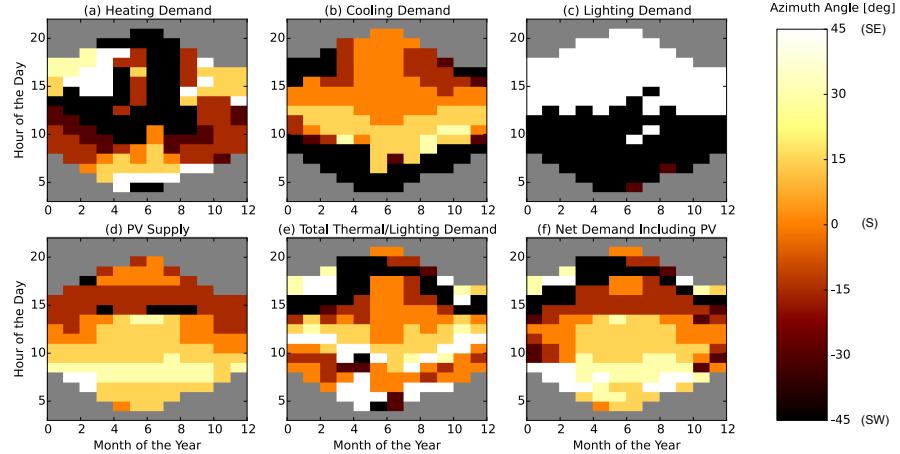


Figure 3.2: Carpet plots detailing the optimal azimuth angles to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) maximise PV electricity production. Figure (e) details the combinations for optimum building thermal management without PV production, (f) also includes the PV production. Negative angles correspond to the panels facing west, whereas positive angles represent east-facing panels. The corresponding altitude angles for each hour can be seen in the previous figure (3.1).

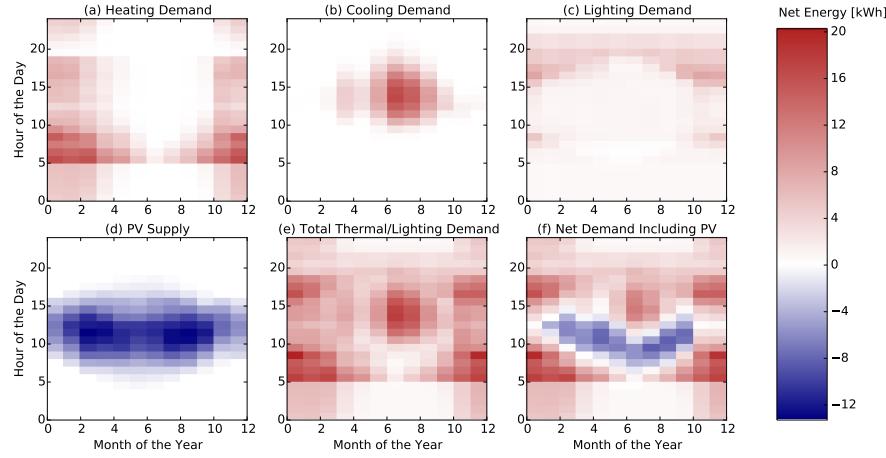


Figure 3.3: Carpet plots detailing the net energy consumption. Each square represents the total energy consumption for that specific hour of the entire month. Red colours detail the energy demand, while blue colours detail the energy supply.

whereas negative angles represent the panels facing towards south-west (dark colours). It can be seen that for heating and lighting, the facade takes positions that let the sun in, whereas for cooling the facade follows a sun-tracking pattern which prevents radiation to enter the room. The PV optimisation also follows a sun-tracking pattern, though with a deviation towards facing east. This is caused by the PV-layout and the effects of longitudinal shading [17]. The optimisation minimises longitudinal shading in order to maximise PV electricity production.

Figure 3.3 shows the net energy use at these optimum angles. (a) shows that heating is mainly dominant in the winter and in the mornings, cooling (b) is primarily needed in the summer afternoons, lighting (c) at hours of low or no solar insolation, whereas PV electricity production (d) is dominant at hours with high solar insolation. (e) shows the total building energy demand and (f) visualizes the net energy demand including the PV electricity production. It can be seen that there is a net negative energy demand for most sunlit hours, meaning that the ASF is generating more energy than is used by the building for these hours.

Overall, the optimization yields an energy benefit of 9% compared to the best performing fixed solar facade solution, and the PV electricity production is able to compensate for 41% of the total building energy demand.

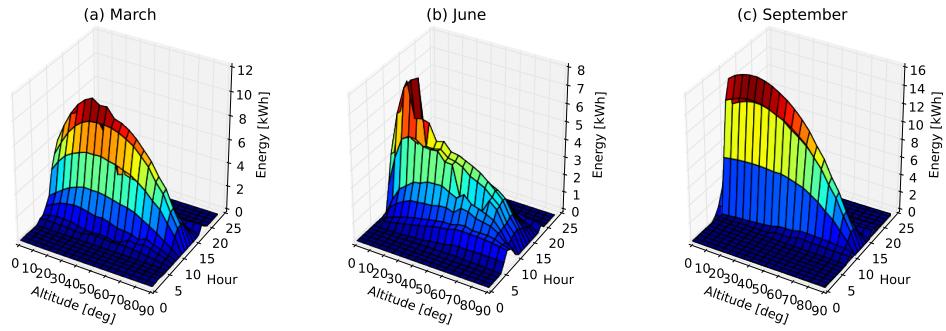


Figure 3.4: Energy benefits of the altitude actuation for the months of March (a), June (b) and September (c). Each plot displays one cumulative day in hourly resolution. The x-axis represents the altitude angles, the y-axis corresponds to the hour of the day, and the z-axis represents the energy benefit of the actuation, i.e. the difference in energy usage between the evaluated angle and the angle that yields the worst overall energy usage for each hour.

### 3.1 Influence of Angle Actuation

In order to evaluate the influence of the actuation, three dimensional plots can be used to display all possible configurations and their corresponding energy benefit. In figure 3.4, the energy benefits of the altitude actuation are visualized for the months of March (a), June (b) and September (c). Each plot displays one cumulative day in hourly resolution. The x-axis represents the altitude angles (19 different angles were evaluated with a step size of  $5^\circ$ ), the y-axis corresponds to the hour of the day, and the z-axis represents the energy benefit of the actuation, i.e. the difference in energy usage between the evaluated angle and the angle that yields the worst overall energy usage for each hour. It can be seen that the energy benefit is by far the largest around noon. Furthermore, positions that are rather closed tend to have the highest influence for the said mid-day hours. Open positions normally yield the worst benefits, except for some early morning or evening hours, where heating and lighting become important. This overall behaviour corresponds well to the results depicted in figure 3.1, and shows why the angles that yield the optimum total energy, generally match the angles that optimise cooling and PV electricity production. A further interesting observation that can be made from this figure is the non continuous curves for midday hours in summer. At an altitude angle of around  $30^\circ$ , the energy benefit reduces over proportionally. This is caused by the PV electricity production, larger angles will increase longitudinal shading and therefore over proportionally reduce the energy yield.

## 3.2 Comparison of Sun Tracking to Optimised Solution

In order to evaluate the optimum configuration for PV electricity production, simulations using sun-tracking were compared to simulations evaluating 49 different combinations (i.e. 7 different azimuth and altitude angles). Figure 3.5 shows the radiation on the panels in the first plot (a), also comparing it to the maximum radiation. The second plot (b) shows the PV electricity production for the two different control strategies, whereas the third plot (c) compares the corresponding efficiencies. It can be seen that while the radiation on the panels is pretty similar for both sun tracking and the optimised solution, there are large losses in summer due to shading. Because of the shading, the total radiation on the panels is lower in summer than in spring and autumn. This can be explained by the higher altitude of the sun during summer months, the higher sun position results in increasing self-shading. Another observation is that the PV electricity production - as well as the corresponding efficiency - of the optimised 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 optimised solution decreases the longitudinal shading compared to sun-tracking. Therefore, an optimising solution should be preferred over a sun-tracking approach for control strategy considerations. Finally, the temperature dependency of the PV electricity model can be observed from the graph that is detailing the efficiency, even though the radiation in the winter months is significantly lower than during the rest of the year, the corresponding efficiency is comparatively high because of the lower temperatures in the winter months.

## 3.3 Sensitivity on Control Strategy Approach

To evaluate further possibilities and limitations of the control strategy of the ASF, the tradeoffs between different strategies were visualised, as can be seen in figure 3.6. (a) shows the total energy demand used for heating, cooling, and lighting, the PV electricity production, as well as the total building demand and the net energy demand (building demand minus PV electricity production) for various control strategies. In (b) the corresponding differences in energy of the control strategy to the individually optimised solution is shown. As expected, the overall optimisation is able to have the smallest deviations from the individually optimised results. When comparing the different control strategies, one can see that especially cooling and PV need to be optimised, while the heating and lighting demand have a lower sensitivity on the control strategy. Another observation that can be gained, is that the optimisation for cooling is not very beneficial for the PV

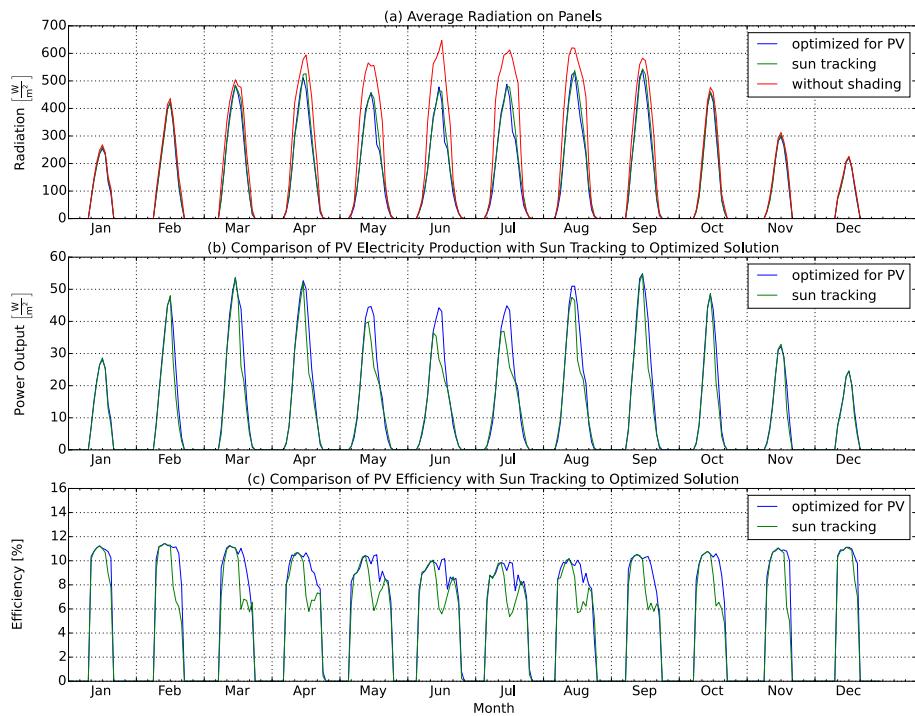


Figure 3.5: Comparison of optimised solution to sun-tracking. a) Average radiation on panels compared to radiation without shading. While the radiation for sun-tracking is very similar to the radiation with the optimised angles, there are large losses caused by shading. b) PV electricity production comparison. The optimised solution yields a significantly larger power output. c) PV efficiency comparison. The optimised solution is able to stay at higher efficiencies than the sun-tracking approach.

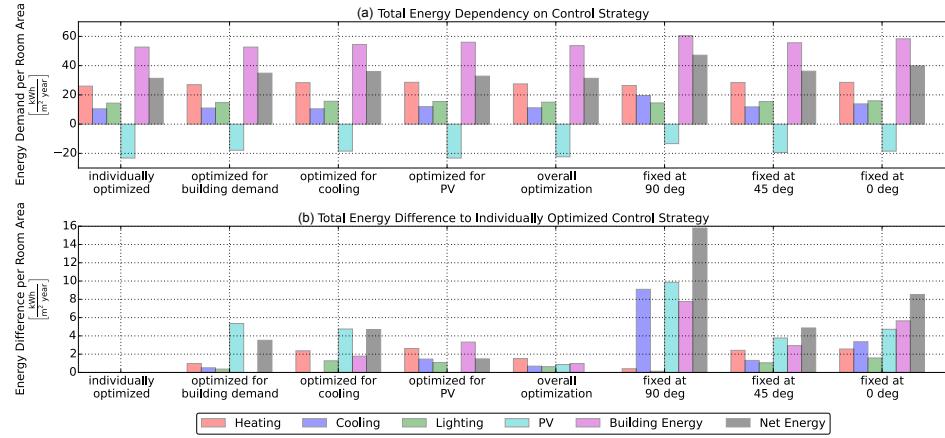


Figure 3.6: Comparison of different control strategies. (a) Total energy demand per room area. (b) Energy difference to individually optimised solution.

electricity production. This corresponds to the results in the previous section (3.2), and is caused by the longitudinal shading, which naturally the cooling optimisation does not take into account. However, the optimisation for PV electricity production has a smaller negative influence on the cooling demand. This graph is part of the parametric simulation model, and can easily be adjusted to evaluate different building system parameters, as well as time periods.

### 3.4 Orientation Analysis

Evaluations of the facade for different building orientations were done with the base case of 5 azimuth and 5 altitude angles. Figure 3.7 shows the performance of the building and the facade for west, south-west, south, south-east and east orientations. (a) details the total energy demand for the optimised solution, (b) compares the performance of the optimised solution to a fixed solar facade at a 45° altitude angle, and (c) compares the performance of the optimised simulation to a simulation without external shading. Non surprisingly, the south facing facade produces the most electricity. It also has the lowest building energy consumption, mainly because of a low energy demand for heating and cooling. It was found that the PV apertures should be oriented parallel to the upper left edge for facades that are west or south-west oriented, whereas they should be oriented parallel to the upper right edge for east or south-east oriented facades. This is caused by the shading patterns, longitudinal shading needs to be prevented as described in section 3.2. Furthermore, it can be observed that an east facing building uses less

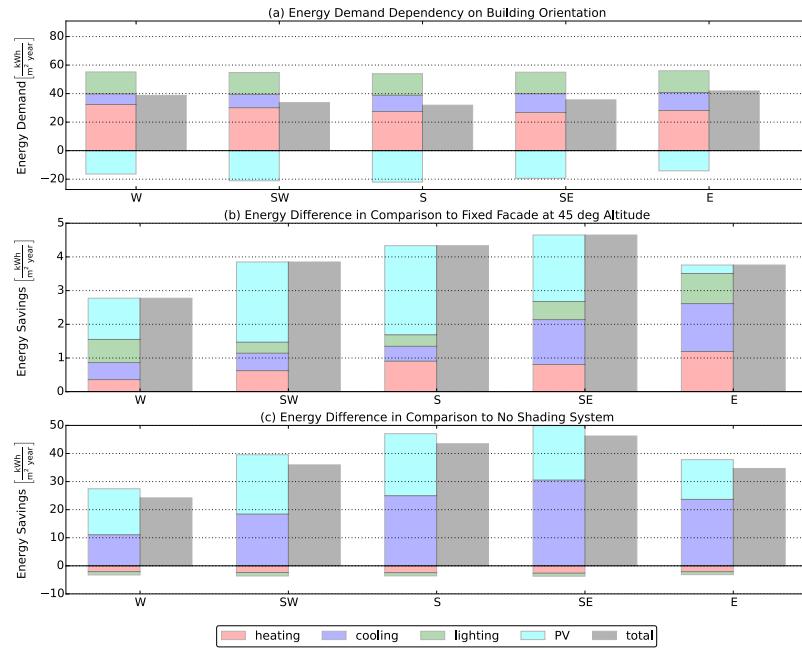


Figure 3.7: Energy demand in dependence of building orientation. (a) Total Energy Demand per room area, a south facing room has the lowest building energy demand while simultaneously maximising the PV-electricity production. (b) Energy Savings per room area of optimised solution compared to a fixed solar facade at 45° altitude. (c) Energy Savings per room area of optimised solution compared to a building without external shading. The energy benefit of the south-east facing ASF is the highest, mainly due to a better cooling performance.

heating than a west facing building, which could be explained with the previous observation that heating is most important during morning hours. For similar reasoning the east facing building needs more cooling energy than the west facing building, because the room heats up in the morning and will not naturally cool down before outdoor temperatures drop in the evening. Interestingly, PV production is higher for the west facing facade than for the east facing facade. The cause for this is probably because of conflicts in optimising cooling and PV electricity production at the same time, as cooling is more dominant for the east facing building. Overall, the south-east facing facade performs the best, when compared to the corresponding reference cases. It can clearly be seen, that this performance increase mainly comes from the high cooling demand, the benefits of the facade for the cooling energy use outweigh the lower benefit of the PV electricity supply.

### 3.5 Location Analysis

Similarly to the orientation analysis, the location of the building was evaluated. In figure 3.8, the corresponding energy performance of an ASF is shown for the locations Helsinki, Zurich, Madrid, and Cairo. (a) shows the net energy demand for the different locations, (b) details the energy savings compared to a fixed solar facade at a  $45^\circ$  altitude angle and (c) compares the net energy demand of a building with an ASF to a building without external shading. As for the building energy demand, it can clearly be seen that the further south a building is, the higher the cooling load and the lower the heating demand. The lighting however is similar in all cases. Interestingly, the PV electricity output is highest in Madrid. This can be explained by the altitude of the sun, in Cairo the average altitude is higher and therefore also the self-shading on the panels. As Madrid also shows the lowest net building energy demand, it can be said that the system is most efficient for this location. An analysis of the energy savings visualizes the impact of the location on the performance of the ASF even better. It can clearly be seen, that the warm and sunny locations of Madrid and Cairo have significantly larger energy savings than the ones in Helsinki and Zurich. This is caused by the large benefits of the ASF on reducing cooling as well as increasing the PV electricity output.

### 3.6 Sensitivity on Building System Parameters

A sensitivity analysis was done for heating COP, cooling COP, lighting load, and infiltration rate. The results are shown in figure 3.9. The top row (a) shows the energy savings per square meter of room area compared to a fixed solar facade at an angle of  $45^\circ$ , whereas the bottom row (b) shows the energy savings compared to a building without any PV modules or shading devices. The highlighted bar in each subplot represents the base case of the simulation with the same settings, therefore it has the same height for each parameter evaluation in the same row and serves as a reference. It can be seen that while the heating and cooling COP have large influences on the energy savings, the influence of the lighting load and the infiltration rate are significantly smaller. Especially a low COP for heating and cooling have a strong impact on the performance. For cooling, it becomes clear that an ASF is especially beneficial with inefficient cooling. As for the heating, it depends on the comparison case. While the energy savings are larger for a small heating COP when comparing it to a fixed solar facade at a  $45^\circ$  angle, they are smaller when comparing it to a building without external shading. This can be explained, with the importance of heating for each of the two reference cases. A building without any shading naturally has a lower heating demand than a building with shading. When the heating

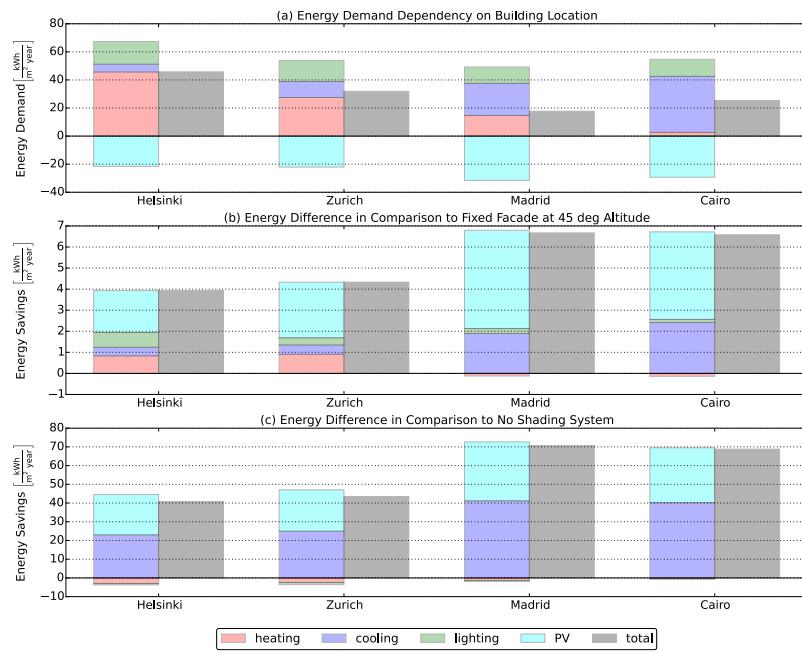


Figure 3.8: Energy demand in dependence of building location. (a) Total Energy Demand per room area, Madrid yields the lowest building energy demand while simultaneously maximising the PV-electricity production. (b) Energy Savings per room area of optimised solution compared to a fixed solar facade at 45° altitude. (c) Energy Savings per room area of optimised solution compared to a building without external shading. The energy benefit of the ASF for the warm and sunny regions is much greater than for the colder regions, this is due to a higher significance of cooling and increased electricity production of the PV panels.

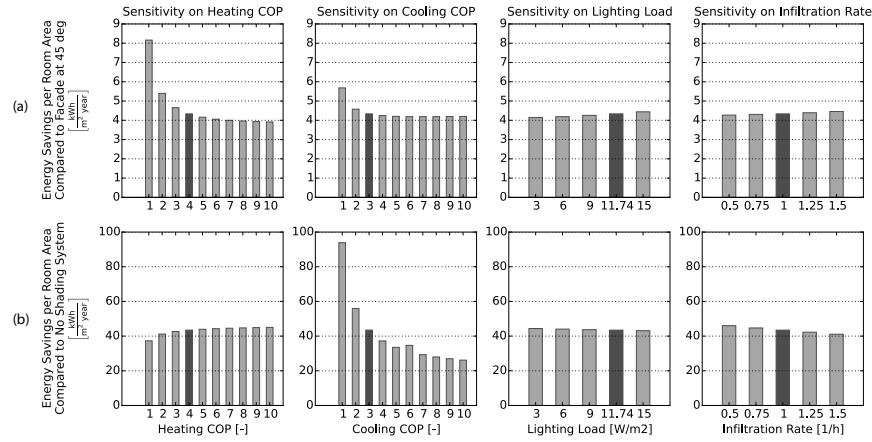


Figure 3.9: Sensitivity analysis of energy savings during one year. From left to right, sensitivities on heating COP, cooling COP, lighting load, and infiltration rate. The top row (a) shows the energy savings compared to a fixed solar facade at a  $45^\circ$  altitude angle, the bottom row (b) shows the energy savings compared to a room without shading or PV modules. The emphasized bar in every subplot corresponds to the basecase settings, all of them have the same height as they correspond to the same simulation.

COP is very small, which means that the energy demand for the heating is larger, it is relatively more efficient to have a building without shading than with shading. However, an ASF is still beneficial, as even with the lowest evaluated heating COP of 1 - corresponding to electrical heating - there are still significant overall energy benefits.

### 3.7 Evaluation of Different Combination Settings

With the parametric model, it is possible to evaluate every thinkable set of angle combinations. However, computational limitations require a discrete set of angles. In order to assess the influence of the chosen angle combinations on the performance of the ASF, various different combinations have been evaluated. In figure 3.10, the energy savings of various simulation combinations are shown, compared to a fixed solar facade at a  $45^\circ$  altitude angle (a), as well as to a building without external shading (b). Variations include evaluations of using only one axis actuation (i.e. either a fixed azimuth or a fixed altitude angle), as well as using multiple angles for both altitude and azimuth actuation. The angles were always distributed equally between  $0^\circ$  and  $90^\circ$  or between  $-45^\circ$  and  $45^\circ$  for the altitude and azimuth variations, respectively. When using multiple angles, the maximum and minimum ac-

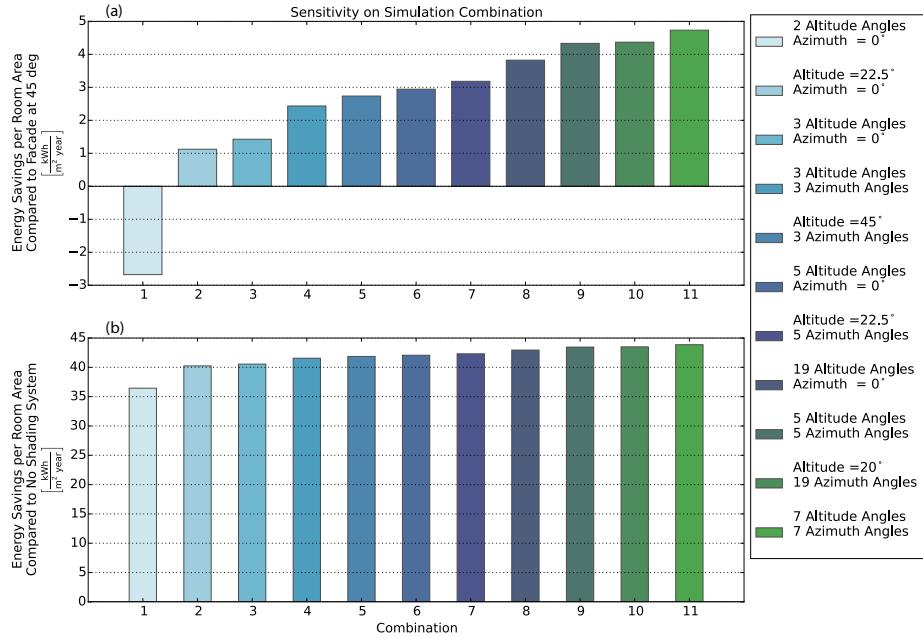


Figure 3.10: Comparison of different combination settings. (a) shows the energy savings compared to a fixed facade at a  $45^\circ$  altitude, (b) shows the savings in comparison to a building with no external shading.

tuation angle was always included. For example an analysis using three altitude and three azimuth angles was using  $0^\circ$ ,  $45^\circ$  and  $90^\circ$  for the altitude variations, while the azimuth variations would include the angles  $-45^\circ$ ,  $0^\circ$  and  $45^\circ$ . It can be seen that the more angles are used, the higher the energy savings become. However, with an increasing number of combinations comes a corresponding increasing amount of computation time. Higher energy savings will definitely be possible with the use of an increasing number of combinations, though the benefit of increasing the number of combinations will gradually go down to zero.

### 3.8 Potential of Independent Actuation

Independent actuation of the panels is one of the key advantages of the ASF that have to be closely evaluated. In order to quantize the potential of individual actuation, evaluations were performed by splitting the ASF into clusters. Due to computational limitations, especially on the radiation part, simplified geometries were used for the radiation evaluation, using only ten panels in four rows with two clusters and eight panels in three rows with three clusters, rather than the 50 panels of the reference case

with one cluster. Furthermore only the months of March, June, September and December were evaluated. The two cluster evaluation was done for the reference case with five azimuth and five altitude angles. The evaluations with three clusters was done only for altitude variations, with 5 angles in each cluster. A visualization of the cluster comparison is shown in figure 3.11. The left column details the comparison of two clusters against one cluster, whereas the right column shows the comparison of three clusters to one cluster. (a) shows the net power use of the building for an average day of June, (b) depicts the corresponding power difference, and (c) details the average energy saving for the months of March, June, September and December. When looking at the power difference, it can be seen that the main benefit of using multiple clusters comes from deviations around noon and in the afternoon. This can be explained with the self-shading on the panels, as the facade has to optimise the longitudinal shading mainly in the afternoon (as described in section 3.2). Therefore the losses due to conflicts between cooling and PV can be reduced with the use of independent actuation. The comparison of the energy savings shows the impact on the conflicting energy yields. In the two cluster case, the energy benefits from heating and PV electricity are reduced, while cooling and lighting become more beneficial. The corresponding total energy demand could be reduced by approximately 1%. For three clusters, there are benefits for cooling, lighting and PV, though heating still brings some drawbacks. However, the corresponding total energy demand was reduced by 2.3%.

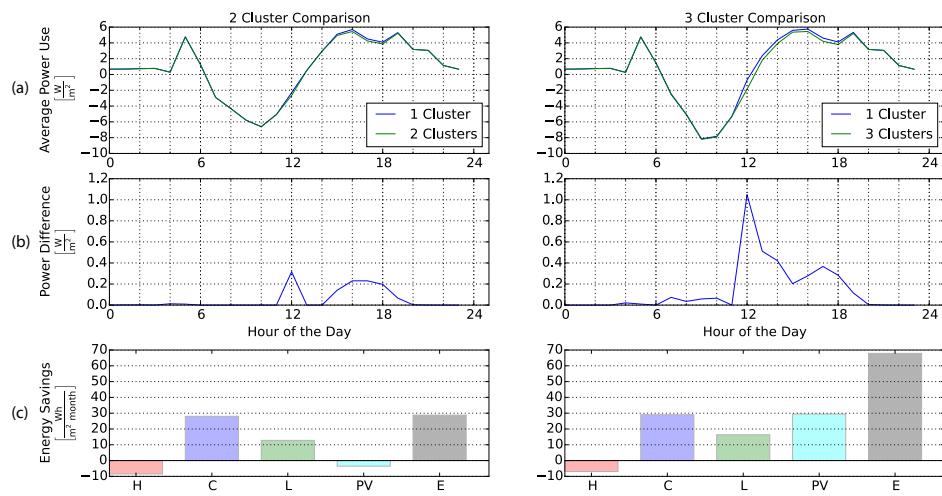


Figure 3.11: Cluster analysis of the ASF. The left column details the analysis with 2 clusters, whereas the right column corresponds to the 3 cluster analysis. (a) shows the average power use per room area for the month of June, (b) details the corresponding power difference, and (c) visualizes the total energy savings, averaged for the months of March, June, September and December.

## Chapter 4

# Conclusions

The work in this thesis presents a methodology to simultaneously evaluate PV electricity production and building energy demand of photovoltaic modules as adaptive building shading systems. A parametric model was created, to easily evaluate numerous different influences and designs, and a case study was done for the adaptive solar facade project (ASF). It was possible to find the optimising angles for heating, cooling, and lighting demand as well as for PV electricity production. Furthermore, also the optimising angles that minimise the overall energy use were found. When combining the building energy with the PV electricity production, it could be shown that the ASF is able to generate more electricity than is used by the building for most sunlit hours.

Of particular importance is the optimisation for PV electricity production. It was possible to show that sun-tracking does not optimise the PV power output. While sun-tracking simply follows the sun-angles, the optimising algorithm yields the positions that correspond to the highest electricity output by finding the optimum mediation between maximising radiation and minimising longitudinal shading on the panels. Also very important is the cooling performance of the ASF. The optimisation for PV, however, also yields a good performance for the cooling demand. Heating and Lighting on the other hand are not as important for the performance of the ASF, as they become most dominant at hours where there is no or very little sun. Nevertheless, with the overall optimisation also the heating and lighting yield energy benefits. Of course, these results strongly depend on the building system parameters. With a lower efficiency of heating, cooling or lighting, the corresponding energy demand will become significantly more important in the optimisation and the control in general. For the chosen base case, the optimisation was able to yield energy savings of 9% compared to a fixed solar facade at the optimum angle configuration, and the PV electricity production compensates for 41% of the building energy demand.

Furthermore, various parameters and their influence on the overall per-

formance of the system were analysed. Simulations done with different building orientations showed that the ASF performs best on a south-east facing facade due to increased cooling benefits. The most electricity - however - is generated from a south facing facade. Location evaluations were done for Helsinki, Zurich, Madrid and Cairo. Because of the significantly higher solar insolation and the warmer climate, the ASF performs best for the sunny regions of Madrid and Cairo. The highest PV electricity production was achieved for Madrid, this is because of the altitude angles of the sun, which are higher in Cairo and therefore generate increased self-shading on the panels. A sensitivity evaluation of the building system parameters showed that heating and cooling COPs strongly influence the performance of the ASF, whereas lighting and infiltration rate do not have a very strong effect on the performance. Evaluations of the number of simulation combinations showed that the discrete optimisation becomes more beneficial with an increasing number of evaluated combinations. Naturally the use of a smaller stepsize yields more accurate results of the optimisation. Finally, the potential of independent actuation was analysed with simplified simulations using two and three clusters of independently moving panels. It was possible to show that with two clusters, the overall benefit increased by 1%, whereas for three clusters, it would rise up to 2.3%.

This work ultimately presents a methodology for the planning and optimisation of sophisticated adaptive BIPV systems. 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. Through various simulations, it was possible to demonstrate and quantize the benefits of such a system, as well as suggesting factors that should be taken into account for future design considerations and further system performance evaluations.

## **Chapter 5**

### **Outlook**

While the results of this thesis are promising, further research must be done on many aspects. Optimisation algorithms must be found to determine the best state of the system with individual actuation while taking into account all influences. The optimisation algorithms could be included into the control of a real system, so that it can be at the optimum position at all times. Influences of user satisfaction and comfort have to be evaluated as well and must ultimately be included in the optimum control methods. Furthermore, the PV panels must be connected into strings for the evaluation and the influence of bypass-diodes should be included. In order to evaluate the building performance in more detail, the methodolgy needs to be changed to calculate building energy demand for single hours, taking into account the inertia of the system. Also the energy needed for the actuation of the panels should be modelled and included into the optimisation, to determine whether the energy savings from the improved position are higher than the actuation energy needed to get to that position. Other influences that can be evaluated in more detail include the reflectance of the panels, the ventilation, or the user interaction. In order to increase the accuracy of the simulations, an iterative optimisation algorithm could be developed and implemented in the future, in order to increase the accuracy of the simulation results. Finally, even though life cycle analysis was done before for this project, it should now be done again with the enhanced energy performance results, and could ultimatively even be integrated into the simulation environment.

# Appendix A

## Further Results

### A.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 A.1 and A.2 show the optimizing altitude and azimuth angles for heating, cooling, lighting and total building energy demand. In figure A.1, darker colours represent closed positions, whereas brighter colours correspond to open positions. To optimize heating and lighting, open positions (corresponding to large altitude angles) are favourable, 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. The azimuth angles in figure A.2 correspond to the deviation from the facade normal. For a south facing facade, this means an angle with a positive sign represents the panels facing towards south-east (bright colours), whereas negative angles represent the panels facing towards south-west (dark colours). It can be seen that for heating and lighting, the facade takes positions that let the sun in, whereas for cooling the facade follows a sun-tracking pattern which prevents radiation to enter the room.

Figure A.3 depicts the corresponding energy demand of the building for the whole year corresponding to the optimum positions presented in figures A.1 and A.2. It can be seen that the heating heating is most needed during the winter and in the morning, whereas cooling is mainly apparent in summer afternoons. Lighting on the other hand is most important in the evenings and at times where there is not much sun. In the combined plot, this behavior be seen clearly as well, the main overlaps of different building energy consumptions take place during winter between heating and lighting in the morning and in the evening, and between cooling and lighting during summer evenings.

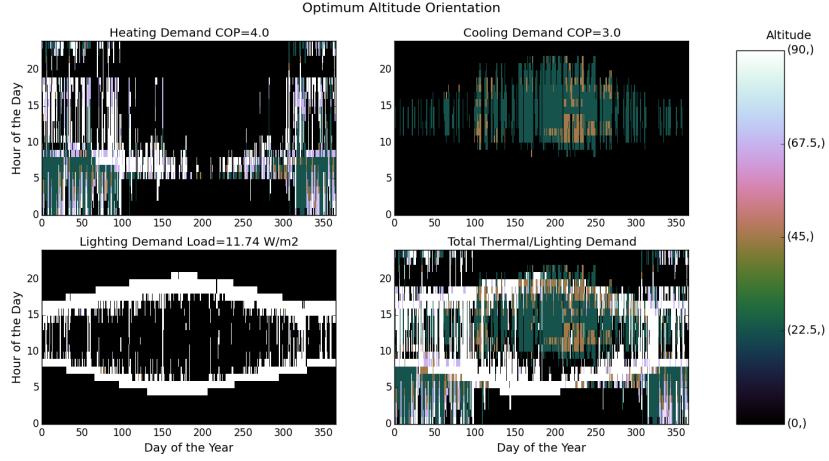


Figure A.1: Carpet plots detailing the optimal altitude angles to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) total building energy demand. Darker colours represent closed positions, whereas brighter colors correspond to open positions. To optimize heating and lighting, open positions are favorable, cooling is optimized by using closed positions.

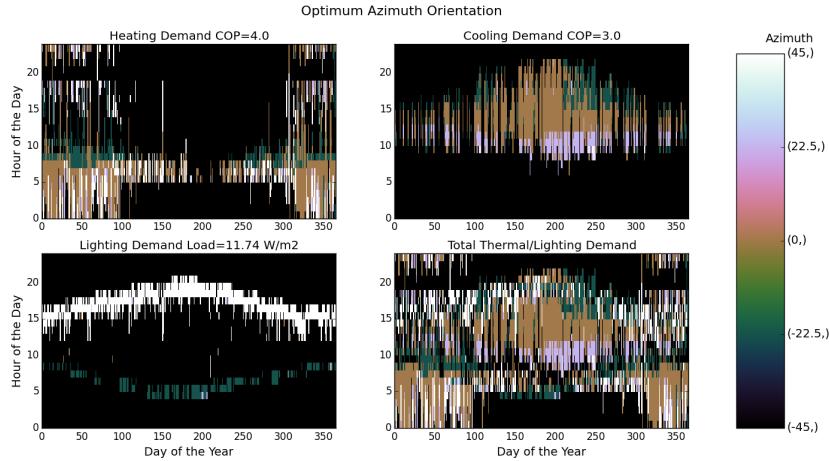


Figure A.2: Carpet plots detailing the optimal azimuth angles to minimise the (a) heating demand, (b) cooling demand, (c) lighting demand, and (d) total building energy demand. Cooling is minimized by blocking the sun, whereas lighting and heating is minimized by opening the facade to let the insolation in.

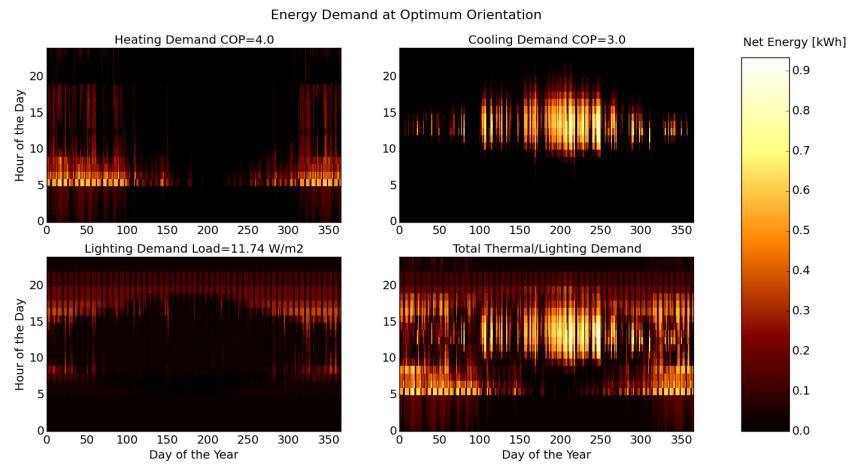


Figure A.3: Carpet plots detailing the net energy consumption. Each square represents the total energy consumption for that specific hour of the entire month. Red colours detail the energy demand, while blue colours detail the energy supply.

## Appendix B

# Usage of Simulation Environment

### B.1 Get ASF\_Simulation Folder

In order to use the ASF simulation framework, you can either download the .zip file and unpack the folder or you can use the following commands within git:

#### B.1.1 Git Setup

In Your working directory type

‘git init’

Then Checkout the repository

‘git clone https://github.com/architecture-building-systems/ASF\_Simulation.git’

To download the files type

‘git pull’

More information on using git can be found in the section [[Using Git]]

### B.2 Installation Guides

Rhino <https://www.rhino3d.com/download> You will need at least Rhino5  
Talk to Daren about licences

Grasshopper Open Source <http://www.grasshopper3d.com/page/download-1>

Grasshopper AddOns \* GHPython: Grasshopper Python <http://www.food4rhino.com/project/gh>  
\* DIVA/VIPER: <http://diva4rhino.com/> + You will need to add the Zuerich-Kloten weather file to C:/DIVA/WeatherData \* Hoopsnake: For looping grasshopper scripts <http://www.food4rhino.com/project/hoopsnake?etx> \* Ladybug/Honeybee: Thermal and radiation simulations, follow the instructions given within the following link: <https://github.com/mostaphaRoudsari/ladybug/blob/master/re>

*Human : some additional functions for GH* [http://www.food4rhino.com/project/human?etx\\*](http://www.food4rhino.com/project/human?etx*)  
*MeshTools : http : //www.food4rhino.com/project/meshedittools*

Python Anaconda is recommended as it is easier to create virtual environments and manage python <https://www.continuum.io/downloads>

If you do the installation manually (like how PJ did), follow this guide:  
<http://www.lowindata.com/2013/installing-scientific-python-on-mac-os-x/>

You will need numpy, scipy, matplotlib, ipython

### B.3 Grasshopper Simulations

#### Installation

You will need to download all Rhino and Grasshopper plugins found here  
[\[Installation Guides\]](#)

Open an empty rhino file, type ‘grasshopper‘ in the command line to open grasshopper. Open ‘main.gh‘ from the folder *SimulationEnvironment\grasshopper*.

How it works GHpython scripts generate the geometry of the ASF of every possible configuration. We then loop through every configuration and run an energy plus simulation and a ladybug simulation on every geometry for each hourly time step. The results are then post-processed to acquire the best configuration for each timestep. Special attention has to be given to the sections in the script which have a red frame, these sections should be checked before every simulation, to make sure that it is running correctly. Furthermore, one has to be aware of the places the results are stored, and the instructions given [\[here\]](#)(<https://github.com/architecture-building-systems/ASFsimulation/wiki/Grasshopper – Simulation save – data>) and [\[here\]](#)(<https://github.com/architecture-building-systems/ASFsimulation/wiki/Grasshopper – Radiation – results>) on how to save the data should be closely followed.

Set Geometry User Interaction on general geometry and simulation inputs

ASF Simulation Inputs Angles, number of clusters and the desired grid point size that will be used for the simulation are set in this section. The desired grid point size is only relevant for the ladybug analysis.

Geometry Inputs General inputs for the room and the asf geometry.

Geometry Calculations Processing of the geometry inputs, creates the geometry and saves inputs. Save Inputs Python script that saves asf geometry and simulation inputs.

Render the Building GHpython script ‘RenderRoom‘ creates the building geometry for simulation. T

Render the ASF Generate Diamond Array: Produces a matrix of coordinates of where a PV panel should exist Combination Maker: Determines the combination of PV panels. When running a simulation, \*\*it must always be made sure that the right combination is connected\*\* (either EplusComb or RadiationComb, framed in red) Render Diamond Array: Generates the geometry based off the chosen combination and array

### E+ Simulation

DIVA Interface Conversion \* Converts ASF panels into DIVA shading elements \* Converts all interior walls into adiabatic surfaces \* Converts the front wall to a facade element \* Converts the glazed section into a window element

Run the Simulation Run through the Viper interface. \*\*It is important that the right settings are used.\*\* Especially the weather file is subject to change. For the DIVA analysis, this can only be done in the Viper settings.  
 \* Lx set point: 300 \* Heating COP=variable (usually 4 or 5) \* Cooling COP=3 \* Lighting Load: Default is 11.74 W/m<sup>2</sup>

Save Data Python script that saves the DIVA data for post processing. The folder where it will be saved is set automatically in the script 'set DIVA data path' to 'SimulationEnvironment/data/grasshopper/DIVA/DIVA\_results'.  
*\*After a simulation finishes, the acquired data has to be moved to a separate folder with a unique name, which is good practice to always save a backup of the data. Alternatively, the folder 'DIVA\_results' can simply be renamed. It is good practice to also save a backup of the data. Alt+s] saves a backup, this should then also be moved to the corresponding data folder.*

Loop E+ Uses hoopsnake to iterate through all possible configurations - Note that sometimes the hoopsnake algorithm is not connected correctly

Set Weather File The weather file used for the ladybug radiation analysis is set in this section. The desired .epw file must already be in the WeatherData folder and the full name of the weather file has to be input to the python weatherPath python script.

Save details of weather file The weather file that was specified is read and relevant information is on the sun position and the temperature is saved to the folder 'SimulationEnvironment/location'. If a new weather file is used, the main.py file has to be run in the location. The file is introduced.

Loop LadyBug In this section ladybug is looped according to the specified angle combinations and for relevant hours (see 'Set Evaluation Period')

Set Evaluation Period Analysis period is set according to the loop number and the auxiliary data on the sun positions.

Ladybug Solar Analysis First of all, you have to let ladybug fly. For this the ladybug\_ladybug component has to be put onto the GH screen. This component has to run first, if there is no component A, then disable and enable again components that show the warning. This ensures, that the ladybug\_ladybug component runs.

Create Mesh for Radiation Analysis Creates a mesh of the asf for the radiation analysis according to the desired grid point size. The normals of the ASF geometry are flipped so that they face away from the building.

Create Sky Matrix In the selectSkyMtx component, it is possible to either choose a specific hour of the year or a period of time, which can be chosen with the Analysis Period component. \*\*WARNING: This component is not working correctly in the current version of ladybug.\*\* The bug has been found, fixed, and reported to the developers [here](<https://github.com/mostaphaRoudsari/ladybug/issues>)

Calculate Radiance on Panels Calculates the radiance on a specified geometry. The simulation is done for the chosen settings given by the Select-SkyMtx component. \*\*Toggle runIt to start the evaluation\*\*, this can take

up to 20 seconds on a fast computer.

**Sky Dome** for reference This component creates sky domes, that show where the radiation is coming from.

**Save Radiation Results** The detailed radiation results are saved to a .csv file with a C script. The results are saved to the folder `SimulationEnvironment/data/grasshopper/LadybugResults`. \*After a simulation finishes, the acquired data has to be moved to a separate folder with a unique name, which should then also be renamed. Alternatively the 'radiation\_results' folder can be renamed. It is good practice to also save a backup of the current results. `Alt+s` saves a backup, which should then also be moved to the corresponding data folder).

## B.4 Python Evaluation

**How it works** The data that was previously generated by the `main.gh` script is read in and post processed to output several graphs and a `summary.csv` file.

**main.py** This is the main file for the python evaluation. There are two modes: 'initialize' and 'postprocessing'. If an evaluation is done for the first time for a specific location,

## B.5 Set Up

All the files that are necessary to perform simulations of the ASF are in the folder `SimulationEnvironment`. There are two main simulation files, one for grasshopper, the other one for python.

1. Open the `main.gh` file.
2. Assign the desired weather file that will be used for the radiation simulation in the section "Set Weather File".
3. Make sure that the component 'LadybugSunPath' is enabled in the section 'Saved details of weather file'.
4. Open the `main.py` file.
5. In the "user interaction" section, the `mainMode` must be set to 'initialize' and the `geoLocation` must be set to the folder that was generated in grasshopper (for the zurich-kloten epw file, the corresponding folder is called 'Zuerich-Kloten'). The other options do not yet require any change, as they are only important for the post-processing mode.
6. Run the `main.py` script. Be aware that the first time the file is run, it will take some time, as the lookup-table for the pv-electricity-generation needs to be generated first.
7. Once the `main.py` script has finished without errors, the 'LadybugSunPath' component in the section 'Saved details of weather file' is enabled.

Now, simulations can be performed using grasshopper. See [[Run Grasshopper]]

## B.6 Run Grasshopper

After carefully following the instructions given in [[Installation Guides]] and [[Set-Up]], simulations can now be done using grasshopper as follows:

General Set-Up

1. Open main.gh

2. Make sure the 'run' switch in the 'E+ Simulation' section as well as the '*runIt*' switch in the 'Ladybug Solar Analysis' section are set to *False*

3. Set the building geometry and the facade geometry for the simulation in the section 'Set Geometry'

#### LadyBug Radiation Simulation

1. Set the weather file in the section 'Set Weather File' (If you want to use a new weather file, follow the instruction given in [[Set-Up]])

2. Reset HoopSnake in the section 'Loop Lady Bug'

3. Go to the folder 'ASF<sub>simulationEnvironment</sub>, results' and make sure it is empty.

4. Connect 'RadiationComb' to the 'combination' input of the 'Combination Maker V2' in the Section Geometry Calculations

5. Test loop hoopsnake and make sure the combinations are run as desired. It can be stopped by right clicking on hoopsnake and selecting 'stop'.

6. Reset hoopsnake again.

7. Toggle the '*runIt*' input in the 'Ladybug Solar Analysis' section to *true*.

8. Go again to the radiation, *results* folder and see if the .csv file for the first iteration was created. All

9. If everything looks fine, start to loop hoopsnake again.

10. Check that the 'LayoutAndCombinations.txt' file was created in the 'radiation, *results*' folder and look at the csv files to see if the results are reasonable.

11. Wait until the simulation is done. This step will generally take several hours, so it is a good idea to let it run over night.

12. When the simulation is over, the folder 'radiation, *results*' has to be renamed to have a unique name

13. Turn off the radiation analysis (set '*runIt*' to *False*). This will automatically create a new and empty

15. Save a backup of the main.gh file [CTR + ALT + S] and move it to the folder where the results are saved.

#### E+ Building Simulation

1. Set the desired weather file and other options in the Viper component settings in the section 'E+ Simulation'

2. Set all other options in this section.

3. Connect 'EplusComb' to the 'combination' input of the 'Combination Maker V2' component in the 'Geometry Calculations' section.

3. Loop hoopsnake in the 'Loop E+' section while looking at the rhino scene to make sure the desired combinations will be evaluated.

4. Reset hoopsnake in the 'Loop E+' section.

4. Turn the run input toggle in the 'E+ Simulation' section to true.

5. Go to the folder 'ASF<sub>simulationEnvironment</sub>, results' and check the 'LayoutAndCombinations.t

6. Check the output of the VIPER component in the 'E+ Simulation' section, there should be no errors and no warnings.

7. When everything looks fine, loop hoopsnake in the 'Loop E+' section.

8. Check the rhino scene and the result files to make sure everything is working correctly while looping.

9. Rename the 'DIVA<sub>results</sub>' folder to a unique name, such as 'DIVA<sub>Kloten5x1y2clustS</sub>E'.

10. Turn the 'run' input of VIPER to False. This will create a new, empty 'DIVA,*results*' folder.

11. Save a backup of the main.gh file [CTR + ALT + S] and move it to the folder where the results are saved.

Next Steps

The results can now be post-processed as described in [[Run Python]]

## B.7 Run Python

Once the grasshopper simulations are finished (see [[Run Grasshopper]]), the results can be post-processed as follows:

1. Open main.py
2. Set all the post-processing options in the user interaction section (each variable is described before its definition)
3. Run main.py (you can press F5)
4. Done

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