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ADVANCING SOLAR CONTROL AND ENERGY HARVESTING THROUGH THE USE OF PNEUMATICALLY ACTUATED ELASTIC ADAPTIVE FAÇADES

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Abstract. Adaptive facades can greatly impact a building’s energy balance by responding to external climates and by regulating internal conditions. With the integration of solar energy harvesting components, they have the potential not only to reduce the energy loss of buildings but also to gain energy. This premise has been tested within the framework of bio-inspired compliant mechanisms for adaptive façade elements, developed at the University of Stuttgart. Due to the flexible kinematic behavior of bio-inspired adaptive architectural elements, an innovative and simple alternative to common, more complex applications of adaptive façade components is obtained. The research presented aims at establishing the environmental criteria that will lead to an improved energy performance of a building using elastically deformable, adaptive façade elements with integrated photovoltaics. Through simulations and physical testing, the influence of daylight, solar radiation, and the building´s thermal balance are evaluated. The findings of this research are showcased on an adaptive façade consisting of pneumatically actuated, glass fiber-reinforced plastic laminates with integrated photovoltaics, assembled at Botanical Garden in Freiburg, Germany. Relying on environmental sensing, this façade is able to adapt over time in response to solar conditions with the goal of finding the right balance between low-energy building operation, high indoor environmental quality, and high energy harvesting. This study provides a novel, integrative design method utilizing adaptive building envelopes that successfully react to varying environmental conditions in an energy-efficient and cost-effective manner.

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Key words: Adaptive Façade, Fiber-Reinforced Plastics (FRP), Pneumatics, Photovoltaics (PV), Daylight, Radiation, Thermal Balance, Compliant Mechanisms.

1 INTRODUCTION

Studies on activity patterns show that people in urban areas spend, on average, 87% of their time indoors [1]. These results show the importance of creating buildings with the user's comfort as the main driver of design. Indoor comfort is the result of the environmental quality of buildings, which will be determined by environmental factors such as lighting, noise, air temperature, and air quality [2].

Façades are a building´s mediator between interior conditions and the external environment, and therefore play an important role in creating energy-neutral buildings [3]. Façades should be able to adapt to the constant changes in environmental conditions to preserve the desired comfort without requiring a substantial amount of energy [4].

While adaptive façades can enhance the building performance by reducing energy consumption, they also have the potential of producing renewable energy that could be later stored and used in the buildings [5].

Adaptive shading devices that regulate incidental solar radiation are among the types of adaptive façades most extensively used and researched [6]. On the other hand, building-integrated photovoltaics (BIPV) are a popular renewable energy solution as they can provide a cost-effective source of energy. These two complementary approaches have the potential to become an integrative solution for designing sustainable buildings, optimizing both comfort and energy efficiency.

The investigation of this holistic approach is performed within the context of the "Flectuation" research project carried out at University of Stuttgart. It focuses on creating reliable, elastically deformable, adaptive façade components made from fiber-reinforced plastics (FRP). This novel approach relies on bio-inspired compliant mechanisms that create adaptive shading elements that are less complex and less prone to failure compared to current implementations of adaptive shading mechanisms.

This research builds up on projects like Flectofin® inspired by the bird-of-paradise flower (Strelitzia reginae) [7], Flectofold taking inspiration from the Aldrovanda vesiculosa [8], Flexafold borrowing principles from Graphosoma lineatum italicum and the beetle Dorcus titanus platymelus [9] and the ITECH Research Demonstrator 2018–19 [10]. The findings of these projects have established the foundation for the latest iteration of elastically deformable adaptive elements: FlectoLine. It consists of FRP plates with hinge zones, which allow for the integration of a pneumatic actuator. Different stiffness on the upper and lower side of the hinge determine the folding direction in response to the applied air pressure of the integrated actuator.

As a FlectoLine demonstrator, an adaptive façade is being developed. The facade components serve on the one hand to shade the interior and on the other hand as the base for thin-film photovoltaics (PV). The adaptive FRP components are placed in pairs, allowing a mirrored actuation (Figure 1). They will be installed at the façade of the existing greenhouse in the Botanical Garden of University of Freiburg and will cover a total area of 105 m².

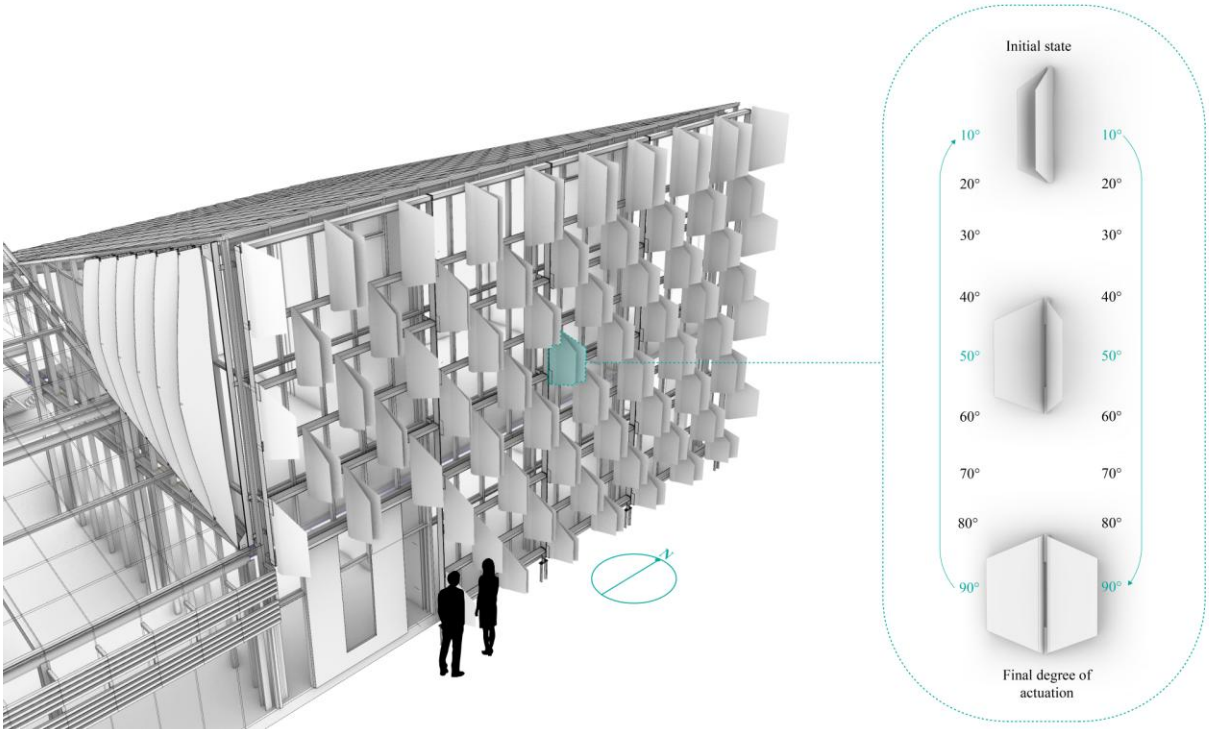

Figure 1: Rendering of the demonstrator façade and actuation of the elastically deformable FRP modules.

2 METHODS

Achieving an optimal balance between the three building performance goals daylight comfort, thermal comfort, and PV gain, could be attained with the proposed adaptive shading elements in the building. To that end, the main objective is to optimize the parameters based on the aperture angle of the adaptive modules. This requires a well-organized coordination process between different areas in energy building analysis, from which two initial strategies could be drawn, optimizing for user comfort and optimizing for energy harvesting (Figure 2).

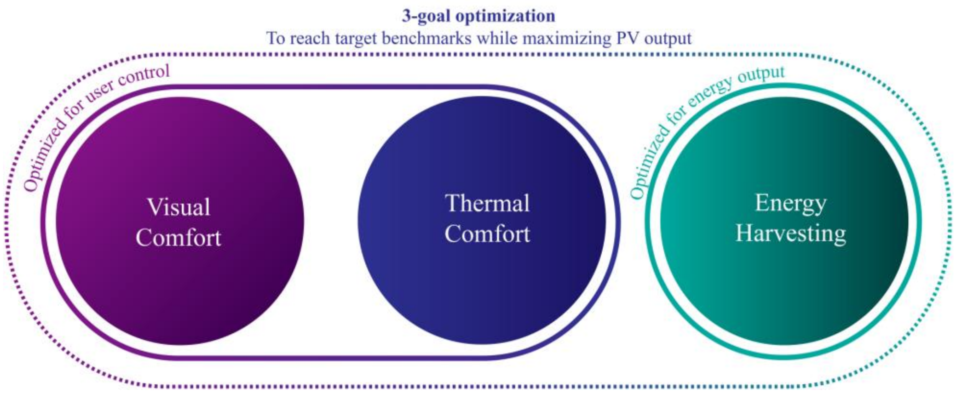

Figure 2: Optimization strategies for façade/building performance goals.

To evaluate the potential for integrating daylight and thermal control, as well as energy harvesting, a simplified model of the building is created. This model allows for the modification of the façade's state by adjusting the opening angle of the FRP panels, considering different weather conditions. For the simulations, a weather file for Freiburg was selected. The use of a site-specific weather file improves the simulation results and leads to a more accurate assessment for building control. Figure 3 shows the abstracted Rhino model with the room used for lighting and thermal simulation and the adjustable FRP panels used for PV simulation.

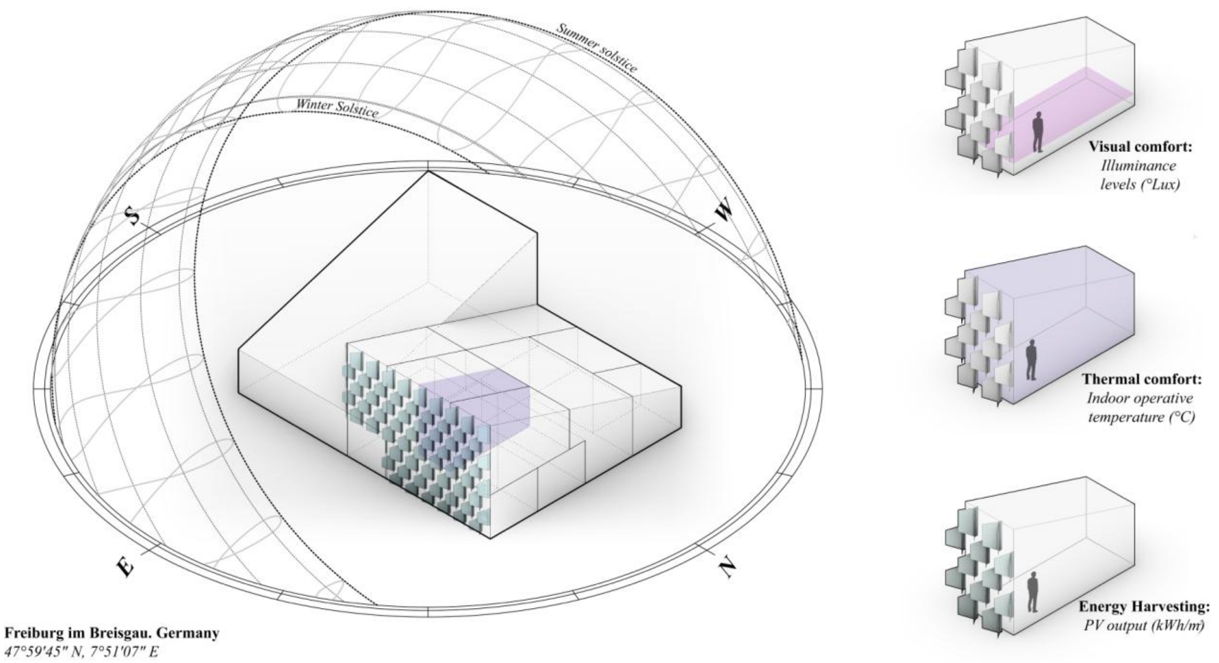

Figure 3: Abstracted model for simulation of the three main performance goals.

The model generation is done with Rhino3d [12]. The Grasshopper plug-in, along with Ladybug and Honeybee tools, is used to create a workflow for simulating illuminance levels, PV output and indoor temperature using with Radiance and Open Studio as the simulating engines. The building´s geometry and materiality as well as the weather data serve as fixed inputs for this simulation environment, while the panel´s opening angle and analysis period are variable inputs that can be adjusted to simulate various scenarios.

The outcomes of the simulated dynamic behavior of the façade provide valuable insights and a more comprehensive understanding of the adaptive façade performance. The results are then compared to benchmarks and performance indicators extracted from literature review.

2.1 Benchmarks

For the visual comfort analysis, two parameters are evaluated. Firstly, studies on Daylight Factor (Df) are performed, considering a target average range between 2-5%. These studies show the effects of the window-to-floor ratio of the room analyzed and the effect of the adaptive shading on the light penetration and distribution in the room. In-depth simulations on illuminance levels (Lux) are also carried out with the recommendations for daylighting according to the European Standard DIN EN 17037, that provides metrics on daylight provision, based on building typology. In this case, the areas of the greenhouse that are shaded by the adaptive façade are used as office areas, meeting rooms, break rooms, and technical facilities. Based on the DIN standard, a range of 300 to 500 Lux is recommended for the spaces to be used comfortably without the presence of glare [13].

For the studies on indoor thermal comfort the EN 16798-1 standard provides the comfort temperature ranges to consider for heating and cooling seasons [14]. These are based on four different levels of expectation, see Table 1.

Table 1: Temperature ranges for indoor environments based on EN 16798-1 standard.

Category	*Temperature range for heating seasons (°C)*	*Temperature range for cooling seasons (°C)*
I	21.0 - 23.0	23.5 - 25.5
II	20.0 - 24.0	23.0 - 26.0
III	19.0 - 25.0	22.0 - 27.0
IV	17.0 - 25.0	21.0 - 28.0

For thermal simulations, information on the materiality of the building and the occupancy patterns are essential for creating accurate results. Table 2 shows the components and properties of the building envelope. This information was taken from observations from site visits. This building does not have regular schedules that can be abstracted for the simulation, in this case, a regular office schedule was used.

Table 2: Building components and thermal properties of the Greenhouse.

Building element	*Material*	*U-Value [W/(m²/K)]*
Roof	Glass roof with internal insulated ceiling panels	1.2
Glazing	6 mm double glazed panels with 6 mm air gap	2.6
Internal Walls	Timber panels with 85 mm wool insulation	0.46
Floor	Concrete slab (150mm)	0.28

To get an idea of the potential PV output of the panels integrated into the adaptive FRP modules, the Radiance-Honeybee extension of the Ladybug tools was used to simulate the solar radiation hitting the faces of the modules. The resulting radiation reading is then multiplied by the PV common efficiency factor of 15% and the inverter efficiency factor of 98%. The base geometry of the simulations is one pair of modules to get accurate values from the overshadowing of modules caused by the mirrored actuation.

3 RESULTS

The simulations ran for a yearly analysis, these results create a matrix with hourly information on the resultant illuminance levels, operative temperature, and PV output. With these results it is then possible to extract the actuation angle that leads to the best performance for solar control and energy harvesting.

For this paper results on a typical summer and a typical winter day will be shown to identify the impact of the adaptive shading in two critical scenarios.

3.1 Visual comfort

Since the façade faces east, and the window-to-floor ratio in the spaces is very high, the most problematic time of the day is during the morning, due to the direct solar radiation the façade receives.

Figure 4 shows the resulting Daylight Factor of four different degrees of actuation of the adaptive façade. Due to the room dimensions and the window-to-floor ratio, when there is no solar control there is a high variation in the light distribution that could lead to glare and visual discomfort.

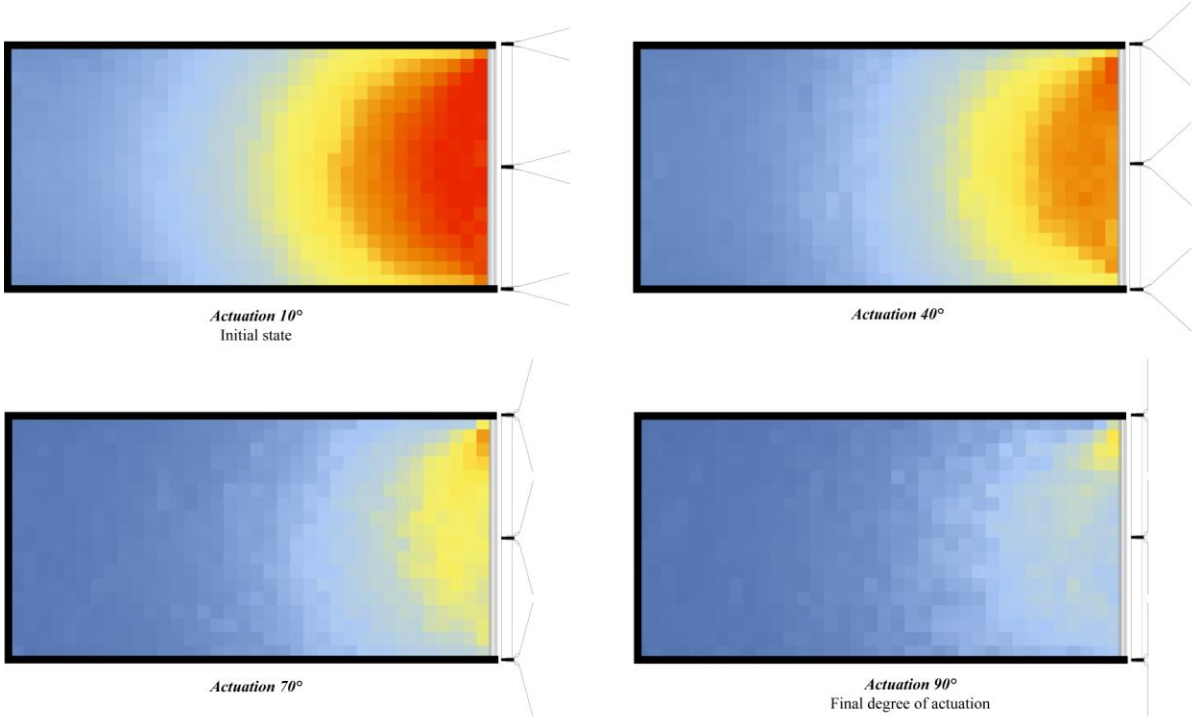

Figure 4: Daylight Factor with overcast skies and considering four different degrees of actuation.

During a typical summer day, the range of illuminance levels throughout the day is higher than in the winter season (Figures 5-6). When using adaptive shading, daylight could be controlled in an effort to provide stable lighting conditions.

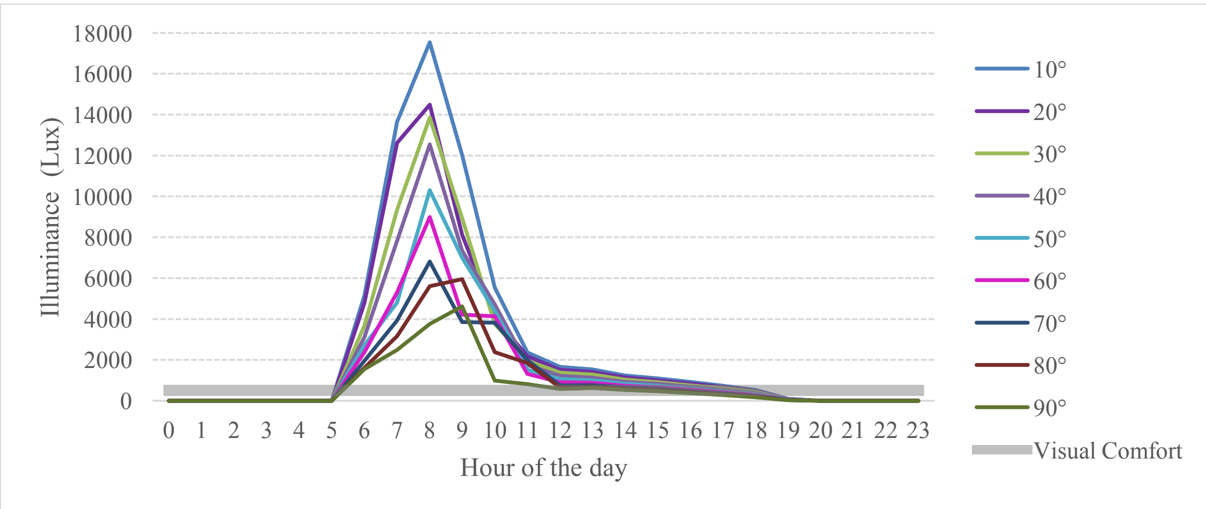

Figure 5: Illuminance values of different degrees of actuation of the façade modules on a typical summer day.

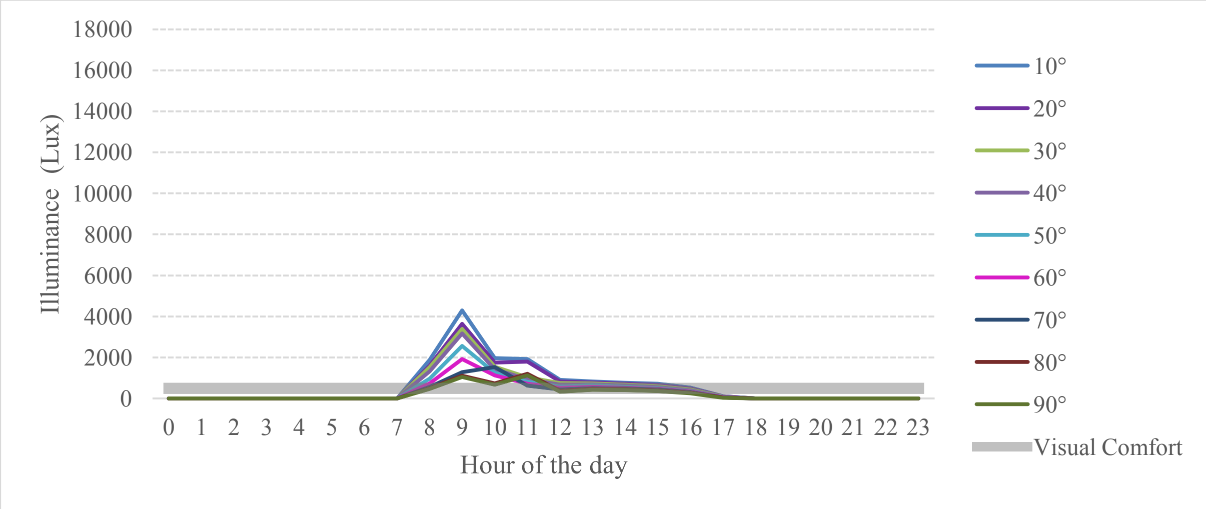

Figure 6: Illuminance values of different degrees of actuation of the façade on a typical summer day.

3.2 Thermal comfort

The typology analyzed is a greenhouse, and it was built to trap heat gains, however, for the spaces that are used as office areas, this becomes problematic during summer when the indoor temperature could increase up to 10K in relation to the outdoor temperature. This rise in temperature is beneficial during winter to get closer to comfort levels.

When implementing outdoor shading to block solar radiation from hitting directly the glazing areas, the temperature drops significantly, reaching comfort levels during summer. When the shading is adaptive, then the opposite strategy could be implemented during cold periods, to allow for the passive solar heating of the spaces.

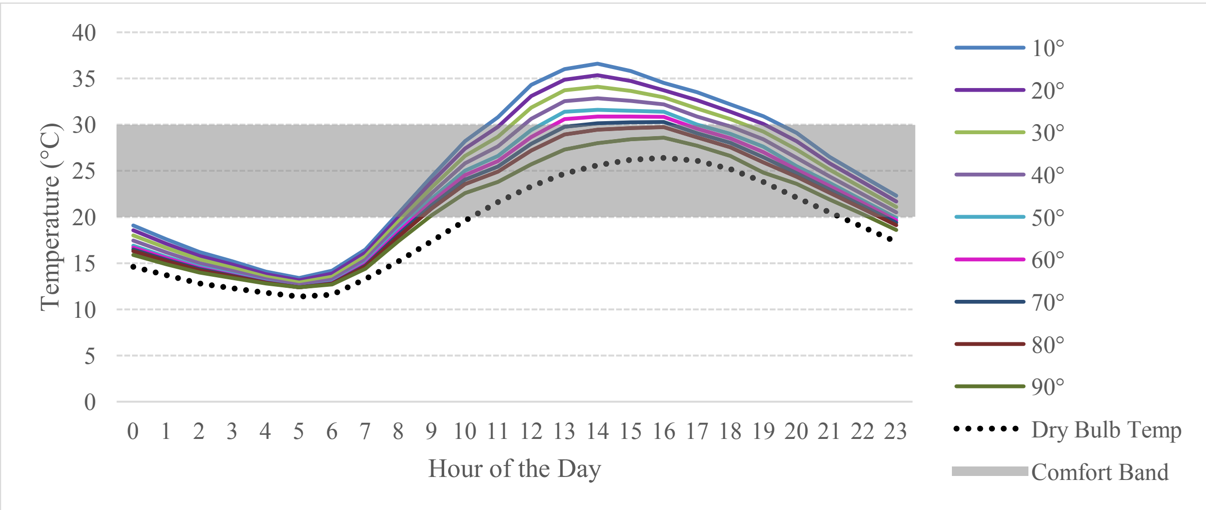

Figure 7: Indoor temperature with different degrees of actuation of the façade modules on a typical summer day.

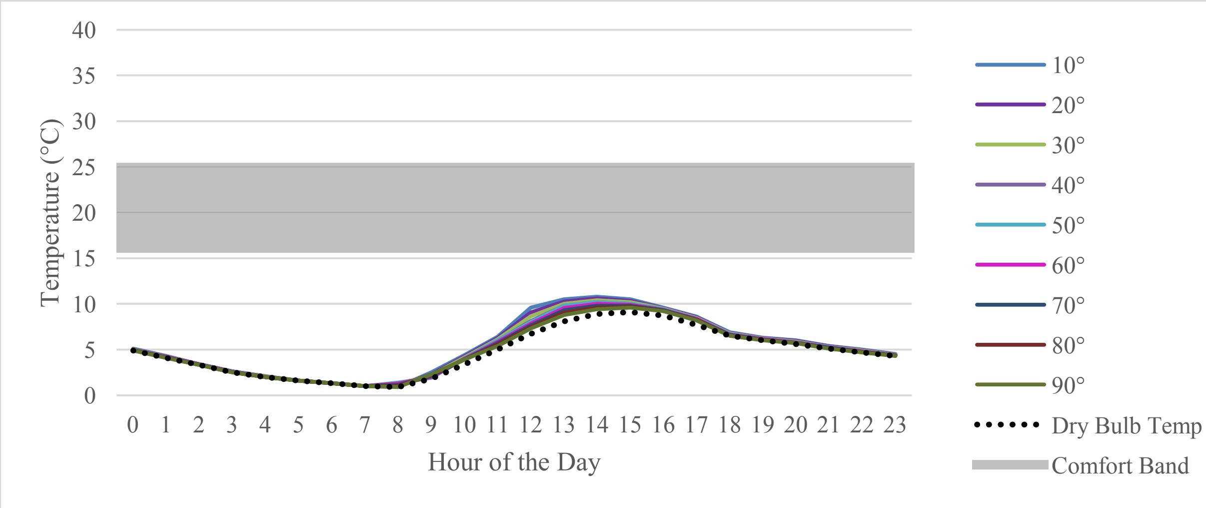

Figure 8: Indoor temperature with different degrees of actuation of the façade modules on a typical winter day.

3.3 Energy Harvesting

The simulations on PV show expected results, higher output during the morning hours due to the orientation, and better performance when the panels are completely actuated to 90° since there is no self-overshadowing. However, it is noted that in the afternoon the smallest angle is the best-performing position for solar energy harvesting, the reason for this is that the panels in this position have the potential to receive more sun hours, throughout the day. These results already hint at the best aperture strategy to get the maximum output possible from the PV.

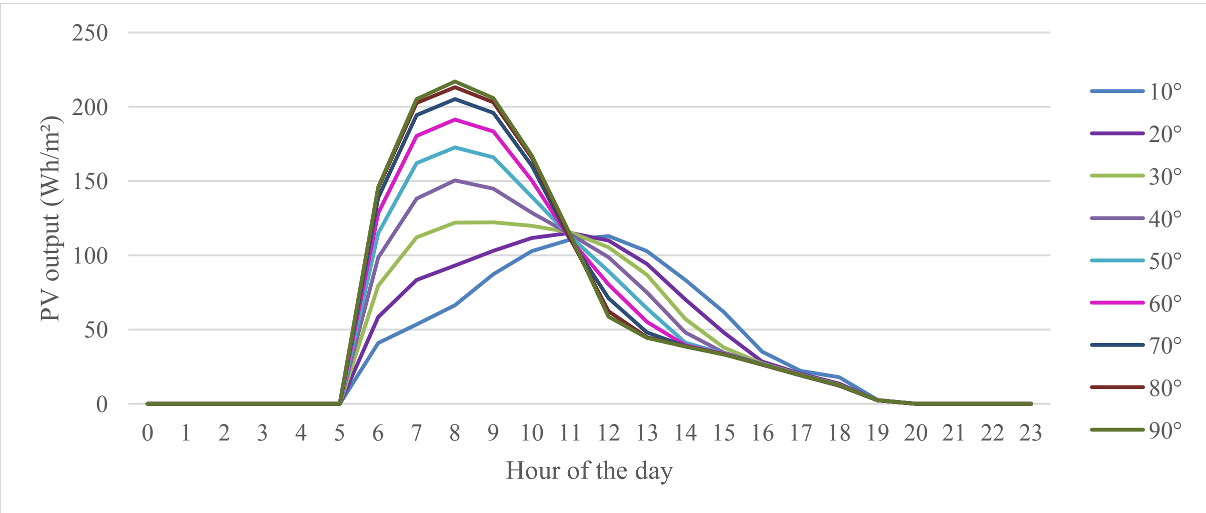

Figure 9: PV output with different degrees of actuation of the façade modules on a typical summer day.

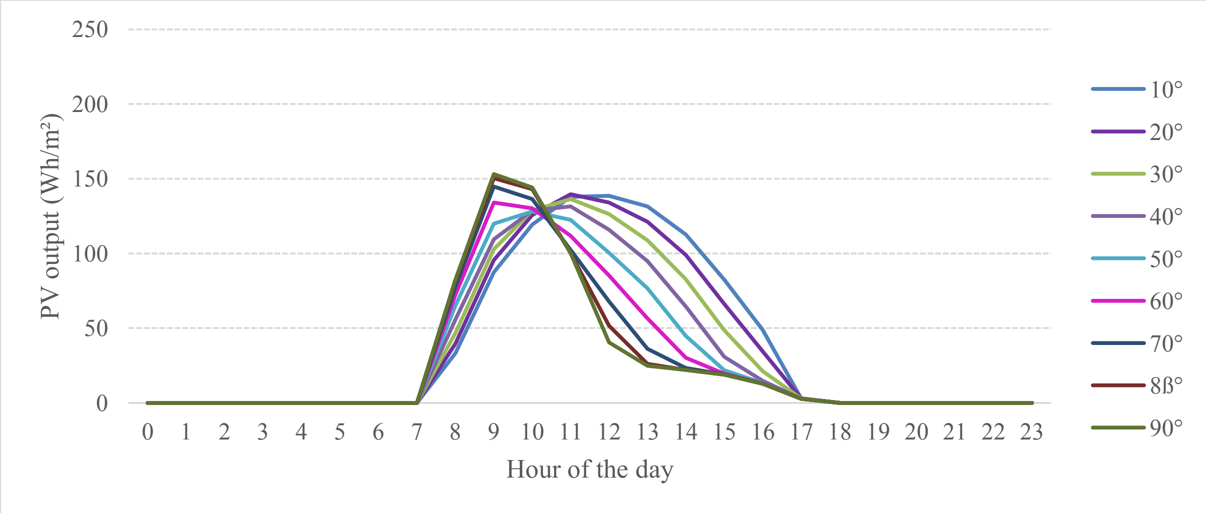

Figure 10: PV output with different degrees of actuation of the façade modules on a typical winter day.

4 CONCLUSIONS

These initial studies have given insight into how the building could perform with the different levels of actuation of the adaptive façade proposed. Moving forward, the extracted yearly results will be used to create an optimization function that will calculate the best possible opening angle of the panels in a time step on the façade for every hour of the year.

These results will serve as the base for creating an alternative control system for the façade to be operated for user comfort or maximum energy harvesting. Subsequently, a three-objective optimization will be tested.

Most solar control strategies aim at maximizing visual and thermal comfort by reducing solar gains and direct sunlight at certain times, which results in rooms becoming gloomy and often requiring artificial lighting to compensate for the reduction in available daylight, however in this case due to the high window-to-floor ratio, these solar control strategies create a positive effect on both visual and thermal comfort.

The building analyzed does not have fixed occupancy patterns, without this information, the thermal simulations could lose accuracy. To solve this, in the next stages of the research, the users will be given surveys about their schedules that would be used to update the thermal simulation script to create more accurate results.

For future studies on indoor thermal comfort, an equation for adaptive thermal comfort such as the ANSI/ASHRAE 55:2020 [15] will be implemented for analyzing the transitional periods between cooling and heating seasons.

After the completion of the adaptive façade installation, it is intended to install temperature and light sensors in different rooms, with the idea to calibrate the simulation models and to use as input for the final control system.

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