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Assessment of Adaptive Photovoltaic Envelopes

Diss. ETH No. ?

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presented by

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To Someone

ABSTRACT

English abstract here.

ZUSAMMENFASSUNG

Deutsche Zusammenfassung hier.

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I would like to thank . . .

CONTENTS

NOTATION

FREQUENTLY USED SYMBOLS

E	energy
m	rest mass
p	impulse

PHYSICAL CONSTANTS

c speed of light in vacuum, $c = 299\,792\,458\,\mathrm{m\,s^{-1}}$

(CODATA 2014 [1])

1

INTRODUCTION

I'm drinking a gin and tonic, without gin
— Alex Millane

A building, in its original manifestation, is a shelter. A means to protect the human body from harsh external conditions. And within this we ascribe the notion of the envelope, the barrier between the external and internal environments. It is the barrier that protects us from frigid temperatures, shades us from solar rays, and keeps us dry when a storm passes by. And over time, we have not just developed the quality of our envelopes, but also technologies that enable us to manufacture interior environments. The combination of heating, cooling, lighting and air handling enables us to exclude the energies of the exterior and form hermatic envelopes. Buildings transformed from mere shelters, to places of comfort where we now spend 87% of our lives [2]. We have in essence, become an indoor species.

Unfortunately, the manufacture of interior environments comes with a large environmental impact. Buildings are currently responsible for 32% of our final energy use and 19% of our total greenhouse gas emissions [3]. There is, however, a 50% - 90% emission reduction potential using existing technologies [3]. On one hand, the efficiency of our manufactured interior environment can be increased. We can install more efficient systems to manufacture this energy at a lower environmental cost. We can further increase the isolation properties of our envelopes, thus reducing the energetic loss to the exterior. On the other hand, we can rewind the clock of architectural history and move back to a time where we did not manufacture internal environments, but rather mediated the external energies to fulfil that of the interior. These strategies, commonly described as passive design strategies, include aspects such as natural ventilation, thermal storage, and static shading.

Instead of rewinding the clock of architectural history, there is also the possibility to look ahead. With new technologies the mediation of the external environment is not restricted to passive strategies, but also active ones. The mediation of solar radiation through responsive shading is one such example. A responsive shading system will open when solar radiation levels are low to maximise natural lighting, and close when the radiation reaches a critical peak at which the building begins to overheat. Iconic examples include the Al Bahr Towers in Dubai [4], the Arab World Institute in Paris, and the ThyssenKrupp Headquarters in Essen.

In an ideal setting, as shown in Figure 1.1, the envelope does not just exist in an open or closed state, but in a multitude of states fullfilling various functions. The modularity described in this schematic enables certain parts of the envelope to respond for optimal daylight distribution, whereas others are optimised for heating / cooling demand reduction, and enhancing views to the exterior. If we also replace the envelope material with light weight thin film solar panels, we can also harvest solar energy onsite and use it to meet the demands of the interior space. It is through this modularity that we can best balance user comfort, with building energy saving.

This modularity however introduces new challenges in terms of control. In a responsive system the designer sets threshold radiation levels at which the envelope opens and closes. This modular envelope however, can have thousands of possible states, and needs to find the optimum balance between building energy demand reduction, occupant comfort, and PV electricity production. It is in this context that we coin the term adaptive. An adaptive envelope senses it's environment, such as the occupancy, interior temperature, exterior temperature and radiation levels, and then determines the optimum envelope configuration to mediate a comfortable interior environment while minimising the total net energy consumption.

This adaptive nature can span different time durations. In the short time span, if the sun goes behind a cloud, or the occupancy dramatically increases, the envelope will be able to adapt to meet this new environment. Likewise, the envelope will also adapt to long term variations such as global warming.

This dissertation is written in the context of the Adaptive Solar Facade (ASF), an adaptive photovoltaic envelope designed for a research and innovation unit known as the HiLo [5]. The ASF is a modular facade of 40 x 40 cm copper indium galium selenide (CIGS) PV panels that can be actuated in two degrees of freedom with a range of 90°. An example of this, mounted on a testing site can be seen in Figure 1.2.

1.1 RESEARCH QUESTIONS

The four questions addressed in this research are

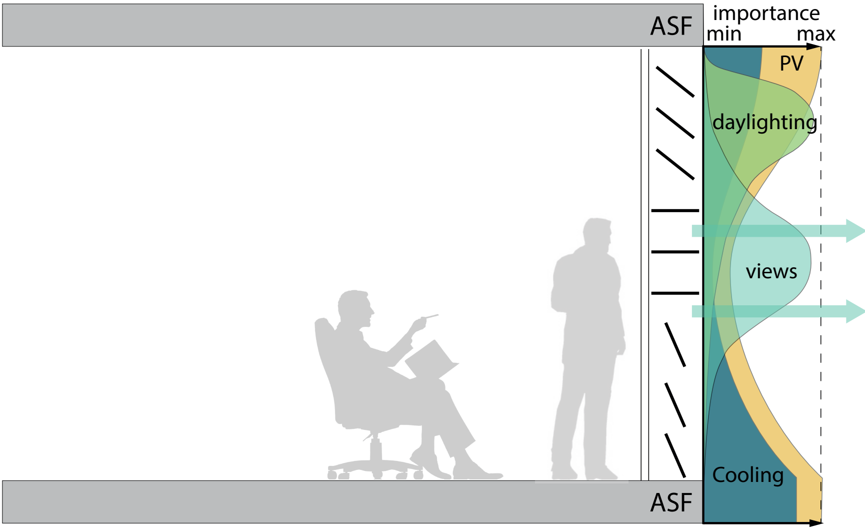

FIGURE 1.1: A modular facade adpative to various functions for optimising occupant comfort

- How can complex architectural components, such as the ASF be designed and constructed?
- How can a photovoltaic envelope be controlled to be adaptive?
- What is the energy saving potential of an adaptive photovoltaic envelope?
- How does the energy saving potential vary for different building types?
- What is the life cycle CO_2 saving potential of an adaptive photovoltaic facade?

1.2 ORGANISATION OF THE THESIS

The remainder of this thesis is composed of three journal papers and one conference paper. Chapter 2 introduces the parametric design environment, which was created for rapid iterative development of the ASF. This chapter also introduces some of the design elements of the ASF. Chapter

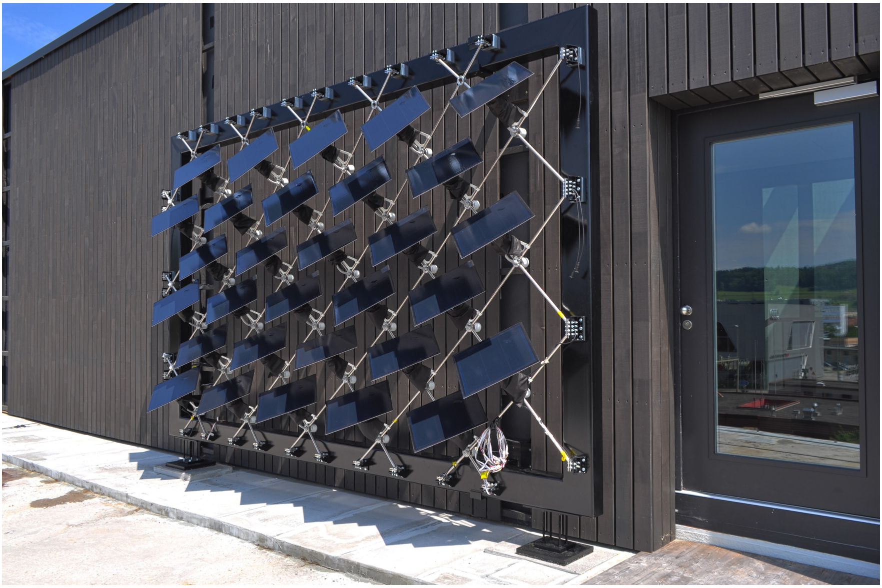

Figure 1.2: The final Adaptive Solar Facade, mounted on a testing site prior to assembly on the HiLo Module

3 introduces the model predictive control strategy to allows for adaptive control. This chapter first introduces the simulation methodology, and then discusses the energy saving potential of an ASF system. Chapter 4 takes on the model from Chapter 3 and runs an evaluation on eleven different building use types spanning six construction periods. Chapter 5 then takes the results of the energy simulation methodology and assesses the carbon life cycle cost. Finally Chapter 6 concludes the thesis.

2

PARAMETRIC DESIGN ENVIRONMENT FOR KINETIC PHOTOVOLTAIC ARCHITECTURE

3

OPTIMISING BUILDING NET ENERGY DEMAND WITH DYNAMIC BIPV SHADING

4

SENSITIVITY OF BUILDING PROPERTIES AND USE TYPES FOR THE APPLICATION OF ADAPTIVE PHOTOVOLTAIC SHADING SYSTEMS

5

LIFE CYCLE ASSESSMENT OF DYNAMIC BUILDING INTEGRATED PHOTOVOLTAICS

6 CONCLUSION

This thesis presents a hollistic analysis of adaptive photovoltaic envelopes from design and control, to evaluation. We first present the performative design environment for the fabrication of kinetic architectural elements. Here we show how the multiple fields of structural engineering, energy engineering, control engineering, industrial design, and architecture can be combined into a single automated workflow that accelerates the design process. We then present how the adaptive system can be controlled using a model predictive algorithm which combines building energy demand and solar radiation simulations. From the simulation outputs, the adaptive system can determine the best physical configuration to minimise the net energy building demand. We can use this framework to not only control the facade, but to evaluate the energy saving potential of an adaptive photovoltaic envelope over a static system. Our results show that there is a 20% - 80% energy saving potential compared to an equivalent static system. The range of these results are large as they are heavily dependent on the building type. We therefore run this framework for 11 different building use types spanning six construction periods. Our results show that the ASF performs best in environments where there is a mix of both heating and cooling demands. For buildings that predominantly have cooling demands, a simple static system at an optimum solar angle would be the most cost effective solutions. Likewise for a building that predominantly consists of heating demands, a window without shading, or a manually controlled Venetian blind may be optimal. The ASF performs best in modern offices, retail stores, food stores and schools. Finally, we extract the results of a modern office based simulation and conduct a CO_2 life cycle analysis. Our results show that the ASF, running purely as an electricity producing device, is outperformed by static PV systems by 50%. However when we include the energy saving to the building interior, the ASF becomes favourably competitive to a traditional PV system.

6.1 OUTLOOK

- So what does this mean for the future of adaptive architecture?

- In essence, this thesis is a feasibility study. We have shown that with modern design tools, and in house software, it is possible to design and construct complex adaptive envelopes. We have proposed an adaptive control methodology, and shown that for certain building types there is a large net CO_2 saving potential.

- Adaptive architecture, however is not limited to just kinetic solar facades. This is just one of many possible adaptive systems that could be brought to reality. Any technology that has the potential to vary its property, can in principal be reprogrammed with adaptive algorithms. Examples could include walls with varying thermal resistances, or variable ventilation systems.

- Architectural expression of kinetic skins. A building is not longer a static system, but one that changes its form with the changes in the season, the day, the weather, or its use.

- The one remaining step in this technology is the interaction with the users. The building users currently have the ability to overide the adaptive algorithm, however this overide should be included in a machine learning algorithm to improve the user comfort of the adpative algorithms.

Next steps in this research involve, testing the constructed ASF's in the HiLo building and comparing the performance against the models. When complete the algorithms should also be complemented with machine learning feedback from the occupant.

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A

APPENDIX

Here be dragons.

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PUBLICATIONS

Articles in peer-reviewed journals:

1. Jayathissa, P., Caranovic, S., Hofer, J., Nagy, Z. & Schlueter, A. Parametric Design Environment for Kinetic Photovoltaic Architecture. *In Production* (2017).
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