An affective kinetic building façade system: Mood Swing

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Abstract

Kinetic façades employ sensor-based automation systems to sense and respond to external environmental conditions. These kinetic control systems optimize energy consumption by blocking the environment to achieve thermal and/or visual comfort. However, they have yet to account for occupant emotion or affect. Attention Restoration Theory (ART) explains the cognitive and affective benefits arising from experiencing the natural world. Research shows nature has restorative benefits for mood and cognition. This paper describes an affective kinematic building façade system, named “Mood Swing”. This senses, interprets, and responds to varying moods of room occupants. We use a commodity camera-based system with polarized light to sense both room occupants and their current mood. The mood state is an input to a model-based-control system (MPC) that intelligently responds and controls a dynamic kinetic façade. This system opens the façade so occupants can see and experience varying amounts of nature based on their interpreted affective state. Our approach integrates research on smart buildings with human behavior to more fully study the effect of putting the human back into the kinetic façade control loop

1. Introduction

Adaptive building skin façades consist of highly multifunctional adaptive systems. The building’s skin reacts to the exterior environment weather conditions to optimize a building’s energy performance. This optimization is important since the built environment is a leading contributor to total energy consumption. Figure 1 illustrates various famous kinetic building skin facades that react to their surrounding environment to increase energy efficiency. In the United States, Architecture 2030 has estimated that commercial, industrial, and residential buildings are responsible for 48 percent of the total energy use in our country. Adaptive building skin façades may reduce a building’s energy footprint. However, consumption alone should not be

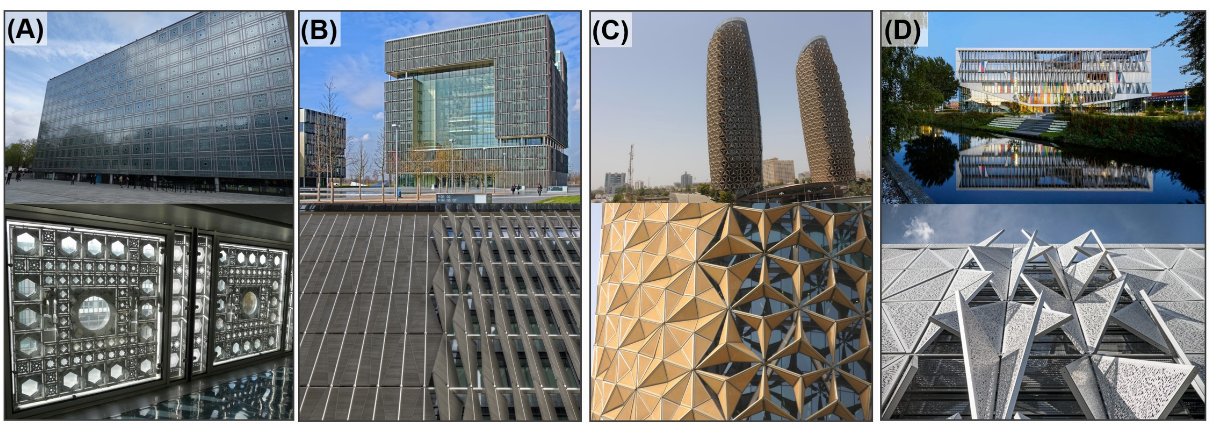

Figure 1: Famous kinetic facades found around the world: (A) Musée de L’Institut du Monde Arabe - featuring a portal kinetic facade design (Jean Nouvel, Architecture-Studio, Pierre Soria and Gilbert Lezenes, 1987); (B) SDU Campus Kolding featuring adaptive triangle panels (Henning Larsen Architects, 2014); (C) Q1 Building, ThyssenKrupp Quarter featuring a kinetic panel system (SWD Architekten + Chaix & Morel et Associés, 2010); (D) Al Bahar Towers featuring a mashrabiya inspired facade (Aedas Architects, 2012).

the only driver in the architectural design and retrofitting of buildings. Sustainable building design, analysis and construction should also consider building occupants when integrating adaptive building skin façades.

One strategy for enhancing occupants' well-being is optimizing daylight to affect mood. Daylighting is important for physical and mental health, from the sunlight's ability to increase vitamin D, to the alleviation of Seasonal Affective Disorder (SAD). The exposure to daylight has many restorative benefits to improving health and well-being. Building designers should take a holistic view by keeping the human in-the-loop and making an effort to understand how daylighting affects building occupants. Research has shown that daylighting and nature have positive impacts on well-being [1]; benefit cognitive processes [2]; and renew attention after exerting mental energy [3], [4]. Computational tools and mechanical systems tend to optimize quantitative parameters such as: daylight levels (lux, watts per meter squared), temperature, humidity, and noise. While these metrics directly affect a building's overall energy consumption, the underlying point is that buildings should also provide visible and thermal comfort to occupants, to improve human performance and health. To achieve this goal, we suggest building designers additionally consider qualitative social science parameters, such as: observing and assessing occupant mood, attention and cognition, physical and mental well-being.

This paper proposes a dynamic façade system, Mood Swing, which seeks to improve occupant emotion or affect by adjusting a building's skin to vary daylighting and views of nature. Mood Swing senses emotion from a passive non-invasive camera system similar to Poh et al [5]. The occupant's mood is the primary input to a control loop which modifies an adaptive façade to control daylighting levels and view factor. Therefore, this system puts the human back into the dynamic façade control loop. The visible comfort level integrates quantitative and qualitative parameters to respond to mood and affect. In sum, to achieve a desired daylighting level, Mood Swing uses outside environmental sensors, sun path, and simulation to fine-tune lux levels in the space based upon occupant mood. The overarching goal of Mood Swing is to stimulate biological and psychological processes by adapting daylighting lux level for pattern of use, affect, and mood; and increase view factors of nature.

2. Architectural Concept

Dynamic façades are rapidly growing in popularity as sustainable building elements due to the ability to computationally simulate and mechanically control their performance [6]. These kinetic building skins adapt to the environment and provide better energy efficiency. The skins also add to the ascetic architectural appeal of the building by changing their appearance to reflect the location and weather around them [7].

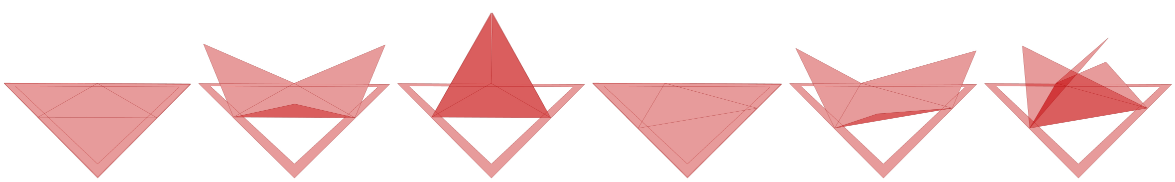

Figure 2: An individual façade unit with Sierpinski and Golden configurations with wings closed and open.

Our kinetic façade concept consists of an interlocking array of equilateral triangular units supported by framing hardware intended to be mounted over any naturally lit glazing surface. Each triangular unit of the façade is subdivided by an inner equilateral triangle, denoting its center and primary shading surface. To allow for kinematic control, the remaining space resulting from the subdivision of the outer and center equilateral triangles is then filled by three triangular shading surfaces we call "wings". Each façade unit wing is then controlled by a servo motor that rotates it toward the center of the unit. The basic architectural façade elements and various configurations are visualized in Figure 2. These multifunctional façade elements provide shading, glare reduction, and daylighting distribution depending on their configuration. Figure 3 illustrates how the façade elements of our design connects to the building skin. The components can move both globally and independently of each other. The response to different environmental conditions, such as direct sunlight, allows for adaptive glare reduction while maximizing view factors and skylight.

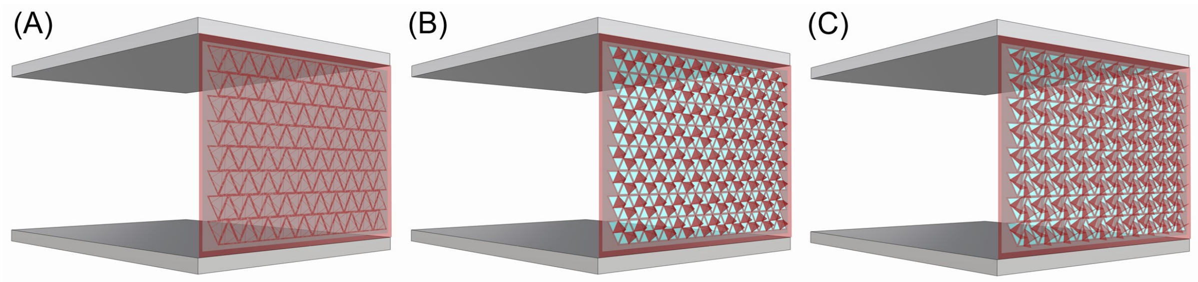

Figure 3: Our kinetic façade design concept in various configurations. (A) Shows a Sierpinski configuration fully closed; and (B) shows it fully opened; (C) shows a 30° open Golden configuration.

To give the building designer more options, the center equilateral shading triangle of each façade unit can be initially set to any ratio of the outer triangular bounds, provided all façade units maintain the same ratio. This allows for numerous interesting design and natural lighting configurations. Consider a center shading triangle that bisects its outer bounds by half on each side. We call this a Sierpinski design because it mimics a Sierpinski fractal. We call the design where the center shading triangle bisects its bounds at a ratio of 1/φ, the Golden design, for the golden ratio. This architectural concept allows for a variety of different dynamic configurations to modulate the daylighting levels in the building. Figure 4 and Figure 5 illustrate various façade configurations that our multifunctional adaptive elements create. These tiled units are not confined to any predetermined number or size, and many complex shading and daylighting patterns are possible. We designed this building skin to respond to numerous external environmental conditions and interior occupancy scenarios.

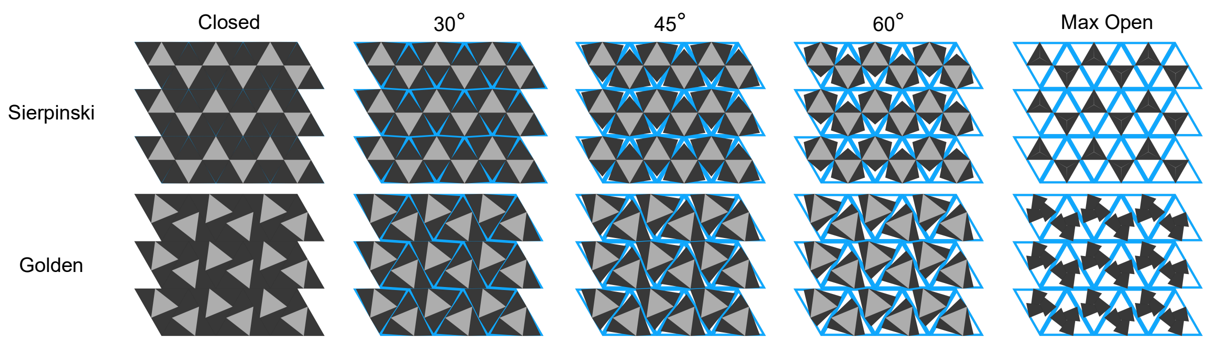

Figure 4: The façade concept with Sierpinski and Golden configurations at various actuations.

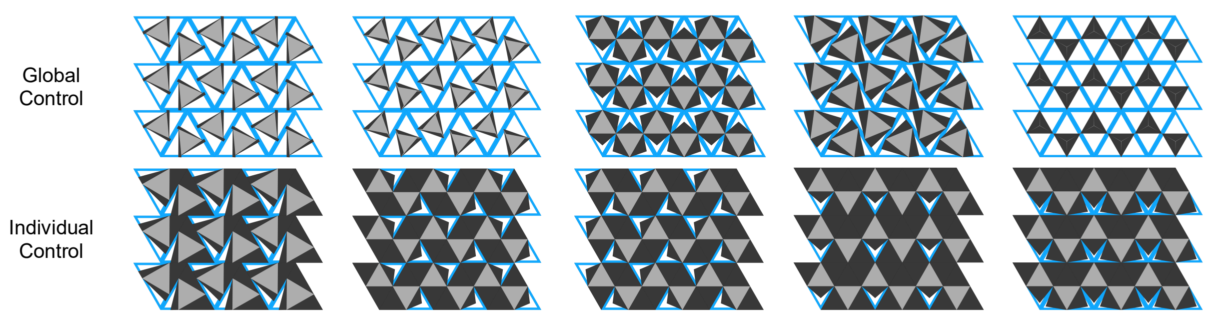

Figure 5: The façade concept supports both global and individual façade unit control. This provide a variety of fine-grain control to the system to manage the lux levels in a space.

3. Psychology of Daylighting

Research on lighting and psychology goes back decades, highlighting the important relationship between lighting type and amount, and human responses. Daylight is argued to be preferable to artificial light (e.g., fluorescent lighting) for evolutionary reasons [9] and because it provides a more balanced spectrum of colors compared to various forms of artificial lighting [10]. Further, natural light supports a number of biological functions that promote health [11]. Early research on natural light showed that virtually all employees preferred it to artificial lighting, that workers were more content in their jobs when exposed to natural light [12]. Later studies examined emotional responses and found that daylighting was associated with improved moods and greater productivity [13][14]. Relatedly, a study of different views from windows found that views of natural landscapes (mountains or meadows) led to lower levels of sickness compared to views of man-made environments such as courtyards or buildings [15].

Summarizing early findings, Kaplan and Kaplan [3] noted that research documents a relation between natural light and psychological response. In particular, natural lighting has a positive influence on mood by making people happier. Even light therapy, designed to mimic natural light, can improve symptoms of Seasonal Affective Disorder by altering brain chemicals to improve mood. Recent research shows the robustness of this early research and has extended findings with more experimental control and with new methods. For example, studies find that building occupants prefer mixed direct/indirect lighting to direct lighting and that this benefits mood and well-being [16]. Further, neuroscience research is being used to document a relationship between lighting type, brain activity, and mood states. In a study of the physiological and psychological effects of direct only lighting compared to a combined direct/indirect lighting, the latter produced a more pleasant experience for participants [17]. Furthermore, electroencephalography (EEG) data found that theta band activity was related to emotion processing. In particular, right fronto-temporal and left temporo-parietal regions showed increased theta band power in subjects when exposed to the direct/indirect light. But it is important to note that this effect did not correspond to changes in arousal levels. As such, although there was a more positive mood, it did not alter emotional intensity [17]. In short, daylighting can have a significant positive effect on building occupants by decreasing fatigue and eyestrain as well as improving mood [18]. We turn next to a discussion of Attention Restoration Theory (ART) and follow-up with a discussion of emotion theory. We describe these physiological and psychological principles to emphasize the interdisciplinary and integrative foundation for the Mood Swing. These provide a stronger base of theory combining modern engineering and human factors theory to study lighting level effects on occupants.

3.1 Attention Restoration Theory

Although not directly related to natural lighting, Attention Restoration Theory was developed by Kaplan and Kaplan [3] to integrate a number of findings showing the beneficial effects of nature exposure on cognitive functioning and emotional well-being. Their work addressed how the human visual system was automatically, or naturally, drawn to scenes of nature, whereas less natural scenes required more cognitive control [2]. The general idea was that exposure to nature activates involuntary attention, and, therefore, allows one's resources for voluntary or directed attention to be restored [4]. Though it is also important to note that the restorative benefits of natural scenes affect more than just attention. Specifically, research finds that exposure to nature can do more than simply improve attention, it also has beneficial effects on emotion and can reduce stress [19]. Indeed, a large body of research has studied how exposure to nature [1] alters a variety of outcomes. This includes the actual experience of nature through active involvement such as walking in the woods, as well as passively experiencing nature such as a view through a window. For example, viewing images of nature improved performance on cognitive tasks [2]. Because Mood Swing focuses on emotional responses of occupants, we next describe the foundational theory of emotion on which our technology is based.

3.2 Emotion Theory

In this section, we provide a brief overview of emotion theory to provide a foundation for understanding how we integrate theory and application in Mood Swing. In a diverse array of fields, from neuroscience, to psychology, to sociology, emotion is shown to play a central role in simple cognitive processes such as attention and memory, to more complex cognitive processes like planning, reasoning, and decision making. As such, these core emotional processes drive much of human behaviour. In particular, feedback regarding a person's emotional state is critical in establishing their "position" in an interaction, their intent, and the reliability of the information they may be providing [20]. Emotions can be triggered by external events – for example, positive emotions emerge when some need or motive is satisfied and negative emotions arise from threatening and/or painful experiences. Breazeal [20] noted these experiences signal some kind of need for behavioral change (e.g., a goal has been met or some action is required).

Despite the foundational role of emotion in human behavior, studies on emotion and lighting tend to draw from simplistic theories of emotion (e.g., characterizing only positive or negative affect). Our engineering system pursues a more sophisticated conceptualization of emotion and draws on the psycho-evolutionary theory of emotions that links emotional states across a set of inter-related dimensions [21]. This is depicted in Figure 6 (left) and is based on the work of Plutchik [21]. This figure illustrates how emotions vary along four related spectra (joy/sorrow, anger/fear, acceptance/disgust, surprise/expectancy), coupled with an intensity level. This circumplex model illustrates 3-dimensions through which to conceptualize the relationship between emotions. Lending itself readily to visualization, colors are used to illustrate similarities and intensities akin to a color wheel.

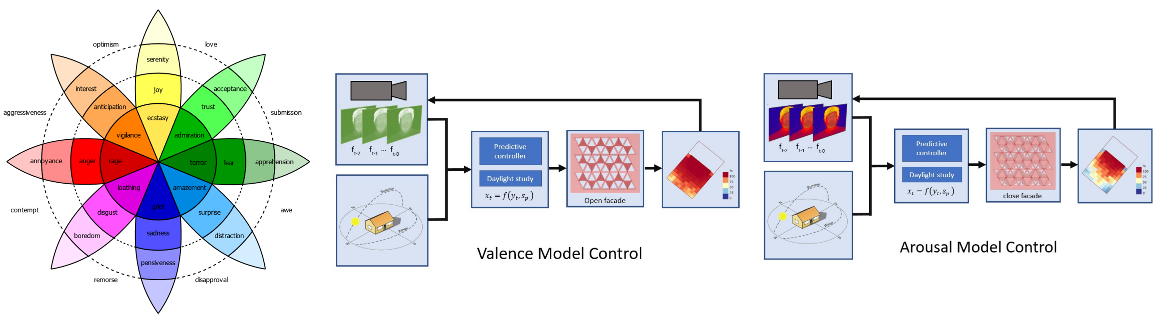

Figure 6: (Left) The Plutchik wheel [21] which differentiates the major emotions and intensities. (Right) the two model prediction control loops used by Mood Swing for valence and arousal.

The control system model of Mood Swing builds off this psychological foundation. Specifically, the core elements of our control model are: intensity (or state) of arousal, and valence of the emotions. Intensity is represented along the vertical with emotional intensity decreasing when moving from inside to the outer portions of the Plutchik wheel [21]. Further, this model has eight sectors that represent primary emotions (acceptance, anger, anticipation, disgust, joy, fear, sadness, surprise) with an opposite emotion for each sector (e.g., sadness vs. joy; disgust vs. trust). In addition to these dimensions, color is used to convey the various degrees of particular emotions. But there are also emotions that do not have any color. These are viewed as emotions emerging from a blend of primary emotions (e.g., optimism emerges from joy coupled with anticipation). In sum, these dimensions provide a broad spectrum of ways to characterize emotions. We use this to facilitate a more nuanced response system that can calibrate lighting levels and mood. For our initial proof of concept, though, we focus on the two primary dimensions of valence and arousal. Again, valence is related to the experience of pleasure (degrees of pleasant of unpleasant response), whereas arousal is related to the intensity of the emotional experience. Note that we do not specify the precise amount of natural light. Rather, for our initial design, we only provide 8 levels of natural light with two main groupins (arousal and valence) with the general idea being that, when occupants show lower levels of mood (negative valence), more daylighting can be provided. We do this in order to illustrate that the system is dynamic and responsive, and note that future research can more precisely examine the relationship of the daylighting necessary to alter emotion of occupants.

The goal of MoodSwing is to dynamically control the level of light to affect the emotional response of the building's occupants based on the measured mood of the occupant and the light level of the site. To measure mood we rely on the system developed by Poh et al. [5] which uses remote measurements of the cardiac pulse from a commodity RGB camera to determine a state of the emotion wheel [21]. Figure 6 (right) shows two state controllers of the control loop system that inputs the mood and environmental conditions and controls the opening and closing of the building skin façade to increase or decrease light.

4. Numerical Analysis

Recent developments in computational modeling and simulation tools bridge the gap between architecture and engineering. Simulation and analysis software such as Ladybug Tools, DIVA-for-Rhino, EnergyPlus, and Radiance provide multiple ways to analyze and test a variety of parametric designs and configurations. In this work, we utilize Ladybug tools [8] to numerically simulate and measure the daylight from our architectural concept from Section 2. To achieve the 8 levels of natural light (with the arousal and valence grouping) needed for the emotional response of the system, we first look at the range of lighting levels our design produces under different configurations (Figs. 3,4,5). As expected, the level of light varies based on the configuration. Figure 7 demonstrates the daylighting analysis of the light level for a 1m working plane in the built space. We then run this simulation on different days and times throughout the year in Figure 8 to measure the varying light levels.

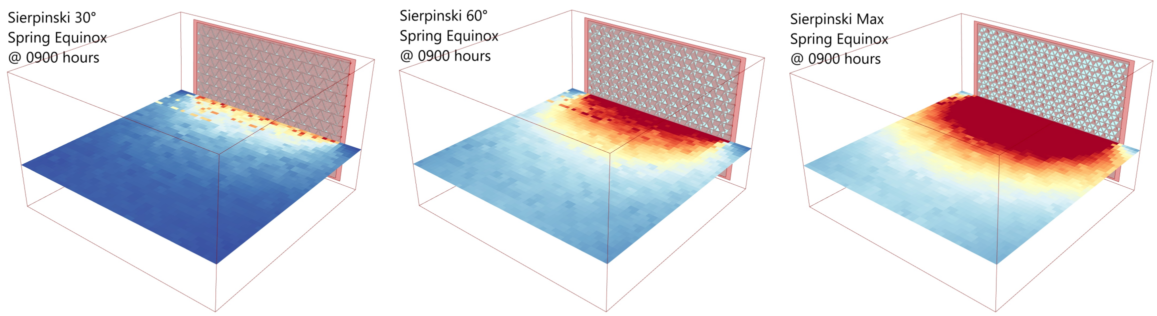

Figure 7: Daylight analysis of Sierpinski design at 30°, 60°, and max actuation, at a target height of 1m.

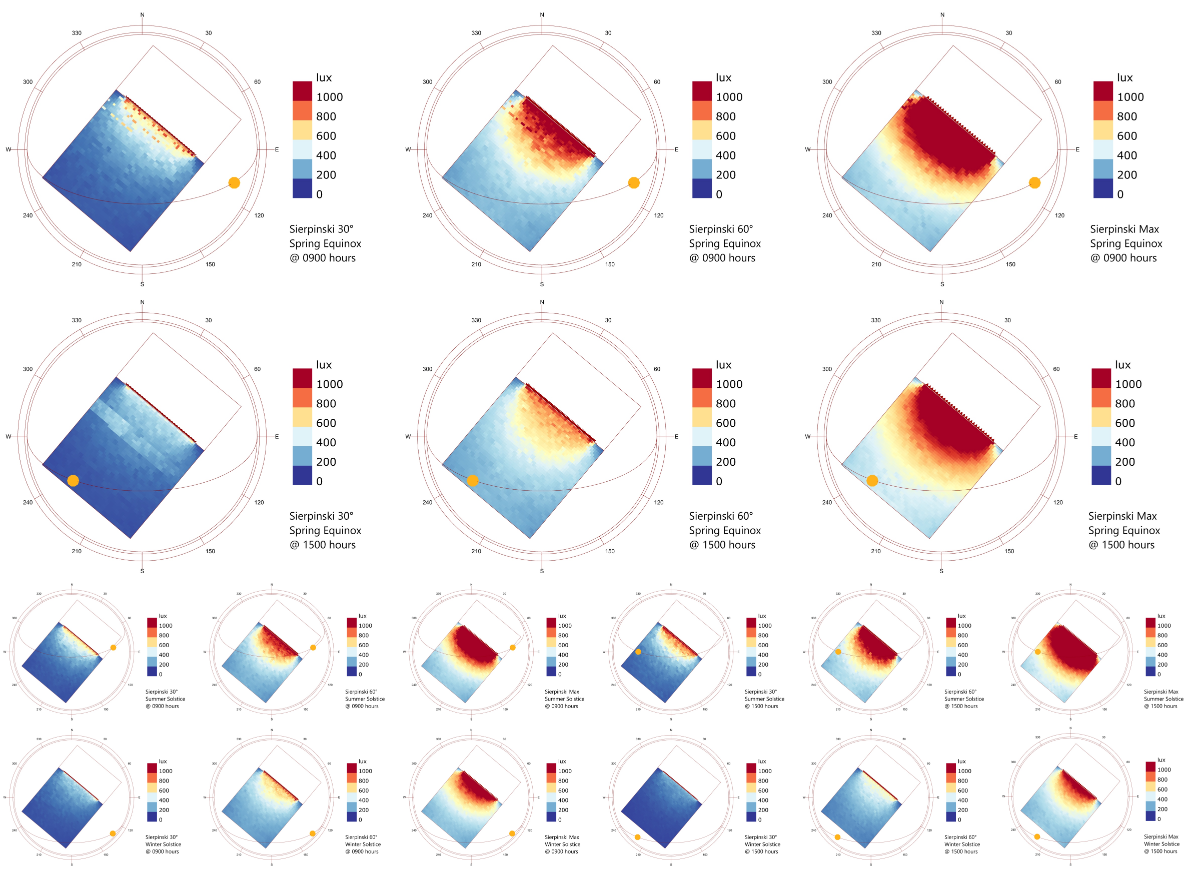

Figure 8: Daylighting analysis with Sierpinski 30°, 60°, and max open designs throughout the year.

Figure 9 visualizes three design configurations (Sierpinski 30°, 60°, and max open) and their effect on natural lighting throughout the year. Simulation allows us to explore the capabilities of the system for a given site location, architectural concept, and annual weather conditions. Data from this simulation is stored in the control system so Mood Swing knows how to control the individual façade unit to either damp or increase the light at any time of day. This allows for a robust building skin control system that is able to adapt to individual occupant mood conditions and adjust the building skin based on exterior conditions.

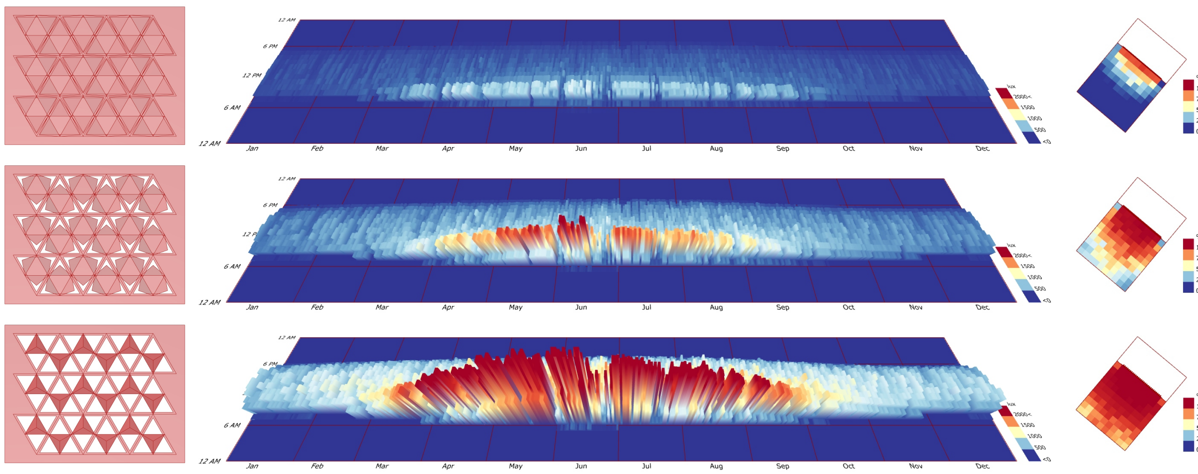

Figure 9: Light levels (Z-axis) of Sierpinski 30°, 60°, and max open configurations throughout the year plotted hourly for all days of the year. Right-most plots show continuous daylight autonomy (CDA) >= 200 lux.

5. Case Study

The case study site we choose is a standard office space located in Orlando, Florida. This site is representative of typical office working environments in North America. Figure 10 shows the building, solar path, and office we modeled and simulated as a proof of concept simulation for our MoodSwing building skin system. The case study site was approximately 18 ft x 16 ft, with roughly one-fourth of the space being floor to ceiling glazing where the façade was tested. The reflectivity of the different materials in the office was measured and set to simulate realistic conditions at the site. The aim of this paper is to evaluate the façade of a single room before deploying the design to an entire structure. We selected an office space to initially test and simulate the system with a single occupant, but in the future plan to expand the system's capabilities to handle multiple people and activities in the space.

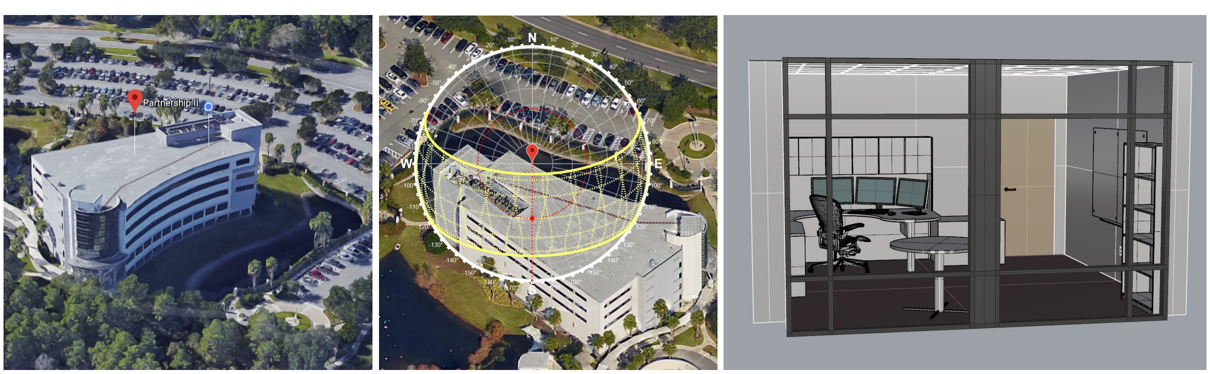

Figure 10: Site location: UCF, IST, 3100 Technology Parkway, Orlando, FL, 32826, United States, DMS: 28°35'09.8"N 81°11'57.6"W, DD: 28.586056, -81.199343. Natural lighting surface of office faces northeast.

Figure 11 shows the lighting impact the kinetic façade design has in the case study site. Our design allows for fine grain control of light, both direct and indirect, cast into the space, as opposed to static glazing.

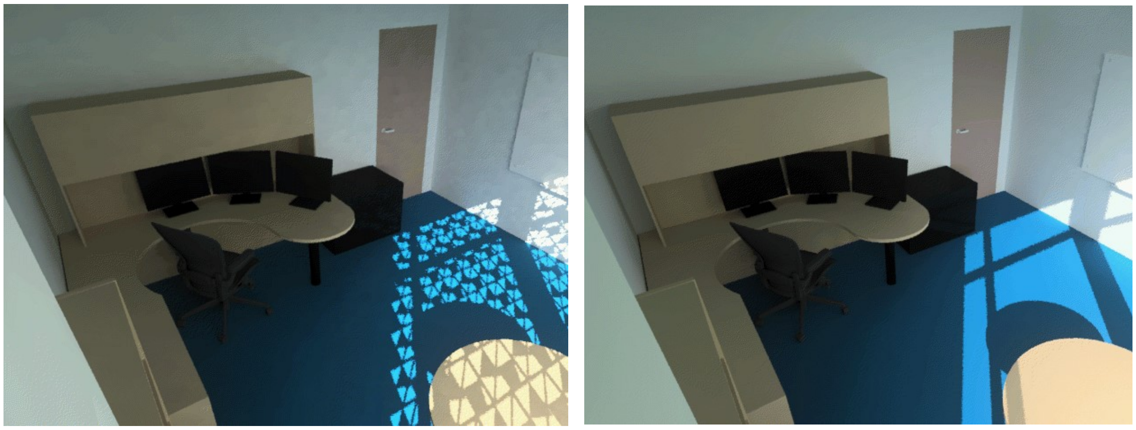

Figure 11: Here we show our case study office with (at max open) and without façade concept (right).

Figure 12 demonstrates changing the parameters of the space to increase or decrease the lighting based on input from the MoodSwing control system. MoodSwing demonstrates configurations for arousal, Figure 12 (left), where we have an intense emotional reaction and want to start to dynamically limit light and nature view factors in the space to help with attention, health, and cognition. Figure 12 (right) is the reaction to valence where MoodSwing recognizes the degree of unpleasantness of the occupant and allows more light and nature views into the space. The façade has the ability to adjust to a wide range of configurations. In the future, we hope to dive deeper into the emotion wheel [21] and provide even more variation based on the emotional affect of one to many occupants in the space.

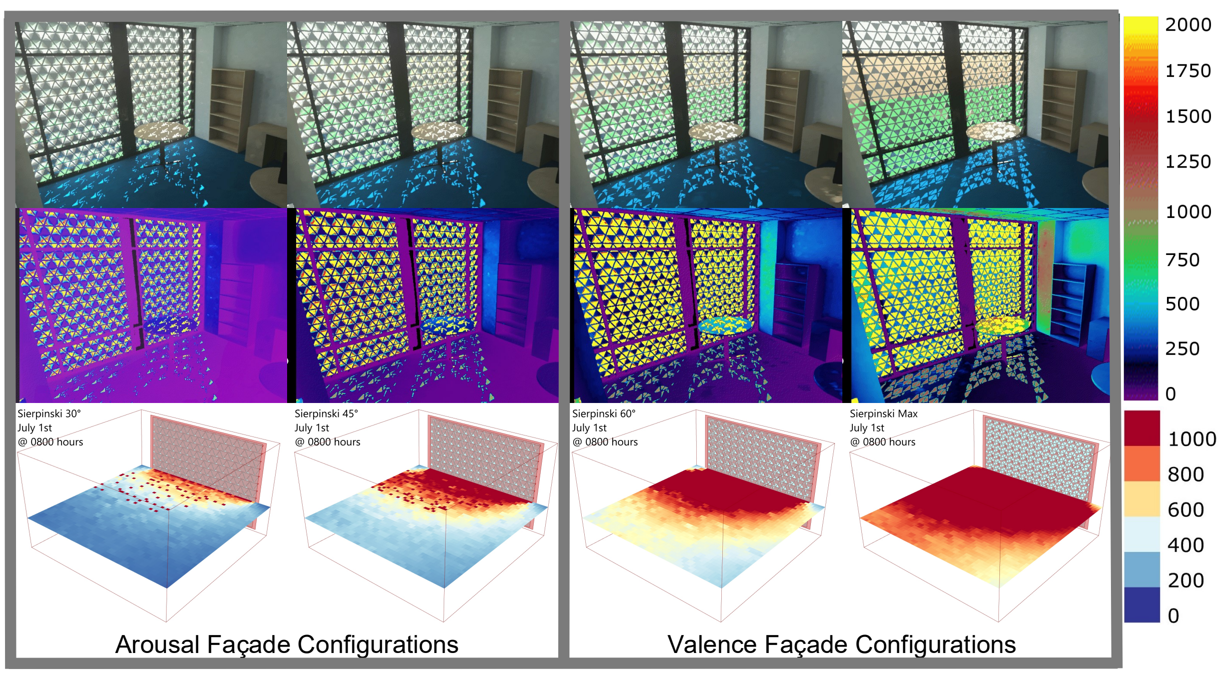

Figure 12: (Left) Mood Swing configurations for the arousal emotional states. The façade components are adjusted to either 30° or 45° depending on the degree of arousal intensity. (Right) Mood Swing configurations for the valence emotional states. The façade components are adjusted to either 60° or max depending on the degree of arousal intensity. These configurations were chosen based on the precomputed simulated lighting levels for the site's location and given time. These two inputs adjust Mood Swing.

6. Conclusions

This work introduced a kinetic façade system, Mood Swing, which drew focus back to the human-in-the-loop occupying the space. The system proposed and simulated a control system that used the detected emotional state of the occupant and the outside environmental sky conditions to adjust an adaptive kinetic façade system. Any controllable kinetic façade system that had a wide range of lighting level would work with Mood Swing. The design we chose was simply for a proof of concept simulation, however one could use different geometric shapes, automatic blinds, or dynamic glazing to produce similar light ranges. In the future, we hope to test a variety of different designs and parameters and measure their impact on the occupants.

Given the interaction between psychological and physiological responses and the different spectrums associated with different forms of artificial lighting, others have also explored how systems can respond to humans. For example, an illumination control method linked with general circadian rhythms (morning, early afternoon, later afternoon), was shown to increase productivity in office workers [22]. More closely related to Mood Swing is a study that created an interactive emotional lighting system that responded to human occupants from Kim et al. [23]. Designed to enhance the experience while viewing multimedia, this system captured physiological signals such as galvanic skin response via an emotion recognition system wired to participants. In a proof-concept experiment, Kim et al. [23] showed that their system could automatically measure emotional responses and change lighting to alter occupant experience. They found that red lighting induced arousal while blue lighting induced a more relaxed state.

In sum, architects are no longer bound by quantitative measurements and optimizations. We provide a system, Mood Swing which prioritizes occupant comfort and emotion in a novel way. Mood Swing introduces a set of unique characteristics that represent a significant advancement from state-of-the-art. First, it is unobtrusive, relying only on a commodity video camera for occupant monitoring. As such, it does not require any effort on the part of building occupants (e.g., cumbersome body connections). Second, it alters not artificial light, but, rather the amount of natural light to which the occupant is exposed. Thus, it builds from the long line of research showing the beneficial effects of natural light and does not merely change the level of artificial light. Third, by connecting to a façade, it represents the first integration of architectural design with occupant monitoring systems. Finally, it acts more intelligently by using external sensors to measure the amount of natural light available and adjust the façade accordingly. Future advances to this system could include linkages to health monitoring applications occupants may already be wearing. For example, smart accessories such as watches or rings are now able to monitor some aspects of human physiology. It is feasible to connect these applications to Mood Swing in such a way that it can more precisely measure changes in emotion when compared to camera monitoring.

This work proposed, modeled, and simulated a model-based control system that responded to varying moods of room occupants. Future work involves deploying a real-world cyber-physical prototype of this design at the case study site. This work will allow us to investigate important research questions crossing a number of fields (i.e., architecture, engineering, and psychology), by measuring the direct impact of natural lighting on mood and cognitive tasks.

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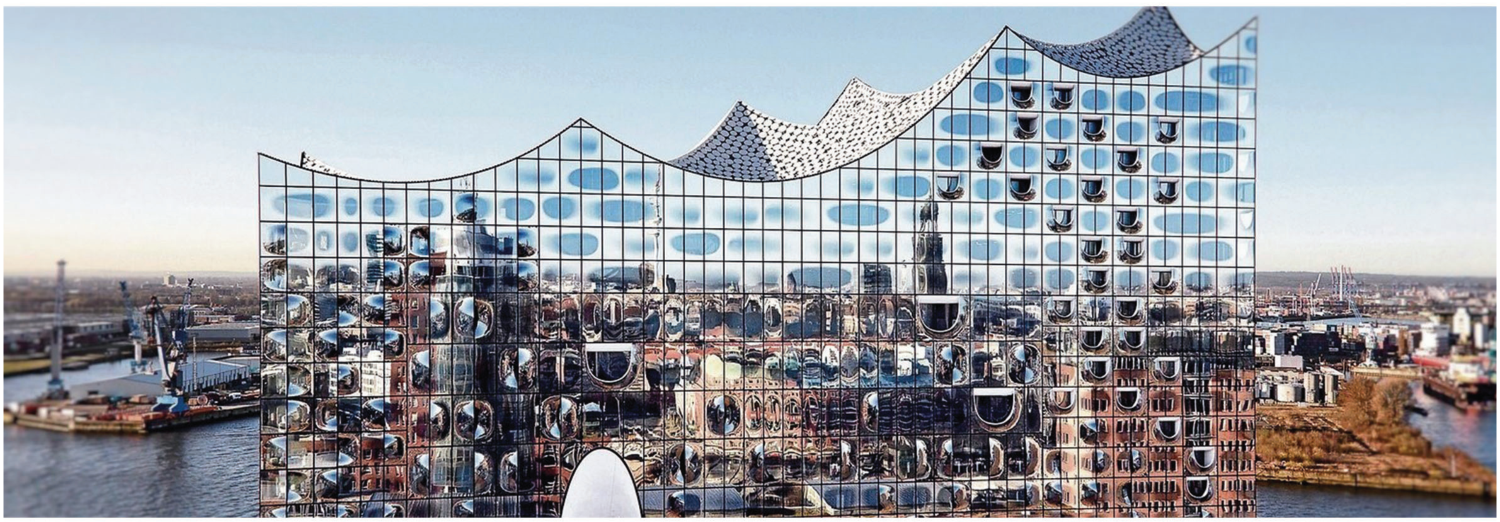

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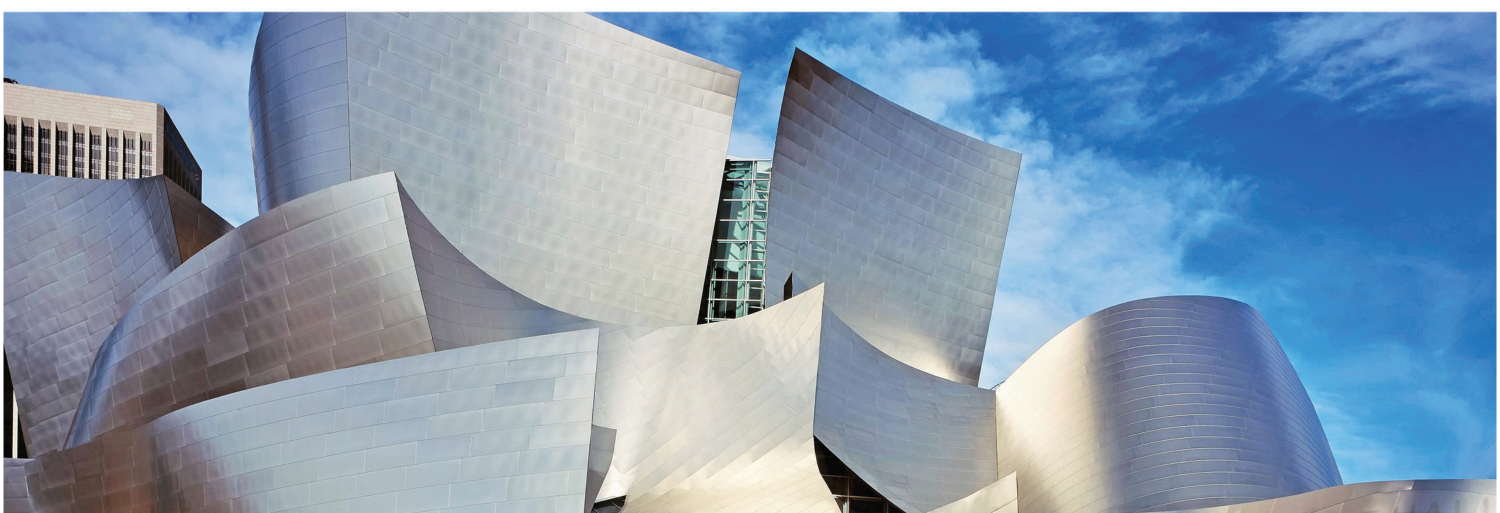

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