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Poster: An Energy-Harvesting Facade Optimization System for Built Environments

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ABSTRACT

Daylighting is the exploitation of solar energy in the form of natural lighting indoors and it plays an integral role in minimizing the energy footprint of a building. Smart daylighting enables us to design buildings that provide comfort and energy savings simultaneously. In this work, we propose a dynamic facade system for buildings that aims to maximize user comfort, while also maximizing energy savings by harvesting solar energy optimally. The solar panels on the facade can harvest the highest amount of energy when they are positioned perpendicular to the sun's rays. However, this may result in unsatisfactory lighting conditions inside the room and we approach the trade-off as a multi-objective optimization problem. We present a preliminary exploration of the concept of smart skins for buildings, contributing to the creation of future sustainable buildings with zero energy footprint.

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1 INTRODUCTION

Presently, the world is consuming fossil fuel at an alarmingly high rate. The CO_2 emissions from industries worldwide in 2015 was a whopping 36.2 B tonnes. Indeed 2015 was the hottest year since 1880[1]. A significant percentage of this energy is spent by the artificial lighting systems in the buildings. Efficient exploitation of *daylighting* can reduce this energy usage significantly.

With respect to lighting requirements of users, many studies have been conducted. The concept of daylighting strives to optimize the availability of glare-free natural daylight to light up the interior of buildings and is predominantly used in the context of commercial buildings in which the availability of daylight and building occupation largely overlap [2]. However, high-rise buildings experience direct sunlight causing sub-optimal lighting conditions to their indoor environments due to glares or excessive light. Traditionally, blinds or facades are used to solve this problem, but they require manual adjustments throughout the course of a day and usually they block natural light. Building integrated photovoltaics (BIPVs) are photovoltaic materials that are used in place of conventional building components like windows or facades to harvest energy. However, such energy harvesting plays a contradictory role with daylighting.

The goal of this work is to design a modular facade and develop a smart control algorithm that maximizes both the users' comfort level and the facade's energy-harvesting capabilities. The facade optimizes light intensity for users by controlling the daylight entering the room while lowering the dependency on artificial lighting. The algorithm controlling the facade computes the solar energy generating capabilities of the facade for various angles of tilt. A multi-objective optimization is then performed to find the optimal solution for the given time instant. The proposed facade optimization system (FOS) ensures even distribution of daylight in office spaces and uses minimal artificial illumination by incorporating light fixtures into it so that the desired light level is adequate at all times of the day, adjusting for weather and season. This is achieved while also optimizing the energy that is harvested from the sides of high-rise buildings. To our knowledge, this research work is the first to propose the concept of multi-objective optimization of light and solar energy for facades.

2 SYSTEM OVERVIEW

The facade is made up of flaps capable of folding themselves to control the daylight entering the room. The flaps are connected column-wise and are controlled by a single servo motor through a rack and pinion mechanism. Solar cells are embedded on the surface of the flaps as shown in Figure 1. Daylight entering the building is controlled by varying the angle of tilt of the flaps. Multiple such blocks are connected to form the FOS system for the sides of high-rise buildings. Sensor nodes embedded on the facade monitor the lighting conditions outdoor. These nodes wirelessly transmit the data to a hub that runs the algorithm optimizing the facade movement. Instead of deploying a large number of sensor nodes, correlation-based estimation method can be employed to compensate few sensor measurements [4].

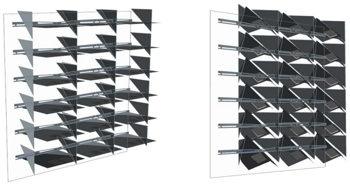

Figure 1: FOS when fully open and fully closed, respectively.

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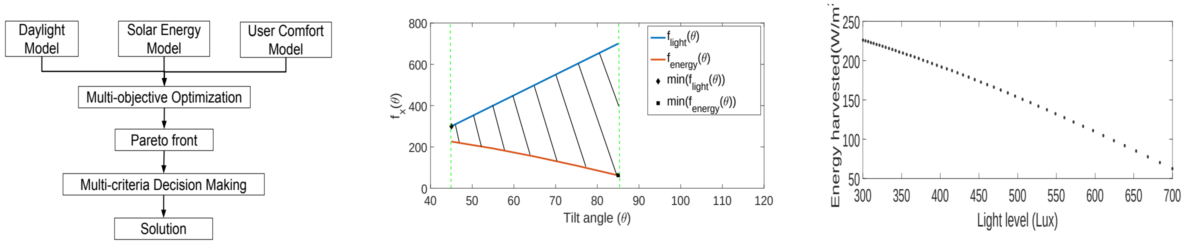

(a) high-level workflow of the system

(b) trade-off region

(c) pareto optimal solutions for weights in 50 equal steps in [0,1]

Figure 2: Data was gathered from advanced simulations and the plots interpret the initial step of the process.

3 FUNCTION FOR OPTIMIZATION

The objective of FOS is to ensure maximum comfort to the occupants of the building while optimizing energy harvested from the solar cells on the facade. User comfort is translated into lighting conditions inside the building and hence our goal is to optimize the daylight entering the building. This is achieved by changing the tilt angle θ of the facade, which in turn affects the tilt angle of the solar cells embedded on the facade, dictating the amount of energy harvested.

3.1 Collection of data

Simulations for daylighting analysis were performed with Rhinoceros 5, DIVA and MATLAB for the location of Delft, The Netherlands. Illumination levels were logged at various points inside a simulated room facing true South and on the facade outside the window. Data for the solar energy model was simulated with MATLAB [5] and correlated in time with the daylighting analysis, enabling a data set with daylighting levels and the orientation of sun's rays falling on the facade. The initial data set was defined as comprising of four days: June 23^{rd}, September 23^{rd}, December 22^{nd} and March 21^{st}, each simulated for three different sky conditions: clear, intermediate, and overcast. For reducing the initial computations, the tilt angle θ was varied in steps of 10° in the range [5°, 85°] for every combination of day and sky condition.

3.2 Formulation of the optimization problem

Figure 2a shows the high-level workflow of FOS. Multiple objectives in the form of models serve as inputs and constitute a multi-objective optimization problem. Sarkar *et al.*, devised a method to collect and interpret information regarding how occupants preferred various lighting levels [3]. After studying data from multiple users, the lighting preference was presented as a beta function. As defined by the work, light levels ranging from 300 lux to 800 lux was above the amicable range, with around 500 lux being the preferred level. The preferred light level to be maintained in indoors is denoted as L_{in}. On the energy frontier, E_{POA} is defined as the plane of array irradiance falling on the solar panels, both of which are functions of the tilt angle θ. Thus we formulate the problem as,

$$Maximize \begin{cases} L_{in} = \|500 - f(\theta)\| \\ E_{POA} = g(\theta) \end{cases}$$

subject to, $5 < \theta < 85$ and $300 < f(\theta) < 800$. Another crucial dictating factor for user comfort will be the frequency of operation of the facade, denoted as the operating frequency T_{on}. We need to investigate further to ascertain a value or devise a method to dynamically change this.

4 RESULTS

The functions of light distribution and harvesting energy both depend on the tilt angle θ. Figure 2b is a plot showing this relationship between the two objectives at 9 AM on June 23^{rd} with a clear sky. The region confined between the lines and the two minima is the trade-off region for the optimization. Figure 2c shows the pareto front, the set of solutions obtained by setting different weights to each of the objective, forming a unique trade-off solution every time. The challenge in such a system is to understand how to set the weights, i.e., higher level of user comfort or more harvested energy. This demands more investigation to be performed to understand the requirements of users.

5 CONCLUSION AND FUTURE WORK

Through this work, we have introduced a conceptual facade system that optimizes two objectives simultaneously to achieve high comfort levels and high energy savings for buildings. The method also provides a wide range of set-point choices, thus enabling a comfortable and an optimized environment. The influence of artificial lighting and how it can be incorporated into the system needs to be investigated. Furthermore, this work warrants more in depth analysis to ascertain how to optimally select a solution from the set of solutions at various times of the day, depending on occupation status of the room, preferences of the occupants and the potential to harvest solar energy.

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