R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 127–136. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

SEMI-TRANSPARENT BUILDING INTEGRATED PHOTOVOLTAIC FACADES

Maximise energy savings using evolutionary multi-objective optimisation

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Abstract. The optimisation of semi-transparent building integrated photovoltaic facades can be challenging when finding an overall balanced performance between conflicting performance criteria. This paper proposes a design optimisation method that maximises overall energy savings generated by these types of facades by simulating the combined impact of electricity generation, cooling load, and daylight autonomy. A proof-of-concept demonstration of the proposed method is presented for a typical office facade.

Keywords. Multi-objective optimisation; semi-transparent building integrated photovoltaic.

1. Introduction

With the current global emphasis on sustainable design, there is a trend to design multifunctional semi-transparent building integrated photovoltaic (BIPV) facades. Such facades use PV materials to replace conventional materials, such as glazing systems integrated with PV cells. Semi-transparent BIPV facades can provide good daylight availability, reduce the solar heat gain through the building envelope, and also have the ability to generate electricity to supplement the building's electricity consumption. It has been shown that semi-transparent BIPV facades are effective in improving energy efficiency and reducing the overall electricity consumption of a building (Fung et al., 2008; Robinson et al., 2009).

The challenge of designing semi-transparent BIPV facades is to optimise the multiple conflicting performance criteria. Unlike typical roof mounted photovoltaic systems, where performance is only focused on the amount of electricity generated, the design of semi-transparent BIPV facades has an impact on a wider range of factors, including solar radiation and daylight penetration into the rooms in the building. To optimise the performance of such facades, optimisation systems can be used that leverage existing simulation tools for performance evaluation. However, the types of simulations that are required are often complex in their own right, and may take a significant amount of time to execute. Optimisation systems typically need to execute these simulations many times in an iterative manner and as a result, optimisation systems can have very long run times, with a single run possibly taking weeks to complete (Rutten, 2011).

In order to test the run time of an evolutionary algorithm, a base-case optimisation of a semi-transparent BIPV facade was conducted. A parametric model was created and an evolutionary algorithm was used to evolve an optimised population of designs. The evolutionary algorithm ran for almost 14 days. Such run times clearly do not align well with a designer's process of working.

This paper will propose an alternative method for the optimisation of semi-transparent BIPV facades. Section two gives an overview of the proposed method, and section three presents the results of a proof-of-concept demonstration where a semi-transparent BIPV facade is optimised. Finally, section four briefly draws conclusions and highlights avenues for further research.

2. Semi-transparent BIPV Facade Optimisation Method

The proposed method is based on a general design method developed by Janssen and Kaushik (2012). This generalised method is adapted to the design of semi-transparent BIPV facades using an evolutionary optimisation approach.

The method consists of three phases: 1) calibration, 2) optimisation, and 3) validation. In the calibration phase, simulation models are selected and simulation programs are configured and tested. Simulations that are deemed too slow are replaced by faster proxy simulations, which are configured in order to ensure that appropriate trade-offs are achieved between speed and accuracy. In the optimisation phase, the simulations are used within the iterative optimisation process in order to explore design variants with improved performance. Finally, in the validation stage, the final designs from the optimisation phase are analysed and evaluated in more detail. Any proxy simulations are now once again replaced by the slow simulations in order to verify the performance improvements.

2.1. CALIBRATION PHASE

For the calibration phase, the first step is to decide on the performance criteria that will be considered. For semi-transparent BIPV facades, a wide range of performance criteria could be included. However, for this paper, the focus will be on maximising the total electrical energy saved by the semi-transparent BIPV facade. Such facades impact energy savings in three distinct ways: electricity generation, cooling load, and daylight savings.

- Electricity generation is the electricity produced by the PV cells in the semi-transparent BIPV facade. Maximising electricity generation will reduce external electricity consumption from the grid.
- Cooling load is the amount of electricity required to cool a room to a set temperature. Cooling load is affected by the amount of solar radiation entering through the facade. Minimising solar radiation will reduce the electricity consumption for cooling.
- Daylight savings is the amount of electricity saved by using daylight instead of artificial lighting in order to light a room to a set minimum illuminance level. The daylight savings is affected by the daylight autonomy, which is the percentage of occupied hours per year when the minimum illuminance level can be maintained in a room by daylight alone (Reinhart, 2010). Maximising daylight autonomy will also maximise daylight savings.

For each of these components, an appropriate simulation model will be chosen and tested. If the execution time of the simulation is excessively slow, a proxy simulation will then be developed that is faster to execute, but that nevertheless stills has sufficient accuracy to guide the evolutionary process.

The total electricity saved is defined by the following formula:

$$ES = EG - CL + DS \tag{1}$$

where ES is the total electricity saving (kWh.yr), EG is the electricity generated (kWh.yr), CL is the cooling load (kWh.yr), and DS is the daylight savings (kWh.yr).

2.2. OPTIMISATION PHASE

For the optimisation phase, an evolutionary algorithm will be used to evolve a population of design variants. The evolutionary algorithm consists of three key procedures: development, evaluation, and feedback.

- The development procedure will generate design variants using a parametric model. Typically, a Visual Dataflow Modelling (VDM) (Janssen and Chen, 2010) system will be used to define the parametric model. Genes in the genotype are then associated with parameters in the model.
- The evaluation procedure will evaluate design variants. In this case, the evaluation procedure will calculate the total electricity savings, which includes the electricity generation, the cooling load, and the daylight savings.

- The feedback procedure will kill design variants that perform badly and will reproduce design variants that perform well. A variety of different strategies can be used for selection and reproduction.

2.3. VALIDATION PHASE

For the validation phase, the best designs emerging from the evolutionary process are analysed and re-simulated. At this final stage, if possible the proxy simulations are discarded, and instead the more accurate but slower simulations are used. Performance characteristics of the final design variants can then be verified.

3. Demonstration

To demonstrate the feasibility of the proposed method, an experiment was conducted.

3.1. DESIGN SCENARIO

The experiment involves optimising the pattern of PV cells on a semi-transparent BIPV facade in order to maximise the total electricity savings. The PV pattern affects both the solar radiation and the daylight penetrating into the room through the glazing, and it will therefore have an impact on all three components of the electricity savings calculation: electricity generation, cooling load, and daylight savings.

A typical north oriented office space for one person occupancy with 4m (width) x 4m (depth) x 3m (height) is modelled for the experiment, as shown in Figure 1 (left). The facade is separated into 4 zones (Figure 1, left): vision glass panel A, B, C and spandrel glass panel. Each zone is independent from each other. The PV cell

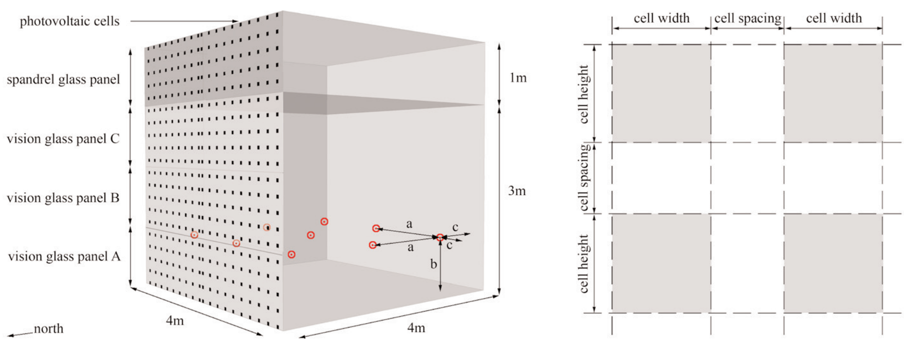

Figure 1. (left) Simulation model with sensors (a = 1.50m, b = 0.85m, c = 0.50m), (right) schematic of cell arrangement for semi-transparent BIPV façade.

pattern for each independent zone is defined by three parameters (Figure 1, right): cell height, cell width, and cell spacing. Cell height and width vary from 5 – 15.5cm at 0.5cm steps but are independent from each other. Cell spacing varies from 0.5 – 5cm at 0.5cm steps. All the cells of the semi-transparent BIPV facades will be similar in shape. The pattern occupies a facade with a height and width of 4m.

3.2. SOFTWARE TOOLS

The main tool that is used is Grasshopper (Rutten, 2011), a plugin for the Rhinocerous computer aided design modelling software (McNeel, 2010). Grasshopper (Rutten, 2011) is a VDM system that allows designers who are not trained in scripting to quickly generate parametric models. A number of specialist Grasshopper components are used for running optimisation algorithms and for executing simulations.

For running optimisations, the Galapagos component is used (Rutten, 2011). This component is an evolutionary optimisation solver which can be used to optimise designs for a single performance criterion.

For executing cooling load and daylight autonomy simulations, the DIVA component is used (Jakubiec and Reinhart, 2011). DIVA links to the EnergyPlus (Crawley et al., 2001) and Daysim (Reinhart, 2010) simulation programs.

EnergyPlus is a building performance simulation software that is based on fundamental heat balance principles. Daysim is a Radiance-based daylighting analysis tool that couples the Radiance (Ward and Shakespeare, 1998) algorithms with a daylight coefficient approach that efficiently simulates illuminance distribution in a year without executing thousands of individual ray tracing runs for all sky conditions which is impractical.

EnergyPlus is used to simulate cooling loads and Daysim is used to simulate daylight autonomy. In both cases, an EnergyPlus weather data file (NREL, 2012) for Singapore is used. The daylight autonomy is then used as a basis for calculating daylight savings.

3.3. CALIBRATION PHASE

For the calibration phase, each of the three components of the total electricity savings calculation will be considered in turn.

3.3.1. Electricity generation

The annual electricity generation of a photovoltaic module can be simulated using EnergyPlus. Ideally, it would simulate with the equivalent one-diode model

(Crawley, 2001). However, this model requires the electrical characteristic of a module to be known in advance. For an untested type of photovoltaic module, the electrical characteristic can only be obtained by fabricating the module. This poses a problem when designing semi-transparent BIPV facades with non-standard PV cell patterns, since each design option would need to be fabricated. Hence a simpler model needs to be used that is independent of the electrical characteristics. Note that the reason for using this simpler model is due to lack of input information rather than simulation speed.

EnergyPlus already has such a simple model, as an alternative to the equivalent one-diode model (EnergyPlus, 2011). In this research, we propose to use the simple model. The mathematical equation used is as follows:

$$P = A_s \text{ x } f_a \text{ x } G_t \text{ x } eff_{cell} \text{ x } eff_{invert} \quad (2)$$

where P is the electrical energy produced by photovoltaic (kWh), A_s is the net area of photovoltaic module (m^2), F_a is the fraction of surface area with active solar cells, G_t is the total annual solar radiation energy incident on PV array (which is set at 561 $kWh.m^{-2}$), eff_{cell} is the semi-transparent BIPV facades module efficiency (which is set at 12%) and eff_{invert} is the inverter efficiency (which is set at 90%).

In order to verify the accuracy of the simple model, a set of commercially produced photovoltaic modules (for which the electrical characteristics were already known) were simulated using both the equivalent one diode model and the simple model, and the results were then compared. In total, simulations for 16 different modules were carried out for the four different cardinal directions. The annual electricity generation was simulated with EnergyPlus for both models (EnergyPlus, 2011). The trend-line of 64 pairs of results for the simple and the equivalent one-diode models were plotted in Microsoft Excel. The electricity generation for the simple model resulted in an R^2 correlation of 0.98. This shows that the simple model has a good correlation and can be used in place of an equivalent one-diode model.

3.3.2. Cooling load

The cooling load for the room can also simulated using EnergyPlus. For cooling load, the study is interested in the cooling load affected by heat gain through the semi-transparent BIPV facades hence internal heat gains from lights, equipment and occupants have been set to 0. Default materials from the material library in DIVA are used. With reference to Figure 1 (left), the walls, floor and ceiling are assigned as “adiabatic” and spandrel glass panel are assigned as “opaque spandrel glass”.

A window module is defined to represent a typical 6mm thick clear glass window with U-value of 5.8, solar heat gain coefficient (SHGC) of 0.82 and visible transmittance (VT) of 0.88 (Pilkington, 2010). For the photovoltaic cells, there are two different approaches with different trade-offs between speed and accuracy. The slower more accurate approach to modelling the PV cells is to assign them as external shading elements. Each cell is assigned a solar reflectance of 0.1 and visible reflectance of 0.1. The amount of solar radiation affected by the shading from photovoltaic cells is calculated for each photovoltaic cell and for each time-step for an entire year in the simulation. Each time step calculation is different from the next because each value is dependent on the time and location of the sun. A range of 156 to 4224 photovoltaic cells with different patterns are input as external shading elements for each simulation. This large number of shading elements causes the simulation to run relatively long, with the longest simulation taking approximately 30 minutes. This caused the optimisation of the base case, mentioned in Section 1, to run for almost 14 days.

A faster proxy simulation is therefore proposed that uses a less accurate approach to the modelling of the PV cells. With this approach, the solar heat gain coefficient (SHGC) and visible light transmittance (VLT) for the facade are adjusted to take into account the effect of the PV cells. The equations for SHGC and VT used in the proxy simulation are shown below:

$$SHGC_{sst} = A_{pv}/A_{sst} \text{ x } SHGC_{st} \tag{3}$$

$$VT_{sst} = A_{pv}/A_{sst} \text{ x } VT_{st} \tag{4}$$

where $SHGC_{sst}$ is the solar heat gain coefficient of semi-transparent BIPV facade ($Wm^{-2}K^{-1}$), $SHGC_{st}$ is the solar heat gain coefficient of the vision glass panel (which is part of the semi-transparent BIPV facade) without photovoltaic cells ($Wm^{-2}K^{-1}$), VTsst is the visible transmittance of the semi-transparent BIPV facade ($Wm^{-2}K^{-1}$), VT_{st} is the visible transmittance of the vision glass panel (which is part of the semi-transparent BIPV facade) without photovoltaic cells ($Wm^{-2}K^{-1}$), A_{pv} is the area of photovoltaic cells (m^2) and A_{sst} is the area of semi-transparent BIPV facade (m^2).

In order to check the accuracy of the proposed proxy simulation, a total of 164 cooling load simulations for different BIPV facades were conducted using both the slow simulation and the proxy simulation. The trend-line for both the slow and proxy simulations were plotted in Microsoft Excel, and an R^2 correlation of 0.93 was calculated. This shows that the proposed proxy simulation for cooling load has a good correlation and can be used in place of the slower more detailed cooling load simulation.

3.3.3. Daylight Savings

Daylight savings is calculated based on the daylight autonomy for the room, which can be simulated using Daysim. Since Daysim is already an optimised simulation method (Reinhart, 2010), the simulation executed relatively quickly and there was no need to create a proxy in this case.

With reference to a recent study on various lighting standards around the world by Halonen et al. (2010), it was found that minimum illuminance for interior spaces ranges from 200lx to 500lx. Hence, for the simulation of daylight autonomy, the minimum illuminance level of 500lx is set for the simulation. Working hours are set from 9:00 to 18:00. A 3 x 3 nodal grid of daylight sensors are drawn 0.85m from the floor and 0.25m away from the vertical walls (Figure 1, left). Since daylight autonomy is more critical for areas further way from the windows, only the back 2 rows of 6 daylight sensor nodes are used for the daylight autonomy simulation.

Default materials from the material library in DIVA are used for the simulation. Based on research done by Protogeropoulos and Zachariou (2010) which shows that a typical photovoltaic module has a reflectance of below 10%, the photovoltaic layer is assigned a reflectance of 10%.

The following settings were used in DIVA/Daysim: ab = 2, ad = 1000, as = 20, ar = 300 and aa = 0.1, where ab is ambient bounce, ad is ambient resolution, ar is ambient resolution and aa is ambient accuracy. The detailed explanation of the settings is beyond this paper. They can be referred to in the Radiance manual. Daylight savings were then calculated according to the following formula:

$$DS = (DA_{sim}/100) * LPB * FA * WH \tag{5}$$

where DS is the total daylight savings ($kWh.yr^{-1}$), DA_{sim} is the simulated daylight autonomy (%), LPB is the lighting power budget ($kW.m^{-2}$), FA is the floor area of simulation model (which is $16m^2$) and WH is the working hours per year. LPB is set based on the Code of Practice (SPRING, 2006) which recommends an LPB for offices of $0.015kW.m^{-2}$. WH is set based on a 5 work days per week with 9hrs of work per day, which results in 2,340hrs per year.

3.4. ITERATION PHASE

The evolutionary solver, Galapagos, is used for the optimisation. Galapagos is executed with a population of 30, initial boost of 2%, and the maintain level is set at 10% and inbreeding at 75%. The system was executed on a single computer with an i5 Intel core CPU of 3.5GHz with 8GB of RAM, on a 64 bits Windows.

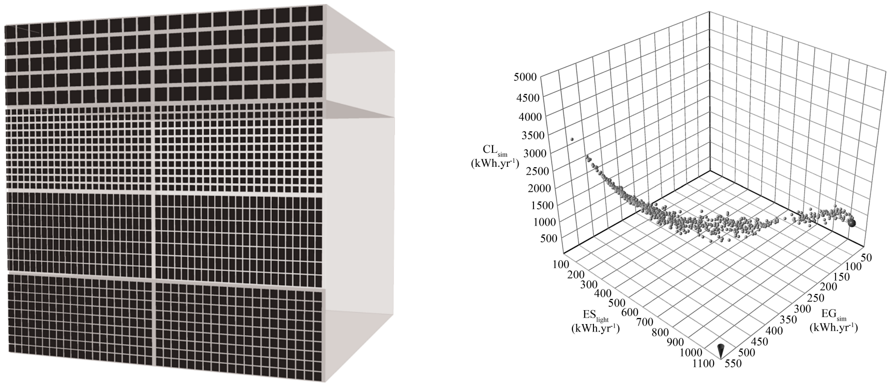

Figure 2. Optimised design.

Galapagos ran for 2 days, 17 hours. Compared to the base case which ran for almost 14 days, this method reduced the run time by 80%. The optimised design that was found at the 544th iteration is shown in Figure 2. The orange dot represents the ideal design performance and the red dot represents the design with the best performance. The fast mode optimisation process completed 1471 iterations of simulations. The optimised design is similar to the optimised design found in the base case.

3.5. VALIDATION STAGE

In the final validation phase, a set of designs from the Pareto front were selected and analysed. In order to verify the performance improvements in cooling load, these designs were re-simulated using the slow cooling load simulation. In all cases, the results from the slow mode simulation confirmed the performance improvements. In the case of the example shown in Figure 2, the optimised final design showed an overall improvement of 61% of the overall electricity over the initial design.

4. Conclusion

A design method for the multi-objective optimisation of semi-transparent BIPV facades is proposed. The overall objective is the maximisation of energy savings, but this objective embodies three distinct sub-objectives, defined as the maximisation of energy generation, the minimisation of cooling loads, and the maximisation of daylight savings. The method also significantly reduces the optimisation runtime by using a proxy simulation for calculating cooling loads.

The proposed design method simplifies the task of finding an overall balance performance for semi-transparent BIPV facades, especially where conflicting performance criteria may prove to be challenging to explore manually. This design method need not be restricted to the design of semi-transparent BIPV facades but can also be extended to optimise other design elements in a building and also include other performance criteria.

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