MULTI-OBJECTIVE OPTIMISATION OF SEMI-TRANSPARENT BUILDING INTEGRATED PHOTOVOLTAIC FACADES

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ABSTRACT

Multi-objective optimisation of semi-transparent building integrated photovoltaic (BIPV) facades can be challenging when aiming to find an overall balanced performance between conflicting performance objective. This paper is a further development of the design optimisation method proposed by Choo and Janssen (2013) which maximises overall energy savings of a typical office with a semi-transparent BIPV façade. It proposes the enhancement of the optimisation method by considering not just daylight autonomy as a factor for daylight savings but also considers daylight glare probability as an additional factor for a more realistic simulation scenario. A demonstration of this enhanced method is presented for a typical office façade in Singapore.

INTRODUCTION

As mentioned by Choo and Janssen (2013), the design of typical roof mounted photovoltaic systems only focuses on the amount of electricity generated. The design of semi-transparent BIPV facades in contrast has an impact on a wider range of factors, including heat gain and daylight penetration into the rooms in the building. To optimise the performance of such facades, optimisation systems that leverage on existing simulation tools for performance evaluation can be used.

This paper continues from the study conducted by Choo and Janssen (2013). In the paper, they proposed a three-phase method: 1) calibration, 2) optimisation, and 3) validation. The multi-objective optimisation considers three performance metrics, namely daylight savings, cooling load and electricity generation of the BIPV façade. The proposed method reduces the optimisation run time from 14 days for a base case to less than 3 days with the use of faster proxy simulations.

In addition to the existing three performance metrics used by Choo and Janssen (2013), this paper considers daylight glare probability (DGP) (Wienold and Christoffersen 2006) as another performance factor that affects the daylight savings within the multi-objective optimisation process. The section on optimisation method gives an overview of the proposed enhanced method and the section on demonstration presents the application of the method based on a typical office façade in Singapore. At the end, the paper concludes and highlights avenues for further research.

OPTIMISATION METHOD

The method consists of three phases (Figure 1): 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 a way where appropriate trade-offs are achieved between speed and accuracy. The optimisation phase makes use of the simulations within the iterative optimisation process in order to explore design variants with improved performance. Lastly, in the validation stage, the final designs from the optimisation phase are analysed and evaluated in more detail. In order to verify the performance improvements, slow simulations will replace all proxy simulations.

Calibration Phase

Semi-transparent BIPV facades affect energy savings in three distinct ways, namely daylight savings, cooling load and electricity generation of the BIPV façade. The enhancement to the method proposed here is the addition of daylight glare probability (DGP) as a reduction factor to daylight savings. This reduction factor is termed the glare coefficient in this paper.

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. Daylight autonomy affects the daylight savings, hence maximising daylight autonomy will in turn maximise daylight savings. On top of that, the enhanced method proposed takes into consideration a glare coefficient, α, as a reduction factor to daylight savings to reflect the reduction in daylight savings when blinds are drawn due to glare. The following

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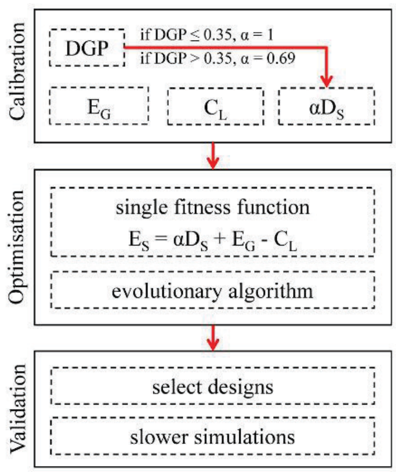
equation defines the total electricity savings, which considers the glare coefficient:

$$E_S = E_G - C_L + \alpha D_S \quad (1)$$

where E_S is the total electricity saving ($kWh \cdot a^{-1}$), E_G is the electricity generated ($kWh \cdot a^{-1}$), C_L is the cooling load ($kWh \cdot a^{-1}$), D_S is the daylight savings ($kWh \cdot a^{-1}$) and α is the glare coefficient.



E_S - total electricity savings ($kWh \cdot a^{-1}$)
E_G - electricity generated ($kWh \cdot a^{-1}$)
C_L - cooling load ($kWh \cdot a^{-1}$)
D_S - daylight savings ($kWh \cdot a^{-1}$)

Figure 1: Schematic of three phases during optimisation process

Optimisation Phase

For the optimisation phase, the evolutionary algorithm consists of three key procedures, which includes 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 define the parametric model. Genes in the geno-type are then associated with the 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 daylight savings, cooling load and electricity generation.

The feedback procedure will kill design variants that perform badly and reproduce design variants that perform well. The selection and reproduction can use a variety of different strategies.

Validation Phase

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

DEMONSTRATION

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: daylight savings, cooling load and electricity generation.

A typical north oriented office space for one person occupancy with 4 m (width) x 4 m (depth) x 3 m (height) is modelled for the experiment, as shown in Figure 2 (top). The facade is separated into four zones: vision glass panels 1, 2, 3 and spandrel glass panel. Each zone is independent from one another. Three genes such as cell height, cell width and cell spacing as shown in Figure 2 (bottom), define the PV cell pattern for each independent zone. Cell height and width vary from 5 – 15.5 cm at 0.5 cm steps but are independent from each other. Cell spacing varies from 0.5 – 5 cm at 0.5 cm 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 4 m.

For this paper, a roller blind with an openness factor of 3 is modelled behind vision glass panel 2. It is only activated when DGP (Wienold 2009) is above 0.35 where glare is perceptible.

Software Tools

The main tool used is Grasshopper (Rutten 2011), a plugin for the Rhinoceros computer aided design modelling software (McNeel 2010). Grasshopper (Rutten 2011) is a VDM system that allows designers untrained in scripting to generate parametric models quickly. A number of specialist Grasshopper components are used for running optimisation algorithms and executing simulations.

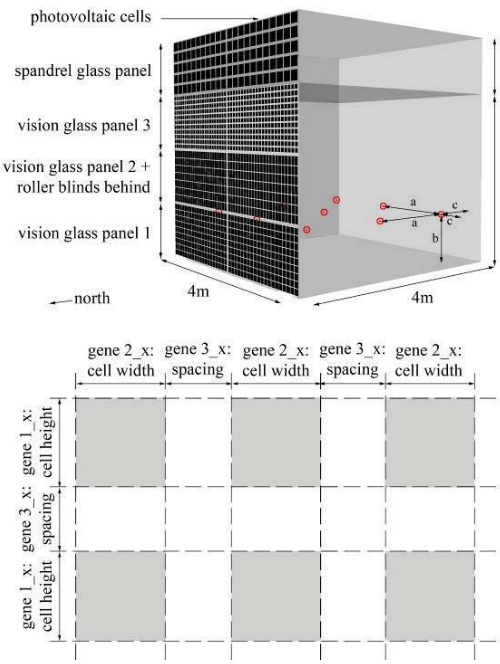


Figure 2 (top): Simulation model with sensors (a = 1.50m, b = 0.85m, c = 0.50m)

Figure 2 (bottom): Schematic of cell arrangement for semi-transparent BIPV façade with gene 1_x, 2_x and 3_x, where x is the glass panel numbers (1-3)

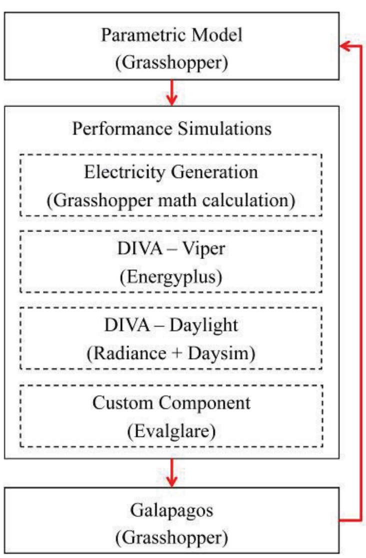


Figure 3: Workflow of different software tools for the optimisation process

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 2011). DIVA links to the simulation programs such as EnergyPlus (Crawley *et al*., 2001) which simulates cooling loads and Daysim (Reinhart 2010) which simulates daylight autonomy.

Both cases make use of an EnergyPlus weather data file (NREL 2012) for Singapore. The daylight autonomy is then used as a basis for calculating daylight savings.

An additional customised simulation component is developed within grasshopper to link to Evalglare (Wienold 2006). Evalglare is a radiance-based tool for glare simulation and analysis. The workflow of the different software for the optimisation process is shown in Figure 3.

Calibration Phase

For the calibration phase, the three components of the total electricity savings calculation will be explained below.

Electricity Generation

The annual electricity generation of a photovoltaic module can be simulated using EnergyPlus. In this research, we propose to use EnergyPlus, which has a simple model, as an alternative to the equivalent one-diode model (EnergyPlus 2011). The mathematical equation used is:

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

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 a DIVA-calculated value of 561 $kWh.m^{-2}$), eff_{cell} is the semi-transparent BIPV facades module efficiency (which is set at 12%) and eff_{invert} is the average 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. A comparison is then made. In total, we carried out simulations for 16 different modules for the four different cardinal directions. The annual electricity generation was simulated with EnergyPlus for both models

(EnergyPlus 2011). After which, the trend-line of 64 pairs of results for the simple and the equivalent one-diode models were plotted using 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 is suitable as an alternative to equivalent one-diode model.

Cooling Load

The cooling load for the room can also be simulated using EnergyPlus. For simplification, the study considers the heat gain through the semi-transparent BIPV facades but not the internal heat gains from lights, equipment and occupants. Default materials from the material library in DIVA are used. With reference to Figure 2 (top), 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 6 mm thick clear glass window with a U-value of 5.8, a solar heat gain coefficient (SHGC) of 0.82 and a 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 but 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. For each simulation, there are various external shading elements of different patterns with number of photovoltaic cells ranging from 156 to 4224. The large number of shading elements resulted in a relatively long time taken for the simulation to run, with the longest simulation taking approximately 30 minutes. This caused the optimisation of the base case, mentioned in the introduction, to run for almost 14 days.

Hence, in view of the time factor, a faster proxy simulation is 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:

$$SHGC = A_{pv}/A \times SHGC_{vg} \quad (3)$$

where SHGC is the solar heat gain coefficient of semi-transparent BIPV facade ($Wm^{-2}K^{-1}$), $SHGC_{vg}$ is the solar heat gain coefficient of the vision glass panel (which is part of the semi-transparent BIPV facade but without photovoltaic cells) ($Wm^{-2}K^{-1}$)

$$VT = A_{pv}/A \times VT_{vg} \quad (4)$$

where VT is the visible transmittance of the semi-transparent BIPV facade ($Wm^{-2}K^{-1}$), VT_{vg} is the visible transmittance of the vision glass panel (which is part of the semi-transparent BIPV façade but without PV cells) ($Wm^{-2}K^{-1}$), A_{pv} is the total area of PV cells (m^2) and A is the area of semi-transparent BIPV facade (m^2)

In order to check the accuracy of the proposed proxy simulation, 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 using 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 is suitable as an alternative to the slower and more detailed cooling load simulation.

Enhanced Daylight Savings

In this paper, the enhanced daylight savings is calculated based on the daylight autonomy and daylight glare probability for the room, which can be simulated using Daysim and Evalglare (Wienold 2006) respectively. In this case, since Daysim is already an optimised simulation method (Reinhart 2010), the simulation can be executed relatively quickly with no need to create a proxy. For Evalglare, a customised Grasshopper component is created to simulate daylight glare probability and output into the evolutionary optimisation process.

Daylight Autonomy

A recent study on various lighting standards around the world by Halonen *et al.* (2010), 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 0.85 m from the floor and 0.25 m away from the vertical walls as shown in Figure 2 (top). Since daylight autonomy is more critical for areas further way from the windows, only the last 2 rows furthest away from the windows 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), a typical photovoltaic module has a reflectance of below 10%. Hence, a reflectance of 10% is assigned to the photovoltaic layer.

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 described in the Radiance manual.

Glare Coefficient

It is impractical to use an annual glare simulation for the optimisation process because of the long runtime per iteration. For example, it takes about 6 hours to conduct a base case annual glare simulation. Hence, a proxy simulation of using a fixed point in time glare simulation is proposed.

A custom Grasshopper component is created as a wrapper to Evalglare (Wienold 2006) in order to calculate the point-in-time glare within Grasshopper. Figure 4 shows a schematic of this custom Grasshopper glare component. Glare is measured as DGP. 0.35 > DGP is considered imperceptible, 0.4 > DGP ≥ 0.35 is considered perceptible, 0.45 > DGP ≥ 0.4 is considered disturbing and DGP ≥ 0.45 is considered intolerable.

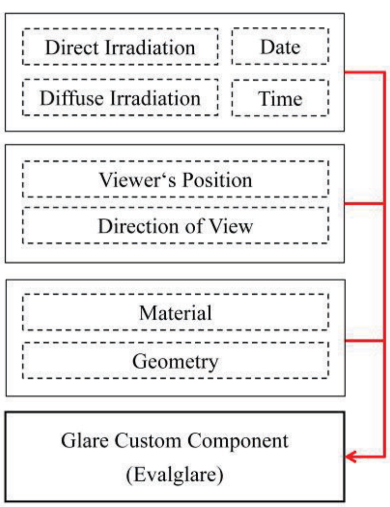


Figure 4: Schematic of custom Grasshopper glare component

To determine the point-in-time to use for the glare simulation, 20 runs of annual glare simulation are done for a range of selected design variations within the solution space of possible designs to determine the day and time which has glare for all the design variations. The point-in-time was found to be 21 June, 12:00PM which is the solstice. This day and time is used for the point-in-time glare simulation using the customised glare component to activate the roller blinds and reduce the daylight savings. The same 20 runs of annual glare are run with the roller blinds drawn down. It shows that for the entire year there is only imperceptible glare with DGP less than 0.35. In turn, if glare is eliminated for this point-in-time, glare for all other time in the year is also eliminated.

The reduction factor of daylight savings is represented by the glare coefficient, α, which is added as a factor to daylight savings, D_S shown in equation 5. This is to take into account the reduction of the daylight savings when the blinds are drawn due to the presence of glare. When the DGP for point-in-time glare is greater than 0.35, the roller blinds are drawn affecting the daylight savings. Enhanced daylight savings, $D_{S'}$ in equation 5 can be reformulated to equation 6:

$$D_{S'} = \alpha D_S \quad (5)$$

$$D_{S'} = (\alpha D_A/100) * LPB * FA * WH \quad (6)$$

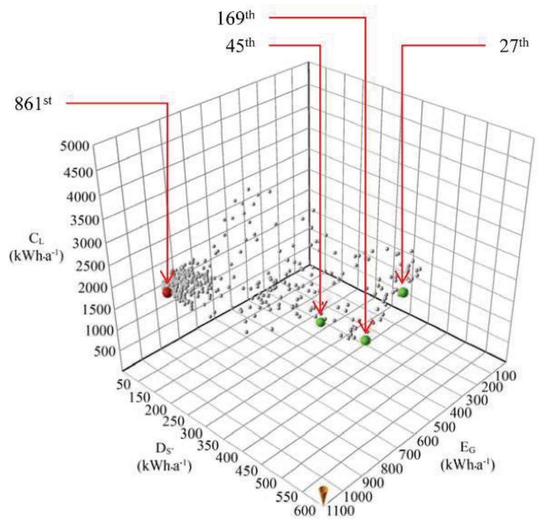
where D_S is the daylight savings ($kWh \cdot a^{-1}$), $D_{S'}$ is the enhanced daylight savings ($kWh \cdot a^{-1}$), D_A is the simulated daylight autonomy (%), LPB is the lighting power budget ($kW \cdot m^{-2}$), FA is the floor area of simulation model (which is 16 m^2), WH is the working hours per year and α is the glare coefficient.

LPB is set based on the Code of Practice for Singapore (SPRING 2006) which recommends an LPB for offices of 0.015 $kW \cdot m^{-2}$. WH is set based on a 5-day work per week with nine hours of work per day, which results in 2,340 hrs per year.

As shown in equation 6, glare coefficient, α is a factor to D_A. Hence, α can be defined as the scale factor of reduction of daylight autonomy, D_A. Daylight autonomy is simulated using 125 selected designs with and without the roller blinds on 21 June, 12:00PM and plotted using Microsoft Excel. The regression coefficient of 0.69 from the linear regression is then appropriated as the glare coefficient. The coefficient of determination R^2 is 0.9, which displays good correlation.

Optimisation Phase

Galapagos is executed with a population of 30 and initial boost of 2%. 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 64 bits Windows.



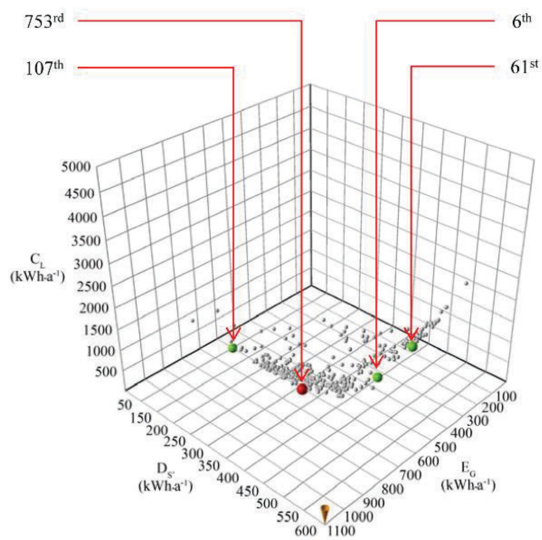


Figure 5 (top): 3D plot of results for optimisation with enhanced daylight savings

Figure 5 (bottom): 3D plot of results for optimisation without enhanced daylight savings

The optimised design was found at the 861st iteration as shown in Figure 5 (top). The orange point represents the ideal design performance and the red dot represents the design with the best performance. While the optimisation without daylight savings takes 2 days, 17 hours, the computational time increases to 14 days 17 hours when including this fourth variable. This shows that for multi-objective optimisation, the addition of performance objectives to the optimisation process can increase the run time drastically. However, evolutionary algorithm is useful in simplifying the task of finding an overall balance performance for semi-transparent BIPV facades, especially where conflicting performance objectives may prove to be challenging to explore manually. In addition, it also allows the designer to review other designs along the Pareto front. The Pareto front consists of designs that have good overall performance but with different performance trade-offs. This method provides the designer the choice to select the designs they better prefers and have a good idea on the pros and cons of picking it in relation to its various performance objectives.

Validation Phase

In the final validation phase, the designs from the Pareto front were selected and analysed. In order to verify the performance improvements, the proxy simulations were replaced with the original simulation used in the base case and the designs were re-simulated. In all cases, the results from the original simulation confirmed the performance improvements with respect to the base case. Additionally as shown by both the annual glare simulation with and without roller blinds, the glare is eliminated for the entire year for the optimised design with enhanced daylight savings. The proposed design method with enhanced daylight savings maybe more realistic in consideration but the performance values are not considered as absolute. The performance values should be used as a relative comparison to a base case, as shown in Figure 6 (left).

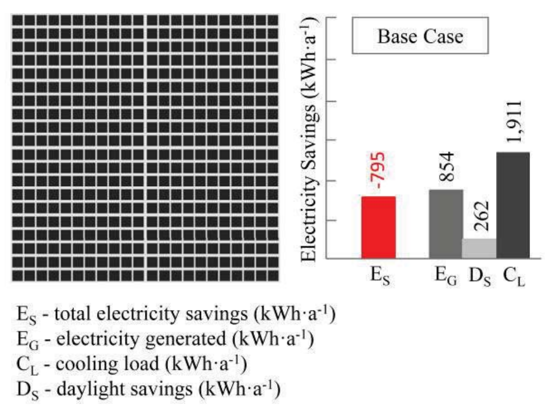
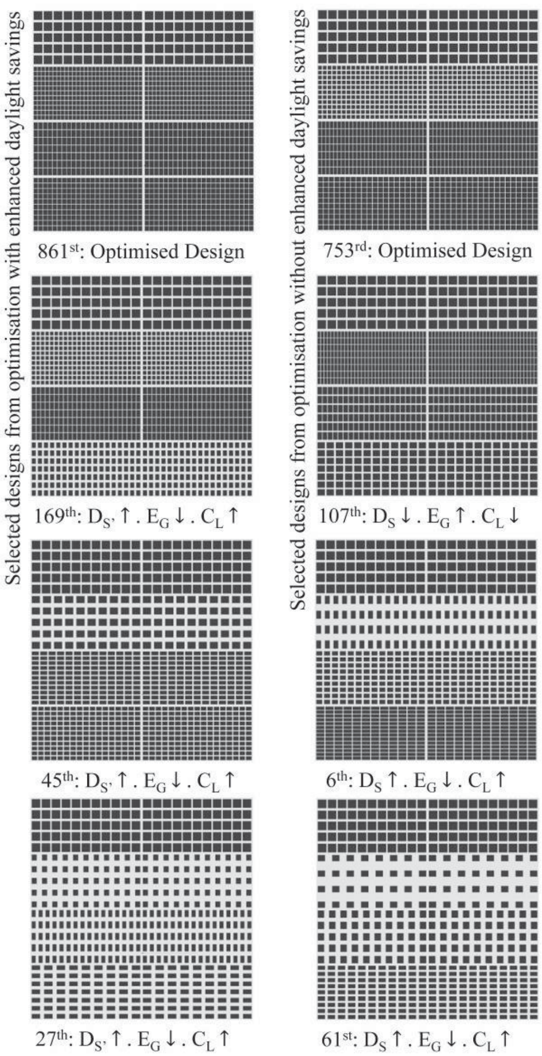


Figure 6 (left): Base case design with standard PV cell arrangement.

Figure 6 (right): Barchart of E_S, E_G, D_S and C_L for base case design.

Figure 7 and 8 shows that the optimised design with enhanced daylight savings showed an overall improvement of 15% of the total electricity savings over the base case design shown in Figure 6.

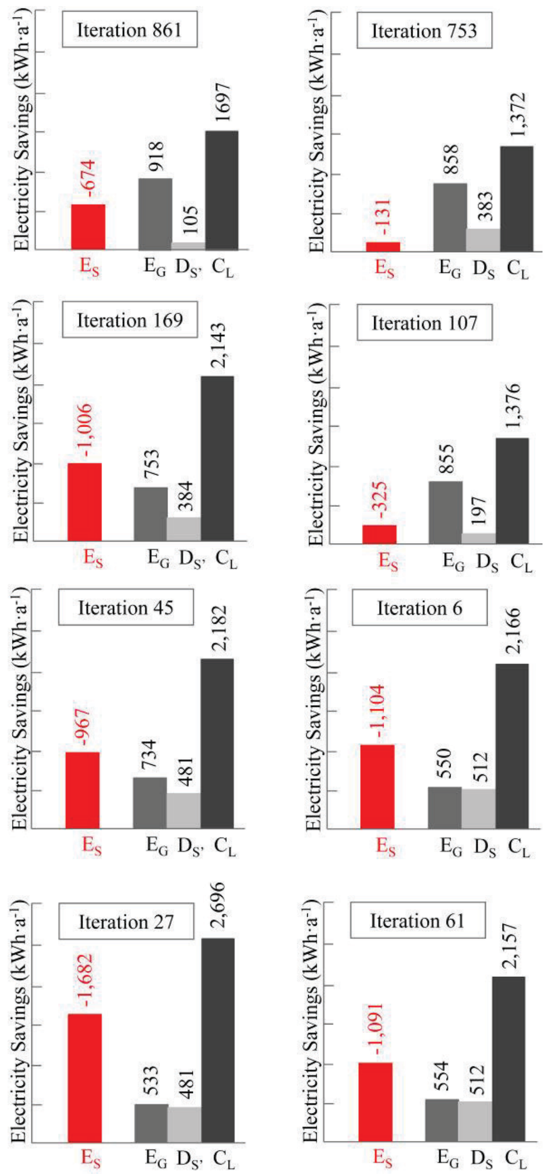
Comparing with the optimised design without enhanced daylight savings, an overall improvement of 84% of the total electricity savings over the base case design was calculated. This shows that without the enhancement, there is an overestimation of 69% of overall electricity savings. Hence, the optimisation with enhanced daylight savings gives a more accurate performance closer to the real scenario with occupants drawing down the blinds when there is glare.



E_S - total electricity savings ($kWh \cdot a^{-1}$)
E_G - electricity generated ($kWh \cdot a^{-1}$)
C_L - cooling load ($kWh \cdot a^{-1}$)
D_S - daylight savings ($kWh \cdot a^{-1}$)
$D_{S'}$ - enhanced daylight savings ($kWh \cdot a^{-1}$)

Figure 7 (left): Optimised design and selected designs along Pareto fronts of both optimisations with enhanced daylight savings

Figure 7 (right): Optimised design and selected designs along Pareto fronts of both optimisations without enhanced daylight savings



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D_S - daylight savings ($kWh \cdot a^{-1}$)
$D_{S'}$ - enhanced daylight savings ($kWh \cdot a^{-1}$)

Figure 8 (left): Performance bar charts of optimised design and selected designs along Pareto fronts of both optimisations with enhanced daylight savings

Figure 8 (right): Performance bar charts of optimised design and selected designs along Pareto fronts of both optimisations without enhanced daylight savings

Figure 7 and 8 shows a comparison of the best performance with three other betters designs along the Pareto front for optimisation using both enhanced daylight savings and non-enhanced daylights savings.

The designs for both optimisations using with and without enhanced daylight savings show that, as the façade gets more porous, more daylight is allowed into the office and the daylight savings increases but electricity generation decreases and cooling load increases due to increase in the solar heat gain.

CONCLUSION

The enhancement of the design method for the multi-objective optimisation of semi-transparent BIPV facades was proposed in this paper. The enhanced daylight savings within the optimisation process provides a more realistic scenario for the optimisation, which considers not just the amount of usable daylight within the space but also the possible reduction of daylight savings due to glare. However, this will cause a significant increase in the runtime compared to the method proposed by Choo and Janssen (2013) without the enhanced daylight savings. Although this enhanced design method is not appropriate for use in early design stage, it does simplify the task of finding an overall balance performance for semi-transparent BIPV facades, especially where conflicting performance objectives may prove to be challenging to explore manually. However, the absolute run time of 14 days and 17 hours for the optimisation process is considered long in the early stage design for designers where the design process is fluid and fast, and decisions for the design iteration are made quickly. If this method is adopted during early stage design, we need to apply additional proxy simulation techniques to reduce the run time of the optimisation process.

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