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Investigating the performance of a hybrid PV integrated shading device using multi-objective optimization

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Abstract. PV integrated shading devices (PVSDs) are an interesting case study for an optimisation problem as their design is non-trivial and they must balance competing parameters and uses of solar energy. In this study, the case of a south-facing, exterior louvre blade PVSD was used to investigate how multi-objective optimisation (MOO) coupled to a parametric design approach can be used as a support tool to improve the performance of the system in four different cases. The parameters optimized were the individual tilt angle of each louvre-blade (0, 15, 30 or 45 ° from the horizontal), the vertical distribution of the blades, and the type of material on the upper surface of each louvre (reflective coating or PV cells). The objectives of the optimisation were to minimise the total annual net energy electricity use and to maximise the daylighting level in the zone. The results of the investigation showed that PVSD configurations with higher louvre counts performed better as hybrid systems as they allowed to increase daylighting compared to classic, fully PV coated systems and did not increase energy use in the zone significantly. However, for systems with lower counts of louvres, the results of the optimisation showed that the surface of the louvres was more useful as a PV element, as reflective materials had little effect on the daylighting in the zone and the reduction in energy converted noticeably affected the energy performance of the building.

Nomenclature

cDA	Continuous Daylight Autonomy [%]
E_C	Annual cooling energy demand [kWh/m^2]
E_H	Annual heating energy demand [kWh/m^2]
E_L	Annual lighting energy demand [kWh/m^2]
E_{PV}	Annual PV-converted energy [kWh/m^2]
E_{TOT}	Annual net energy demand [kWh/m^2]

Acronyms

BIPV	Building Integrated Photovoltaic
BIPV/T	Building Integrated Photovoltaic/Thermal
CIGS	Copper Indium Gallium Selenide
MOO	Multi-Objective Optimization
PV	Photovoltaic
PVSD	Photovoltaic Shading Device

1. Introduction

Building integrated photovoltaics (BIPV) systems such as PV integrated shading devices (PVSDs) are an interesting application aiming to combine the benefits of reducing energy use with those of providing indoor spaces with comfortable visual and thermal environments. Existing research has shown that shading devices and shading strategies should be considered at an early point in the building design process to ensure that the shading system will provide optimal management of solar heat gain and light distribution in daylit spaces [1,2]. This is especially crucial when PV cells are integrated on the shading system since the energy conversion aspect will complexify the nature of the trade-offs between different uses of solar radiation. As a result, the design of optimal PVSD systems is non-trivial and requires more advanced studies to ensure that the shading system is well designed. This study investigates how multi-objective optimization (MOO) can be used to support the informed design of PVSDs, as well as improve their performance by letting an optimization algorithm explore a larger design space defined by key parameters. This research builds on previous work by Taveres-Cachat et al [3] but extends its scope to include the effect of optimizing the type of material used on the louvre blades in addition to the previously considered parameters, which were the vertical distribution of the louvre blades and their individual tilt angle. This supplementary optimization parameter, i.e. the choice of the material used on the top surface of the PVSD blades, is interesting because the use of PV cells adds to the carbon footprint of the system and represent an additional financial cost.

The goal is to define a new layer in the optimization framework which allows to evaluate the performance of what will be referred to as a hybrid PVSD, meaning that the parameters of the optimization allow to modify the type of material used on the blades and select either photovoltaic material or a reflective material that can act as a light shelf. This design approach is innovative as it allows to incorporate climate adaptive building design principles and energy efficiency as the driving forces in the design of a façade, while at the same time opening for the possibility to reduce both the carbon footprint of the system and its cost.

2. Methods

2.1. Simulation environment

The basis of this work is the case study of a photovoltaic integrated shading device (PVSD) installed on a reference office building modelled in the Rhinoceros environment using Grasshopper [4], a visual programming language for parametric modelling; while Ladybug [5], a Radiance-based plug-in for Grasshopper, was used to conduct grid-based solar irradiation and daylighting analyses. The energy calculations are provided by Honeybee which uses the EnergyPlus engine. The optimization of the shading device was done by coupling the building model to the multi-objective optimization algorithm plug-in Octopus [6]. The simulations for this study were run over one year with climate data for the location of Oslo, Norway (EnergyPlus weather file (.epw), Typical Meteorological Year – TMY).

2.2. Case study

The geometry of the reference building is given by the Bestest Case 600, which is a 48m^2 rectangular room (6m x 8m x 2.7m) with two large south facing windows (3m x 2m) [7]. The building envelope properties, building operation schedules, and internal loads were defined to comply with the Norwegian technical standard NS3031. The HVAC parameters were modelled as ideal air loads and the energy source for the case study was assumed to be a heat pump with a pre-set seasonal performance (COP heating = 3; COP cooling = 5). The PVSD system is based on the design of an existing non-PV integrated shading system with 105mm wide louvres that can be tilted between 0 and 45° in 15° increments. Both windows are equipped with the PVSD system, with a centre blade to windowpane distance of 16 cm. All the parameters in the model can be controlled parametrically to accommodate any change in the building geometry, building loads and schedules or in the PVSD configuration. The PV material was assumed to have a total, constant net efficiency of 15%. More information about the case study and the model used for the PVSD system are provided in [3]. The Radiance parameters for the materials used in the model are described in Table 1.

Table 1 Overview of the optical parameters used in the model (Radiance material library)

Object	Type of material	RGB reflectance
GenericCeiling_70	Opaque	0.7; 0.7; 0.7
GenericFloor_20	Opaque	0.2; 0.2; 0.2
GenericInteriorWall_50	Opaque	0.5; 0.5; 0.5
GenericFurniture_50	Opaque	0.5; 0.5; 0.5
Glazing_TriplePane_Argon90	Transparent glass	-
Aluminium_65	Opaque metal	0.65; 0.65; 0.65
CIGS_PV	Opaque plastic	0.1; 0.1; 0.1

Table 2 Input parameters of the multi-objective optimization algorithm

Inputs for the optimisation	Range of values	Unit
Angle of louvre blades	0; 15; 30; 45	Degrees from the horizon
Z coordinate of the centre point of each blade	[0.20; 2.20]	Meters
Material on the upper part of the louvre blade	CIGS or aluminium	Reflectance (see Table 1)

2.3. *Optimisation*

The optimization process was carried out using the genetic MOO algorithm implemented in Octopus. Genetic algorithms use principles similar to those found of evolutionary processes in Nature to find one or a set of good solutions to a problem according to given objectives. The problem must be modelled in a parametric manner where several variable inputs (see inputs in Table 2) are used to generate changes in the measured outputs of the model (i.e. E_{TOT}, cDA). The outputs are evaluated by the algorithm according to a fitness function that allows quantifying the performance of a set of solutions. The basic procedure a genetic algorithm follows is to start by building a random initial population of solutions and to assess the fitness of that population. Then, a loop starts where each iteration represents what is called a generation. The loop consists in selecting the best-fit individuals from the population to use for reproduction, then breeding new individuals followed by evaluating the fitness of the new offspring and finally, replacing part of the population with the fittest offspring. To ensure that the genetic algorithm is assessing a large enough space of solutions (possibilities) and can discover new alternatives, the breeding of new individuals is based on genetic operators such as crossover- and mutation rates, as well as crossover- and mutation probabilities. This loop could in theory run endlessly unless a defined end criterion is reached. Here it was set to be 20 generations with 100 individuals each. for the simulations with 10 and 13 louvres. Unfortunately, due to time constraints, the simulation for 16 and 19 louvres had to be stopped after 10 and 16 generations respectively.

The results of the simulation are visualized as a Pareto front where the configurations that offer the best trade-offs for the given objectives are outlined. For this study, two separate design options for an external fixed louvre blade PVSDs are investigated using MOO. The difference between the design options is that for the first case, all the louvres in the system are covered with PV material and for the second case, referred to as the hybrid PVSD case, the optimization algorithm is free to define which louvres are coated with the PV material and which are coated with a reflective material to increase the amount of light reflecting in the zone studied. Additionally, in both cases, the optimization algorithm can change the vertical distribution of the blades by moving them up or down within a 5cm range, as well as it can change the individual tilt angle of each louvre-blade. A summary of the parameters used in the optimization is given in Table 2. The two objectives set in the optimization are to minimize the total annual net electric energy use E_{TOT} [kWh/m^2] defined as the sum of the yearly electrical energy use for heating (E_H [kWh/m^2]), cooling (E_C [kWh/m^2]), and artificial lighting (E_L [kWh/m^2]) discounted for the energy converted by the PV cells (E_{PV} [kWh/m^2]), and to maximize the daylighting level in the zone measured as the continuous daylight autonomy (cDA [%]). The minimum threshold for the cDA calculation was set to 500lx on a working plane at 0.8m height from the floor. In order to assess the benefit of using multi-objective optimization, the results for each case are compared to a reference configuration (defined in [3]) and which corresponds to a setting where the louvres are homogenously distributed along the window, meaning they are equally spaced and tilted at 15° from the horizontal for cases with 10 and 13 louvres and 0° for cases with 16 and 19 louvres.

3. Results

In the rest of this work, two Pareto configurations were selected for each case and their performance analysed in more detail (Figure 1). For all 4 cases investigated, the results showed that, as expected, the hybrid PVSD system allowed increasing the daylighting level in the zone thanks to the reflective material, while the amount of energy converted was smaller due to there being a reduced PV surface.

For configurations with 10 louvres, the cDA was improved by a relative 6% for the hybrid cases comparatively to the reference, but the total net energy use E_{TOT} increased by 15% in the case of the Hyb. 1 and nearly 20% in the Hyb. 2. Comparatively, the optimized classic PVSD was able to improve the daylight by 3 and 2% respectively for configurations Cla.1 and Cla. 2; while E_{TOT} was also possible to improve by a relative 5 and 7% in comparison to the reference. With 13 louvres, the effect of the hybrid PVSDs on E_{TOT}, E_{PV} and the cDA were similar to those seen previously, but the reduction in electric energy demand for artificial lighting EL was more significant. In this case, the improvement in the cDA set against the reference was larger than for the case with 10 louvres and represented a relative 11% increase, outperforming the optimised classic configurations to a greater extent than in the first case. However, the total net electric energy use E_{TOT} was increased by 12 and 16% respectively for the hybrid PVSD Pareto configurations 1 and 2. On the other hand, the classic PVSD systems were able to reduce E_{TOT} by 5 and 3% respectively.

For the cases with 16 and 19 louvres, the hybrid PVSDs provide slightly higher levels of cDA with a 2% improvement for both 16 and 19 louvres in comparison to the references, which were previously suspected of being near Pareto configurations [3] and left little room for improvement. In terms of E_{TOT}, the two hybrid configurations with 16 louvres reduced energy use by approximately 5 and 3% compared to the reference case, a noticeable change in the trends previously described for 10 and 13 louvres. The classic PVSD systems were, on the other hand, able to reduce E_{TOT} by more than a relative 7% but not without reducing the cDA by over 4% in the worst case. With 19 louvres, the two hybrid PVSD configurations were not only able to improve the cDA as mentioned earlier but also performed noticeably better than the classic PVSDs which had reduced cDAs between 7 and 11% set against the reference. E_{TOT} for the hybrid PVSDs increased at the most by 7% relatively, a smaller increase than for 10 or 13 louvres, but also an indication that the case with 16 louvres is the most interesting for the use of a hybrid system.

4. Discussion

4.1. Potential of using hybrid PV integrated systems

Globally for the cases with 10 and 13 louvres, the results showed that having a hybrid system allowed to improve the daylight, lower energy use for artificial lighting and slightly reduce the heating load, but that the combined energy savings from these parameters was not enough to make up for the reduction in energy converted by the PVSD. For these cases, the surface of the blades was still more valuable from an energy point of view as an energy converting area than as a light redirecting one, and these systems provided an all-around better performance for the case study chosen. Hybrid systems, on the other hand, showed to be an interesting option when there are larger numbers of louvres in the PVSD and daylighting levels are reduced. For example, hybrid configurations using 16 louvres allowed improving both objectives, something the classic cases could not achieve. This behavior was however seemingly non-linear, as the case with 19 louvres could not provide the same benefits. This leads to the idea that there is a possibility that other cases with louvre counts close to 16 which could provide similar or even better results.

In this study, the evaluation of the different PVSD configurations and the possibility to use hybrid systems is evaluated based on two criteria: E_{TOT} and the cDA. Progress in PV material technology documented in the literature also indicate that even if cost and life cycle parameters were considered, classic PVSDs would still be preferable due to their short payback time and carbon balance. However, despite having lower E_{TOT} values, classic systems also create a more intensive demand for the grid as the timing of the energy converted may not match the demand and vice versa. Thus, if the building was required to have a high rate of self-consumption or if one considered grid tariffs, the trade-offs of using a classic system versus a hybrid one could become more complex.

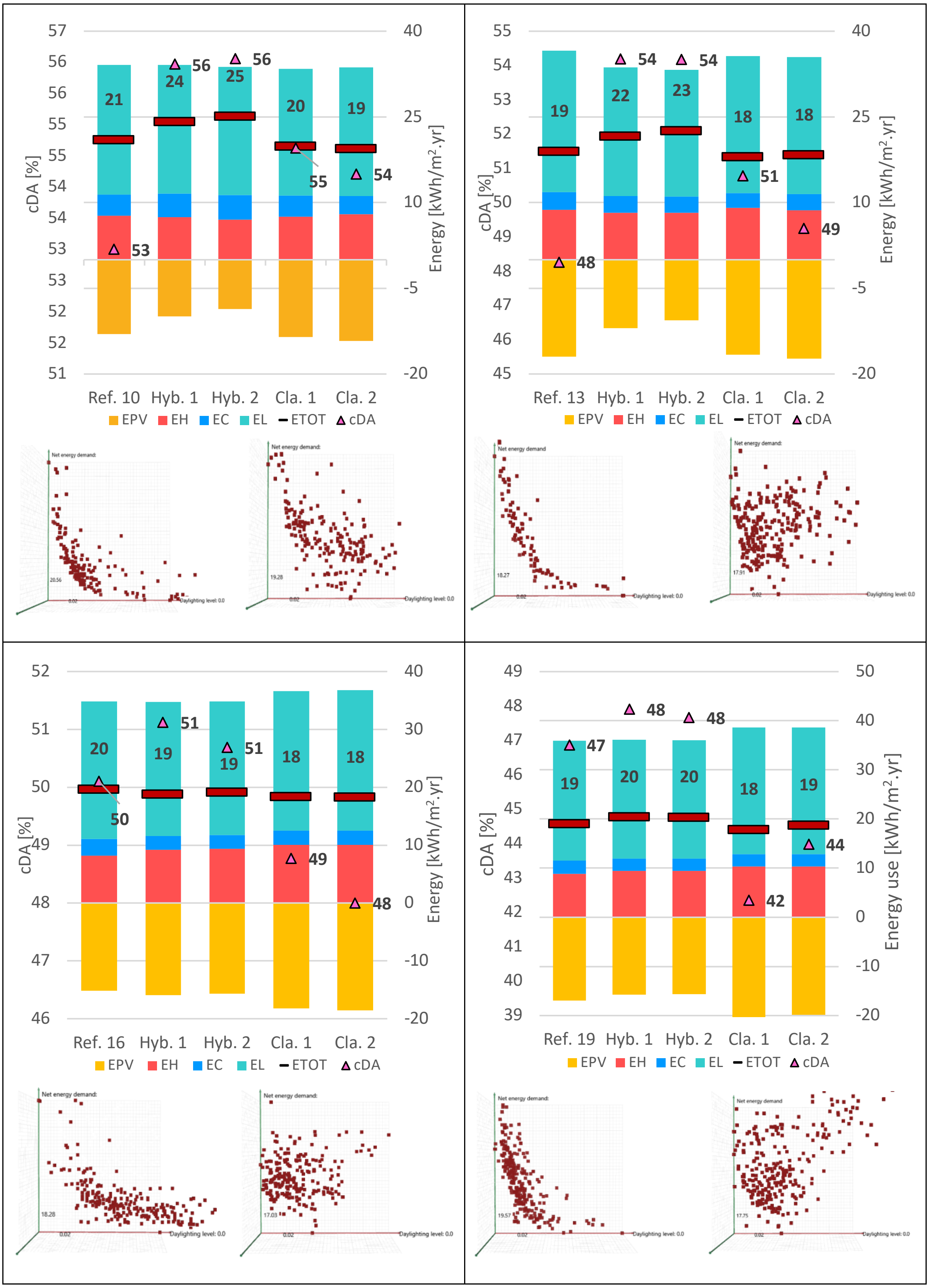

Figure 1 Results of the optimisation for from left to right, top to bottom: 10 louvres, 13 louvres, 16 louvres and 19 louvres in hybrid (Hyb.) and classic (Cla.) PVSD. Pareto and elite points: left Hyb. results, right Cla. results.

4.2. Limitations

One of the limitations of this work relates to how Honeybee considers shading from context elements. The PVSD system modelled in this work is a non-conventional shading system modelled using the HB_ContextSurface component. This component attributes a default reflectance of 0.2, regardless of the radiance settings. This means that the real reflectance of the object is only considered in the daylighting calculations and not for the thermal simulations. However, since the simulation of the hybrid system yielded Pareto points despite this, it appears this limitation may not have had a large effect on the simulation. The second limitation of the study is connected to the number of generations in the optimization, which is a trade-off between computational time and accuracy and the solutions yielded may not be real Pareto points.

5. Conclusion

The results of the study show that for external louvre blade hybrid PVSD configurations, with different types of material on the upper surface of the blades, are more advantageous when there is a higher density of louvres in the window. This finding can be understood intuitively as larger numbers of blades create larger masks for daylight and a higher risk for self-shading in the system, meaning that the output of the PV per m^2 is reduced. For the case study chosen in this work, systems with fewer louvres were a better option as they provided more daylight and required no more energy use than systems with larger amounts of louvres. However, hybrid systems could still prove to be interesting, e.g. in climates where cooling loads are greater and solar gains must be reduced while still maintaining satisfactory daylighting levels.

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References

[1] K. Konis, A. Gamas, K. Kensek, Passive performance and building form: An optimization framework for early-stage design support, Sol. Energy. 125 (2016) 161–179. doi:10.1016/j.solener.2015.12.020.
[2] S. Attia, E. Gratia, A. De Herde, J.L.M. Hensen, Simulation-based decision support tool for early stages of zero-energy building design, Energy Build. 49 (2012) 2–15. doi:10.1016/j.enbuild.2012.01.028.
[3] E. Taveres-cachat, G. Lobaccaro, F. Goia, G. Chaudhary, A methodology to improve the performance of PV integrated shading devices using multi-objective optimization, Appl. Energy. 247 (2019) 731–744. doi:10.1016/j.apenergy.2019.04.033.
[4] D. Rutten, Grasshopper - Algorithmic modeling for Rhino version 0.9.0076, (2017). http://www.grasshopper3d.com/ (accessed October 9, 2017).
[5] Ladybug tools, (n.d.). https://www.ladybug.tools/ (accessed May 30, 2018).
[6] R. Vier, Octopus, (n.d.). http://www.grasshopper3d.com/group/octopus (accessed October 9, 2017).
[7] R. Judkoff, J. Neymark, International Energy Agency building energy simulation test (BESTEST) and diagnostic method, Natl. Renew. Energy Lab. (1995) Size: 296 pages.