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A methodology to improve the performance of PV integrated shading devices using multi-objective optimization

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HIGHLIGHTS

- A parametric design methodology for PV shading devices (PVSD) is presented.
- Multi-objective optimization is used to balance competing uses of solar energy through the PVSD.
- Total solar energy exploitation can be enhanced through an optimized PVSD system.

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ABSTRACT

Solar energy can be exploited efficiently in building façades using building integrated photovoltaics (BIPV). This study presents a methodology to optimize the design of fixed, parametrically modelled PV integrated shading devices (PVSDs) based on multi-objective optimization (MOO) coupled with integrated thermal, electric, and lighting simulations. The goal of this work is to gain insight into the potential benefits of using optimization algorithms for PVSD design. This task is carried out by evaluating the extent to which competing solar energy uses can be balanced with regard to thermal, visual and electrical parameters; and investigating whether existing simulation tools successfully characterize the complexity associated with PVSDs.

The methodology developed is used to design and assess the performance of different optimized configurations of a fixed exterior louvre PVSD installed on the southern face of an office building in a Nordic climate. The parameters used for the optimization were the number of louvre-blades as well as their individual tilt angle and position along the vertical axis. This allowed the introduction of a higher degree of eclecticism through the optimization process compared to standard shading systems. The three objectives of the optimization were the total net energy demand, the energy converted by the PV material, and the daylighting level in the zone measured as the continuous daylight autonomy. The results highlighted that configurations with smaller louvres counts were preferable for the specific case study and that optimization increased the performance of the PVSD compared to a reference case. The results of the study also demonstrated that the application of the proposed methodology was able to improve the exploitation of solar energy through a multi-domain façade, and thereby that advanced simulation tools, in this case, allowed overcoming the limitations of more standardized façade configurations. Based on these findings, it is assumed that methodologies like the one developed in this article can be a starting point to stimulate successful discussion and foster fruitful collaboration between researchers, stakeholders, and façade manufacturers, resulting in the development of innovative technological solar integrated façade solutions.

1. Introduction

1.1. Context of the research activity

The European Union has pledged to cut CO_2 emissions associated with energy use in buildings by one fifth by 2020, a decision which has resulted in a set of policies to make all new buildings nearly net-zero energy and improve the performance of the existing building stock. In this push for a less carbon-intensive built environment, building integrated photovoltaics (BIPV) and building integrated photovoltaic/thermal (BIPVT) systems have emerged as one of the most relevant technological solutions to mitigate CO_2 emissions and support the use

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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

of renewable energy conversion in new and existing buildings [1–4]. In fact, the demand for photovoltaics (PV) conversion technologies is expected to grow in the coming years given that electricity consumption is globally surging [5], and in the EU 27 alone, BIPV systems are projected to provide over 20% of the energy needs by 2030 [6].

The first BIPV solutions emerged in the 1980s, but at the time, high costs and complex technical applications obstructed their market uptake [7]. It wasn't until the 1990s when increased monetary and research investments to support BIPV as a key application were made [8–10], that a renewed interest in the technology spurred rapid growth in the solar industry. Nowadays, the rising popularity of BIPV application can be attributed to their suitability for newly developed zero-energy and zero-carbon building design [11,12], as well as their ability to help reach benchmarks defined by building energy labels. Despite the progress made from a technology point of view, implementing BIPV/BIPVT in shading systems still remains non-trivial from a technical standpoint and often requires balancing different uses of solar energy (i.e. passive solar heating vs. solar gain leading to cooling load, daylighting vs. PV-conversion). There is, therefore, a need to establish robust methodologies to support the design and development of new BIPVT systems with optimized behaviors and increased cost efficiency.

1.2. Balancing competing roles of solar energy through building integrated PV

Building integrated photovoltaic and thermal applications such as Photovoltaic Shading Devices (PVSDs) combine the benefits of shading systems with renewable solar energy harvesting strategies since the light that is refrained from entering the space is converted to electricity (Fig. 1). These advanced fenestrations components make up a complex boundary between the outside- and the inside space of a building, the dynamics of which strongly affect the visual and thermal quality of the indoor environment and the energy converted by the system. For this reason, implementing PVSDs requires additional design considerations in order to find the correct balance between the competing roles of solar energy. For example, the transmission of large amounts of solar radiation through glazed elements has both benefits and drawbacks. Good daylighting increases productivity in workspaces by improving visual comfort [13] and solar gains contribute to lowering energy use for space heating and electric lighting. However, too much direct solar radiation can also lead to overheating and glare issues for the user [14–16]. But if too much solar radiation is blocked out, despite the fact that the photovoltaic material will convert more energy, the heating and artificial lighting demand will increase as a result and negate some of the original benefits. Therefore, modulating sunlight using PVSDs is a complex, yet essential measure to keep thermal and visual conditions pleasant, and is reported to be particularly useful in perimeter spaces of office buildings where direct sunlight is undesirable [17].

Existing studies have evaluated the potential of PVSDs and highlighted that when the systems are well-designed, they may be more advantageous than both traditional shading devices and unshaded windows in terms of energy use [18–21]. Optimal use of PVSDs has also shown to prevent overheating in summers while allowing the penetration of maximum daylight during winter, which translates into ideal high-quality indoor environments [22,23]. Previous research efforts aiming to find optimal balances of solar energy through PV integrated [24] and non-PV integrated shading devices have focused on specific topics such as visual comfort [14,25], energy use for space conditioning [26], artificial lighting loads [27], and energy conversion [28]. The findings have led to the consensus that the "optimal" shading system depends on a large number of variables related to the building's features (e.g. building category, efficiency of the building systems, efficiency of the building envelope, etc.) [29]; to its location (i.e. weather, solar angles, orientation, etc.) [30,31]; to the type of shading device [20]; and to the configuration of the shading device itself (i.e. size of blinds, blind angle control strategy, etc.) [32–36]. The complexity associated with designing optimal PVSDs and the large number of input parameters required to ensure high performance, are thus too numerous to use any kind of simplistic approach or "rule of thumb". Instead, a promising approach to PVSD design is to use advanced building simulation tools coupled with input-flexible methodologies to design systems with optimal performance.

1.3. Using advanced simulation tools with multi-objective optimization (MOO)

Accurate simulation of shading devices requires integrated energy simulation tools that can efficiently couple the thermal and optical domains of the models [37,38]. When some of the parameters in the models are variable, these simulation tools can be coupled with optimization approaches based on single- or multi-objective optimization

Fig. 1. A PVSD product from SOLARLAB at the BIPV demo site of the Danish Technological Institute in Høje-Taastrup (Denmark).

(MOO) [39–41], which is particularly useful to balance competing design parameters in high-performance buildings (e.g. low energy buildings) [42]. Of these two methods, single objective optimization is more frequently used because of its simplicity, but most real-life design challenges involve several design criteria or antagonistic goals which makes MOO a more valuable approach to managing tradeoffs [43,44].

Conventional louvre blade shading system geometries (i.e. symmetrically built, homogenous tilt angles) are not usually originally fully optimized to balance uses of solar energy and instead offer a "one size fits all" solution. This makes MOO a potentially interesting method to explore the extent to which PVSD performance could be improved by changing some of the parameters of the system such as the shape, orientation, or inclination angle of the louvres (e.g. [39,45–47]); while at the same time limit performance degradation due to environmental causes such as self-shading [48,49]. The advantage of using an optimization algorithm versus, for example, conducting a parametric analysis, is that it allows investigating a larger space of solutions.

1.4. Aims and innovative aspects of the paper

This study aims at developing a design methodology based on MOO with a twofold goal: first, to evaluate the extent to which several it is possible to balance competing uses of solar energy in PVSDs; second, to investigate whether existing simulation tools coupled with MOO are able to address the complexity associated with designing and modelling systems for optimal use of solar energy.

The methodology developed is novel in that it introduces the possibility to design PVSDs and by extension BIPV systems by exploring a larger space of design solutions with a bottom-up approach where the environmental context and the goal of the system define its geometry. This process leads to out-of-the box solutions to complex design problems that require meeting multiple challenges simultaneously (i.e. balance competing uses of solar energy, responding to facade control strategies, energy performance targets, material emission thresholds, etc.). The focus of the study will then not be on the specific final solutions yielded by the optimization, but the process itself as a mean of improving design methods and gaining insight on possibilities for balancing solar parameters. In the larger scheme of things, the ambition of the proposed approach is to have enough impact to create a starting point for stimulating successful discussion and fostering fruitful collaboration between researchers, stakeholders, and façade manufacturers, resulting in the development of innovative, technological solar integrated façade solutions.

This remainder of this work is organized as follows: Section 2 presents the proposed design methodology developed to generate and assess optimal configurations, including the overall research strategy, the case study used to demonstrate the methodology, and the assumptions made for the different parameters. This section also provides a detailed overview of the process of the optimization and the different simulation and modelling tools used, in addition to presenting the method used to determine the reference cases used in the analysis. The results and discussion of the application of the methodology to the case study are presented in Section 3 and a critical assessment of the study is presented in Section 4. Finally, Section 5 summarizes the conclusions and implications of this study for future work.

2. Methods and materials

2.1. Overall research strategy

This work is part of a wider research initiative about PVSD applications lead by the authors. The initial study available in Ref. [50] focused on design solutions defined by a simple preliminary parametric analysis of a similar PVSD's impact on the heating and cooling demand of a building. The methodology presented in this paper is a step up from the existing work in that it uses MOO and a fully parametric PVSD model to evaluate both daylighting and energy-related parameters while being flexible enough to accommodate any shading device design for commercial or residential projects.

The overall research goal is to develop a methodology that aspires to overcome the difficulty of balancing solar energy in building envelopes, and in particular for PVSDs, as discussed in Section 1.2. The idea is to break away from the limitations of the more traditional designs with symmetrical features, and attempt to balance competing uses for solar energy in PVSDs by letting the system adopt any of the resulting configurations created from the combination of parametrically defined geometrical inputs.

2.2. Description of the case study

The reference building and the blades system were modelled in the *Rhinoceros* environment [51] using *Grasshopper* [52], a visual programming language for parametric modelling; while *Ladybug* [53], 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* [53] which use the *EnergyPlus* engine [54]. EnergyPlus is a whole building energy simulation program based on the best features and capabilities of BLAST and DOE-2.1, developed under the auspices of the US Department of Energy and is widely used both in research and industry.

The geometry of the reference building is given by the Bestest Case 600, which is a 48 m^2 rectangular room (6 m × 8 m × 2.7 m) with two large south facing windows (3 m × 2 m). The PVSD system is based on the design of an existing non-PV integrated shading system with 105 mm wide louvres that can be tilted between 0 and 45° in 15° increments. In the model, both windows are equipped with the PVSD system, with a center blade to windowpane distance of 16 cm. All of 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 simulations for this study were run over the period of one year with climate data for the location of Oslo, Norway (*EnergyPlus* weather file (.epw), Typical Meteorological Year – TMY). Table 1 shows the mean monthly dry bulb temperatures, heating degree days for a set point temperature of 21 °C, and the average monthly global solar radiation for the selected location.

The internal loads and schedules were set according to the Norwegian Standards NS 3031:2016 and NS3701:2012 using the standardized values for the office-building category. A proportional response artificial lighting control strategy was also implemented to ensure a minimum illuminance level of 500 lx on the work plane at a height of 80 cm above ground. The properties of the building envelope and the technical systems are listed in Table 2.

Table 1
Average monthly weather data extracted from the .epw file for Oslo, Norway.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average dry bulb temperature	−3.8	−0.9	0.9	4.6	11.9	14.7	17.5	16.5	11.1	6.7	1.8	−1.6
Average monthly global radiation (W/m^2)	12	31	77	77	202	207	208	155	92	46	15	6
Heating degree days	676	594	530	416	194	112	44	59	216	351	498	608

Table 2
Thermal properties of the building model and building equipment.

Component	Value	Unit	Note
U-value external wall	0.18	$W/(m^2 K)$	Under the maximum value from NS3031
U-value roof	0.10	$W/(m^2 K)$	Slightly above the recommended value from NS3701
U-value external floor	0.10	$W/(m^2 K)$	Slightly above the recommended value from NS3701
U-value window (3 panes)	0.8	$W/(m^2 K)$	Maximum value according to NS3701
g Value	0.54	–	N/A
Air tightness	0.6	h − 1	Maximum value according to NS3701
HVAC system	Ideal air load	–	Honeybee setting with no air economizer
Internal load lighting	9.6	W/m^2	During occupation hours, dimming function to maintain 500 lx on work plane at 0.8 m from floor
Maximum Internal load occupants	382	W	Variable according to schedules defined in NS3031
Maximum internal load equipment	21	W/m^2	Variable according to schedules defined in NS3031
COP heating system	3	–	Heat pump
COP cooling system	5	–	Heat pump
Set points (heating-cooling)	21–26	°C	Set back to 19° for heating outside occupation hours
Occupation hours	7–18	–	Weekdays

Custom *Radiance* materials were defined in a Radiance library for Honeybee to take into account the optical properties of the room's surfaces and characteristics of the shading system (Table 3). The values were set to be conservative and in compliance with the recommendations from the Illuminating Engineering Society found in standard IES-LM-83. The window used in the simulation is a triple pane window with a low-E coating (total U-value = 0.8 $W/m^2 K$), with a 16 mm gap and 90% Argon gas. The light-transmission was defined as 60% (65% transmissivity) and the reflectance as 21%, following calculation from NS-EN 410:2011. A moderate assumption of 65% solar reflection was made for the frame of the shading device and for all the non-PV-coated surfaces of the louvre blades. The PV material used, CIGS (copper indium gallium selenide), was assumed to have a reflection of 10%.

2.3. Description of the numerical model's objectives and settings

The proposed methodology was built around integrated whole building energy (*EnergyPlus* based plug-ins *Honeybee* [53]), and daylight simulations (Ladybug is Radiance based). Fig. 2 provides an overview of the complexity of the workflow developed and the three main sections of the model script: Part I) Inputs parameters, climatic reference, occupancy schedules, energy loads, geometry data of the buildings and louvres, Part II) Performance simulation in which energy and daylight simulations are conducted, and Part III) Optimization process using MOO.

In this study, the input parameters that the optimization algorithm can modify are the individual tilt angle and the vertical distribution of the louvre-blades (Table 4). The way the model is scripted, the blades can freely distribute along the vertical axis z with the only constraint being that the interspace between the blades must be of at least 5 cm to avoid the geometry of the blades overlapping. Naturally, as the number of louvre blades increases, this constraint reduces the number of possible configurations by diminishing the interval of possible z coordinate values each blade can adopt.

The three objectives set in the optimization were to minimize the total annual net energy electricity use (E_{TOT} [kWh/m^2 year), maximize the amount of energy converted into electricity by the PV cells (E_{PV} [kWh/m^2 year), and maximize the daylighting level in the zone measured as the continuous daylight autonomy (cDA [%]). The annual total net energy use (E_{TOT} [kWh/m^2 year]) is the sum of the electrical energy use for heating (E_H [kWh/m^2] year), cooling (E_C [kWh/m^{2}year]), and artificial lighting (E_L [kWh/m^2]) discounted for the energy converted by the PV cells (E_{PV} [kWh/m^{2}year]). The PV output was chosen as an objective despite its influence being partially accounted for in the calculation of the net energy demand. This choice was motivated by the wish to support maximizing the return on investment associated with using PV material and because of the high environmental footprint of PV material [55,56]. To account for self-shading of the PVSD from blade to blade, the energy converted by the PV material is determined using a detailed radiation analysis of the light impinging on each blade. Solar radiation is converted to electricity assuming that 95% of the blades area is covered with PV material, and 95% of this defined area is a photovoltaic cell. The PV conversion rate is set to 15% accounting for all the system losses. The metric used for daylight, the continuous daylight autonomy (or cDA) calculates the number of working hours a year a specific surface in a room receives an amount of light over a given threshold [14]. Hours with illuminance values above the set limit receive full percentage points, while hours with daylighting levels below the threshold are awarded a proportional fraction of a percentage point. The cDA was chosen as the daylight measuring metric as opposed to the daylight autonomy because of its suitability for office buildings with regard to larger ranges of user-preferred illuminances, and the possibility for a softer transition between compliance and non-compliance situations [57].

For this case study, the threshold was set to a minimum of 500 lx received on a work plane modelled as a point located 0.8 m above the floor level and 2 m inwards on the center line one of the windows. The settings used for the *Radiance* daylighting analysis are given in Table 5. The main contributor to simulation time (apart from complex geometry) is the number of ambient bounces (ab) which is a numerical parameter representing the maximum number of diffuse bounces a ray of light will go through before being considered fully dissipated.

The value of the ab parameters for the daylighting analysis was selected after conducting a sensitivity analysis of its impact on the cDA and simulation runtime. The results of this analysis (Table 6) demonstrated that the differences in the calculated cDA were marginal (at most 2% of the value) when the number of ambient bounces varied from 3 to 6 bounces and the quality was kept constant. The additional computational time required for the daylight analysis, on the other hand, was significant and judged unacceptable for a preliminary analysis when the quality setting was set to a higher value. Given the scope of this methodology, it was deemed acceptable to use a slightly simplified and conservative daylighting calculation with a number of ambient bounces set to 3 and the "low quality" *Radiance* setting in *Grasshopper* to reduce computational time. Note that for this study

Table 3
Optical properties of the surfaces used in the case study.

Material name	Material type	RGB reflectance	Transmissivity
Generic Ceiling_70	Plastic, opaque	0.7, 0.7, 0.7	–
Generic Floor_20	Plastic, opaque	0.2, 0.2, 0.2	–
Generic IntWall_50	Plastic, opaque	0.5, 0.5, 0.5	–
Generic Furniture_50	Plastic, opaque	0.5, 0.5, 0.5	–
Triple Pane Argon90	Glass, transparent	–	0.65, 0.65, 0.65
Aluminium_65	Opaque	0.65, 0.65,0.65	–
CIGS_10	Opaque	0.1, 0.1, 0.1	–

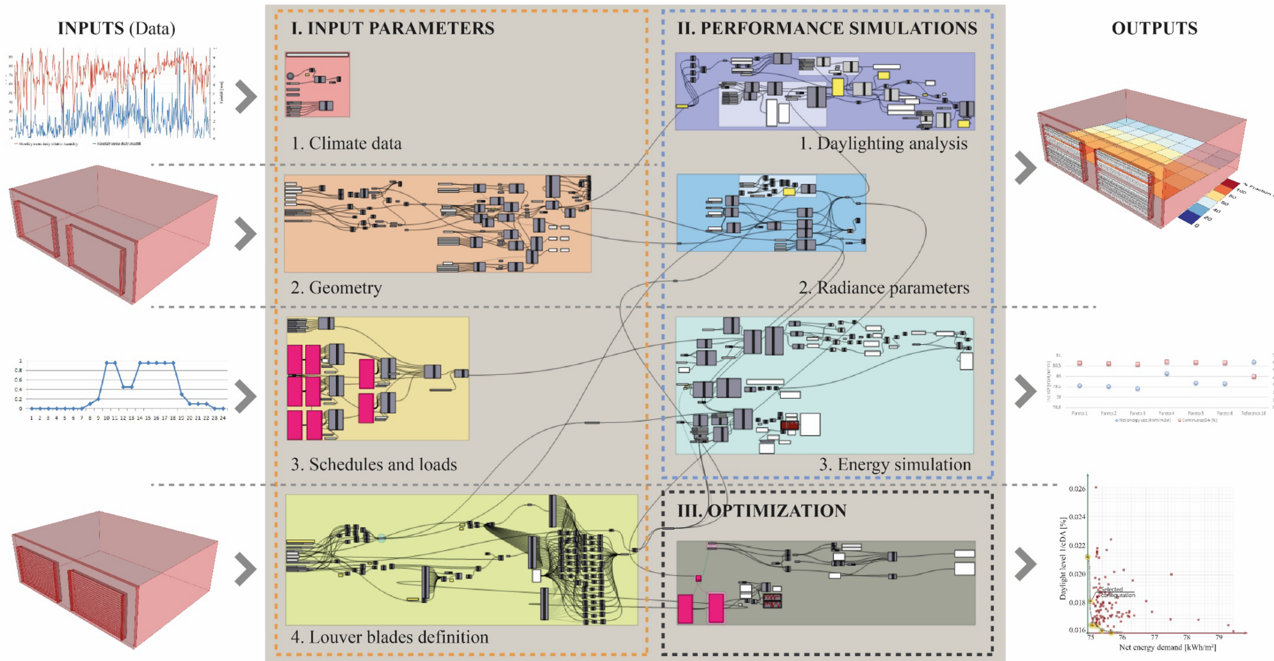


Fig. 2. Visualization of the workflow developed in the Grasshopper environment.

relied on a workstation with 11 CPU allocated to the daylight simulation. The computer used has 24 GB RAM and a 3.46 GHz processor. On average, each complete run of optimization as described in the next section took 10 days to run with the listed settings.

2.4. Description of the optimization process

The optimization process was carried out using the genetic MOO algorithm Octopus and the logic flow given in Fig. 3. Genetic algorithms use principles similar to those displayed in evolutionary processes in Nature to find one or a set of good solutions to a problem according to given objectives. In order to do that, the problem must be modelled in a parametric manner where a number of variable inputs (i.e. in this work the tilt angles of the louvre blades and their disposition along the z-axis) are used to generate changes in the measured outputs of the model (i.e. E_{TOT}, E_{PV}, 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 is able to discover new alternatives, the breeding of new individuals is based on *genetic operators* such as crossover- and mutation rates, as well as a crossover- and mutation *probability*. This loop could in theory run endlessly unless a defined end criterion is reached. For this study, the end criterion was chosen to be 18 generations with 100 individuals each. More information about genetic algorithms can be found in Refs. [58,59].

The number of solutions generated is chosen as a compromise between computational time and having a meaningful number of cases for the algorithm to be able to find Pareto-optimal solutions. These solutions form what is called the Pareto front when plotted- which in our case is a 3-dimensional plot. All the points on the Pareto front represent non-dominated solutions meaning that they embody the best compromise (tradeoff) of performance with regard to competing objectives. All the other points generated in the optimization process are called dominated solutions as there is always at least one other solution that outperforms them.

Table 5
Radiance setting for the daylighting simulation.

Ambient bounces	Ambient divisions	Ambient sampling	Ambient accuracy	Ambient resolution
3	1000	100	0.1	300

Table 6
Sensitivity analysis of the number of ambient bounces and quality setting for the Radiance daylighting analysis for a set configuration with 16 louvre blades.

Number of ambient bounces	Low-quality setting cDA [%]	Medium quality setting cDA [%]
3	50	50
4	51	52
5	51	53
6	51	53

Table 4
Description of the parameters for the optimization process.

Variable	Range of values	Unit
Angle of louvre blades	0; 15; 30; 45	Degrees from a horizontal plane
Z coordinate of the center point of each individual blade	[0.20; 1.20]	Meters

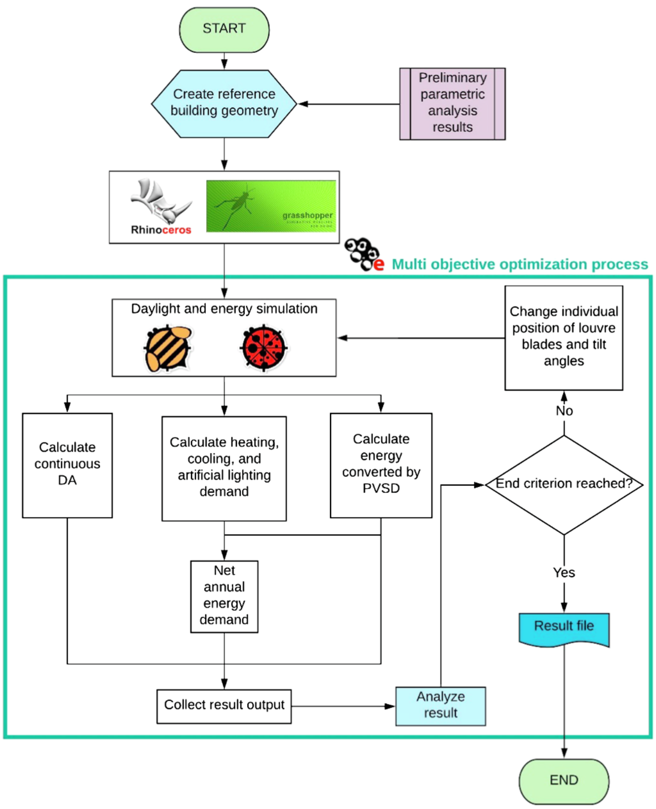


Fig. 3. Flowchart summary of the design methodology.

2.5. Reference cases for MOO performance verification

While MOO is a tool often used to evaluate how different parameters can be tuned to improve the overall performance of a system, the results of the optimization must be put in context using a reference configuration in order to be able to quantify the improvement the optimization brings about. For this study, the preliminary groundwork was done using a parametric analysis which allowed characterizing the performance of more standard PVSD configurations (i.e. with equally spaced- and homogenously tilted blades). The study was done in the same software environments with the same assumptions as described previously, only without the optimization process.

3. Results and discussion

3.1. Selection of reference cases

The results from the parametric analysis are presented below in Fig. 4. The procedure followed for this preliminary analysis resembles the logic described for the MOO study, but the system is constrained to having homogenously tilted louvre-blades with even spacing. This means that the number of configurations is limited by the possible tilt angles of the blades and the number of case studies investigated. For this study, four cases with four tilt angles and one configuration with no shading system present were investigated, which resulted in 17 configurations in total. The goal of this procedure was to obtain a picture of the performance of possible reference cases that could serve as a point of comparison for the results of the optimization.

The results of the preliminary parametric analysis (Fig. 4) were in line with the anticipated effect of the shading system: the cooling load was reduced significantly (up to 60%) while the heating and artificial lighting loads increased compared to a case with an unshaded window. Interestingly, even as a non-optimized design, implementing the PVSD system reduced the total net energy use by 1/3 thanks to the conversion of solar energy. The results also outlined a trend in some cases where increasing tilt angles provided smaller solar gains, which as mentioned previously reduced the cooling demand in the zone, but only up until a certain point where the artificial lighting demand became so large as a result of the loss of daylight, that it created excess heat and required

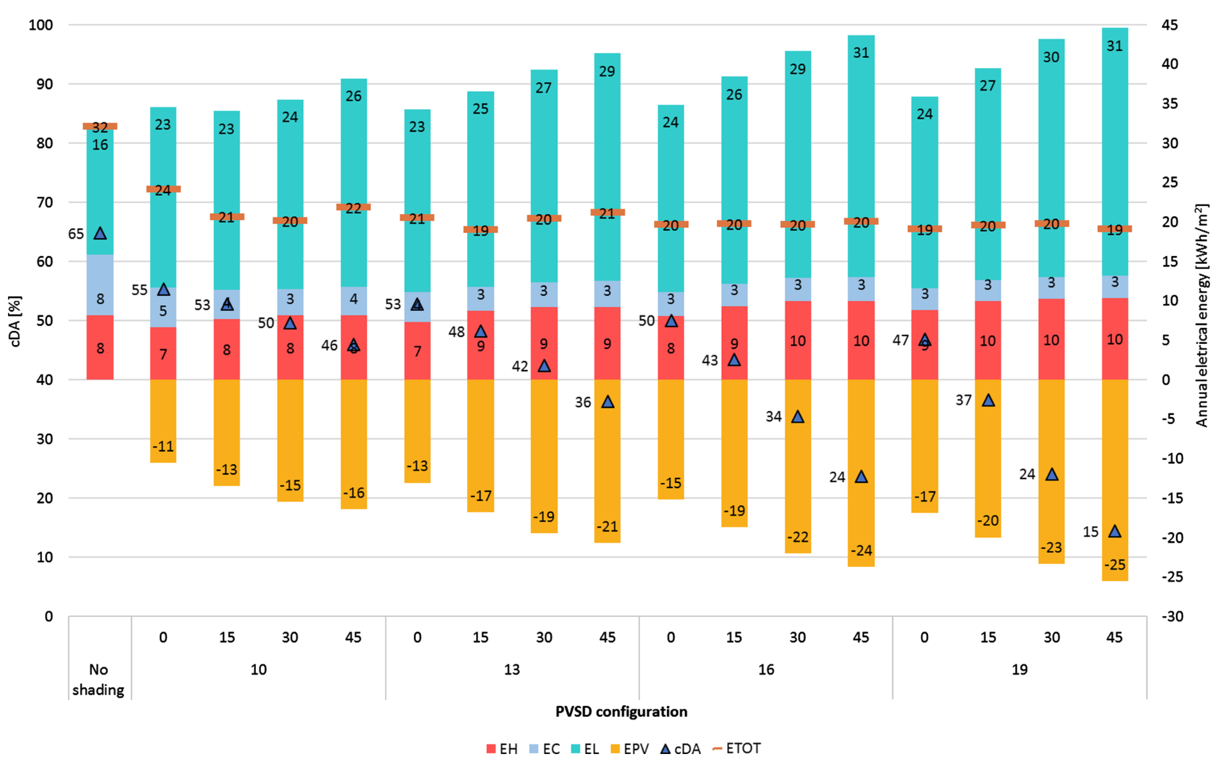


Fig. 4. Results of the preliminary parametric analysis of the PVSD. The best performing configuration for each case is selected and later used as a benchmark to evaluate the performance of the optimization results.

additional cooling. The existence of this trend highlights what appears to be a "sweet spot" in which the parameters were balanced in a way that the total net energy use was minimized before it increased again. This finding supported the idea that optimization could be useful to exploit this "sweet spot" further.

Based on the results of the parametric analysis, it was chosen to use a reference configuration with a tilt angle of 15° for the configurations with 10 and 13 louvre blades, and 0° for configurations with 16 and 19 louvres. For 10 and 13 louvres, this choice is based on the fact that an angle of 15° provides more energy conversion than a 0° tilt angle, smaller values of net energy use and only reduces daylighting levels by a small amount. For the cases with 16 and 19 louvres, a 0° tilt angle provides significantly more daylight and a very similar value for the net energy use as a 15° tilt angle despite the PV conversion being less meaningful.

3.2. Results of the multi-objective optimization

3.2.1. Global results of the optimization

The 2D Pareto fronts for each combination of 2 objectives are shown in Figs. 5–7. While the Pareto front was clearly defined for the tradeoff between the cDA value and the PV conversion (Fig. 5) and for the cDA vs net energy use (Fig. 6), there is no clear relationship for the tradeoffs between energy use and PV conversion (Fig. 7). This finding supported the idea that the optimization problem is non-trivial and the relationship between the objectives is complex. An important observation from these plots is that for each case study (10, 13, 16 and 19 louvres) there are Pareto points from the optimizations that performed better than the references with regard to at least two objectives simultaneously. This indicates that the optimization was consistently able to improve the performance of the systems and validates the assumption behind the study, which is that optimization can be used to improve the design of PVSDs. However, it is also worth noting that some of the results from the parametric analysis, and thus the references used, are very close to the Pareto points meaning that there is little room for improvement especially with regard to daylight levels. The implications of this observation are discussed later in this section.

For the rest of this section, the references from Section 3.1 were used as a benchmark to evaluate the performance of five selected Pareto points for each case study. The Pareto points used from here on in the analysis were picked as according to two criteria: (i) solutions that best balanced the cDA value and the net energy use (ii) solutions within that first selection with highest energy conversion including solutions that improved all three objectives when they existed.

3.2.2. Case specific results

In this section, 5 Pareto points in each case study were chosen to be investigated more in depth and selected on the basis of prioritizing the cDA and the net energy use. This choice followed the reasoning that these parameters represent direct costs and user comfort variables, whereas the PV conversion is seen as secondary in addition to being partially accounted for in the net energy use. Fig. 8 shows the performance in terms of daylight availability and energy use for the five Pareto points from each case study along with the reference used for comparison. From this graph, one can identify early on the range of the effect the optimization had on different cases. For example, for a case with 10 or 13 louvres, both daylight and total energy demand parameters were possible to improve. However, for a case with 16 or 19 louvres, only one of the two objectives was possible to improve with the given number of generations in the optimization. Note that in this section, all of the percentages described are relative changes in the value of the parameters.

The performance of each Pareto point was then analyzed in more detail to understand how the optimization changed the balance of the different parameters measured. These results are presented in Figs. 9–12. The analysis of the optimization for the 10 louvres case showed that the algorithm was able to create PVSD configurations that could outperform the reference case with regard to all three objectives simultaneously while maintaining cDA values above 50%. The cDA was, however, only possible to improve by 3% while E_{TOT} could be reduced by almost 6% and E_{PV} could be improved by up to 10%. This last finding is interesting given that this value was achieved for configurations that were not predominantly selected to perform well with regard to PV conversion alone, yet still provided a significant improvement compared to the reference. Overall, the cDA was the parameter with the least potential for improvement, this is likely because the values were relatively high and possibly close to the upper threshold of what can be achieved in a Nordic climate.

In the case of a PVSD with 13 louvres, the simultaneous improvement for all three objectives was also possible, but only for one of the Pareto points (Pareto point 5). The four other Pareto points are only able to improve two of the three objectives at a time. Because of the point selection being focused on daylighting levels and net energy use, the Pareto points shown in the analysis are solutions that mainly improved these objectives, and this was done at the expense of a reduced E_{PV} value compared to the reference. Despite the fact that only one solution could improve the performance on all fronts, the results show the optimization of the 13 louvres configuration provided the most potential for increasing the cDA compared to the reference configuration. Pareto point 1–4 all improved the cDA, with Pareto point 2 achieving a 7% increase in the cDA. In terms of E_{TOT}, the case with 13 louvres only showed moderate possibilities to reduce net energy use through the optimization, the maximum reduction being 3% in Pareto point 5. Other Pareto points, which were not selected for this analysis, showed cDA levels similar to the 13 louvres 0° tilt case but performed no better in comparison to the latter in terms of E_{TOT} despite showing increased E_{PV} values.

For the 16 louvres case, there were no optimized configurations that could improve all three parameters simultaneously and no configuration with a cDA above 50% and improved the reference case. This was assumed to be in part because the reference case used was already high performing in terms of the daylighting level in the zone. However, the performance of both the net energy use and the energy converted by the PV were possible to improve through the optimization. The optimization of the 16 louvres cases was the study that yielded the most potential for reducing the net energy use compared to the reference and the highest increase in PV conversion. Pareto points 1–3 all maintained a cDA at 49% while reducing energy use by up to nearly 7% and increased the amount of energy converted by PV by almost 20% for Pareto point 3. Pareto point 1 represented the solutions that showed the smallest relative loss in daylight (−1.8%) in comparison to the reference, while still reducing the net energy use by almost 3% and increasing the amount of energy converted by the PV by more than 14%.

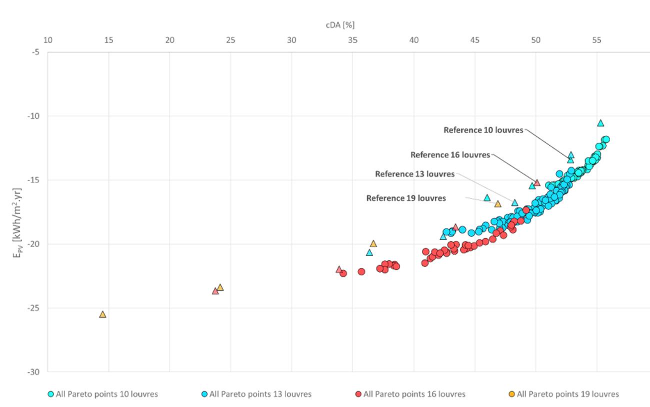


Fig. 5. Visualization of the Pareto points from the optimization study with regard to PV conversion and cDA.

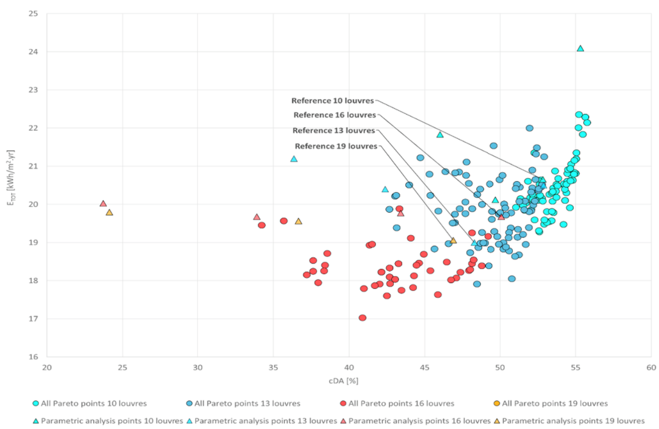


Fig. 6. Visualization of the Pareto points from the optimization study with regard to energy use and the cDA.

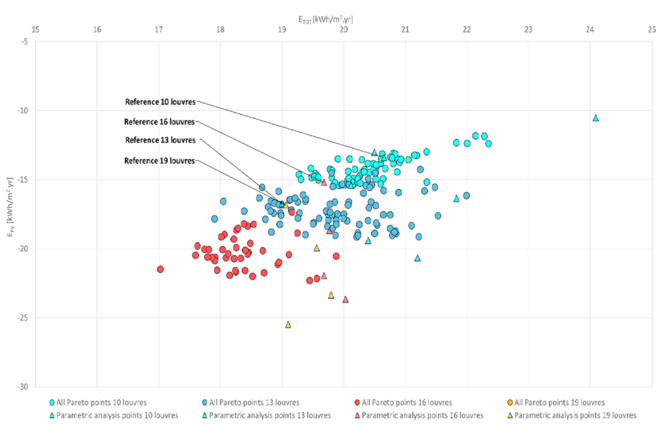


Fig. 7. Visualization of the Pareto points from the optimization study with regard to energy use and PV conversion.

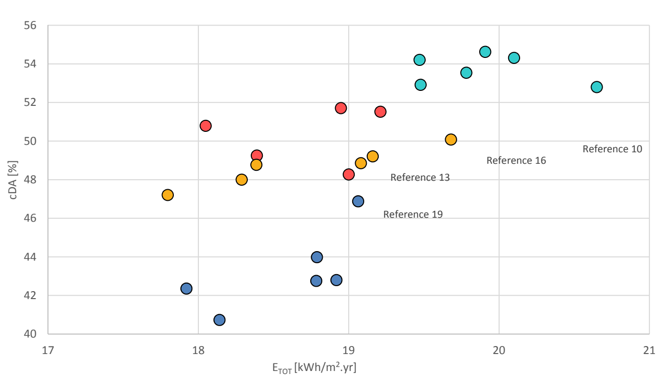


Fig. 8. Visualization of the performance of the selected Pareto points for each case study in terms of cDA and net energy use compared to the references determined in the parametric analysis.

Pareto points 4 and 5 provided the largest reductions in net energy use (7–10% relative reduction) which goes in hand with the fact that they also had the largest increase in PV conversion (relatively 22–23% more energy converted) but the lowest cDA values (48% and 47%). Finally, it is interesting to note that there was very little difference in the net energy use between 13 and 16 louvres, which seems to indicate that 13 louvres was a better option as since it provided better cDA with fewer louvres and the same E_{TOT}.

For the case with 19 louvres, it was not possible to improve the cDA through optimization compared to the reference with a 0° tilt angle, and the smallest loss in cDA (6%) was found for Pareto point 5. The variation in E_{TOT} was limited with at most a 6% reduction in net energy use (Pareto point 1). Naturally, the E_{PV} was the parameter, which had the highest potential for improvement and could be increased up to 23% for Pareto point 1. These results were in line with what could be expected of a system with a high number of louvres blades when compared to a reference that prioritized daylighting over energy conversion. A large number of blades provides a higher amount of area with PV material and thus, higher ratios of energy converted. However, the high density of the blades also reduced the daylighting levels drastically, especially when tilted as they obstruct the windows to a large extent. Furthermore, due to the non-overlapping condition, the range of movement of the blades was highly constrained and reduced the possibility to space out the blades even more in key sections of the window. Globally, the detailed energy profile shows that the use of energy was similar for all of the Pareto points, the main difference compared to the reference case being an increased E_L compensated for with a higher E_{PV}.

For all of the Pareto configurations, the analysis of the cDA grid showed that daylighting levels were very similar to the reference cases, with only slight improvements for all of the cases, especially towards the back of the room (Figs. 13–16). In terms of the distribution of the louvre blades, the optimized configurations showed a common trend where the louvres were more spaced in the upper half of the window than in the lower half. The blade angles also tended to gradually increase towards 45° in the lower half of the window, and in particular for the louvres below the plan of the daylighting grid (located 80 cm above the floor level). This maximized conversion in the area where the louvres had the least impact on daylight penetration. On the other hand, as can be seen by the different sun angles, from a visual comfort point of view, these optimized cases may present risks of glare during the winter if no additional protection is provided to users and depending on the layout of the furniture in the room.

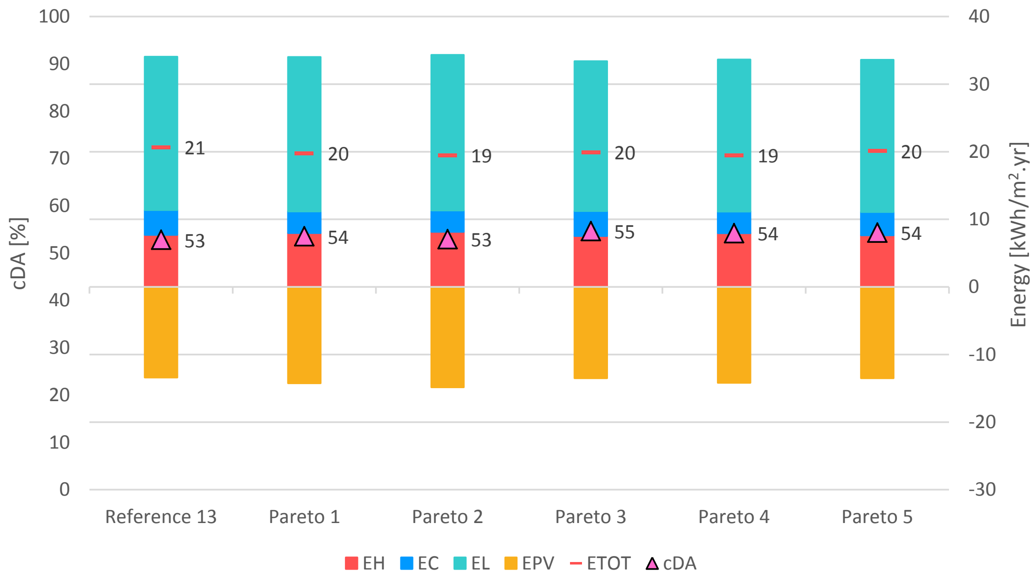
A side-by-side rendering of a configuration with 10 louvres is shown in Fig. 17 as a way to observe the impact of the shading system on the view of the outdoors. Based on this rendering, it is expected that a configuration with few louvres does not significantly obstruct the view, even in its Pareto optimized form. This is because the louvres with the highest angle (and therefore which obstruct the view the most) are mostly located below seated eye level, and still allow a partial view of the outdoors. This rendering provides a promising preliminary response to concerns of user acceptance and esthetics of an optimized fixed PVSD, although these should be evaluated more in depth.

4. Critical assessment of the methodology

4.1. Limitation of the model

The results of the study support the assumption that it is possible to improve the performance of PVSDs by using optimization. The methodology developed in this study is subject to the same issues most optimization problems have, that is the necessity to include enough parameter flexibility to make sure an optimum is not disregarded but without over or under constraining the problem. For this study, the desire to include daylight simulations in the optimization provided a limitation in terms of speed of the process. The algorithms used in *Radiance* require large amounts of computational power, thus if the optimization runtimes are too long, the methodology will be unattractive to a consultant or an architect. It is therefore important to find a certain equilibrium between the accuracy and effort required. When this is reached, the optimization can provide a different set of solutions and may improve the overall performance of the building with possibly only small additional costs. For this study, the simulation took an average of 10 days to run but this time could be decreased substantially if cloud computing was used for example.

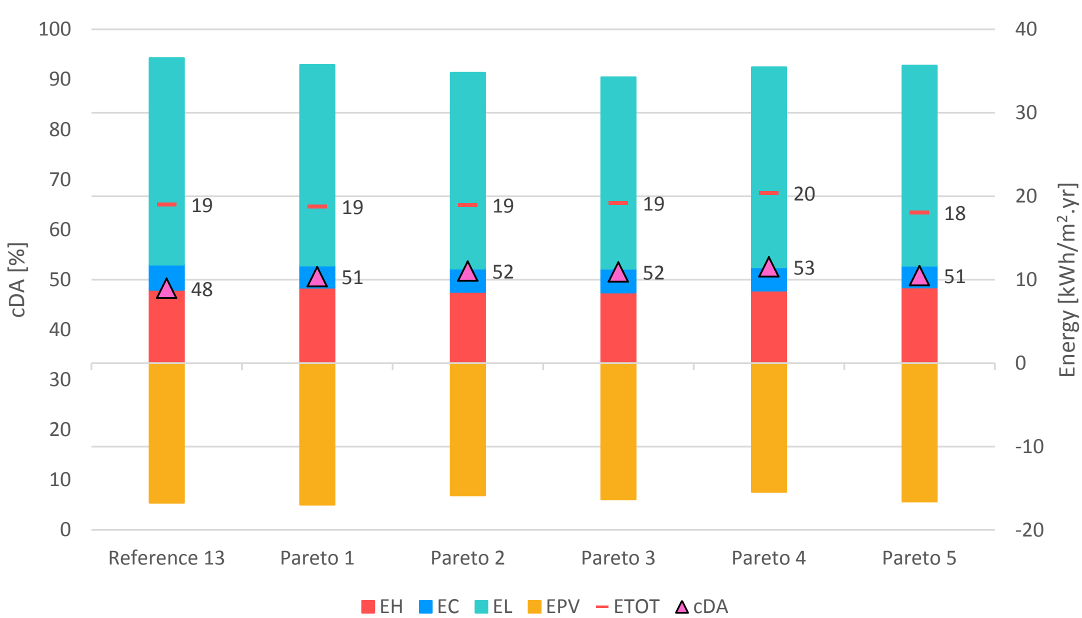
Overall the results of the optimization only provided a small increase in performance. This is suspected to be due to a combination of



	Pareto 1	Pareto 2	Pareto 3	Pareto 4	Pareto 5
Improvement cDA	1.4 %	0.2 %	3.5 %	2.7 %	2.9 %
Improvement E_{TOT}	4.2 %	5.7 %	3.6 %	5.7 %	2.7 %
Improvement E_{PV}	6.3 %	10.8 %	0.8 %	5.9 %	0.9 %

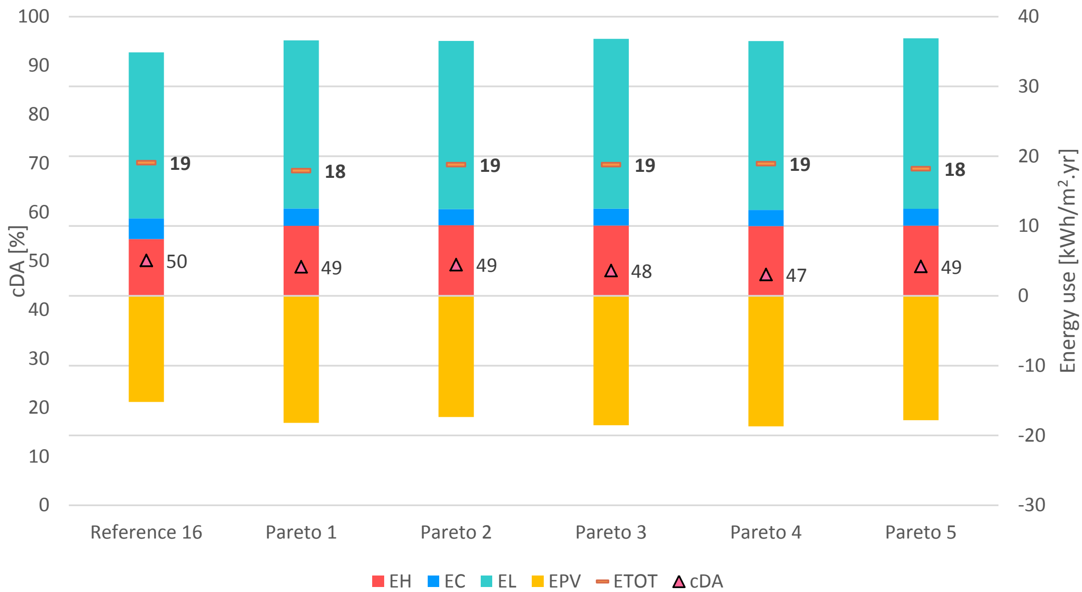
Fig. 9. Performance of the 5 selected Pareto points for the 10 louvres case with a comparison to the reference configuration in terms of cDA and E_{TOT}.

the following points. First, the limitations inherent to the model to avoid configurations with overlapping louvres (i.e. non-physically possible configurations) reduce the possibility to fully optimize the system. Second, if the objectives had been weighted with a hierarchy of importance, the range of improvement could be very different and one could potentially improve the performance of the PVSD with regard to one dominating parameter. In this case study, the optimized solutions chosen from the Pareto front were picked with the equal priority of improving both the daylight levels in the room and the total net energy demand. This means that a large number of Pareto points which



	Pareto 1	Pareto 2	Pareto 3	Pareto 4	Pareto 5
Improvement cDA	4.8 %	7.1 %	6.2 %	8.8 %	2.0 %
Improvement E_{TOT}	1.2 %	0.3 %	1.7 %	-7.2 %	3.2 %
Improvement E_{PV}	1.4 %	-5.4 %	-7.0 %	-7.8 %	3.2 %

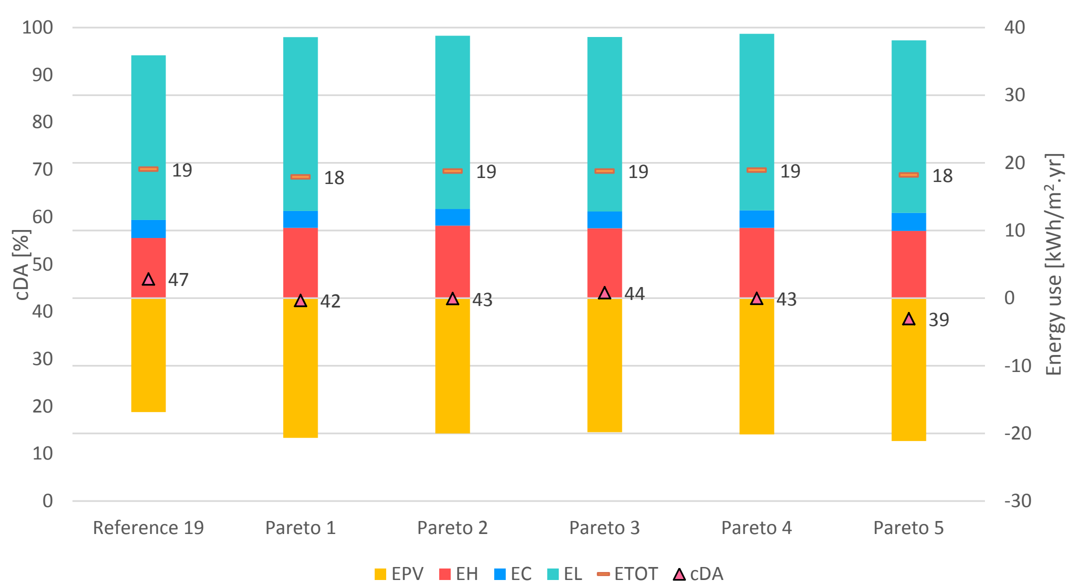
Fig. 10. Performance of the 5 selected Pareto points for the 13 louvres case with a comparison to the reference configuration in terms of cDA and E_{TOT}.



	Pareto 1	Pareto 2	Pareto 3	Pareto 4	Pareto 5
Improvement cDA	-2.7 %	-1.8 %	-4.2 %	-5.8 %	-2.5 %
Improvement E_{TOT}	6.7 %	2.7 %	7.2 %	9.7 %	3.1 %
Improvement E_{PV}	19.8 %	14.2 %	21.9 %	23.0 %	17.2 %

Fig. 11. Performance of the 5 selected Pareto points for the 16 louvres case with a comparison to the reference configuration in terms of cDA and E_{TOT}.

substantially improved a single parameter were not selected in the evaluation. Third, it is reasonable to assume that the results obtained were influenced by the climatic context in which the building was set (heating dominated climate) and the technical assumptions about the building properties and operation. As pointed out earlier, the building had a low energy demand by nature and was operated with ideal building systems with high COPs, while the PV conversion efficiency was relatively low. In a building with a poorer thermal envelope, the PVSD could have a more significant impact on the net energy demand. One can also wonder if in a non-heating dominated climate or in locations closer to the equator, which receive more sunlight, the results of the optimization would lead to very different configurations, as the dynamics of the balance in the objectives will be changed and the cooling demand becomes more important. Additionally, the



	Pareto 1	Pareto 2	Pareto 3	Pareto 4	Pareto 5
Improvement cDA	-9.6 %	-8.8 %	-6.2 %	-8.7 %	-17.9 %
Improvement E_{TOT}	6.0 %	1.5 %	1.4 %	0.8 %	4.5 %
Improvement E_{PV}	22.7 %	18.8 %	17.7 %	19.7 %	25.4 %

Fig. 12. Performance of the 5 selected Pareto points for the 19 louvres case with a comparison to the reference configuration in terms of cDA and E_{TOT}.

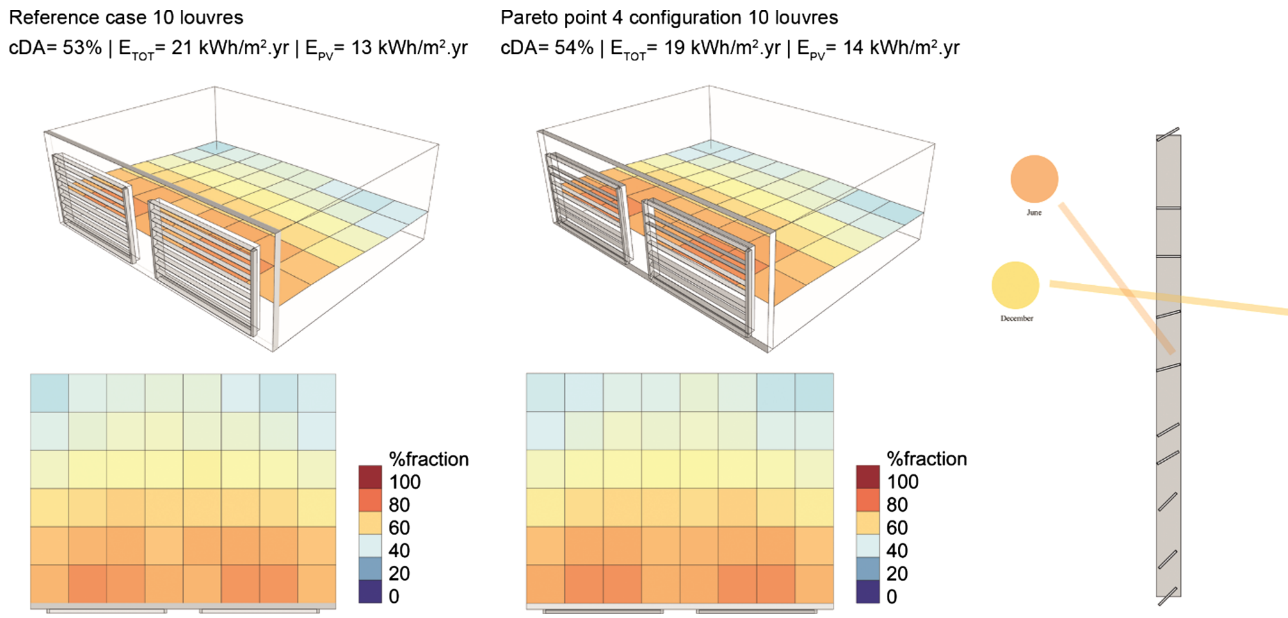


Fig. 13. Louvre system with 10 blades. Visual distribution of the cDA (perspective and top view) for the reference configuration and for selected best solution from the Pareto front, together with the cross section of the louvre system of the optimized solution.

characteristics of the building in terms of internal loads, also affect the outcome of the optimization since different loads would change the energy use profile of the building It is also worth noting that some of the results from the parametric analysis, and thus the references used were very close to the Pareto points and might be Pareto configurations themselves with regard to daylight levels, which makes the task of improving these parameters more difficult. Finally, it's possible that the results of the simulation were somewhat linked to the choice of metrics used, the minimums set for the daylighting standard, and the choice of the reference configuration. For this study, the cDA was judged as the most appropriate metric, but a metric with a harder cutoff, such as the Daylight Autonomy, may have yielded different results. It is also questionable whether a threshold of 300 lx should have been used instead of 500 lx.

4.2. Evaluation of the robustness of the optimized solutions

In this study, the approach of using optimization to help design a shading system was investigated, but this approach is incomplete without a critical assessment of the outputs of the algorithm. Despite their indisputable ability to process larger amounts of data than any human brain could, optimization algorithms are not aimed at replacing designers or provide a human-centered architectural assessment of the solutions they identify as high performing. For this reason and due to the fact that the simulation could in theory run endlessly if no end criterion was provided, the final step of the approach in the proposed methodology is to evaluate the best performing solutions from a designer point of view. This requires assessing the performance according to the objectives of the study and additionally, to consider whether these solutions are (i) obviously possible to improve with small

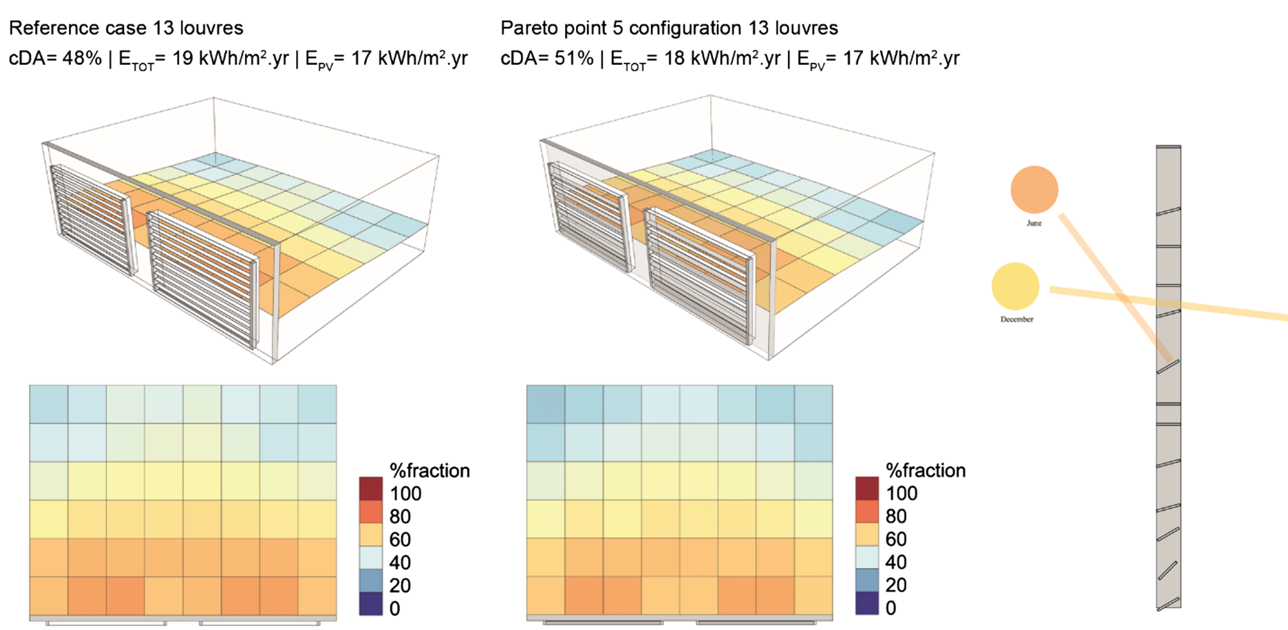


Fig. 14. Louvre system with 13 blades. Visual distribution of the cDA (perspective and top view) for the reference configuration and for selected best solution from the Pareto front, together with the cross section of the louvre system of the optimized solution.

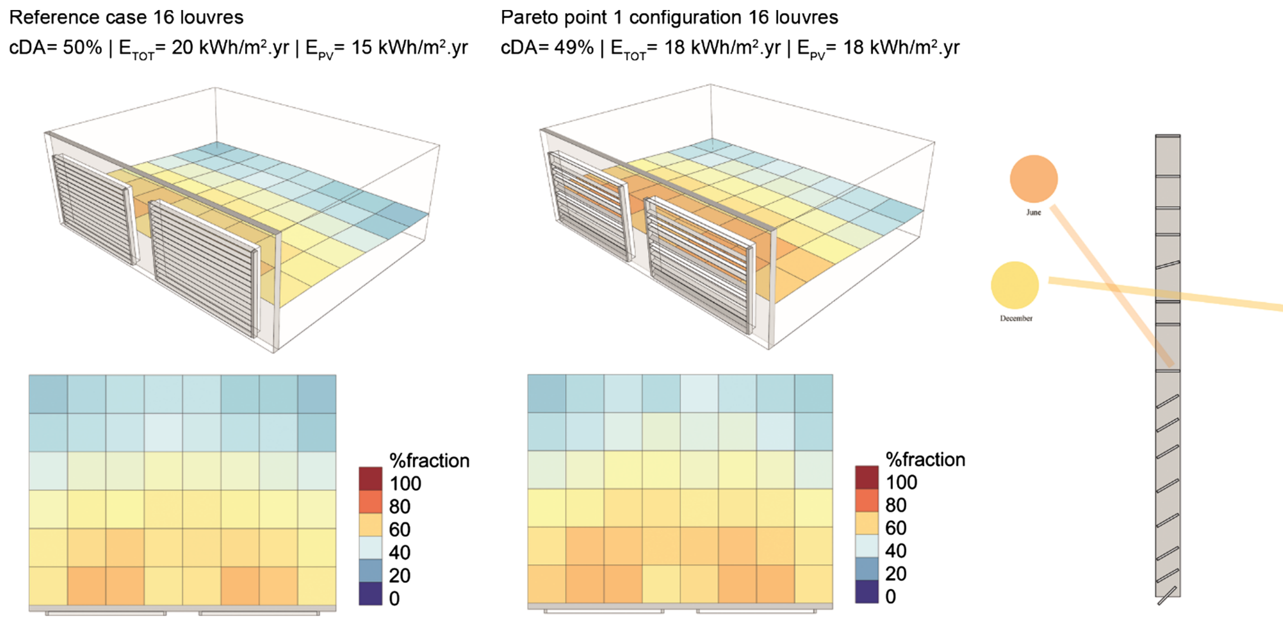


Fig. 15. Louvre system with 16 blades. Visual distribution of the cDA (perspective and top view) for the reference configuration and for selected best solution from the Pareto front, together with the cross section of the louvre system of the optimized solution.

changes, (ii) possible to manufacture as a real shading system, and (iii) architecturally pleasing. For this final step, the two final configurations selected with 10 and 13 louvres were assessed and modified slightly to fit these requirements. In the configuration with 10 louvres, the modifications made were to shift 1 and then 2 louvres in the upper part of the window from a 15 to a 0° tilt to improve the daylight penetration as well as increase the aesthetics of the system. This resulted in no detectable change in the cDA but increased E_{TOT}, signifying that the configuration yielded by the optimization was indeed a non-trivial result of a complex balancing of the parameters. The same test was run on a configuration with 13 louvres with the same results, i.e. the cDA could only be slightly improved but not without increasing E_{TOT}. These findings indicate that the results of the optimization are sufficiently advanced and likely to outperform any "manual" optimization. If this had not been the case, it would be an indication that the optimization had not run long enough and a larger number of generations would be necessary.

5. Conclusion

In this article, a design methodology aiming to improve the performance of a PVSD using multi-objective optimization was developed and demonstrated with the case study of an office building located in a Nordic climate. The findings of the analysis were compared to defined reference cases and demonstrated that the application of the proposed methodology could improve the exploitation of solar energy through a multi-domain façade. The results also supported the assumption that advanced simulation tools can be used in some cases to overcome the limitations of more standardized façade configurations. In particular, it was found that the increase in performance of the system was more

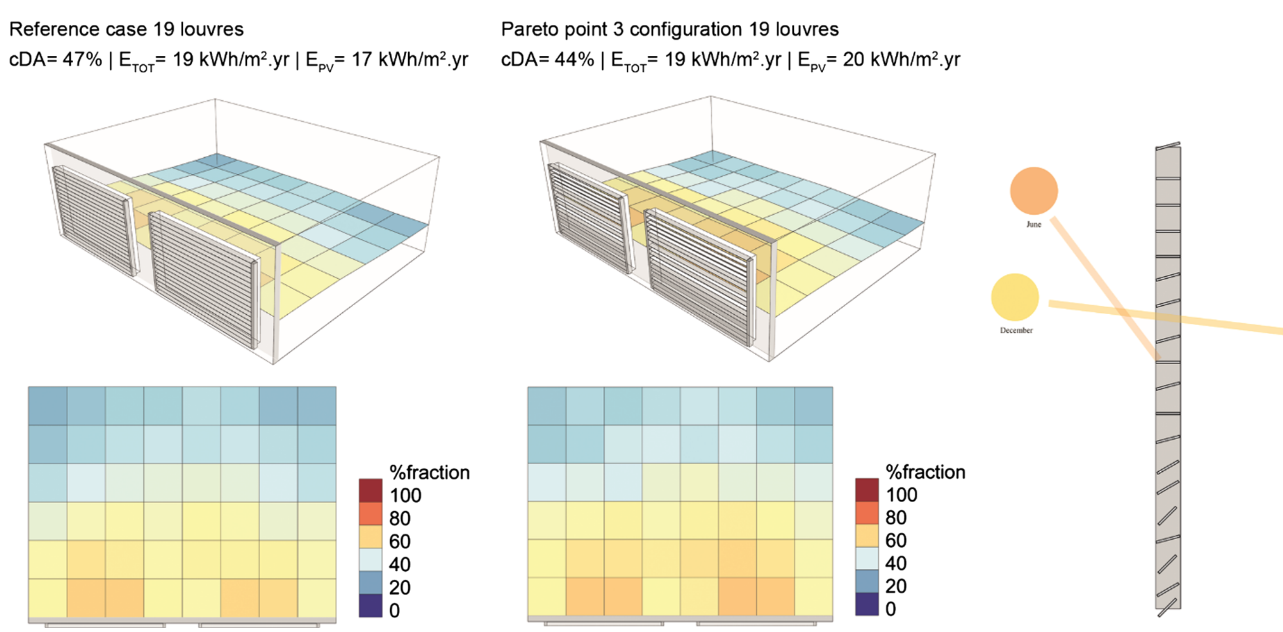


Fig. 16. Louvre system with 19 blades. Visual distribution of the cDA (perspective and top view) for the reference configuration and for selected best solution from the Pareto front, together with the cross section of the louvre system of the optimized solution.

Fig. 17. Side-by-side rendering of the reference case (a) with 10 louvres and the Pareto optimized configuration (b).

significant for configurations with fewer louvres as it allowed the louvres to move vertically in a larger space than when the louvres were more numerous. This finding was also confirmed by the observation that optimized configurations with fewer louvres were most likely to yield results which improved all three of the objectives simultaneously, something the configurations with higher counts of louvres could not achieve. In fact, above a given number of louvres, it appeared that one could only improve two parameters at a time with clear tradeoffs.

Overall, in this study, only a relatively small increase in the global performance of the PVSD could be achieved with the use of optimization. This is believed to be a consequence of the limitations in the structure of the script used to build the methodological framework and the boundary conditions chosen for the study. The analysis of the detailed energy profile of the Pareto configurations resulting from the optimization showed that the total net energy demand was similar for all of the Pareto configurations regardless of the number of louvres (about 19 kWh/m^2). The main difference in the energy demand profiles between the final configurations was that as the number of louvres grew, so did the amount of energy required for artificial lighting, but this was in turn compensated for with a larger amount of energy converted by the PV. As one would expect, in terms of daylight, the configurations with 10 louvres provided the highest cDA and hence, the optimization could only improve it by another relative 3% compared to the reference case, approaching the upper limit of what is achievable in the chosen climate. The total energy demand E_{TOT} could be reduced by nearly 6% and the energy converted by the PV E_{PV} could be improved by up to 10% for the same 10 louvres case. For cases with 13 louvres, the simultaneous improvement for all three objectives was also possible but in a relatively smaller range of values than for 10 louvres. However, when focusing on only two objectives, the cDA could be improved by 7% relatively to the reference case, which made 13 louvres the case with the most potential for improving daylighting via optimization. The case with 16 louvres was not able to provide configurations with a cDA above 50%, but the net energy demand and the PV conversion could be improved by almost 7% and 20% respectively compared to the reference configuration. The configuration with 19 louvres also proved difficult to improve the cDA without sacrificing the net energy demand, and the configuration with the best tradeoffs reduced the cDA by 6% but improved the net energy use by about 1.5% and provided close to 18% more converted energy.

Future work on the optimization methodology presented in this paper could consist of removing some of the constraints in the model, which were put in place to avoid overlapping configurations. A system which would allow the louvre blades to freely distribute but avoid collisions through a different control is likely to provide better results. However, this would require a longer optimization or a larger amount of computational power than what was used in this study. Additionally, the degree of flexibility in the system could be further increased by introducing the possibility to let the optimization algorithm pick the number of louvre-blades in the PVSD, their size, and whether to have PV material on each blade individually or to have a reflective coating instead. Further, the study would be enriched by a multi-climate analysis, under the assumption that the current study is bound by the limited amount of solar energy available during a large portion of the year. The methodology could also be improved with cross-validation of its outputs with data from experimental setups of the system in full-scale laboratories. This future part of the work would allow verifying the in-situ performance of the shading system in different locations, and it would help to determine real system losses due to self-shading of the blades and the effect of temperature on the PV cells. Additionally, these setups could be used to better understand user acceptance of such systems and risk of glare or visual discomfort because of the irregular obstruction of the glazed surface.

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