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Multi-criteria energy and daylighting optimization for an office with fixed and moveable shading devices

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This paper presents an optimization approach to design of an external fixed shading device protecting an energy efficient office from high sun loads. The developed methodology takes into account heating, cooling and energy required for lighting appliances, along with the interaction with an internal moveable venetian blind for direct sunlight protection. The optimization process considers whole year simulations performed with different software codes, specifically ESP-r for energy calculation and DAYSIM® for daylighting analysis, while the modeFRONTIER® tool synchronizes the simulations and drives the optimization for searching optimal solutions. The fixed shading device is a flat panel positioned parallel to the window and inclined by its horizontal axis and the optimization variables change the size, inclination and position of the device respect the building façade. Two exposures are considered south and south-west, the optimized results are reported as a Pareto front highlighting the performance of different solutions, comparing the energy and daylighting performance of the office.

Keywords: daylighting; dynamic simulation; energy performance; optimization; response surface method; genetic algorithms

1 Introduction

Directive 2010/31/CE of the European Parliament defines the performance of a building as the amount of energy required to meet the demand for a typical use which includes the energy used for heating, cooling and lighting. Furthermore it enforces that the performance should be calculated on the basis of a methodology that includes, in addition to thermal characteristics, additional factors such as shading, adequate natural light and building design, additionally requiring that the computation should cover the whole year.

To increase the energy performance of a building, the designer faces an additional effort in order to take into account contemporaneously all the aforementioned terms. This can lead to a daunting design process, since the different terms are not independent, but are strongly linked each other. To deal with this problem in the present paper a multi-objective approach is implemented in which different computer codes are linked together in order to compute the energy consumed into an office room taking into account heating, cooling, daylighting distribution, and window obstruction. An external fixed shading device is considered. The geometry is optimized taking into account the overall energy consumption for building climatization and illumination. To avoid direct sunlight an automated internal venetian blind is considered and the fixed shading device influences the deployment of the moveable internal venetian blind.

The interaction between lighting and energy analysis is attracting a lot of interest among authors dealing with energy performance of buildings. Franzetti, Fraisse and Achard (2004) analysed the coupling between daylight and thermal loads emphasizing the effect of light control devices not only on the reduction of lighting energy consumption, but also on heating and cooling. Shen, H. & Tzempelikos, A. (2012) considered the effect of internal roller shades on daylighting and energy consumption for offices with different orientation in Chicago and Los Angeles; they found that windows covering 30-50 % of the façade can be energy efficient if provided with automated roller shades.

Wienold, Frontini, Herkel and Mende (2011) followed the same approach used in the present paper to deal with the lighting and energy coupling by computing with DAYSIM® the daylighting parameters and then performing energy calculations with ESP-r® for two climate conditions, Rome and Frankfurt. Tzempelikos & Athienitis (2007) performed an integrated thermal and daylighting analysis for perimeter office spaces in Montreal, they analysed different façade designs by changing the window-to-wall ratio and considering the effect of moveable external shadings, they found a decrease in total annual energy demand using external shading, also if they noticed an increase of electrical demand for lighting. Nielsen, Svendsen & Jensen (2011) performed an integrated daylight and thermal simulation for an office building in Denmark with different orientations and three configurations: unshaded window, a fixed external venetian blind and a dynamic fully retractable venetian blind; they highlighted the interdependence of different parameters and the importance of investigating design alternatives starting from an early stages of the design process. Mandalakia, Tsoutsosa, & Papamanolis (2014) considered a photovoltaic system integrated in shading device, they analysed thirteen shading types in Chana, Crete, they found as the Canopy inclined single geometry, the same proposed in present paper, had a very good performance in terms of visual performance, they emphasized also the requirement or further research in direction of combination of internal and external shading systems. Reinhart & Wienold (2011) coupled Daysim and DesignBuilder to analyse the interaction between energy and daylighting distribution in an office with an external venetian blind, they analysed different scenarios for the activation of the blinds considering two kinds of active users, the former the one who avoids direct sunlight, the latter a user who activates the blinds to avoid discomfort glare. The authors showed the difference in daylighting performance between the two choices. Da Silva, Leal & Andersen (2012) conducted a study evaluating the impact of different control modes for the activation of external shading devices on the energy consumption of an office; they considered four window to wall ratio and four glazing systems in three climatic conditions: cooling dominated, they used Porto in Portugal, balanced heating and cooling, heating dominated . They found that different control patterns resulted in different design alternatives with the lowest energy consumption. Also using the climatic data of Porto Leal and Maldonado (2008) analysed the effect of an absorptive glazing placed in front of a common double clear glazing, called SOLVENT window. The authors considered the effect of the new window along with an internal venetian blind using ESP-r for energy analysis and RADIANCE for visual computation, they found that the SOLVENT window shows better energy performance and also better visual comfort on sunny days.

Nowadays, in engineering design it becomes increasingly important the use of advanced methods of optimization, allowing on one side to be able to execute automatically complex processes from geometry definition to the numerical simulation, and on the other side to choose the appropriate multi-objective optimization algorithms, which are necessary to find, by the minimum number of simulations, optimal solutions with a compromise between different and often contrasting objectives.

In the industrial design optimization is widely used, but also for building design this technique is emerging as an interesting tool for architects and engineers, accordingly a number of applications are available in literature. Manzan (2014) applied Genetic Optimization to design an external shading device considering a single objective, the minimization of primary energy consumption for two climatic conditions in Italy, Lee, Trcka & Hensen (2014) applied a similar approach to the study of industrial hall using TRNSYS for energy computation, performing an optimization with modeFRONTIER®. Diakaki Grigorudis & Kolokotsa (2008) used multi-objective optimization for improving energy efficiency in buildings, for this aim they proposed decision criteria based on simplifying assumption on energy calculation using utility functions to reduce the decision model to a single criterion. Nevertheless they recognised the optimization as a helpful tool for reducing energy costs. Genetic algorithms have been used by Znouda, Ghrab-Morcos & Alouane (2007) for the building design in Mediterranean area emphasizing the trade-off to be made between conflicting options for mixing the best characteristics of a building for summer and winter seasons. They also discovered that the solution for saving energy and saving money can be quite different.

In this paper the simultaneous computation of daylighting and energy performance for a building has been integrated with a multi-objective genetic approach. A multidisciplinary approach has been followed linking together different computing codes, namely ESP-r for heating and cooling computation, DAYSIM for computing internal illuminance distribution, while the optimization tool modeFRONTIER® (http://www.esteco.com) has been used to collect the different codes in an unique computation framework for the automatic run of hundreds of cases required by the optimization process.

DAYSIM is a RADIANCE-based daylight simulator, which uses daylight coefficients for predicting indoor illuminances, the code has been validated by Reinhart & Walkenhorst (2001). ESP-r is a control volume based building energy simulation software, it has been used by Loutzenhiser, Manz, Felsmann, Strachan & Maxwell (2007) for a detailed comparison of solar gain models with external and internal shading systems; the authors demonstrated that accurate results can be achieved when predicting the energy consumption for long period of time for highly glazed buildings.

The main goal of the present work is to identify possible optimal configurations of a fixed external shading device taking into account the multiple interconnected characteristics of the problem as energy consumptions for heating cooling, artificial lighting and the automatic deployment of an internal venetian blind. Two office orientations are considered and two objectives are minimized, the primary energy consumption and the number of hours of blind deployment.

2 Case Study

The office considered in this paper features a floor surface of 13 m^2, only one wall faces the external environment with a thermal transmittance U_W of 0.32 W/(m^2 K) with a window 2.47 m wide and 1.9 m high. The others walls enclosing the office are considered adiabatic because facing similar spaces. The office, to be considered at the first floor of a multi-storey building, is 2.82 m high, 2.87 m wide and 4.5 m deep. The room presents a fixed external shading device consisting of a flat plate, parallel to the external wall and inclined by its horizontal axis. Figure 1 (a) reports the geometry of the room with the external fixed shading device, which extends parallel to the wall to simulate a row of identical offices with a continuous panel. The panel is considered a diffusive surface with a reflectance of 0.62, Figure 1 (a) presents also the external shading device pertaining to the lower floor row of offices which has been modelled in DAYSIM to take also into account the reflective combination of the two devices. The window presents a 0.2 m reveal which has been considered in the model due to its impact on window shading as proved by Manzan (2014).

The window consists in a double glazing with low emission coating and gap filled with Argon. An internal venetian blind covers the whole area of the window in order to protect the office from excessive solar radiation, as presented in Figure 1 (b). Unobstructed window glass has a solar direct transmittance τ_e= 0.48 a light transmittance, τ_V=0.61, and thermal transmittance U_g = 1.4 W/(m^2 K). The slats of the venetian blind system have a width of 25.4 mm, they are spaced 21.2 mm with a tilt angle of 45° and a reflectance of 0.85. When the internal shading device is deployed solar direct transmittance of the glazing system is τ_e=0.35 and light transmittance τ_V=0.20. The thermal characteristics of the considered glazing systems plus venetian blind are computed at runtime using the complex fenestration facility (CFC) of ESP-r.

Internal loads, reported in Table 1, are derived from EN ISO 13790 (2008), while ventilation rate during workday is 3.0 air change rates; on Saturday and Sunday it drops to 0.3 because of infiltration. Occupancy patterns are computed automatically by the Lightswitch algorithm described by Reinhart (2004), incorporated in DAYSIM and consider occupancy from 8:00 a.m. to 18:00 p.m., one hour lunch interval is considered at noon and two pauses of 30 min during morning and afternoon. The location of the building is Trieste in north-east Italy at latitude 45°39' with an annual global horizontal radiation of 635 kWh/m^2 , 1882 Heating Degree Days (HDD) and 594 Cooling Degree Days (CDD). The minimum average temperature in January is 3.7 °C while the maximum average in august is 28.0 °C, the climatic data have been obtained from the IGDG database. In order to account for the impact of the shading devices with building orientation two exposures have been considered. In the former the façade is south exposed, while for the latter the building has been rotated 45° westward generating a south-west façade as reported in Figure 2 (a)

The fixed external device shades the window reducing the cooling loads in summer, but it also affects daylight and heat loads in winter season limiting the sun gains. To protect the office interior from direct sunlight a moveable internal venetian blind can cover the whole window surface. The geometry of the external fixed device modifies interior daylighting, interacting with the internal venetian blind deployment schedule and the energy balance of the room, therefore the impact on the overall building energy consumption is investigated.

In order to minimize the energy consumption the geometry of the external device is to be optimized by changing the three geometrical variables highlighted in Figure 2 (b): shading device height h, width L and inclination angle α. In Manzan (2014) also the distance of the shading device from the external wall was used as a parameter, but the solutions showed that this parameter always attained nearly zero values, therefore the parameter has been neglected.

3 Numerical method

The impact of the combined effect of the external shading device and moveable internal venetian blind on energy consumption has been analyzed using two software tools. DAYSIM is used for computing internal illuminance levels and the artificial lighting power required to obtain a sufficient internal illuminance, in the event of poor or absent daylighting. The lighting power is transferred to ESP-r, which considers it as an internal load that has to be dealt with by the building conditioning plant in order to maintain internal constant temperatures, 20 °C during the heating period and 26 °C during summer.

3.1 Daylight simulation

DAYSIM is an analysis tool which can compute illuminance profiles using RADIANCE coupled with a daylight coefficient approach as explained in Reinhart (2011). For each geometrical configuration a set of daylight coefficients are computed and used to calculate internal illuminance at sensor points with a variable sky luminance distribution. DAYSIM incorporates a user behavior control model Lightswitch, described in Reinhart et al. (2004), which takes into account how occupants interact with light switches and movable blinds. Depending on the daylight availability DAYSIM computes electric loads due to artificial illumination when daylight is not available or insufficient. DAYSIM can also deal with moveable shading devices. Although DAYSIM can treat moveable shading systems in a simplified manner, in the present case the advanced method has been utilized. Different geometries are fed to the simulator with positions of the venetian blinds in retracted and deployed positions. The code computes different sets of daylight coefficients and illuminance values, the drawback of this approach is the time consumed for each simulation and this is a key factor for selecting the optimization approach, since algorithms requiring thousands of numerical analysis, such as the genetic ones, are not a viable selection due to the time required for the whole optimization.

An automated blind control system has been adopted, the blinds are fully lowered as soon as direct solar irradiance above 50 W/m^2 is reached on the sensors, and reopened when this value is no longer met, as reported by Reinhart (2004) this is an ideal blind control which maximizes daylighting. Two sensors are positioned at mid room at 0.85 m from the floor and at a distance of 1 m and 2 m respectively from the window, as described in Figure 1 (b). The control logic used for artificial luminaries is a system with an energy-efficient occupancy sensor, the artificial lighting is dimmed until the illuminance at sensors reaches the minimum threshold of 500 lux, the required value according to table 5.26 of EN-12464 standard for writing, typing, reading and data processing tasks. Electric lighting is switched off automatically when the office is not occupied and a specific power of 12 W/m^2 has been considered. For daylighting simulations the reflectance of internal walls, floor and ceiling have been taken as 0.6, 0.3 and 0.7 respectively.

3.2 Energy simulation

ESP-r has been used for energy computation, the software is based on a control volume discretization of the building and plant system. In order to compute the whole year energy consumption of the building the results of DAYSIM should be transferred to the energy computation module *bps*. The information required for the simulation are the internal loads due to the illumination, the occupancy pattern and the schedule of the moveable venetian blind, which cannot be prescribed since it depends on the climatic conditions, shading geometry and occupancy patterns. All the information has been generated by DAYSIM and transferred to a modified version of ESP-r using the temporal definition file facility, in this way the energy computation is synchronized with the daylighting simulation.

ESP-r computes the whole year energy required for heating Q_h cooling Q_C and artificial lighting Q_{el} which are used to compute the primary energy required by the office defined in Equation 1

$$Q_P = \frac{Q_h}{\eta_h} + \frac{Q_c}{\eta_c} + \frac{Q_{el}}{\eta_{el}} \tag{1}$$

Where the primary energy factors for heating has been set as η_h= 0.8 which takes into account a condensing boiler efficiency near unity and a distribution efficiency of 0.8, a primary energy factor for electricity η_{el}= 0.4, while for cooling η_C= 0.8 which takes into account a seasonal mean energy efficiency ratio EER=2.5 a distribution efficiency of 0.8 and the primary energy factor of electricity η_{el} =0.4.

4 Optimization of shading device

Optimization can be defined as the task of obtaining the best configuration for a system with a defined number of degrees of freedom, the input variables, subjected to certain constraints and criteria to be achieved, the objectives. If there is a single objective to be searched the problem is called single-objective optimization, otherwise we speak about multi-objective optimization problems.

Several algorithms can be used to solve optimization problems. Classical or deterministic techniques, such as gradient-based methods, present some limitations, such as the restriction to continuous variables, as highlighted by Wetter and Wright (2004) and the impossibility of dealing directly with multi-objective optimization problems. On the other hand the most robust algorithms can be considered the ones belonging to the category of evolutionary, or stochastic, algorithms, and in particular the ones based on Genetic Algorithms Goldberg, (1989). However the large number of simulations that might be required represents a limitation, since they generally grow linearly with the number of input parameters and objectives considered.

For the present optimization the range of input parameters, presented in Figure 2, are reported in Table 2 and two objectives have been considered. The first objective is the minimization of the annual primary energy consumption, defined in Equation 1, the second is the minimization of the hours of activation of internal venetian blinds. The second objective has been considered in order to guarantee an optimal level of natural lighting during the year and a free view outside the window, with a great impact on the physical and mental well-being of the occupants, as noted by Akash, Saibal, Jhumoor, Arindam (2014). The input variables are not free, but some constraints have been added by means of Equations 1 and 2. The constraints express geometric conditions to be respected, in order to avoid the shading device to interfere with the architecture of the building.

$$L \cdot cos(\alpha) \leq 2.0\ m \tag{2}$$

$$h - L \cdot sin(\alpha) \geq 2.1\ m \tag{3}$$

The constraint of Equation 2 limits the horizontal protrusion of the panel, while the one of Equation 3 avoids the view of people into the office to be obstructed by the shading device.

4.1 FAST Algorithm: Genetic algorithm combined with Adaptive Response Surfaces Methodology

The algorithm selected for this optimization, among the ones available in modeFRONTIER®, is the FAST, due to its combination of robustness in terms of results obtained and efficiency in terms of the number of simulations required.
This algorithm allows the combination of Multi-Objective Genetic Algorithms, Quagliarella Periaux and Poloni (1997) with Adaptive Response Surface Methodology or RSM, Clarich, Pediroda & Poloni (2006), to combine the high robustness of the algorithm with the efficiency of meta-models, whose accuracy is guaranteed by the adaptive procedure. Response Surface Methodologies (RSM), or Metamodels, are models for time consuming problems. Given a series of training designs, the RSM simulates the behavior of the real system with approximating functions, ad example with parametric surfaces, which can be used to obtain a guess of the unknown function at not evaluated sites.

Starting from a database of randomly selected initial designs which represents the Design of Experiments, or DOE, different Response Surfaces or Meta-models (including Radial Basis Function, Kriging, Neural Network, SVD, etc.), can be trained, and then used for the automatic extrapolation of the responses of the system as a function of the design variables. This step is very quick because no simulation is performed since the results are obtained immediately using RSM functions. The best solutions thus obtained are validated through real simulations followed by an update of the database used for the next RSM training.

An automatic procedure for validation will determine the best performing RSM, which will then be used for the next steps of virtual optimization and validation, repeated until obtaining the convergence to the optimal solutions. The FAST algorithm is able to find solutions pertaining to the Pareto front with less individuals if compared with classical genetic algorithms, as shown by Nicolich and Clarich (2011) for an electromagnetic problem and by Manzan, Padovan, Clarich and Rizzian (2014) for the same problem presented in the present paper.

5 Optimization Results

The optimization has been carried on the office room of Figure 1 for two orientation :south and south-west. A total of 150 real simulations were performed, corresponding to 10 iterations steps of 15 designs each. The complete optimization required 22 hours of computation on a four core computer for the south exposed case, while 19 hours on the south-west exposed one. The greatest part of the computation time is due to DAYSIM analysis with less time spent for the energy calculation with ESP-r and optimization overhead to apply the FAST algorithm. The use of a standard genetic algorithm, such as the NSGA II, would have required a far higher number of generations, for example with 100 generations the number of real evaluations would have been 1500 with an impractical computational burden, as highlighted in Manzan, Padovan, Clarich and Rizzian (2014).

When dealing with multi-objective optimization it is not possible to find an optimal solution, but instead the best performing solutions are collected in the so called Pareto front, which represents the set of not-dominated solutions.

5.1 South façade

Figure 3 shows the obtained results for the south exposed façade: the x-axis indicates the primary energy objective and the y-axis the number of blinds activation hours objective, each point on the graph represents a simulated configuration, and the Pareto front is highlighted with filled squares, Figure 3 (b) represents a particular of the area around the Pareto Front. Among the different configurations three designs have been selected from the Pareto front along with a dominated configuration pertaining to the Initial population or Design of Experiments (DOE) set. The geometries and the objectives are reported in Table 3 along with a reference solution without external shading device but featuring the internal venetian blind. Figure 4 reports the geometry of the considered designs along with the sun maximum altitude for specified days. It is worth noting that the solution with a negligible number of hours of blinds deployed, ID 132, has a fixed shading device capable of blocking the sun rays for the most part of the year. The solution ID 28 reaches the minimum value of energy required, but with a higher number of hours with lowered venetian blinds, since the external shading device allow sun rays to strike the internal sensors for an higher period, especially during winter months with low solar altitudes. ID 001 practically corresponds to an external horizontal overhang and is effective only during the summer season, ID 129 represent an intermediate situation with the shading blocking sun rays but for a lesser extent respect ID 132. The solutions show how the daylighting and energy analysis interfere to obtain an optimal solution.

The inspection of Table 3 shows that the external fixed shading device always reduces the primary energy required if compared with the no-shading case, 21.5 %, 20.3 %, 18.1 % for designs 28, 129 and 132 respectively but also ID 1 gives rise to a reduction of 17 %. Primary energy takes into account the energy required for cooling heating and illumination, therefore Figure 5 visualize the contribution of the different energy components of Equation 1. The expected trend is found, heating and artificial lighting energy consumption increase with the shading effect of the device. Nevertheless, the designs pertaining to the Pareto front exhibit an improvement on both objectives if compared to the no shade case and the non-optimized shading device ID 1. It is worth noting that despite the location in Mediterranean area of the building, the geometry ID 132 with the strongest shading effect doesn't show the best solution for the primary energy consumption, confirming the usefulness of the optimization process.

The external shading device impacts also the interior visual environment. Of great interest is to evaluate the impact on daylighting distribution, since this parameter can influence the productivity of the office occupants. For quantifying this aspect Useful Daylight Illuminance (UDI) distribution has been investigated, in particular the parameter $UDI_{100\text{-}2000lux}$, which represents the percentage of working time for which illuminance values between 100 lux and 2000 lux are obtained in a particular location. Figure 6 reports the distribution of $UDI_{100\text{-}2000lux}$ among a line in the centre of the room at a height of 0.85 m from the floor. The high values in proximity of the wall are due to the window been positioned at 0.93 m from the floor in a higher position respect the height of sensors line. Design ID 132 shows the best performance, with values around 90 % at a distance from the façade greater than 1.5 m, showing that the fixed device has a beneficial effect on internal daylighting distribution. ID 129 shows a similar behaviour, while ID 28 registers low values in proximity of the external wall. Nevertheless, the external shading device always improves the daylight performance with respect the no shade and ID 1 case.

The different illumination levels obtained for the different cases are visualized as temporal maps, which represents the illumination obtained on a sensor for each day of the year as x-axis and each time of the day as y-axis. Figure 7 represents the illuminance distribution for a sensor at a distance of 2 m from the façade at 0.85 m from the floor for two configurations no shading Figure 7 (a) and ID 132 Figure 7 (b). It is worth noting the effect of moveable shading devices in Figure 7 (a); when the blinds are deployed the illuminance level is accordingly reduced, and this happens during winter months when the sun is low on the horizon and direct sunlight strikes the sensors which activate the venetian blinds. During summer months due to the high position of the sun no direct sun light strikes the sensors and the blinds are not activated, the same applies to Figure 7 (b) where the external shading device blocks almost in every condition direct irradiance to the sensors.

5.2 South-west façade

The south orientation is deemed an optimal situation for the shading device configuration presented here, therefore to extend the applicability of the proposed method for the optimal designing of shading devices, also a south-west orientation has been analysed. The geometry is the same presented in Figure 1, but the room is rotated 45° westward and the window faces south-west. The results of optimization are presented in Figure 8 (a) with a particular of the Pareto front in Figure 8 (b). The distribution of the results are much steeper than the ones obtained for the south exposure, accordingly the number of designs pertaining to the Pareto front are lower. To analyse the solutions three designs have been selected from the Pareto front, the design with the lowest primary energy consumption, ID 125, the design with lowest hours of blinds activation, ID 142, and an intermediate result ID 111. The same ID 001 from DOE table, previously selected for the South exposure case is reported as well. Figure 9 shows the geometries along with the direction of the sun rays for selected days when the sun lies in the same plane of the façade normal, since the room is rotated the sun heights on the horizontal are lower respect the ones presented in Figure 4.

Table 4 presents the obtained results along with the reference no external shading case (NS).

The inspection of Table 4 again demonstrates the reduction of primary energy with respect the no-shading case obtained with the optimization, 23.3 % , 23.9 % , 22.5 % for designs 111, 125 and 142 respectively while the not optimal solution ID 1 gives a 14 % reduction. Figure 10 visualizes the contribution of the different energy components of Equation 1. The comparison of Figures 10 and 5 shows that the simple overhang solution (ID 1) performance is reduced for south-west facing window respect the south exposure, with a higher energy required for cooling. Instead the inclined plate is still able to reduce the overall energy consumption to values comparable with the ones obtained for the south façade. Figure 11 reports the distribution of $UDI_{100\text{-}2000lux}$ along a line at the centre of the room, again better results are obtained for the designs with a larger shading effect ID 111 and ID 142, but from a distance greater 2.5 m, they present lower values respect the ones obtained without external shading or ID 1, due to the strong shading effect and to the lack of daylighting with higher values of UDI_{100lux}, that is the percentage of time with values of illuminance less than 100 lux.

The temporal plot of illuminance at a distance of 2 m from the façade are presented in Figure 12 for the (a) no shading case and (b) for ID 142. In the former plot it is well identifiable the timing of the solar entering the room, starting in the afternoon due to the south-west exposure. It is also well identified when the moveable venetian blinds are deployed for glare protection. Figure 12 (b) reveals that the fixed shading device blocks direct sun radiation almost perfectly, for instance for this design the moveable shading device is deployed for very few hours during the year.

6 Conclusions

This paper presented the results of an optimization carried on an external fixed shading device which protects an office room from direct sunlight. The optimization has been performed considering integrated thermal and daylighting analysis taking into account the activation of an automatic deployable internal venetian blind for direct sun protection. The simulations were performed using DAYSIM for daylighting analysis and determination of blinds status while a modified version of ESP-r has been used for energy computation. The optimization has been carried using the modeFRONTIER® code used also for automating the processes required for running and interfacing the different computation codes. Due to the time required for the daylighting simulation a robust and efficient FAST method has been adopted for obtaining the optimization results in a reasonable time.

Several solutions for two exposures have been presented. The result showed that the external shading system has always a positive impact on the energy requirement of the office. Furthermore the fixed shading has a beneficial effect on the daylighting distribution, avoiding direct sunlight inside the room. External shading proved to be also effective for the south-west orientation, were the energy consumption reduction is even better than the one obtained for the south facing façade, also if with a reduction of daylighting at the deep end of the room. The automatic deployable venetian blind is important for direct sunlight protection and it is activated during winter months for the south exposure and throughout the year for the south-west case in absence of external fixed shading. Using the external shading the hours of venetian blinds deployment are highly reduced with also an increase of the daylighting quality of the room. An important result is that the highly obstructive solutions are not the ones with the lower energy consumption, this is a proof that the heating, cooling and lighting energies are interconnected with the geometry of the façade. Multi-object optimization demonstrated to be a very valuable tool, since it takes into account all the parameters involved and can drive a designer towards optimal solutions among with to choose the one to be adopted for the project.

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Znouda, E., Ghrab-Morcos N. & Hadj-Alouane A. (2007). Optimization of Mediterranean building design using genetic algorithms, *Energy and Buildings*. 39, 148–153.

Table 1: Weekday distribution of thermal gains

	0-7 am	7 am – 6 pm	6 – 12 pm
Equipment [W/m^2]	2	15	2
Persons [W/m^2]	0.0	7.5	0.0

Table 2: Range of input variables

	L [m]	h [m]	α [deg]
Min	0.01	2.8	-15
Max	2	3.5	45

Table 3: selected designs from the optimization run

	h [m]	α [□□□]	L [m]	Q_P [W/m^2]	N_{on} [hours]
NS	-	-	-	70.46	356
ID 1	3.03	0.46	0.93	58.22	245
ID 28	3.43	27.2	1.71	55.28	139.5
ID 129	2.89	23.2	1.85	56.16	86
ID 132	2.83	30.8	2.00	57.74	21

Table 4: Selected cases results for the south-west orientation

	h [m]	α [deg]	L [m]	Q_P [W/m^2]	N_{on} [hours]
NS	-	-	-	75.19	338.2
ID 1	3.03	0.46	0.93	64.26	212.8
ID 111	2.98	34.3	2.0	57.67	37.8
ID 125	3.0	20.7	2.0	57.22	60.33
ID 142	2.80	30.0	2.0	58.24	29.0

Figure captions

Figure 1: Office geometry with (a) fixed shading device, (b) venetian blinds and sensors

Figure 2: different window exposures (a), Parameters for the optimization (b)

Figure 3:south exposure (a) designs of FAST solution, (b)Pareto designs

Figure 4: South exposure, geometry of investigated designs

Figure 5: South exposure, energy distribution for selected designs

Figure 6: Distribution of UDI100-2000lux at the center line of room

Figure 7: Temporal map of illuminance for a sensor at 2 m from façade,(a) no shading, (b) ID 132

Figure 8: south-west exposure, (a) designs of FAST solution, (b)Pareto designs

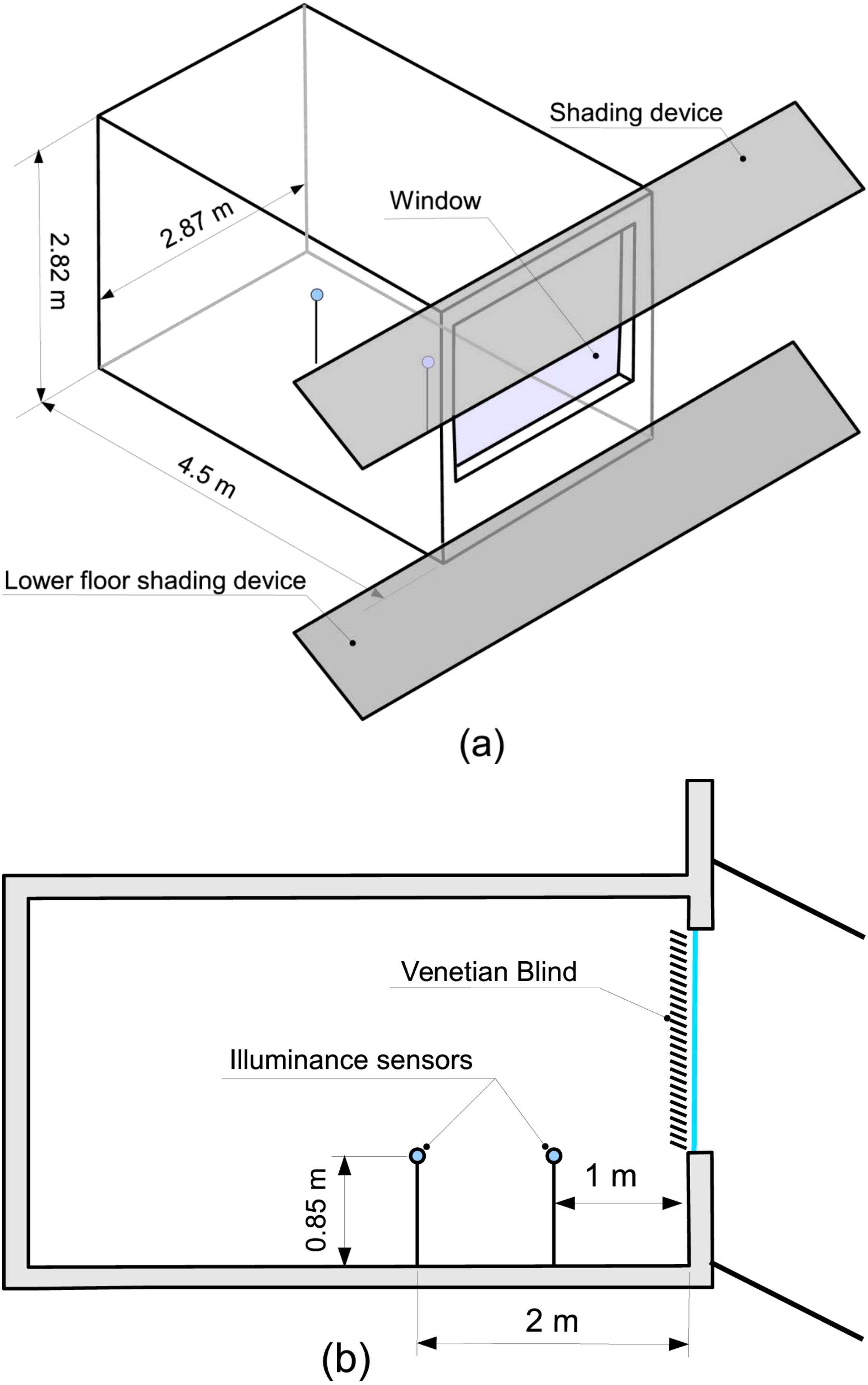
Figure 9: south-west exposure, geometry of investigated designs

Figure 10: south-west exposure, energy distribution for selected designs

Figure 11: south-west exposure, distribution of UDI100-2000lux at the center line of room

Figure 12: south-west exposure, temporal map of illuminance for a sensor at 2 m from façade, (a) no shading, (b) ID 142

Figure 1


Shading device
Window
2.87 m
2.82 m
4.5 m
Lower floor shading device
Venetian Blind
Illuminance sensors
0.85 m
1 m
2 m

(a)

(b)

Figure 2

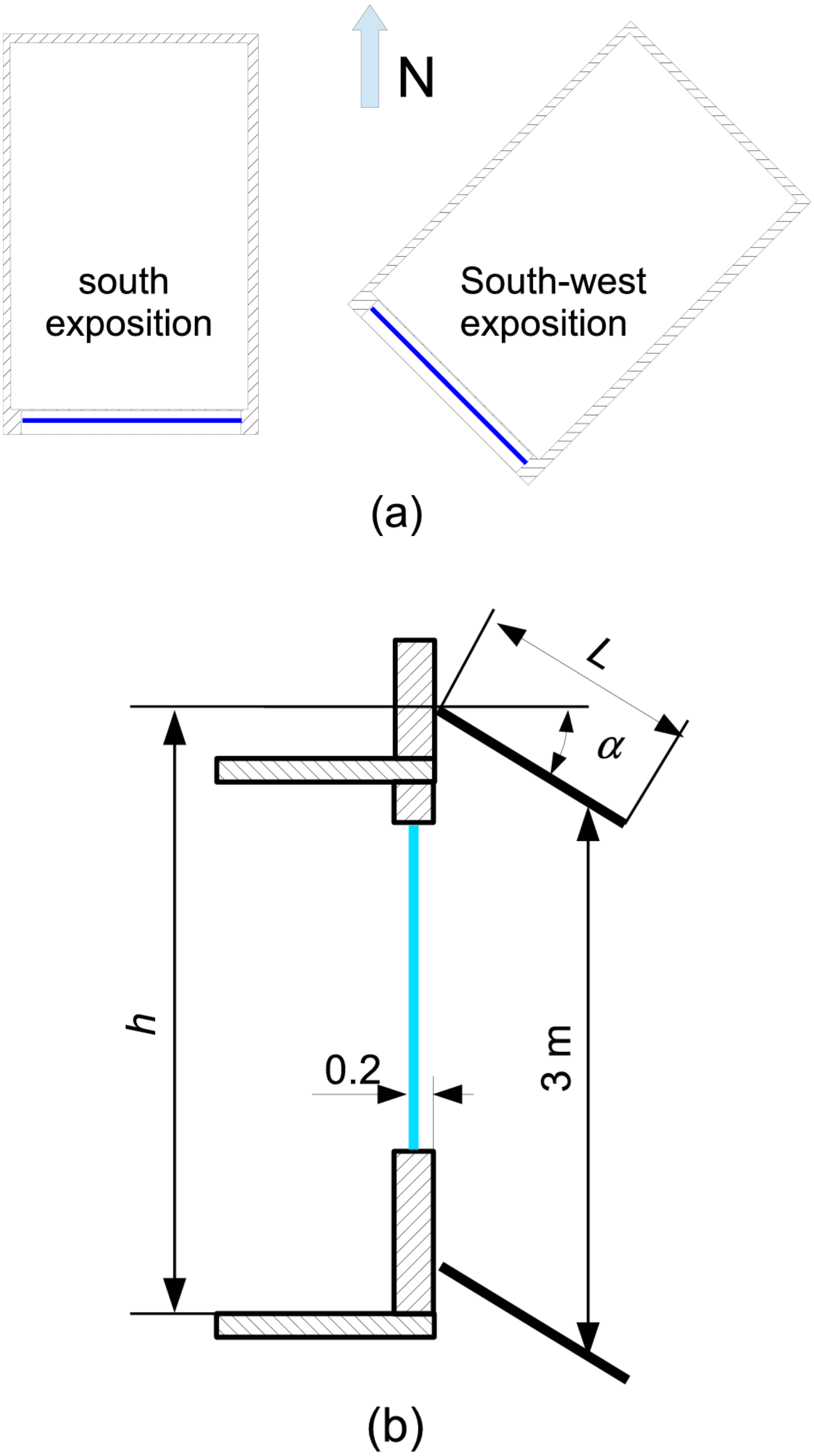


Figure 3

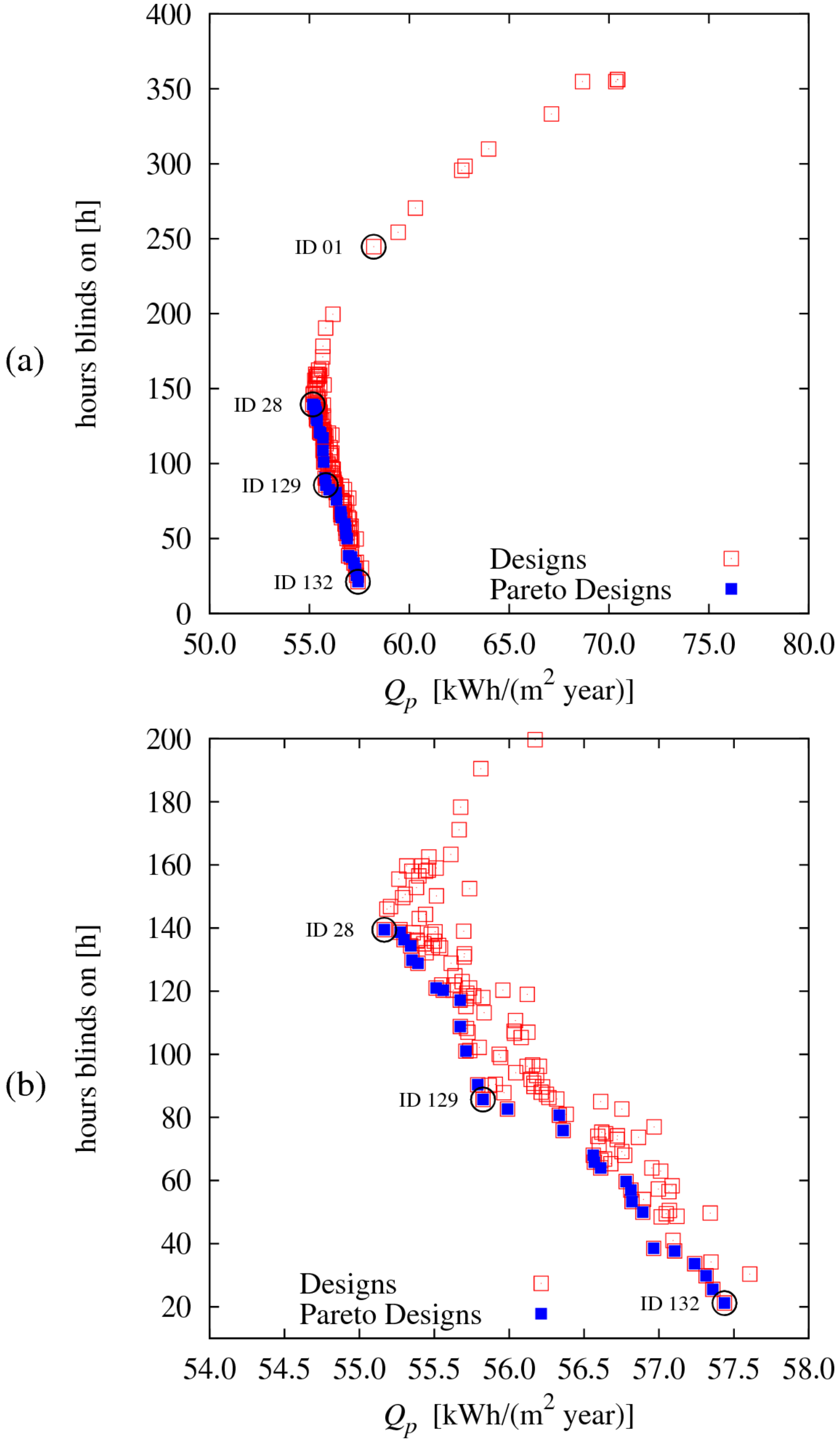
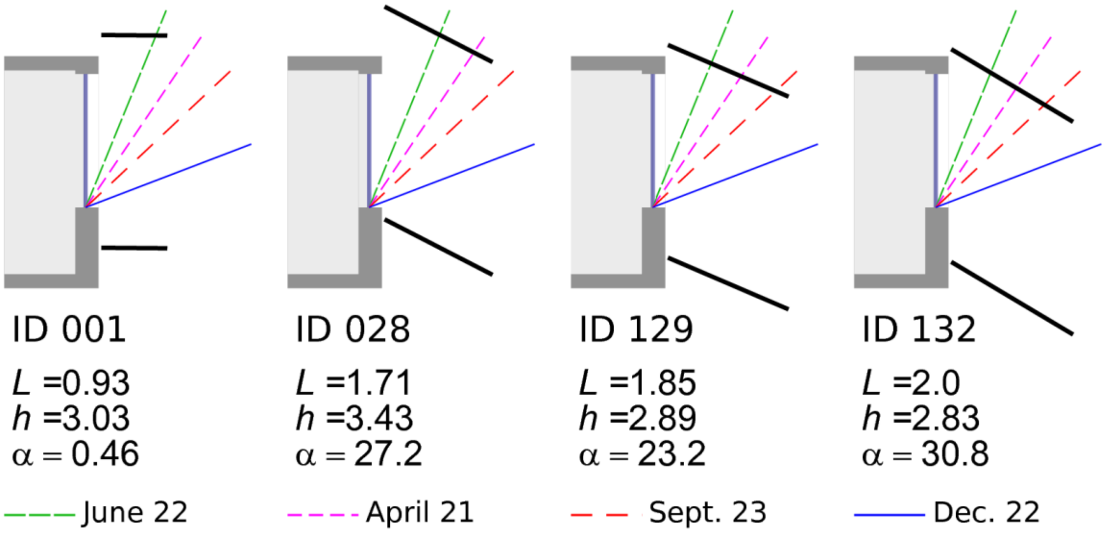

(a)
hours blinds on [h]
400
350
300
250
200
150
100
50
0
ID 01
ID 28
ID 129
ID 132
Designs
Pareto Designs
50.0
55.0
60.0
65.0
70.0
75.0
80.0
Q_p [kWh/(m^2 year)]
(b)
hours blinds on [h]
200
180
160
140
120
100
80
60
40
20
ID 28
ID 129
ID 132
Designs
Pareto Designs
54.0
54.5
55.0
55.5
56.0
56.5
57.0
57.5
58.0
Q_p [kWh/(m^2 year)]

Figure 4


ID 001
L =0.93
h =3.03
α = 0.46
ID 028
L =1.71
h =3.43
α = 27.2
ID 129
L =1.85
h =2.89
α = 23.2
ID 132
L =2.0
h =2.83
α = 30.8
June 22
April 21
Sept. 23
Dec. 22

Figuure 5

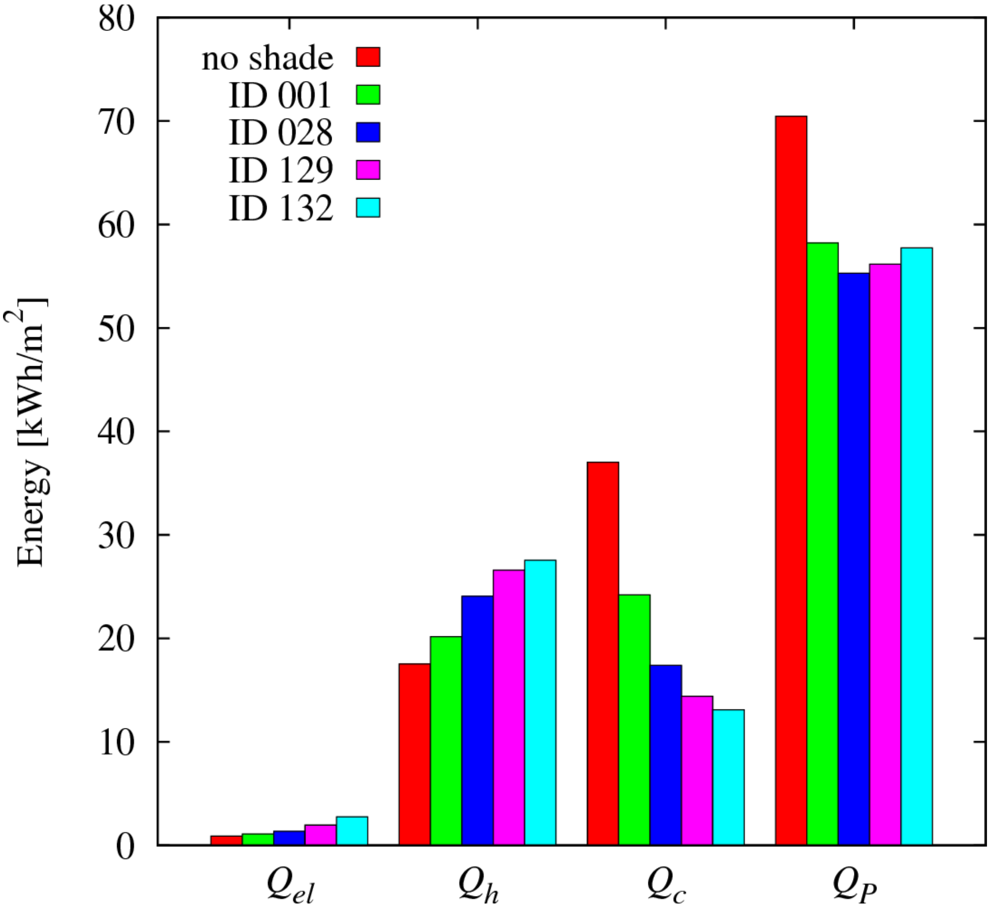
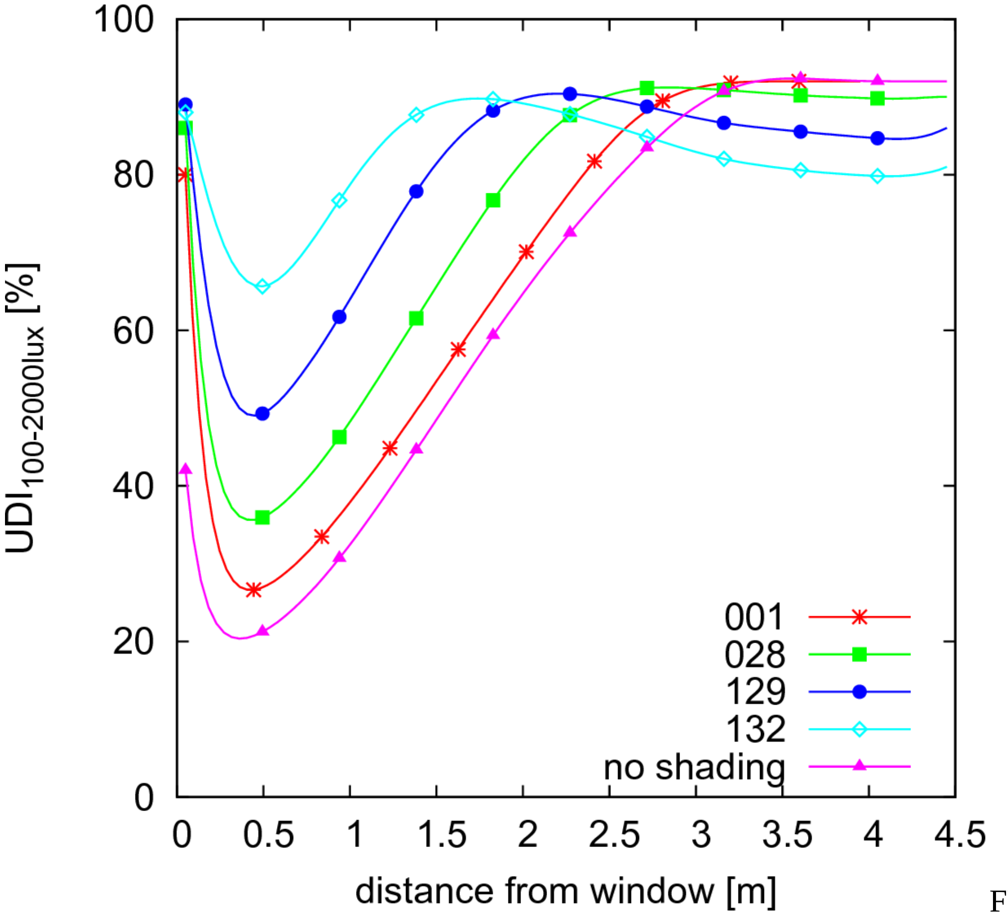

no shade
ID 001
ID 028
ID 129
ID 132
Energy [kWh/m^2]
0
10
20
30
40
50
60
70
80
Q_{el}
Q_h
Q_c
Q_P

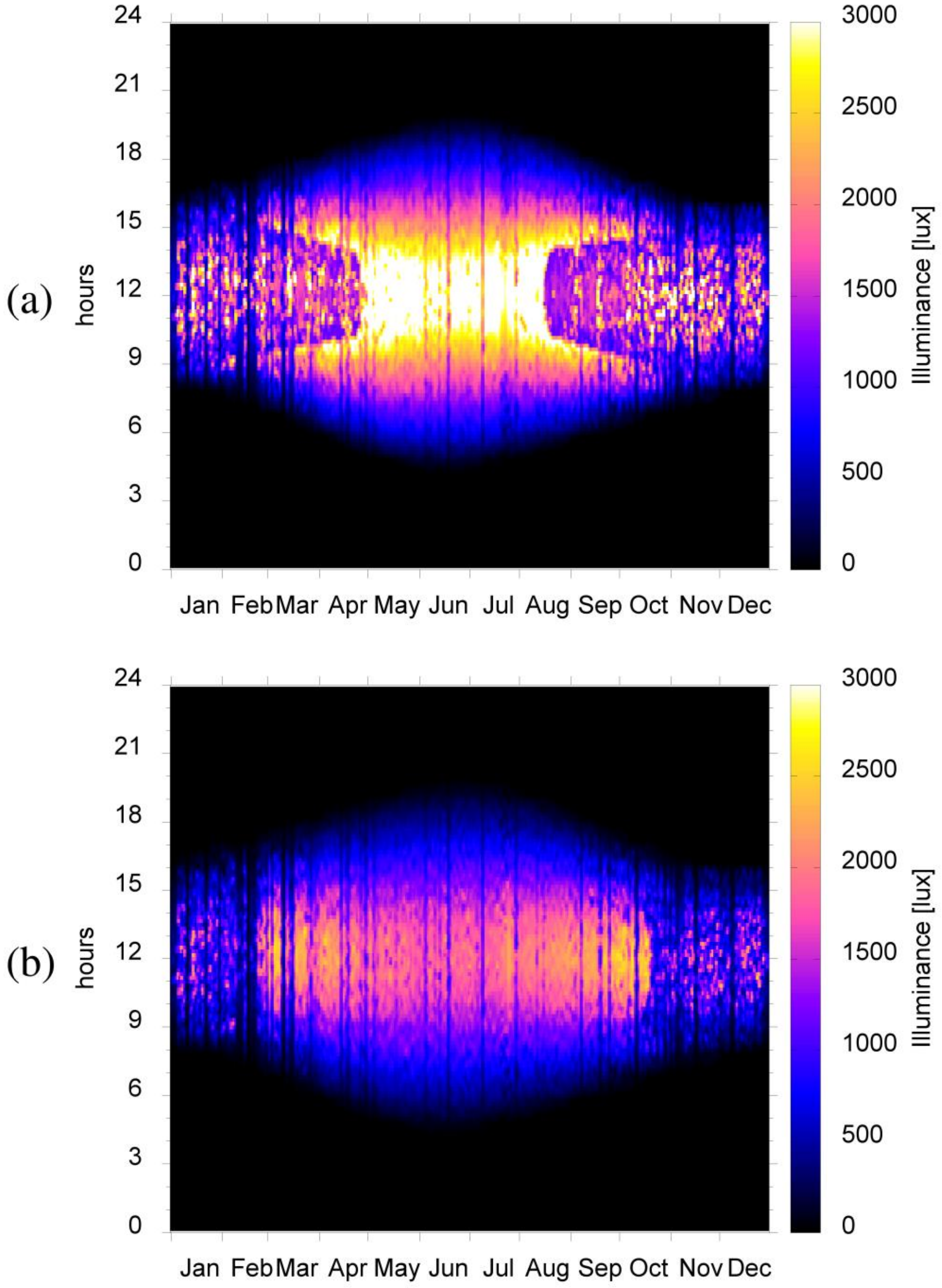
Figure 6



100
80
60
40
20
0
$UDI_{100\text{-}2000lux}$ [%]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
distance from window [m]
001
028
129
132
no shading

FF

Fugyre 7


(a)
24
21
18
15
12
9
6
3
0
hours
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
3000
2500
2000
1500
1000
500
0
Illuminance [lux]
(b)
24
21
18
15
12
9
6
3
0
hours
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
3000
2500
2000
1500
1000
500
0
Illuminance [lux]

Figur 8

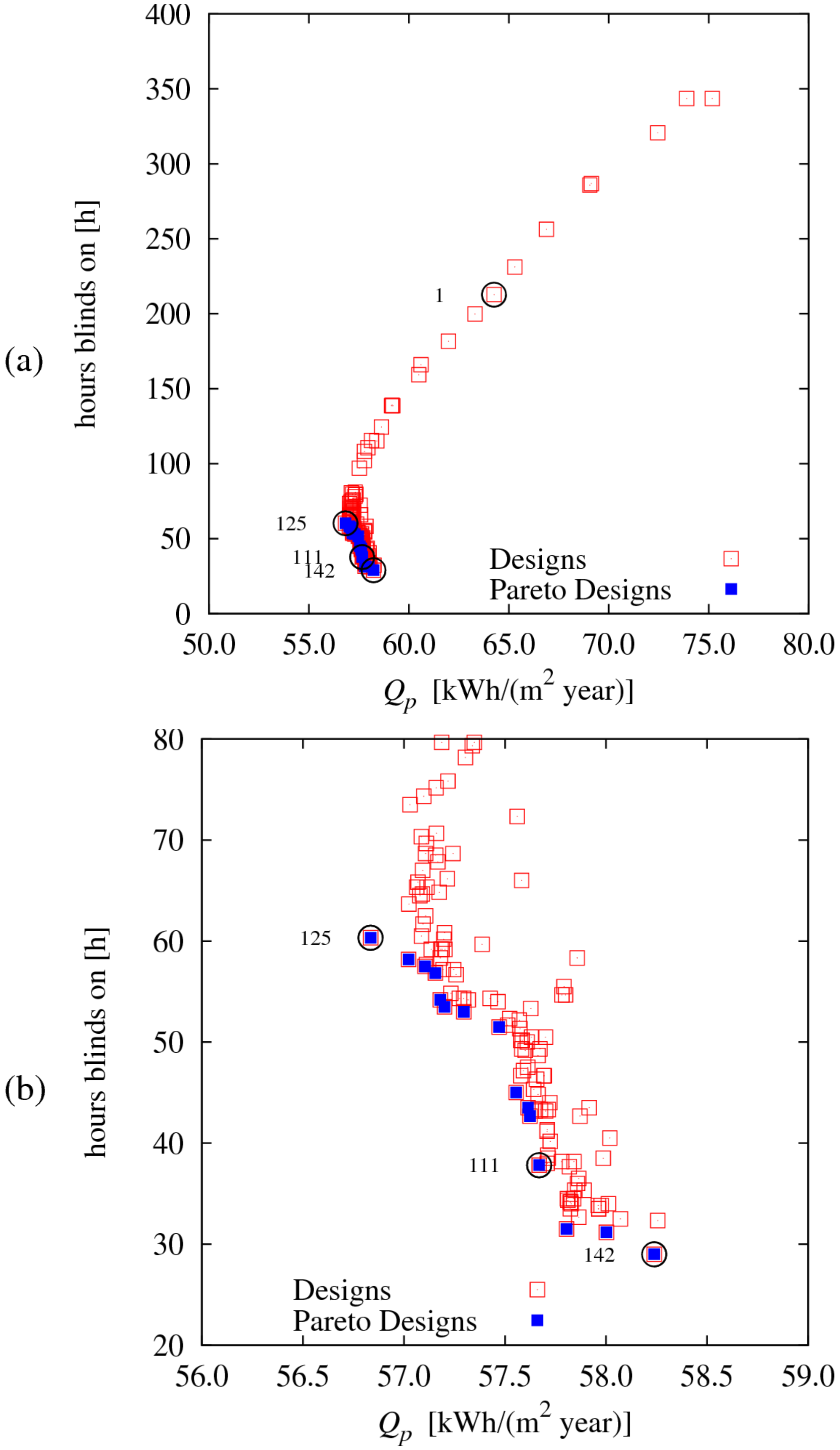

(a)
hours blinds on [h]
400
350
300
250
200
150
100
50
0
1
125
111
142
Designs
Pareto Designs
50.0
55.0
60.0
65.0
70.0
75.0
80.0
Q_p [kWh/(m^2 year)]
(b)
hours blinds on [h]
80
70
60
50
40
30
20
125
111
142
Designs
Pareto Designs
56.0
56.5
57.0
57.5
58.0
58.5
59.0
Q_p [kWh/(m^2 year)]

Figure 9

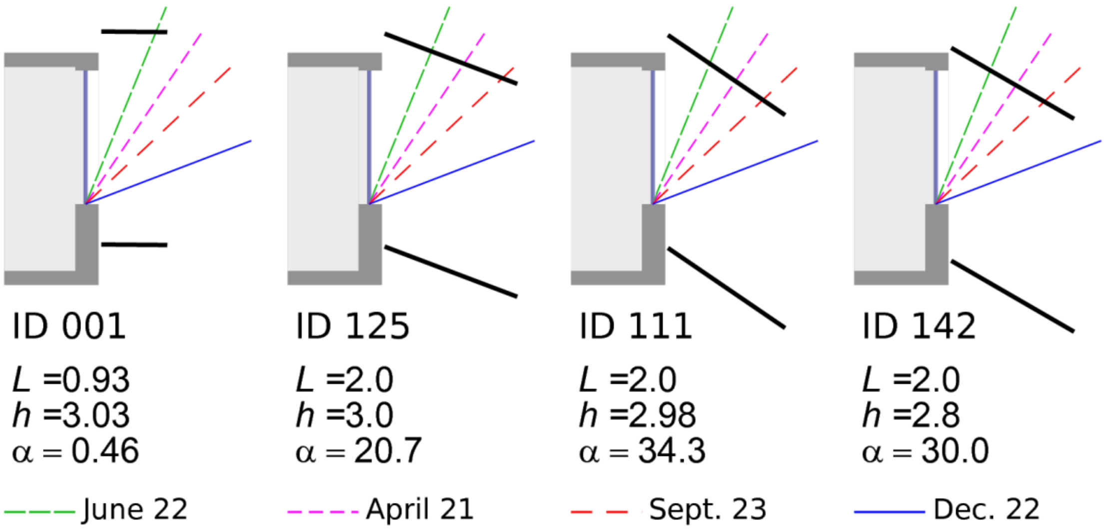

ID 001
L =0.93
h =3.03
α = 0.46
ID 125
L =2.0
h =3.0
α = 20.7
ID 111
L =2.0
h =2.98
α = 34.3
ID 142
L =2.0
h =2.8
α = 30.0
June 22
April 21
Sept. 23
Dec. 22

Figure 10

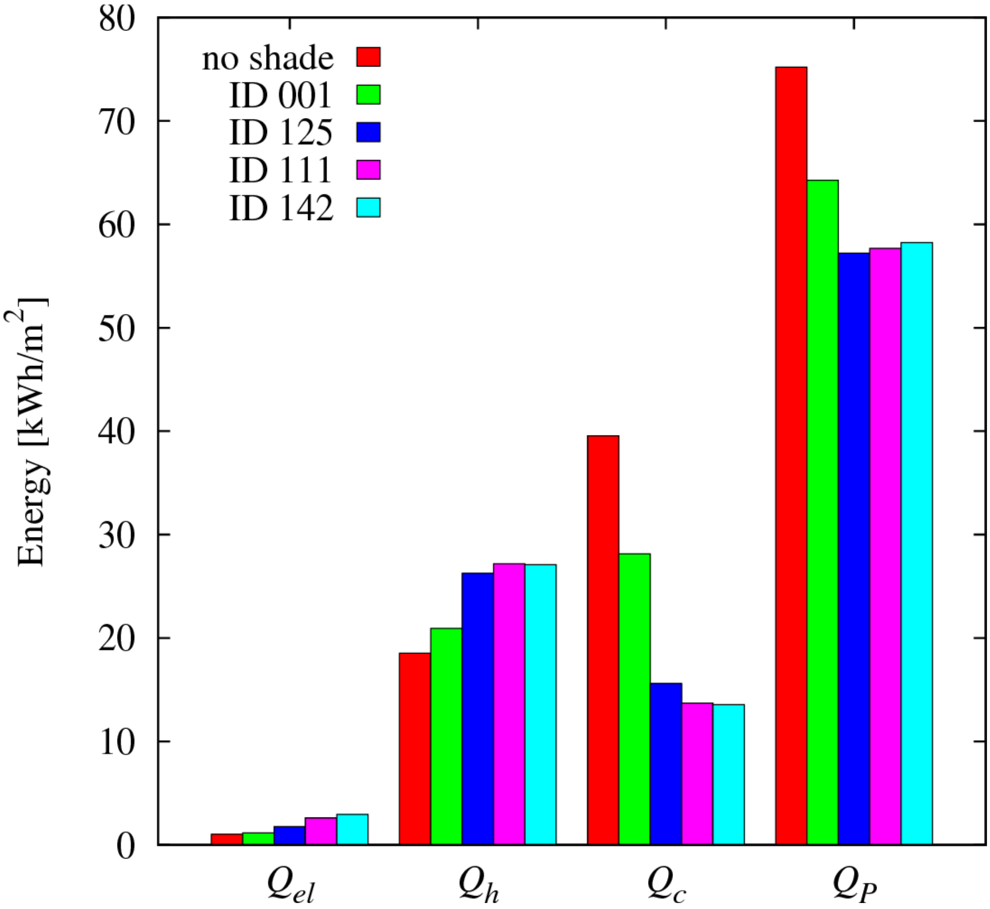
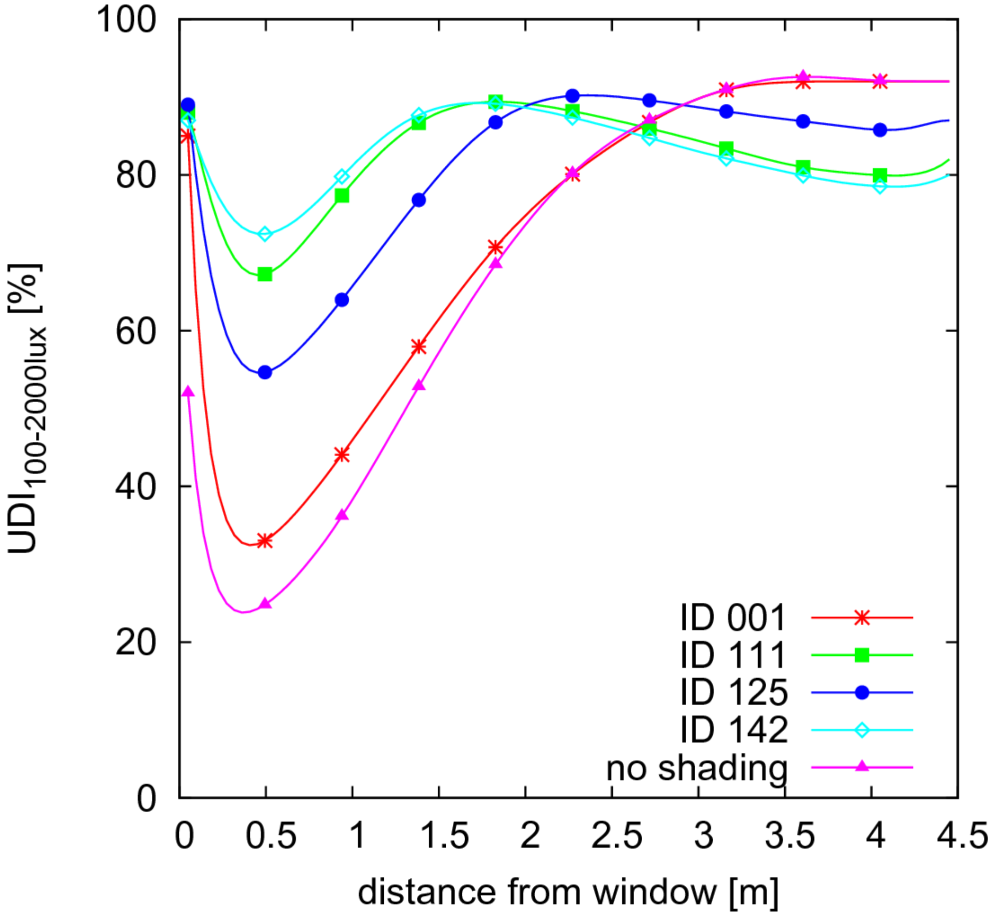
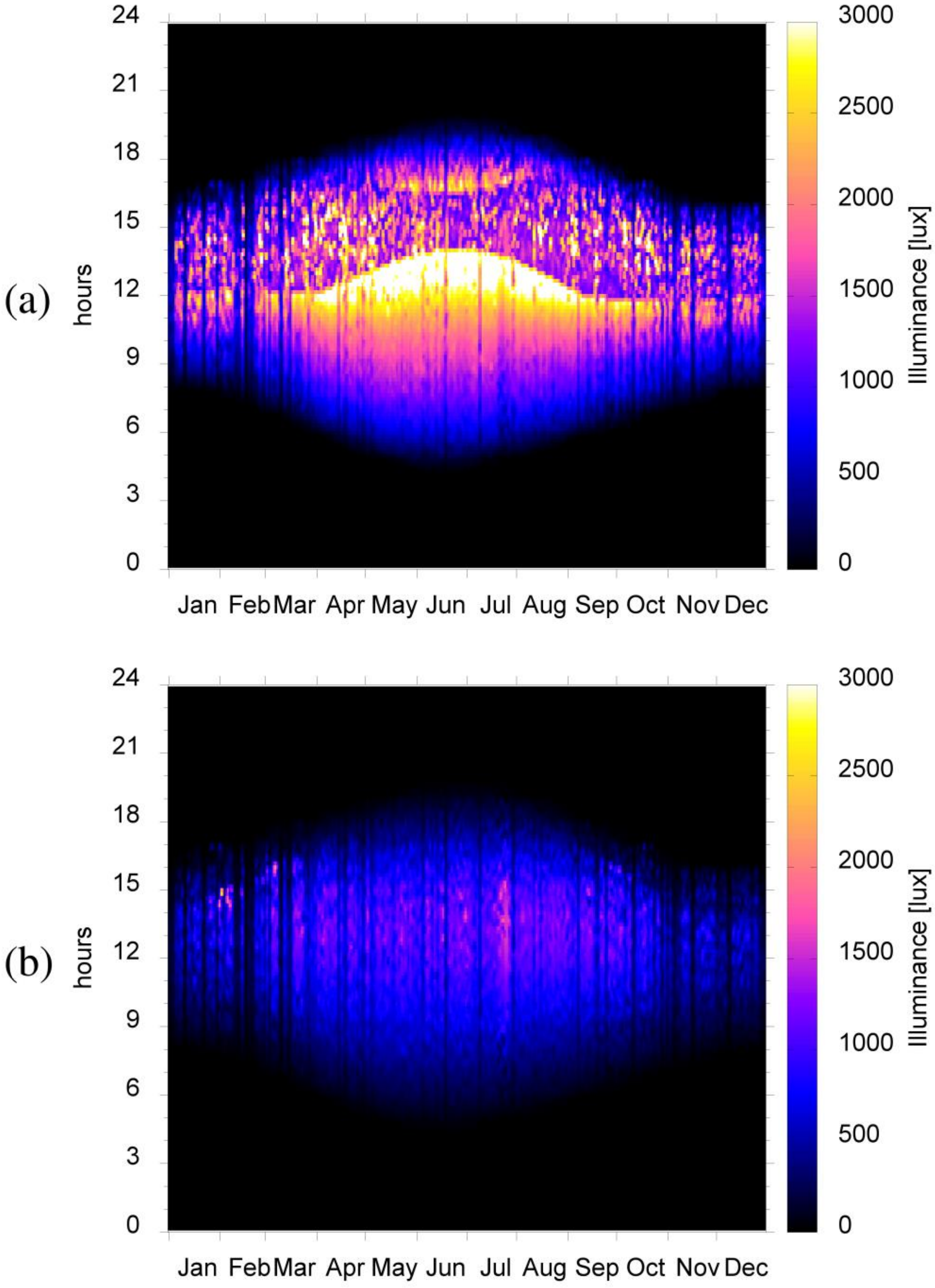

Energy [kWh/m^2]
0
10
20
30
40
50
60
70
80
no shade
ID 001
ID 125
ID 111
ID 142
Q_{el}
Q_h
Q_c
Q_P

Figure 11



UDI$_{100\text{-}2000\text{lux}}$ [%]
0
20
40
60
80
100
distance from window [m]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
ID 001
ID 111
ID 125
ID 142
no shading

Figure 12


(a)
hours
24
21
18
15
12
9
6
3
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Illuminance [lux]
3000
2500
2000
1500
1000
500
0
(b)
hours
24
21
18
15
12
9
6
3
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Illuminance [lux]
3000
2500
2000
1500
1000
500
0