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FAST energy and daylight optimization of an office with fixed and movable shading devices

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ABSTRACT

This paper describes the Energy and Daylighting optimization of a fixed inclined panel which shades an office room with a south exposed window. The window features also user deployable internal Venetian blinds. Energy analysis takes into account the primary energy required for heating, cooling and artificial lights. Different numerical codes have been employed in order to perform the simulations required by the optimization process: Daysim estimates the artificial light consumption based on daylighting distribution, ESP-r computes heating and cooling loads and modeFRONTIER integrates the simulation codes in an automatic optimization loop. The performance of an algorithm specifically designed to deal with problems involving long simulation times (combining response surfaces and genetic algorithms) has been successfully evaluated; the algorithm has then been applied in the optimization loop. The optimized solutions are analysed in this paper, in particular three solutions have been selected: minimum primary energy consumption, minimum hours of blind deployed and an intermediate solution. The analysis compares the primary energy consumption and daylighting performance on the basis of the Useful Daylight Illuminance indicator and the time history of illuminance on predefined locations.

1. Introduction

Healthy conditions in occupied spaces is a common goal for designers and this involve a series of interlocked problems since different aspects of the problem must be taken into account simultaneously. In the process physical and psychological points of view should also be taken into account. Internal condition are usually maintained using air conditioning plants responsible for the constant increase of energy consumption, therefore, passive approaches are drawing great interest from researchers and designers with the aim of reducing the overall energy requirement. The key component of an energy aware building is the façade since it separates the internal comfortable environment from the external ambient. Nowadays office buildings present extensive glazed areas for enhancing daylighting availability but, especially in Mediterranean area, this leads to high cooling loads and increasing problems related to glare. The installation of external shading devices or glazing systems with low solar gain is becoming a natural solution for reducing the aforementioned problems. External shading devices can be fixed or moveable and each solution has its drawbacks and advantages. Fixed shading devices has low maintenance cost, but can be optimized for a single season, on the other hand a moveable device such as an external Venetian blind, can be efficient in reducing cooling loads and glare problems but with the drawback of obstructing the view towards the external environment.

In this paper the coupling between a fixed external shading device and an internal moveable blind system for avoiding excessive direct sunlight is considered. The external device geometry is optimized taking into account the overall energy consumption for building air conditioning and illumination.

The impact of shading devices on building energy consumption has been widely dealt with in scientific literature. Franzetti, Fraisse and Achard [1] analysed the connexion between daylight and thermal loads emphasizing the effect of light control devices on luminaries, heating and cooling energy consumption. Shen, H. and Tzempelikos [2] considered the effect of internal roller shades on daylighting and energy consumption for offices with different orientation showing that automated roller shades are energy efficient with windows covering 30–50% of the façade. Some authors used different numerical codes for solving daylight and energy problems. A common tool for daylighting analysis is DAYSIM, used

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in Ref. [3] together with ESP-r for computing first daylighting parameters and then performing energy simulation. A similar approach, but using TRNSYS for energy analysis has been used be Lee et al. [4]. An integrated thermal and daylighting analysis for perimeter office spaces is a common approach for comparing different façade designs, usually by changing the window-to-wall ratio and considering the effect of moveable external shadings. In Ref. [5] a decrease in total annual energy demand using an external shading is found in spite of an increase of electrical demand for lighting. An integrated daylight and thermal simulation for an office building with three blind configurations and orientations has been performed in Ref. [6] highlighting the interdependence of different parameters and the importance of investigating design alternatives from early stages of design. External shading devices can be also used for the installation of PV modules, Mandalakia [7] analysed thirteen shading types and found that the Canopy inclined single geometry, the same proposed in this paper, demonstrated a very good performance in terms of visual performance. A similar approach has been followed by Li in Ref. [8]: the introduction of an integrated thermal system resulted in a marginal reduction of energy consumption but bringing a beneficial effect on internal illuminance distribution. Coplanar shading systems have been analysed by Hoffman in Ref. [9] developing a complex fenestration system not only for daylighting analysis but also for distributing the solar loads on the surfaces of internal environments. The authors found that the paradigm of reducing window to wall ratio for reducing cooling loads could be relaxed employing shading devices.

Optimization techniques are widespread in industrial design and are attracting further interest in building design. The main goal of an optimization tool is to explore different configurations during the early design phase process allowing the designers to investigate innovative solutions. The main characteristics of an optimization techniques are the robustness, intended as the capability to explore designs without been stuck in local minima or maxima, the possibility of dealing with multiple optimization objectives and the time required by the process [10].

Several algorithms can be used to solve optimization problems. Wetter [11] carried a comparison between deterministic and probabilistic optimization algorithms on non-smooth problems; they highlighted that gradient-based algorithms may typically converge to local optima with problems to reach the global optimal solution for every application problem. 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 [10,12]. One limitation of these algorithms when applied to real practice underlies on the large number of simulations that might be required, since they generally grow linearly with the number of input parameters and objectives considered.

Also in Daylighting analysis optimization techniques are attracting interest among researchers: Futrell [13] compared different algorithms using GenOpt for optimal daylighting, Manzan, one of the present authors, in Ref. [14] applied genetic one-objective optimization to design an external shading system, but without considering moveable shading systems.

The time required by numerical simulation, in particular using raytracing techniques, is the main difficulty a researcher faces in dealing with optimization and daylighting. The same difficulty arises in industrial optimization problems, especially the ones involving CFD simulations. As an effort to reduce the computational burden, surrogate models [10] have been introduced. A common approach is to simplify the problem by training, with a reduced set of solutions, a response surface or RSM [10,15,16]. The method has been applied to the optimization of daylighting and energy consumption for cooling by changing windows geometry [17]. The authors created response surfaces of Daylight autonomy and cooling loads depending on the main geometrical parameters of the window.

In this paper the obstacle of applying optimization techniques with an underlying computational intensive problem, involving large simulation times, has been coped with using an approach which mixes RSM and genetic optimization. A comparison between a classical genetic algorithm and the present method has been carried on, comparing the results in terms of individuals pertaining to the Pareto front and the time required by each optimization. This paper considers the geometry optimization of an external fixed shading device. A similar approach has been adopted by Manzan in Ref. [17], but applying a single slat angular position completely obstructing the external view. Furthermore in Ref. [17] the blinds were driven using an idealized controller yielding the upper bound of usable daylight possible for a given space. In the present paper the limitations of previous approaches have been removed considering a manual control for Venetian blind deployment, with two slats positions. This approach is consistent with existing office rooms operation where the users desire to control internal daylighting while conserving a free outside view if possible. Moreover, the interaction of shading systems with a double and triple glazing systems is taken into account. As in Ref. [17] the software ESP-r, has been used for computing thermal loads, Daysim for computing illuminance levels and luminaries thermal and electrical loads while the optimization has been driven by modeFRONTIER® a product commercialized by Esteco, an Italian company located in Trieste.

The paper first introduces the optimization problem with a description of the office room and shading systems geometry in section 2, then presents in section 3 the Daylighting and Energy simulation codes, the parameters required by DAYSIM for daylighting analysis and ESP-r for energy computation. The description of the optimization algorithm adopted follows in section 4, pointing out the computing performance by comparing it with a classical genetic algorithm. The results of the optimizations carried on are presented in section 5, identifying the individual designs of the Pareto front and considering two glazing systems. Among the solutions three cases has been analysed comparing energy and then daylighting performance using useful daylight illuminance profiles and illuminance temporal maps.

2. Problem definition

Air conditioning loads and internal illuminance levels are strongly affected by the size and position of shading devices. Present paper considers an office room with a floor surface of 13 m^2 with a south facing window 2.47 m wide and 1.9 m high. The window is placed 0.2 m from the external wall surface in order to take into account the shading effect of window reveal. The office has an external fixed shading device and an internal Venetian blind that can cover the whole area of the window in order to protect the office from excessive direct solar radiation. The Venetian blind can be deployed in two positions with horizontal slats or inclined by 45° thus blocking completely the sun rays and also the external view; no other inclinations have been considered since a manual control is adopted and the two positions correspond to the situations in which an user partially shades the window, guaranteeing the view by blinds in horizontal position, either completely shades the window blocking solar direct radiation. Fig. 1 reports the geometry of the office with the shading systems.

The south surface represents an externally insulated refurbished wall with a thermal transmittance U_W of 0.32 W/(m^2 K), whose composition is reported in Table 1. All the other walls are internal

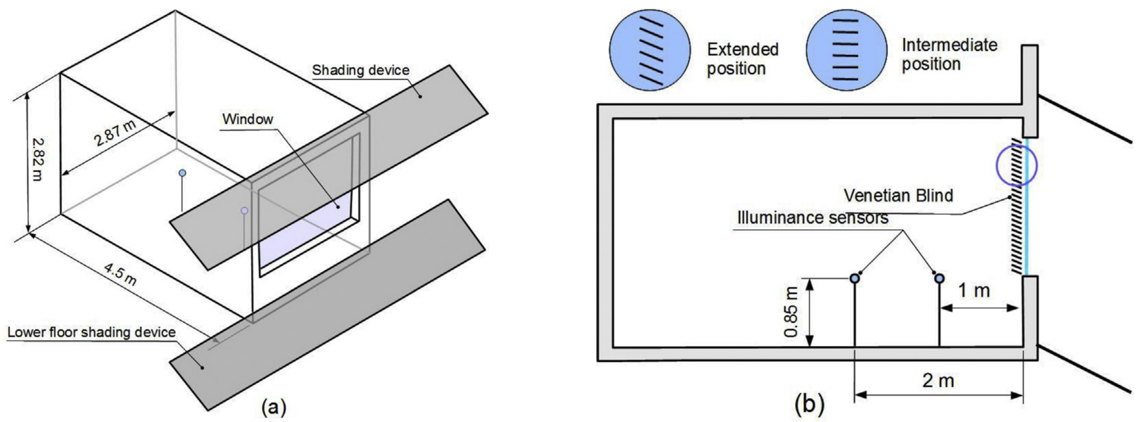

Fig. 1. Office with shading device and Venetian blind, (a) office geometry, (b) Venetian blinds and sensors position.

Table 1
Composition of south external wall.

Layer	s [mm]	λ [W/(m K)]	ρ [kg/m^3]	c [J/(kg K)]
Plaster	10	0.8	1600	840
Brick	250	0.325	1800	840
Plaster	10	0.8	1600	840
XPS Board	80	0.037	30	1250
Plaster	10	0.8	1600	840

ones and are considered adiabatic. Two glazing system are considered: a double glazing with a low emission coating filled with argon and a triple glazing low emission type. The characteristics of both systems are reported in Table 2. The thermal properties of the two glazing systems and of the Venetian blind have been computed using the complex fenestration facility (CFC) of ESP-r, while the numerical code has been modified to let the schedule of Venetian blinds deployment be controlled by DAYSIM by importing the computed configurations via the temporal definition file tool.

Internal loads during weekdays are reported in Table 3, on Saturday and Sunday an equipment load of 2 W/m^2 has been considered. The occupancy schedule is computed by Lightswitch algorithm in Daysim and imported in ESP-r using the temporal definition file. The ventilation rate during workday is 1.1 air change rates, while on Saturday and Sunday this value drops to 0.3 due to air infiltration. The location of the building is Trieste and climatic data have been obtained from the IGDG database. Trieste is located in northeast Italy at latitude 45°39′ with an annual global horizontal radiation of 635 kWh/m^2.

The shading device is a panel positioned parallel to the window and inclined by its horizontal axis, which spans the whole building façade as presented in Fig. 1 (a). The device shades the window reducing the cooling loads in summer, but also affecting daylight and heat loads in winter limiting the sun gains. The geometry of the shading device influences the position of the internal Venetian blind by blocking the direct solar radiation striking the internal sensors.

The optimization proposed in this paper is performed modifying the geometrical variables highlighted in Fig. 2 for a total of three parameters: shading device height h, width L and inclination angle a. The input parameters can variate with continuity, h between 2.8 m and 3.5 m, L between 0 and 2 m, a from 0 to 45°. An additional constraint avoids the lower part of the external shading device to fall below 1.8 m in order to avoid interference with the external

Table 2
Glazing system characteristics.

	g	T_E	T_V	U_g
Double glazing	0.56	0.410	0.695	1.16
Triple glazing	0.40	0.275	0.547	0.568

Table 3
Weekday distribution of thermal gains.

	0 a.m.–8 a.m. W/m^2	8 a.m.–5 p.m. W/m^2	5 p.m.–12 p.m. W/m^2
Equipment	2	15	2
Persons	0	7.5	0

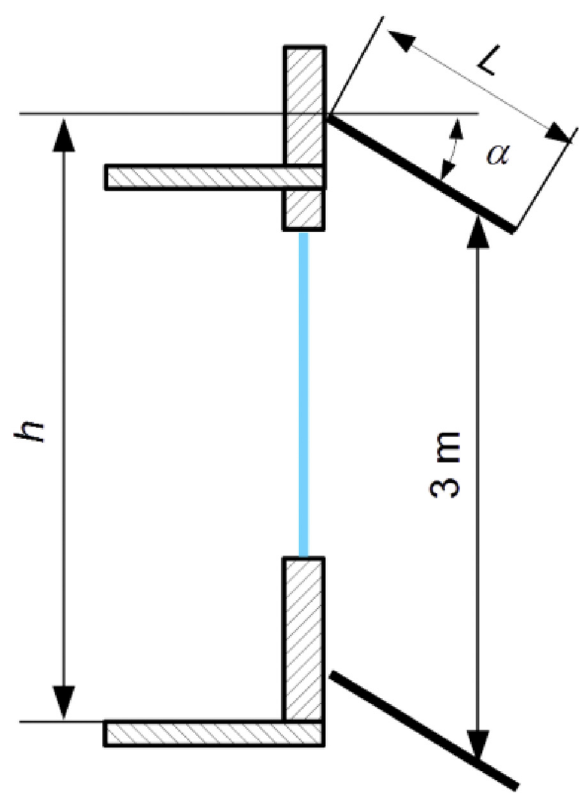

Fig. 2. Input parameters used for the optimization.

view. A multi-objective optimization has been performed identifying two objectives to be minimized. The former objective is Q_P, defined in Eqn (1), the primary energy consumed during a whole year for maintaining healthy internal conditions; the latter is the total number of hours in a year, computed during the occupancy time, with internal blind deployed with an inclination of 45°, N_{45}. This objective has been selected in order to search for solutions during the optimization process with a reduced number of hours without a free view outside the window.

3. Daylight and energy simulation

3.1. Daylighting simulation

The ESP-r code can cope with daylighting simulations, for instance it incorporates different coupling methods, but following the approach used in Ref. [14] the DAYSIM version 4.0 code has been used for an offline daylighting simulation. DAYSIM incorporates a user behaviour control model Lightswitch [18] which takes into account how occupants interact with light switches and movable blinds. Depending on the levels of illuminance evaluated, DAYSIM computes electric loads due to artificial illumination when no daylight is available or it is insufficient. The computed electrical consumption is transferred to the simulation code ESP-r as an internal gain.

DAYSIM can deal with moveable shading devices. Simplified or direct models are available to handle Venetian blinds. In the former case a fast estimate of the impact of blinds is performed : the 25% of diffuse daylight and no direct sunlight when the blinds are deployed is considered. In the latter case alternate geometries, with different Venetian blinds positions, are fed to the simulator. DAYSIM computes different sets of daylight coefficients and illuminance values for each geometry, the drawback of this approach is the increase in computational time, and this problem is crucial for selecting the optimization approach.

Internal or external sensors can control blinds deployment automatically, however in this paper the manual control implemented in DAYSIM has been adopted since it is very common and allows the people inside the space to control the light distribution and the external view. The advanced shading control system of DAYSIM version 4.0 has been adopted allowing the deployment of Venetian blinds as soon as direct sunlight above 50 W/m^2 is reached on the two illuminance sensors positioned at mid room at a distance of 1 m and 2 m respectively from the window and 0.85 m from the floor, as described in Fig. 1 (b). Three blind geometries are considered: blind retracted, system deployed with horizontal blinds, system deployed with 45° blinds inclination. It is worth noting that the former situation can protect the sensors from direct solar radiation without obstructing the external view, while the latter is more effective in blocking direct solar radiation but obscures completely the outside view. Inclination angles higher than 45° have not been considered since the value selected is sufficient in blocking direct solar radiation. DAYSIM can evaluate also annual glare profiles, however the process is very time consuming and therefore has not been implemented in the current optimization process.

The control logic used for lighting is a system with an energy-efficient occupancy sensor: 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 by the occupancy sensor. The reflectance of internal walls, floor and ceiling have been taken as 0.6, 0.3 and 0.7 respectively, while a maximum density of 12 W/m^2 has been considered for internal luminaries.

3.2. Energy simulation

Energy simulations have been carried on using the ESP-r code. Internal conditions are defined by an ideal temperature control which maintains, during working hours, the internal environment at set-point values of 20 °C during the heating season and 26 °C during the cooling season. The energy required for heating Q_h and cooling Q_C, along with the energy consumed by internal luminaries Q_{ill} during the whole year are used for defining the primary energy consumed by the office using Eqn (1).

$$Q_p = Q_{ill} \cdot f_{p,el} + \frac{Q_c}{EER} \cdot f_{p,el} + \frac{Q_h}{\eta_h} \quad (1)$$

in computing Eqn. (1) typical values of coefficients have been used $f_{p,el} = 2.42$, $EER = 3.0$, $\eta_h = 0.8$.

Energy performance is strictly correlated to Daylighting. Solar radiation, which depends on the geometry of the external panel and Venetian blinds position influences all the terms in Eqn. (1). For instance Q_{ill} is obtained by DAYSIM simulation, but the term influences also Q_C and Q_h computed in ESP-r since energy consumed by luminaries is considered a thermal load. Furthermore, solar radiation entering the conditioned space is also considered a thermal load directly computed in ESP-r using the Complex Fenestration Component, with Venetian blinds deploying according to the schedule provided by the DAYSIM run. Fig. 3 presents a schematic diagram of the adopted method. The geometry of the problem, using the appropriate values of parameters of the external blind is provided to DAYSIM and ESP-r. DAYSIM computes the luminaries

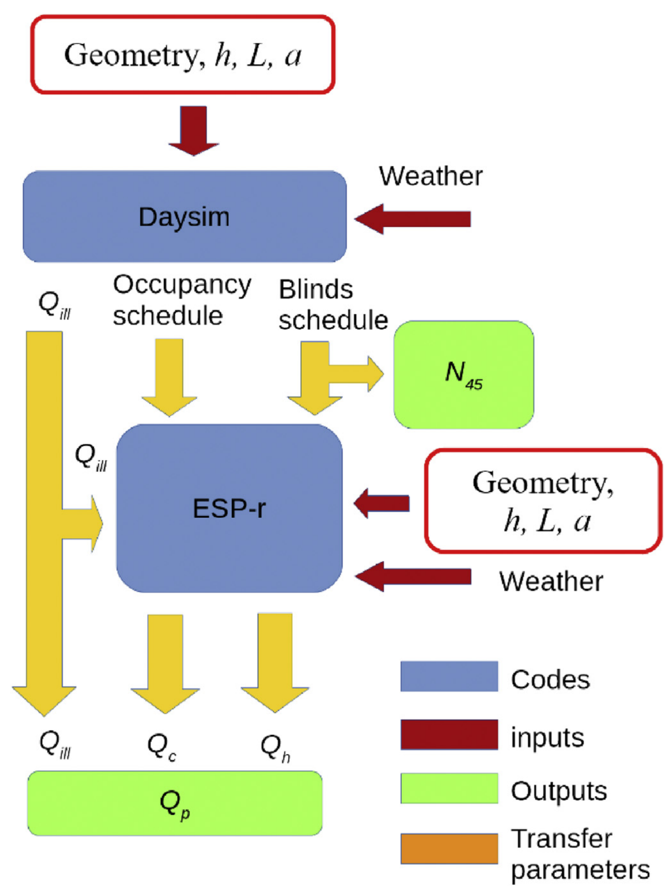

Fig. 3. Schematic diagram of the method adopted for Daylighting and Energy computation.

and occupancy schedules and feed them to the code for energy computation. Esp-r computes the energy required for heating and cooling the office, and the data along with the energy required for artificial lighting is used for computing the primary energy using Eqn. (1).

4. Optimization

4.1. FAST algorithm

The algorithm selected for this problem among the ones available in modeFRONTIER is the FAST®, since it provides an excellent combination of robustness in terms of results obtained and efficiency in terms of minimum number of simulations required.

The algorithm is based on the integration of a robust algorithm for multi-objective optimization [19,20], with adaptive Response Surface Models [16]. The advantage of Response Surface is given by the fact that they can speed up consistently the optimization process [10]. Previously evaluated designs can be used as a training set for building surrogate or meta-models, which are able to extrapolate the system responses in function of the input variables. Subsequently an optimization based on the meta-model responses (virtual evaluations) can be performed. The algorithm works on the analogy of a population of independent designs evolving through successive iterations (generations), like an ordinary genetic algorithm. The total number of generated designs will be equal to the population size multiplied by the number of iterations.

Fig. 4 reports a schematic diagram of the method. Starting from a database of designs chosen by an appropriate Design of Experiments or DoE, different Response Surfaces or meta-models are trained, and in particular: Radial Basis Function [21], Kriging [22], Neural Network [23], SVD, and others. Indicated for simplicity as RSM, they are used by FAST algorithm for the automatic extrapolation of the responses of the system as a function of the design variables. For each objective and each constraint a different set of RSM is trained, whose fitness quality is checked independently to guarantee the usage of the best RSM in each single case.

In this way, the complete virtual optimization can be performed in few instants, since the numerical codes, in present case DASYSIM and ESP-r, are not used directly, but the results are extrapolated directly from the RSM models. The algorithm includes also a local refinement around the best solutions to improve the accuracy of the solutions. At this point, the best solutions thus obtained, pertaining to the Pareto frontier, can be validated through real time expensive simulations, updating in this way the database used for the RSM training. At each iteration the newly evaluated designs enrich the training database, permitting a more and more accurate RSM to be built in an adaptive and iterative way. Sometimes the RSM can be trapped to the local optima, so the virtual optimization and the exploration are accompanied by the "real" optimization, that is a direct optimization without RSM. These processes mutually interact at each generation exchanging information, i.e. the evaluated points, improving the robustness of the algorithm.

An automatic procedure for validation, based on mean squared error performance criteria, will determine the best performing RSM, which will then be used for the next steps of virtual optimization/exploration and validation, which are repeated until the convergence to the optimal solutions.

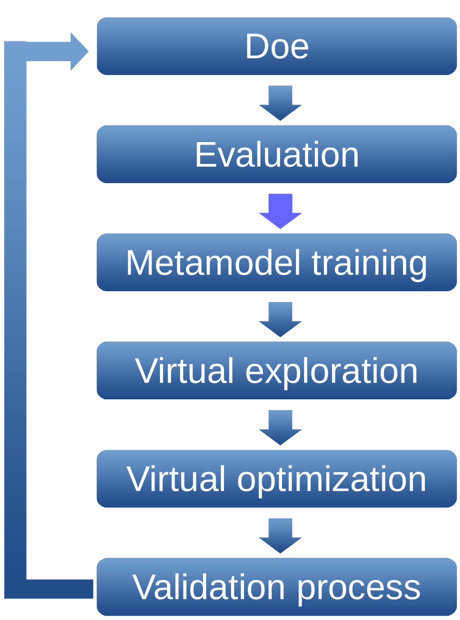

Fig. 4. The FAST optimization algorithm.

Table 4
DAYSIM parameters.

	ab	ad	as	aa	ar	ds
FAST NSGA II comparison	2	250	20	0.2	300	0.2
Optimization run	4	1000	20	0.1	300	0.2

4.2. Performance of FAST algorithm

The performance of the FAST algorithm has been compared with a classical NSGA II [19] genetic algorithm. The genetic algorithm requires a large number of evaluations to be performed, so, in order to limit the execution time, DAYSIM parameters for the comparison of the solutions have been relaxed as reported in Table 4, adopting the simplified shading method since it requires the computation of only one set of Daylight Coefficients. The optimizations have been

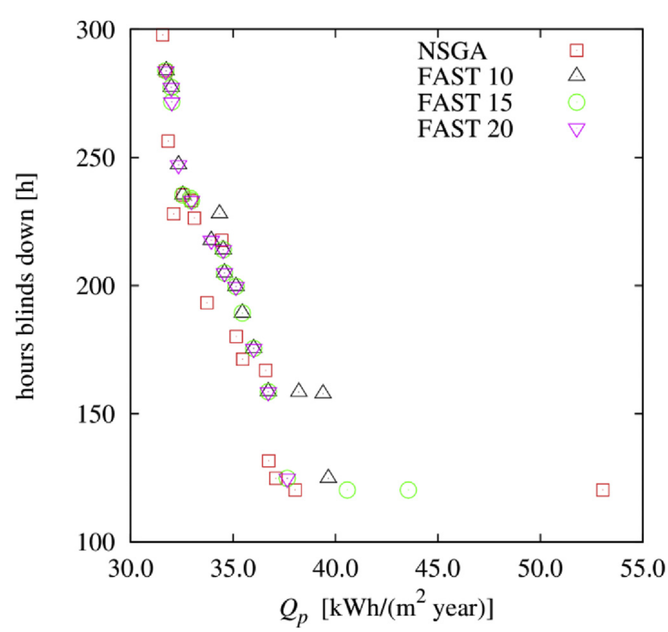

Fig. 5. Comparison among Pareto fronts between NSGA II optimization and FAST with 10, 15 and 20 iterations.

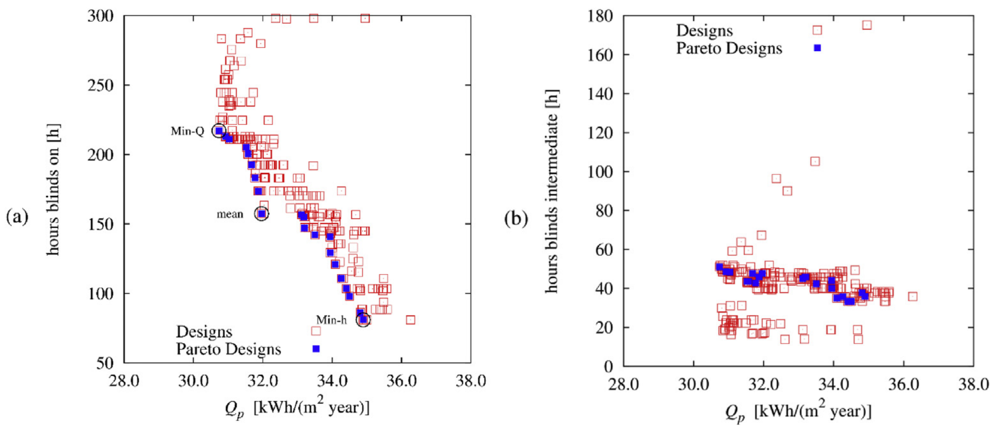

Fig. 6. FAST Optimization results, objectives evolution and Pareto front: (a) energy and hours of closed blinds, (b) energy and hours of blinds in horizontal position.

Table 5
Pareto shading configurations for double glazing.

	h [m]	*a* [degree]	*L* [m]	Q_P [kWh/m^2]	N_{45} [h]	N_0 [h]
No Shading	–	–	–	41.10	306	327
Min-Q	2.93	6.6	1.96	31.15	217	35
Mean	2.81	18.7	2.0	33.20	158	51
Min-h	2.82	30.8	2.0	35.67	81	48

carried on starting with the same initial populations, or DoE, of 16 individuals; the NSGA II optimization has been carried on for 100 generations, while the FAST method has been iterated for 10, 15 and 20 times. Fig. 5 allows a comparison among the Pareto frontiers obtained with the two methods; the x-axis reports the primary energy objective Q_p and the y-axis indicates the number of blinds activation hour objective N_{45}. The Pareto fronts are very similar, proving that the FAST algorithm can explore with accuracy the optimized solutions. After ten iterations the FAST method converges to the same upper part of the Pareto frontier of the NSGA II algorithm. The Pareto fronts differ in the lower part, characterized by a reduced number of hours with deployed blinds, however results of the same Pareto frontier are obtained after 15 iterations, while no great differences are noticed between 15 and 20 iterations. However, the computational time of the two approaches is quite different. The NSGA II optimization required 3 h 55 min, while the FAST required for 10 iterations 26 min, for 15 iterations 38 min and for 20 iterations 58 min. The simulations have been performed on the same i5 computer spawning the concurrent evaluations on 4 cores. In order to capture the Pareto front the full optimization runs for the complete problem have been performed using 15 iterations, a good compromise between accuracy and computational time.

5. Optimization results

The optimization has been carried on changing the parameters of Fig. 1 and Fig. 6 a) reports the results of the optimization for the double glass system, the same behaviour is shared by the triple glazing system and therefore has not been reported here. In Fig. 6 a) the x-axis presents the primary energy objective of Equation (1) and the y-axis the number of hours with Venetian blinds deployed at 45° N_{45}, the position obstructing completely the outside view. Fig. 6 b) reports on the y-axis the number of hours with blinds in horizontal position N_0: the value is nearly constant for the designs on the Pareto frontier.

5.1. Analysis of energy results

To describe the main features of the optimized designs, we have selected three design corresponding to the solution with minimum primary energy consumption, "*min-Q*" the one with minimum hour of blinds deployed "*min-h*" and a trade-off configuration "*mean*" as presented in Fig. 6 (a). The selected designs along with a reference

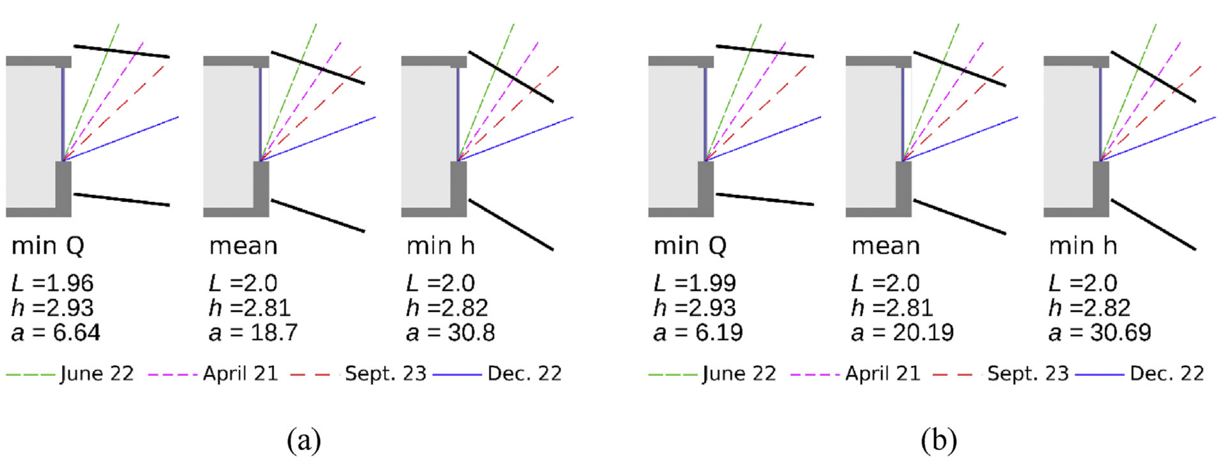

Fig. 7. Optimized geometries for: (a) double glazing and (b) triple glazing.

Table 6
Pareto shading configurations for triple glazing.

	h [m]	a [degree]	L [m]	Q_P [kWh/m^2]	N_{45} [h]	N_0
No Shading	–	–	–	43.16	284	315
Min-Q	2.93	6.2	1.99	31.74	193	48
Mean	2.81	20.2	1.94	33.99	134	50
Min-h	2.82	30.7	2.00	37.16	71	28

case without shading device are reported in Table 5, while Fig. 7(a) present graphically the obtained geometry along with the sun maximum altitude for specified days. The solution with the lowest number of hours with deployed blinds *min-h*, has a fixed shading device capable of blocking the sun rays for the large part of the year, while the solution *min-Q* reaches the minimum value of energy required, but with a higher number of hours with deployed Venetian blinds since the shading device is less obstructing. It is worth noting also that the presence of an external shading device, irrespective of the configuration, allows for less number of hours of blind deployed in horizontal position, with a value of 327 for the no shading case and six times lower in the other cases. Similar solutions are obtained for the triple glazing solution reported in Table 6. The triple glazing system shows a slight increase of primary energy consumption Q_P with respect to the double glazing. Fig. 7 (b) shows the optimized geometries for the triple glazing solutions, the best solution for energy consumption is the one with less obstructing fixed shading device. The contribution of the single terms presented in Eqn. (1) can be observed in Fig. 8 (a) for the double glazing and 8 (b) for triple glazing. The shading device can reduce the primary energy consumption with respect to the no shading case for about 24% in the double glazing solution and 26.5% for the triple glazing solution. In both cases the solution *min-h* shows a higher energy consumption due to the increase of heating and illumination loads not compensated by the decrease of cooling loads. Comparing Fig. 8 (a) and (b) it is worth noting that the cooling loads are higher for the triple glazing; while triple glazing moveable shading devices are less deployed due to the reduced direct solar radiation striking the sensors.

5.2. Daylighting analysis

During the initial design phases, the effect of shading devices on daylighting should be taken into account. Fig. 9 reports the

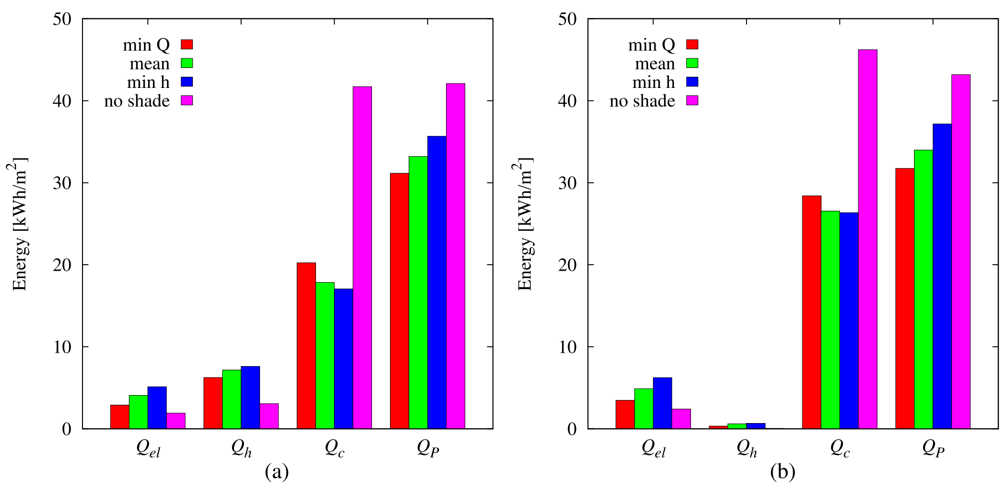

Fig. 8. Energy consumed for each service for (a) double glazing and (b) triple glazing.

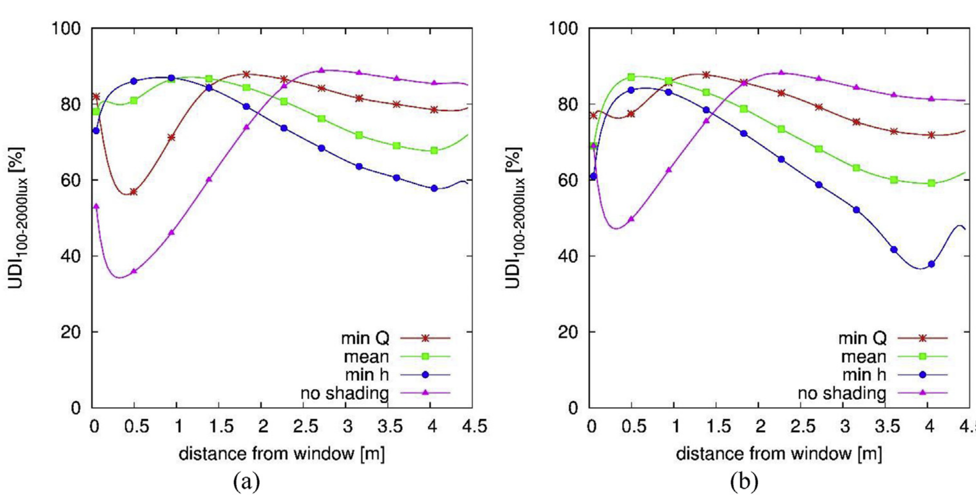

Fig. 9. Distribution of $UDI_{100\text{-}2000LUX}$ in the middle of the room for (a) double glazing and (b) triple glazing.

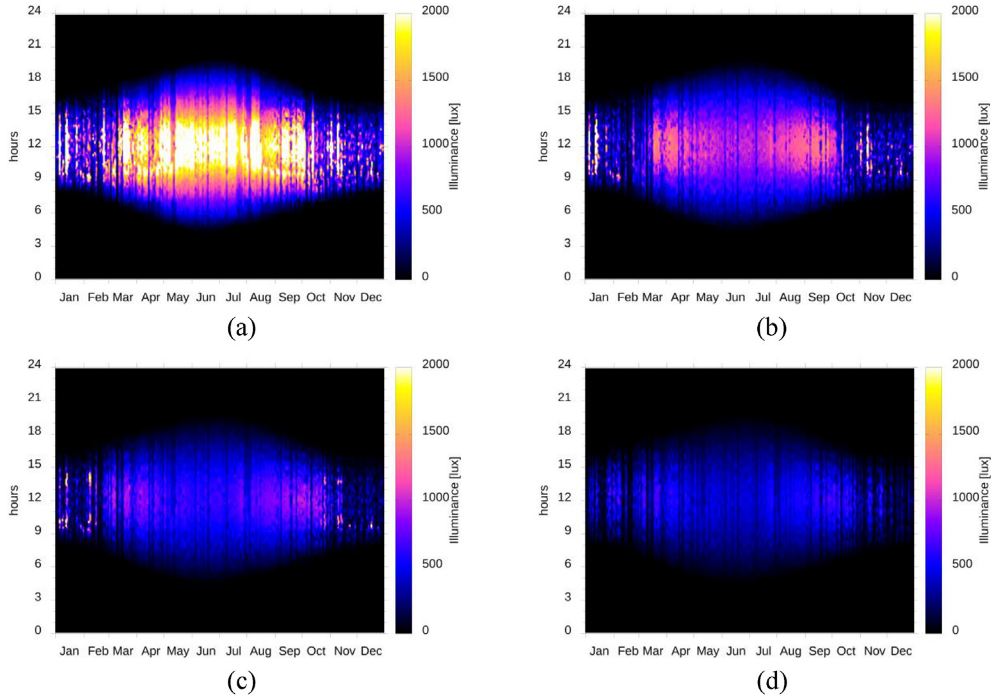

Fig. 10. Double glazing, temporal map of illuminance for a sensor at 2 m from the window for: case (a) without external shading, (b) case *min-Q* (c) case *mean* and (d) *min h*.

distribution of $UDI_{100-2000lux}$ among a line in the centre of the room at 0.85 m from the floor. $UDI_{100-2000lux}$ (Useful Daylight Illuminance) represents the percentage of time for which illuminance values between 100 lux and 2000 lux are obtained. For both cases the values near the window are higher for the *mean* and *min-h* cases thanks to the external shading device which reduce the direct irradiance. However, the *min-Q* case shows lower values near the window, but they increase obtaining values around 80% from 2 m onwards. The behaviour is common between the two glazing systems and is due to the excessive daylighting near the window for

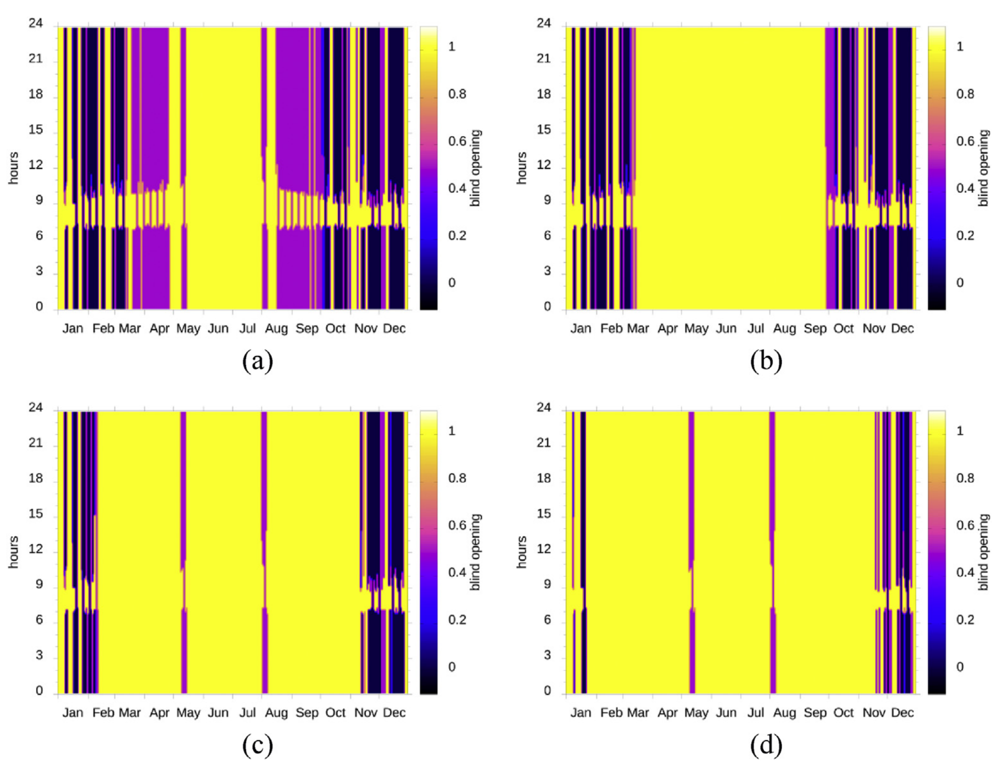

Fig. 11. Double glazing, temporal map of internal shading position for the case: (a) without external shading, (b) case *min-Q*, (c) case *mean*, (d) *min-h*.

the less shaded solutions, while far from it solution with less obstructing shading devices perform better. Comparing the two glazing solutions, near the window the triple glazing performs better thanks to the lower visual transmittance, while far from the window the values are higher for double glazing since in this case more daylighting can be obtained. Fig. 10 reports the temporal map of illuminance for a sensor 2 m far from the window for the double glazing, the plot allows a comparison between analysed cases and the no shading device case. Similar results are obtained for the triple glazing with values reduced due to the lower visual transmittance and therefore have not been included. The no external shading solution is the one with higher illuminance levels, in this case the shading is obtained only by the deployment of Venetian blinds. The *min-Q* solution Fig. 10 (b) shows the effect of the external shading in reducing the illuminance values also when Venetian blinds are not deployed, the other solutions reported in Fig. 10 (c) and (d) show similar results: the more obstructing external device allows for lower illuminance values throughout the year. Moveable shading devices are operated mostly during winter time, when the sun is low on the horizon, since in other positions the rays are blocked by the external panel, as shown in Fig. 7. The way blinds are manually operated is reported in the temporal map of Fig. 11, where a value of 1 means blinds up, a value of 0.5 blinds lowered in horizontal position and 0 blinds deployed with an inclination of 45°. There is a direct correspondence between the temporal map of illumination and the deployment of Venetian blinds. Inspecting Fig. 11 shows also how the manual deployment algorithm implemented in Lightswitch works: the blinds are opened at the beginning of the day and when closed by the user, due to excessive direct solar radiation, they remain in the same position for the rest of the day. Comparing Fig. 11 from (a) to (d) shows that the external shading system reduces the time in which high direct solar radiation occurs forcing an occupant to activate the moveable Venetian blinds.

6. Conclusion

A multi-objective optimization of an external shading device has been performed with the goal of minimizing the overall primary energy consumption and blinds activation hours in an office room using two different window systems featuring double and triple glazing. In order to reduce the optimization time an algorithm available in the modeFRONTIER code which couples genetic algorithms and response surface method has been used. The performance, in terms of optimization time and development of the Pareto front, has been compared to a well known genetic algorithm, showing that Pareto front can be identified with far less computational resources. The FAST algorithm allows therefore the extension of multi-objective optimization techniques to problems with large simulation times difficult to deal with classical genetic algorithms. Different codes have been used for carrying on the optimization: modeFRONTIER drives the optimization, DAYSIM computes internal illuminance and lighting electrical loads and ESP-r performs the building energy simulation. A set of optimal solutions have been obtained, with up to 26% reduction of primary energy consumption with similar results for double and triple glazing. The solutions obtained demonstrate that multi-objective optimization can be a powerful tool in building energy design, which helps designer identify different solutions among which to select the ones which best fit in the building design.

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Nomenclature

c	specific heat capacity [J/(kg K)]
d	shading device distance from the wall [m]
f	primary energy factor
g	Solar Heat Gain Coefficient
h	shading device height [m]
L	shading device width [m]
λ	thermal conductivity [W((m K)]
N	number of hours [h]
Q	energy [kWh/(m2 year)]
ρ	density [kg/m^3]
s	layer thickness [mm]
U	Thermal transmittance [W/(m^2 K)]
UDI	Useful Daylight Illuminance
a	shading device inclination [degree]
η	efficiency
T	light transmittance

Daysim parameters

ab	ambient bounces
ad	ambient divisions
as	ambient sampling
aa	ambient accuracy
ar	ambient resolution
ds	direct sampling

subscripts

c	cooling
d	solar direct
E	energy
el	electric
g	glass
h	heating
ill	luminaries
p	primary
V	visible
T	total
W	wall
45	inclined 45°
0	horizontal

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