Reducing thermal energy demand in residential buildings under Spanish climatic conditions: qualitative control strategies for massive shutter positioning

Juan Pablo San Martin ^(a), Maria C. Garcia-Alegre ^(a), Domingo Guinea ^(a)

^(a) Centre for Automation and Robotics, Spanish National Research Council (CAR,CSIC-UPM), Arganda del Rey, Madrid 28500, Spain.

Abstract.

The effects of dynamic controls on external massive shutter positioning are studied as refurbishment measure to reduce energy demand in residential buildings. This kind of shading device can not only regulate solar radiation, but it also provides additional thermal insulation that reduces heat conduction when closed. Based on their capability for controlling both processes, a comparison of different qualitative shutter positioning control strategies are proposed to minimize thermal energy demand. To this aim, a simulation model based on the constructive characteristics of an experimental building has been developed with TRNSYS. The results show that when more input variables are considered greater thermal demand reduction is achieved. However, the most relevant input variables for reducing thermal demand are solar radiation and real demand of the building. A large reduction in thermal energy demand is also displayed in the comparison between massive shutters, and non-massive blinds, increasing from 23% to 35%. Surprisingly, this improvement can be achieved using simple radiation-based control strategies, whereas the inclusion of heat conduction as control variable only improves the results by 0.2%. Therefore, there is no need to increase the complexity of the shading control of the massive shutters to take advantage of their insulation properties. The thermal energy reduction is comparable to the effect of refurbishment of an ordinary double-glazed window ($U=2.46 \text{ W/Km}^2$) with high-efficiency triple-xenon glazing ($U=0.59 \text{ W/Km}^2$).

Keywords: shading dynamic control strategies; shutters thermal resistance; building refurbishment.

1. Introduction.

The improvement of efficiency in energy consumption by the refurbishment of existing technology is one of the key points for the reduction of greenhouse gas emissions. This is especially interesting in the construction sector, where envelope restoration (including walls and windows) can reduce energy demand with a low economic impact (BPIE, 2011).

1.1. Thermal balance in residential buildings.

Buildings are among the principal consumers of energy, therefore they also have the highest potential to introduce savings in energy demand (EEA, 2015). In 2010, the energy demand of buildings represented 35% of the total primary consumption in the EU (IEA, 2013), forecasting half of the energy demand in 2030 (IEA, 2006). This energy is mainly consumed by residential buildings, raising 70% of the total energy demanded by buildings for EU countries (Pérez-Lombard et al., 2008). With regard to its final use, the energy required for thermal space conditioning represents 67.5% of total energy consumption in the residential sector, which is equivalent to 17% of total primary energy consumed worldwide (Lapillonne and Pollier, 2014). These high rates of consumption underline the relevance of improving the thermal efficiency of buildings to reduce global energy demand.

The thermal demand in buildings is mainly caused by unfavorable weather conditions that are transferred to the building through the envelope, which acts as an interface barrier between these two environments, acquiring a critical relevance for the minimization of the thermal demand. This is why the majority of the proposed solutions in building refurbishment are based on envelope restoration (Ortiz et al., 2015), including both walls and windows. The main refurbishment measure for walls is the implementation of a thermal insulated external layer. Regarding windows, most refurbishment studies have been focused on the improvement of glazing behavior. The study of new materials in windows (Wong et al., 2008), the improvement of the optical properties of glazing (Al-Kuhaili, 2004), and the rupture of thermal bridges in frames (Ibrahim et al., 2014) are the main research fields. These measures are characterized by static thermal behavior; that once implemented it is not possible to adapt to the specific building requirements.

Additionally, thermal refurbishment of windows can be carried out implementing optimally controlled blinds or shutters. On the contrary to previous mentioned restoration measures, the use of these active elements permits a dynamic response adapted to the thermal requirements of the building (Galasiu, 2002). For instance, blocking solar gains may be either positive or negative for energy savings, depending on the thermal needs of the building (positive for cooling and negative for heating). In this situation, dynamic blind control takes advantage of

solar gains whenever required. Consequently, the use of an active system for the dynamic control of energy transference can improve energy savings in comparison with static ones. It is also worth noting that measures to implement shutters optimally controlled entail less time and economic effort than the refurbishment by glazing replacement or walls insulation.

1.2. Review of blinds as energy saving element.

The use of blinds for improving internal comfort of buildings has been deeply proposed in literature. One of the main purposes of these devices is optimizing interior illuminance and reducing visual discomfort and glare, especially in office buildings. With the aim of optimizing these visual parameters, it has been analyzed the influence of the venetian blind geometry and tilt angle, with special attention to the windows-blind optical interaction (Tzempelikos, 2008). Similarly, other studies approaches for visual comfort assessment are the optimization of venetian blinds control, or the analysis of an innovative bottom-up roller blinds performance (Kapsis et al., 2010; Koo et al., 2010). However the majority of studies investigate the impact of shadow devices in the energy demand and thermal comfort in addition to the mentioned visual comfort. Palermo-Marrero et al. analyzed the effect of louvres in thermal demand for different locations such as Madrid, London or Cairo. They concluded that these devices improve thermal comfort and decrease thermal demand for all the analyzed locations, being greater in those with higher solar radiation (Palmero-Marrero and Oliveira, 2010). David et al. proposed an assessment index for comparing the performance of different conventional external shading devices in office building regarding both cooling reduction and visual comfort. They aimed to obtain a tool that easily allows to compare the pros and cons of using shadow devices (David et al., 2011). Similar studied was proposed by Hwang et al. where thermal comfort and cooling demand were assessed for different type of windows and overhang. Results illustrates the potential of building envelopes for energy saving and how the architects need to pay attention to their early design (Hwang and Shu, 2011). Finally there are also studies that analyze blinds performance considering only energy demand and thermal comfort criteria. For instance, Tzempelikos et al. assessed the influence of different type of blinds in thermal comfort developing a two-node thermal comfort model integrated in the global thermal model of a building. They concluded that regardless of glazing type, using a roller shade can improve comfort conditions by decreasing radiant temperature asymmetry and increasing operative

temperature (Tzempelikos et al., 2010). Opposite conclusion was obtained by Frontini et al., who displayed the possibility to reduce inner temperature with blind control (Frontini and Kuhn, 2012). Furthermore, Yao compares external and internal venetian blinds performance concluding that external ones improves results compared to internal, being preferable to low emissivity glasses (Yao, 2014b).

Most of the literature has concerned itself with the analysis and optimization of blinds performance for office building. These buildings are depicted by specific use schedules where the occupancy is given majorly in daylight hours and in fixed locations inside the building. This leads to a strong influence of visual comfort in blinds assessment, which is also illustrated in the major WWR (windows-wall ratio) that characterizes these buildings compared to residential ones. For this reason, literature assess blinds performance for optimizing energy demand and visual comfort at once (Da Silva et al., 2012; Shen and Tzempelikos, 2012; Singh et al., 2015; Tzempelikos and Shen, 2013). These two parameters present an opposite behavior as demonstrated Tzempelikos et al., where the influence of external roller blinds control in cooling demand and inner illumination was evaluated. They concluded that a balance between both parameters for optimally defining blind position was possible depending on building characteristics (Tzempelikos and Athienitis, 2007). Similar analysis was carried out by Nielsen et al., where inner luminosity and thermal demand were evaluated for fixed and automated venetian blinds compared to no use of shading (Nielsen et al., 2011). They demonstrated how the use of automated blinds notoriously improves daylight use. They also emphasized the need for dynamic and integrated building simulations to facilitate envelope design process. The importance of the double functionality of blinds (energy demand and daylight) is also illustrated in Breitenbach et al. where both thermal and optical properties of double glazing windows with integrated venetian blinds was formulated for an optimum characterization of these systems (Breitenbach et al., 2001). Conversely, Yun et al. approach for reaching a balance between thermal and visual comfort was the optimization of blinds control strategies. They concluded that cooling energy reduction by blind control is inversely proportional to the heating and lighting energy increments obtained. They also illustrated how blind control need to be specifically defined for season and thermal priority (Yun et al., 2014).

Despite major number of studies concerned office buildings, there is also literature regarding blinds use in residential sector. Kim et al. proposed an experimental configuration of an external shading device applied to apartment houses in South Korea. Results of energy savings for heating and cooling are compared to conventional devices. They remarked the advantages of external shading compared to internal ones since the internal device absorbs solar heat and radiates to the interior (Kim et al., 2012). On the other hand, Cho et al. analyzes cooling savings and economic feasibility of different shading devices to provide basic information for rational exterior shading planning when designing residential buildings (Cho et al., 2014). Yao analyzed thermal and visual performance of movable external shading for South façades in residential buildings. The results illustrates a notorious reduction of the energy demand and an improvement of the visual comfort compared to no shading device (Yao, 2014a).

One of the main discussions in literature is the correct modeling and evaluation of blinds control performed by user, needed to obtain accurate results of blinds influence in thermal and visual assessments. This issue is highlighted in Gunay et al., where a review of the different methods for evaluating building occupant's behavior (including manual blind control) is discussed, or in O'Brien et al., who reviewed the different methods to characterize blind use schedules in office buildings. Both concluded that occupants are not excessively concerned about blinds control except in case of visual discomfort. They do not optimally control blinds, thus a dynamic and automatized blind control could improve energy demand and visual comfort (Gunay et al., 2013; O'Brien et al., 2013). Similar conclusion is reached by Saelens et al. who compared modelled and real blind control. They affirmed that blind control automation lead to a notorious energy demand reduction compared to occupants control. This study also proposed modelling occupants' blind control in summer periods (inner temperature greater than 25°C) by the prioritization of thermal energy demand reduction instead of inner luminosity availability, assuming artificial lighting (Saelens et al., 2011). This assertion is used in present work considering that in hot climate conditions with elevated cooling demand (Spanish summers), shadow control main aim is to attenuate solar gains (causing cooling demand) instead of incrementing inner luminosity.

The benefits of shadow control optimization for reducing building energy demand has been frequently illustrated in literature (Da Silva et al., 2012; Kuhn et al., 2000; Lee et al., 1998;

Tzempelikos and Athienitis, 2007). However, this optimization is not trivial and different control strategies have been proposed according to several control variables. Van Moeseke et al. analyzed control strategies for external blinds based on incident radiation and inner temperature as control variables. They concluded that strategies based on both variables are shown to be more efficient than strategies based on solar irradiation or internal temperature alone (van Moeseke et al., 2007). Furthermore, Olbina et al. divided windows with venetian blinds in different parts proposing an automatic and independent split-control (Olbina and Hu, 2012). Similarly, Oh et al. propose to include thermal use periods (heating and cooling) as control variables to characterize the specific thermal needs of the building (Oh et al., 2012). This study shows the benefit of the multivariable blinds control strategies. Finally, Tzempelikos et al. compare four different control strategies for inner roller blinds in an office building considering energy consumption, luminosity and glares. Strategies are focused on luminosity control, where main control variables analyzed are inner luminosity, incident radiation and direct radiation. Despite the main purpose of this study is optimizing visual parameters, they remarked the huge influence of the control strategies in energy demand (Tzempelikos and Shen, 2013).

Based in the proven influence of the dynamic action on shadow devices for energy demand reduction, current work is focused on the optimization of the shadow control for minimizing thermal demand in residential buildings. To this aim a comparative analysis of thermal demand associated to different control strategies is proposed. These strategies are defined according to the most relevant variables that characterize both thermal transference in windows and building thermal needs. Notwithstanding literature has analyzed this topic regarding solar gains and luminosity control in office building, there is a lack of information about blinds performance optimization in the household sector. For this, present study assesses shadow performance in residential buildings where, due to the ease of their installation, they can be used both for new construction and for existing buildings as a thermal restoration element. Similarly, in literature blinds are usually characterized only by their optical properties, but few studies analyze the effect of the additional thermal insulation that some kind of shadow devices can provide once closed, which can make increase their energy saving potential. Therefore, the proposed shadow devices are characterized by a non-negligible thermal insulation (massive shutters) that permits

more advanced control on the thermal transference occurring in windows including solar radiation and heat conduction.

Despite one of the main purposes of shadow devices is to maintain inner visual comfort, in current study no luminosity optimization criteria are considered. The aim of this simplification is to deepen in the shutter assessment as energy efficiency element and analyze the performance of massive shutters compared to non-massive ones. Likewise, analysis is carried out for residential building, where luminosity comfort is less significant than in offices. This is partially owed to the usual activity performed in each type of building; office activity is characterized by a static positioning of occupant where glare discomfort or insufficient luminosity can occur more frequently than in residential building, where occupants adopt variable positioning. The no assessment of visual parameters in the proposed control strategies is also justified considering that shutter positioning controlled by energy demand reduction prioritization better describes usual occupants' behavior for Spanish climate, especially in summer periods, when shadows are usually closed to minimize solar gains despite an insufficient natural luminosity.

2. Thermal characterization of window shading devices.

Before defining proposed shutter control strategies, the thermal transference processes occurring in windows equipped with shadow devices are analyzed. The aim is to characterize thermally the shading devices and to select the one that permit a larger controllability in thermal processes to generate a greater reduction in energy demand. The thermal performance of a shading device can be characterized by two criteria:

- According to its thermal resistance, it can be divided into those designed only for shading purposes, without interference in conductive transference (non-massive blinds) and those characterized by a non-negligible conductive resistance (massive shutters).
- Regarding its location related to the windowpane they are classified in internal (including between glass disposition) or external.

The energy control purpose of non-massive blinds is to regulate heat gains caused by solar radiation. They are generally depicted by a thin surface with no insulation properties. One of the

most commonly used is the slat-type blind, or venetian blind. These blinds are formed by a set of parallel slats with a rotary movement that allows the entrance of direct radiation. The scheme of the transference processes occurring in windows endowed with this kind of blind is depicted in Fig. 1a.

Conversely, massive shutters are characterized by non-negligible thermal resistance, which generates an additional thermal insulation in windows once completely closed. The use of these devices allows the control of both the heat conduction and the solar radiation transference. Therefore massive shutters, especially those made of insulating materials, which increases thermal resistance, improve controllability of the thermal processes occurring in windows in comparison to non-massive blinds with only solar radiation control capability (Grynning et al., 2014). The thermal transference scheme for windows equipped with massive shutters is depicted in Fig. 1b. To achieve this additional insulation, the external massive shutter has to occupy the entire surface of the opening, avoiding any airflow between both sides of the shutter once closed. This fact, not only increases the insulation of the window by the addition of the thermal resistance of the shutter, but also creates an air chamber between glaze and shutter that helps to reduce heat conduction transfer (Oleskiewicz-Popiel and Sobczak, 2014).

Fig. 1. Energy transference processes diagram for windows with: (a) non-massive blinds, (b) massive shutters.

As massive shutters not only are able to regulate solar radiation but also heat conduction, they will in all probability generate greater reductions in energy demand than non-massive blinds. Consequently massive shutters are the shading device selected for carrying out the control strategies analyzed in this paper.

Regarding the second classification criteria, the location in relation to the window pane, internal shading devices worsen radiation control, due to the greenhouse effect generated by the reflection of thermal radiation (infrared) on the inner side of the glass. If closed, when radiation loads have to be reduced, internal shading devices block solar radiation inside the building, and the blind, heated by this radiation, emits longwave radiation back into the room and the glazing, which is also reflected it back into the building. The heat loads therefore rise, which is precisely the opposite of the desired effect. In this case, external devices avoid that greenhouse effect through the inclusion of the shading surface externally. Optimally, this reduces the heat loads due to solar radiation (Yoon et al., 2014), so, the use of internal shading leads to an increment of the internal heat loads in comparison with the use of external devices (Atzeri et al., 2014; Kim et al., 2012). In turn, heat convection patterns in windows-shutter system are also altered by the position of the shadow. Similarly to the previously described radiative balance in shutters, for inner positioning, the solar radiation heats the shutter located inside the building once closed, incrementing shutter temperature and the heat convection inside the building (Almeida and Naylor, 2011; Avedissian and Naylor, 2008; Cuevas et al., 2010; Dalal et al., 2009; Shahid and Naylor, 2005). However, for external location heat convection variations can be considered negligible compared to heat conduction and solar radiation, especially for massive shutters. In

this case, when shutter is closed and external layer of shading is heated by solar radiation, heat convection is generated externally to the building. Solar gains affect the external layer of the shutter and heat conduction is reduced by the shutter thermal insulation. Consequently, the inner layer of the shutter is not notoriously heated. This avoids high thermal gradient in the air chamber, and consequently the heating of the glass by the convection inside the air gap is minor. Thus, variations of convective patterns caused by external massive shutter positioning barely affect the building thermal balance. Therefore external shadow positioning avoids heat gains by the convection generated in case of internal location.

3. Simulation model.

A comparative analysis of control strategies for external massive shutters is proposed for minimizing thermal demand in residential buildings. To correctly assess this, information of annual demand is needed for including all weather variations during the year. Due to the complexity of obtaining experimental results of the building demand for different controlled conditions during such long periods, a simulation study is proposed. The model for testing the shutter control strategies was developed with TRNSYS (TRNSYS, n.d.). This software is specialized in energy simulation, including production, storage and consumption approaches. It also integrates a tool for building simulations where thermal demand of buildings can be assessed. The selection of TRNSYS for carrying out this work is based on its capability for modelling thermal performance of shutter, allowing an easy comparison of the annual thermal demand obtained with different control strategies. Moreover TRNSYS has been numerously contrasted in literature for shadow devices control assessment regarding building energy demand (Palmero-Marrero and Oliveira, 2010; Saelens et al., 2011; van Moeseke et al., 2007).

3.1. *Methodology*

The strategies are evaluated for fixed conditions of a residential building including its characterization, time and calendar and weather information, all modeled in TRNSYS. The only variable conditions of the model are the shutter features (massive or non-massive). This constitutes the reference building model where the shutter positioning control strategies are individually implemented. All the strategies use as input variables the weather conditions and the time and calendar data provided by the typical meteorological year database and simulation

environmental variables (time step, time of the year, etc.) defined in TRNSYS. Simulation provides the annual thermal energy consumption for each strategy, classified by use (heating, cooling, humidification and dehumidification). The demand is defined to maintain the inner building conditions between the selected comfort limits: 20-27°C for temperature, and 30-70% for humidity (De Dear and Brager, 2002). The energy demand reductions obtained applying different control strategies are stored for subsequent analysis. A data flow scheme of the simulation processes, is illustrated in Fig. 2.

The logical equations that define each strategy are illustrated in chapter 4. Based on these logical rules shutter positioning is discretized in CLOSE and OPEN. Additional a HALF-OPEN position is defined to assess the influence of incrementing luminosity in the building thermal demand.

Fig. 2. Data flow scheme of the simulation processes

3.2. Building characterization.

The building model is based on the characteristics of the experimental prototype at the LERH ("Laboratorio de Energías Renovables e Hidrógeno") of the Center for Automation and Robotics (CAR, CSIC-UPM) at the Arganda del Rey campus in Madrid, Fig. 3a. These characteristics

include geometry, orientation, layout and the composition of both walls and windows. The building has a floor layout with five divisions: bedroom, bathroom, kitchen, living room, and hall. The external walls of the building are rotated 10° counterclockwise in relation to the Cardinal points. The average height of the inner spaces is 2.72m, and the total area of the building is 67 m². The individual area and external orientations of each room are shown in Table 1a. The external walls are provided with windows with different dimension and orientation, as shown in Table 1b.

Table 1(a). Room area and orientation (rotated 10° counterclockwise). (b) Area and orientation of external windows.

Space	Area (m ²)	Orientation
Hall	8.40	North and East
Bathroom	4.70	North
Kitchen	6.38	North
Bedroom	13.87	North and West
Living room	33.77	South, East and West

Hall	m ²	Bedroom	m ²
North	0	North	1.93
East	1.63	West	1.12
South	0		
Bathroom		Living room	
North	0.25	East	3.67
Kitchen (m²)		South	6.78
North	1.35	West	2.82

The thermal transmission coefficient of the external walls is $U=0.40\text{W/Km}^2$, while the coefficients of both the roof and the floor are $U=0.34\text{ W/Km}^2$ and $U=0.30\text{W/Km}^2$, respectively. The windows are formed of a 6/8/6 double glazing unit with a thermal transmission coefficient of $U=2.46\text{ W/Km}^2$. Additionally, a highly efficient triple-glazing (4/16/4/16/4) unit was used in the simulation to compare the influence of massive shutters on both types of glazing. This point is discussed in paragraph 5. The transmission coefficient of this triple glazing is $U=0.59\text{ W/Km}^2$.

A forced ventilation system was also modeled. Air renovation is defined according to Spanish health standards regulation (CTE HS 3, 2009). Minimum air flow was calculated by taking into account room use, numbers of inhabitants per room, and the preferential airflow direction inside the building in view of applicable health standards. Table 2 shows the minimum flow values imposed in the regulations. Infiltration was considered negligible compared to the thermal contributions of forced ventilation.

Table 2. Air-renovation rates according to Spanish health standards.

Zone	Minimum Flow (l/s)	Calculated air renovation rates (1/h)
Kitchen	2 per m ²	4.2
Bathroom	15 per zone	4.2
Hall	-	0.9
Bedroom	5 per habitant	0.9

Living room	3 per habitant	0.9
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Internal heat gains generated by occupancy, lighting and electric devices were calculated according to building surface and occupancy (ASHRAE, 2009). These gains, affect both heat and humidity conditions. Inhabitants are calculated according to the number of rooms: 1 room-2 inhabitants. Individual occupancy profiles are defined for each room.

3.3. Calendar, time and weather conditions.

The thermal energy demand of buildings is strongly influenced by weather conditions. These are characterized by periodic seasonal cycles. Consequently, the simulation was for a whole year, with time steps of 1 hour.

Datasets of a typical meteorological year for Madrid obtained from the TRNSYS MeteorNorm database libraries were used as the input weather conditions. The weather in and around Madrid is characterized by intermediate conditions between Continental and Mediterranean climate with elevated seasonal changes. Minimum temperatures are below 0°C for cold months and maximums are higher than 30°C for hot ones. The thermal energy of the buildings is therefore strongly influenced by the seasons. In that regard, a distinction between thermal uses needs to be considered: the hot period is defined between May 16th and October 15th (cooling demand), and the cold one defined for the rest of the year (heating demand).

3.4. Thermal properties of massive shutters.

The massive shutters selected for this study are made of polyvinyl-chloride (PVC) sheets. The frames are integrated in the external window jambs avoiding gaps at the edges. Once closed, no air filtrations are possible on both sides of the shutter (Fig. 3b).

The selection of external massive shutters is based on the capability to control not only solar radiation but also heat conduction transfer. Therefore, it is necessary to define both optical opacity and thermal resistance. The first parameter, defined as the percentage of solar radiation that falls on the shading when it is closed, is defined as 1 if closed, i.e., no radiation passes through the shutter, and 0 if open. The second one is characterized by the thermal transmission coefficient U . Two relevant data sources have been found in the literature: $U=4.8 \text{ W/Km}^2$

(Mexican Association of Windows and Enclosures., n.d.), and $U=4.6 \text{ W/Km}^2$ (Wood et al., 2009). The parameter that was finally selected, $U=4.7 \text{ W/Km}^2$, is an average of these values.

Fig. 3. (a) Experimental building (CAR_CSIC_UPM). (b) Massive shutters implemented in the closed position.

4. Qualitative control strategies for shutter positioning.

A comparative analysis is performed between the different shutter control strategies simulated. Regarding weather conditions, two variables are needed to set the control strategies proposed: the incident radiation and the ambient and building temperatures. Incident radiation is a necessary parameter for the automatization of any kind of shading device. However temperatures are only relevant where the shading device also influences heat conduction. This leads to an increment of the data acquisition requirements in case of experimental implementation. The difference between the minimum weather data needed to carry out the qualitative shutter control strategy of any shading device (only incident radiation) and the extra measures needed to control heat conduction (additional temperature data) is used as the initial classification criterion for the proposed strategies. The first tactics are defined as simple, because radiation is the single weather information required, whereas strategies are defined as complex, if temperature information is also needed. The aim is to compare the extra energy savings obtained using complex strategies with those obtained using simple ones. Optimized simple and complex strategies are selected to carry out subsequent comparison.

Simple decision strategies are focused only on the regulation of radiative gains. As the climatic conditions of Madrid are characterized by extreme seasonal changes, thermal demand usage varies greatly during the year. The shutter control strategies take account of these changes through the integration of the seasonal priority for thermal energy use as input variable. Only the current time and the typical meteorological information on the building location are required to

characterize this new variable, without need of additional meteorological data. Consequently the control strategy obtained with the inclusion of this variable is categorized as simple.

On the other hand, complex strategies make use of information on both the external and the internal temperature of the building for defining additional control variables. The heat conduction transference is defined comparing these two temperatures, whereas the inner building temperature provides information on the energy demand of the building; if lower than 20°C, there is heating demand, and if greater than 27°C there is cooling demand. The information is included to define the thermal requirements of the building in the course of the simulation.

Therefore, the number of proposed input control variables progressively increased from 1-2 in simple strategies (solar gains and thermal use period) to 3-4 in complex strategies (solar gains, thermal use period, heat conduction and real demand of the building). The use of these multiple variable qualitative control strategies provides dynamic control of the shutters, and improve their thermal response compared with both non-controlled and mono-variable control strategies (Kang et al., 2015).

All the previous analyzed strategies only rely on energy variables; however one of the main purposes of the shading devices is daylight control. The inclusion of that parameter is done through an illuminance correction factor added to the previously defined optimum simple and complex strategies, to guarantee inner solar illumination in the case of energy and daylight use optimization discrepancies. The scheme of the different strategies under analysis is displayed in Fig.4.

Fig. 4. Simulation of simple and complex qualitative control strategies.

4.1. Simple qualitative shutter control strategies.

Initially defined simple strategies are analyzed, where only meteorological information of solar radiation is required as input variable.

4.1.1. One input variable: solar radiation.

Solar radiation is the most relevant variable to take into account in the shutter control strategies, which is responsible for both radiative energy gains and daylight incidence inside the building. These two variables are dependent, so it is not possible to reduce radiative gains without a daylight decrease. Initially, only the thermal energy optimization criterion is considered with no daylight considerations. The shutter position output variable is defined by two qualitative values: OPEN, where the total incident radiation penetrates through the shading, and CLOSE, where radiation is completely blocked. Two strategies based only on solar radiation as the input variable are proposed:

- Strategy Str_A pursues a reduction in the heating demand. In this case, shutters are CLOSE at night, when incident radiation is lower than the defined threshold. This action optimizes solar heat gains maintaining shutters OPEN when there is radiation.
- Strategy Str_B is focused on cooling demand reduction. Thus, the shutters are CLOSE if incident radiation surpasses the defined limits, during daytime periods. The aim is to reduce radiative heat gains. During nighttime periods, the shutter position is OPEN.

Former shutter qualitative control strategies are displayed in Fig.5. The input control variable is the total horizontal solar radiation with a limit value of $R_{lim} = 50W/m^2$.

4.1.2. Two input variables: solar radiation and thermal use period.

Shutter positioning permits major or minor radiative contributions to the heat loads of the building, which either reduce or increase thermal demand, depending on the building requirements directly related to the weather conditions. In cold periods the radiative heat loads contribute to reduce the heating energy demand, and Str_A behaves better, meanwhile in hot seasons, these heat loads increment cooling and Str_B provides better results. These points illustrate the relevance of the dynamic shutter control proposed for climates with abrupt seasonal weather conditions, such as Madrid. Similar conclusion was presented by Oh et al. (2012) who mentioned the importance of taking into account the seasons for a correct control of shadow performance (Oh et al., 2012). The thermal use period that defines expected demand for these periods is incorporated in the shutter control strategy as an input variable: a heating reduction priority is defined for cold periods and a cooling reduction priority for hot seasons. The control action on this control strategy, defined as Str_C, is depicted in Fig. 5. The different decision possibilities are enumerated in parentheses for each control strategy. The number of total possibilities are defined by 2^n , where n is the number of input control variables. For instance, only two possible control situations can occur in Str_A and Str_B ($Rad > R_{lim}$ or $Rad < R_{lim}$) which are labeled A1-A2/B1-B2, while Str_C includes four possible situations, depending on the combination of radiation and the control criteria for priority periods of thermal use.

The qualitative shutter position control strategies shown in Fig. 5 can be also formulated by a set of crisp rules:

Str_A: IF $Rad > R_{lim}$ THEN shutter=OPEN (A1)

IF $Rad < R_{lim}$ THEN shutter=CLOSE (A2)

Str_B: IF $Rad > R_{lim}$ THEN shutter= CLOSE (B1)

IF $Rad < R_{lim}$ THEN shutter= OPEN (B2)

Str_C: IF thermal use period= hot AND $Rad > R_{lim}$ THEN shutter=CLOSE (C1)

IF thermal use period=hot AND $Rad < R_{lim}$ THEN shutter=OPEN (C2)

IF thermal use period=cold AND $Rad > R_{lim}$ THEN shutter=OPEN (C3)

IF thermal use period=cold AND $Rad < R_{lim}$ THEN shutter=CLOSE (C4)

The selection of the period depends on the local climate conditions of the building location. For the simulated weather conditions of Madrid, the strategy Str_A displays better results between June and September; meanwhile Str_B shows a greater reduction of the thermal demand between November and April. Seasonal transition takes place in October and May, providing similar thermal demand reduction for both control strategies. Therefore, the coldest halves of these months are defined as cold period and hottest halves as hot period.

Fig. 5 Qualitative shutter control strategies Str_A, Str_B and Str_C. $Rad > R_{lim}$ indicates solar gains availability; cold period indicates heating priority; hot period indicates cooling priority.

4.2. Complex shutter position control strategies

As mentioned earlier, massive shutters provide extra thermal insulation once closed. This heat conduction transference has been included as input variable in the control strategy, to optimize the energy saving obtained by this additional insulation. Both inner and external temperatures are required for the correct characterization of this thermal process to show the conductive flux direction. This additional temperature data also provide information on the real demand of the building, characterized by the inner temperature in comparison to the temperature comfort band. This is also used as an input control variable.

These new input variables are added to the most complete simple strategy previously defined Str_C, where the heat radiation and the thermal use period variables were included.

4.2.1. Three input variables: solar radiation, thermal use period and heat conduction.

Heat conduction is included in the shutter control strategy as input variable in addition to the solar radiation and the thermal use period. The strategy that includes these three input variables is defined as Str_D, and it is illustrated in Fig. 6. The heat conduction control is performed by evaluating the difference between inner and external temperature, when conductive heat flux is transferred from high-to-low temperatures. If the internal temperature is greater than the external one, there would be thermal conductive losses, and in the opposite case, conductive gains. These thermal conductive gains/losses improve or worsen energy saving depending on building thermal conditions. For instance, conductive heat losses cause energy savings if there is cooling demand, but they increment energy consumption for heating demand. Therefore, in the first case, the shutter position must be OPEN to increment heat conduction, but CLOSE in the second case to minimize energy losses.

Heat conduction control can differ from solar radiation control. Thus, on a sunny day in winter with cold external temperatures, the heat conduction control gives the shutter position as CLOSE to reduce conductive losses, but the solar radiation control strategy points to the OPEN position to optimize solar gains. In these cases it has been prioritized the solar radiation based criterion due to its greater influence in the thermal demand. The different cases (D1 to D8) of the strategy Str_D are displayed in Table 3.

Fig. 6 Qualitative shutter control strategy Str_D. Rad > R_{lim} indicates solar gains availability; T_{in} > T_{out} indicates conductive heat losses; cold period indicates heating priority; hot period indicates cooling priority.

Table 3. Advantages and drawbacks of different control strategy cases Str_D: D1 to D8.

Case	Output control variable values	Advantages	Drawbacks	Example
D1	CLOSE Prioritization of radiation.	Reduction of gains by solar radiation	Inefficient use of daylight Reduction of losses by heat conduction.	First hours after sunrise hot period daytime
D2	CLOSE	Reduction of gains by solar radiation and heat conduction	Inefficient use of daylight	Hot period daytime
D3	OPEN	Increase of losses by heat conduction	-	Hot period nighttime
D4	CLOSE	Reduction of gains by heat conduction	-	Hot period, extremely hot nighttime
D5	OPEN Prioritization of radiation.	Increase of gains by solar radiation. Use of daylight	Increase of losses by heat conduction.	Cold period daytime
D6	OPEN	Increase of gains by solar radiation and heat conduction. Use of daylight.	-	Cold period daytime
D7	CLOSE	Reduction of losses by heat conduction	-	Cold period nighttime
D8	OPEN	Increase of gains by heat conduction	-	Warm cold-period nighttime (unlikely)

4.2.2. Three input variables: solar radiation, thermal use period and real demand.

The previously defined thermal use periods differentiate demand in two seasons: cold (heating demand) and hot (cooling demand). However, the months of seasonal change between hot and cold, where both kinds of thermal demand can occur, are not well defined using this binary

discretization of the year. Besides, unexpected demand can occur; cooling in cold periods or heating in hot periods. To prevent these situations a new variable has been added to the shutter control strategy, the real demand of the building, which can be described in terms of the inner temperature. If the inner temperature decreases below the lower limit, heating is demanded, meanwhile if it is higher than the upper limit, then cooling is required.

This new variable provides information on the instantaneous real demand of the building, unlike the thermal use period variable that only provides information on the expected demand of the period. Consequently, it is prioritized in the control strategy. Therefore, when the building demands thermal energy, the thermal use period control variable is not used, but if the inner temperature is within the comfort band, which means that there is no thermal demand, then shutter control becomes dependent on the thermal use period priority. This new strategy, defined as Str_E is displayed in Fig. 7, while Table 4 shows the different possible cases.

Fig. 7 Qualitative shutter control strategy Str_E. $Rad > R_{lim}$ indicates solar gains availability; cold period indicates heating priority; hot period indicates cooling priority.

Table 4. Advantages and drawbacks of different cases in strategy Str_E: E1 to E8.

Case	Output control variable value	Advantages	Drawbacks	Example
E1	OPEN	Increase of gains by solar radiation. Use of daylight	-	Cold daytime
E2	CLOSE	Reduction of thermal losses	-	Cold nighttime
E3	CLOSE	Reduction of gains by solar radiation	Inefficient use of daylight	Hot daytime
E4	OPEN	Increase of refrigeration	-	Hot nighttime
E5	CLOSE	Reduction of gains by solar radiation	Inefficient use of daylight	Hot period daytime
E6	OPEN	Increase of refrigeration	-	Hot period nighttime
E7	OPEN	Increase of gains by solar radiation. Use of daylight	-	Cold period daytime

4.2.3. Four input variables: solar radiation, thermal use period, heat conduction and real demand.

This strategy is defined by taking into account the four previously analyzed variables: solar radiation, thermal use period, heat conduction, and real demand. As mentioned, whenever a discrepancy arises, solar radiation control is prioritized to heat conduction, and real demand to thermal use period. Fig. 8 shows the new strategy (Str_F) where the different cases are described in Table 5. It may be observed that cases F9-F16 are a repetition of Str_D and the same comments are valids.

Fig. 8 Qualitative shutter control strategy Str_F. Rad > R_{lim} indicates solar gains availability; T_{in} > T_{out} heat conductive losses; cold period indicates heating priority; hot period indicates cooling priority.

Table 5. Advantages and drawbacks of different cases for strategy Str_F: F1 to F16.

Case	Output control variable values	Advantages	Drawbacks	Example
F1	OPEN Prioritization of radiation.	Increase of gains by solar radiation. Use of daylight	Increase of losses by heat conduction	Cold period (daytime)
F2	OPEN	Increase of gains by solar radiation and heat conduction. Use of daylight.	-	Cold period (sunny day)
F3	CLOSE	Reduction of losses by heat conduction	-	Cold period (nighttime)
F4	OPEN	Increase of gains by heat conduction	-	Warm cold-period (nighttime) (unlikely).

F5	CLOSE Prioritization of radiation.	Reduction of gains by solar radiation	Inefficient use of daylight Reduction of losses by heat conduction	First hours after sunrise of a hot period (daytime)
F6	CLOSE	Reduction of gains by solar radiation and heat conduction	Inefficient use of daylight	Hot period day
F7	OPEN	Increase of losses by heat conduction	-	Hot period night
F8	CLOSE	Reduction of gains by heat conduction	-	Extremely hot night
F9-F16	Repetition of Str_D			

4.3. Illuminance prioritization

All of the previous shutter position control strategies are defined in accordance with their energy saving optimization criterion. This leads to situations where there is daylight availability but the shutters are set to the CLOSE position. This constitutes an inefficient use of natural illumination, associated with an increment in the electric demand for lighting. To balance these two opposite needs (energy saving and natural illumination), a new HALF-OPEN shutter position is allowed.

Study carried out by Alawadhi et al. (2015) shows that sufficient illumination is achieved for at least 5 hours per day by opening the shutter by less than a quarter of its length, despite a high increase in the heating demand (Alawadhi, 2015). According to this conclusion, and with the aim of guaranteeing sufficient illumination for a long period, but trying to avoid excessive radiative solar gains, a new shutter position HALF-OPEN is defined as opening the shutter to one half of the height of the window. In this case, as the shutters are not completely closed no extra resistive layer is added to the window, and only solar radiation control is allowed. For this new position the opacity is defined as 0.5.

The addition of this new output variable in the model is tested for strategies Sr_C and Str_F, the most complete proposed simple and complex control strategies respectively, and therefore, where the major energy saving are expected. To do so, the control strategy cases C1, F5, F6, F9 and F10, where there is a discrepancy between thermal savings and daylight, are redefined to the new shutter position HALF-OPEN. Strategies that arise from using this variation are defined as Str_C_Lum and Str_F_Lum.

5. Shutter control strategies application for alternative heat conduction conditions.

Previous Str_C_Lum and Str_F_Lum are defined as representative of simple and complex control strategies respectively and are used to evaluate energy savings obtained with shutter

positioning control for alternative heat conduction conditions. These include the use of non-massive blinds and the use of high efficiency triple-glazed windows. Table 6 summarizes the nomenclature and heat conduction conditions of the new models.

Table 6. Labels and heat conduction conditions in the models.

Model Label	Strategy	Massive shutter	Window glazing
Str_C_lum	Str_C_Lum	YES	DOUBLE
Str_C_Lum_non-M	Str_C_Lum	NO	DOUBLE
Str_C_Lum_3	Str_C_Lum	YES	TRIPLE
Str_C_Lum_non-M_3	Str_C_Lum	NO	TRIPLE
Str_F_Lum	Str_F_Lum	YES	DOUBLE
Str_F_Lum_non-M	Str_F_Lum	NO	DOUBLE
Str_F_Lum_3	Str_F_Lum	YES	TRIPLE
Str_F_Lum_non-M_3	Str_F_Lum	NO	TRIPLE

5.1. Control strategies for non-massive blinds.

One of the aims of this study is the evaluation of the additional energy saving obtained by the dynamic thermal resistance of massive shutters compared to non-massive ones. Previous strategies include input variables that are able to qualitatively control heat conduction processes in massive shutters, which permits an evaluation of the savings these control processes obtain in thermal energy. However it provides no information on the savings generated by the use of massive shutters instead of non-massive blinds. To carry out this comparison, Str_C_Lum and Str_F_Lum were evaluated using blinds with no thermal resistance (non-massive blinds). They are given the suffix “non_M”, and the results are compared with those previously obtained for massive shutters. In the new models, the additional resistance of the shadows devices is eliminated by maintaining their opacity characterization: 1 for CLOSE, 0.5 for HALF-OPEN and 0 for OPEN. The remaining model conditions are left unchanged.

5.2. Control strategies for high-efficient glazing.

As an alternative to massive shutters, increased insulation of the windows can be achieved through improvements in the thermal resistance of the glazing. It is a commonly used refurbishment solution that reduces heat conduction losses in the absence of a dynamic control option. So, the previously modeled windows ($U=0.59 \text{ W/Km}^2$) were replaced by high efficiency triple-xenon filled window panes (4/16/4/16/4), to analyze this influence. Simulations were performed using both massive shutters and non-massive blinds to compare the improvement in

thermal energy reduction caused by massive shutters in this type of window. The labels for these models have “_3” as suffixes, added to the names of the previous models: Str_C_Lum_3, Str_F_Lum_3, Str_C_Lum_non-M_3 and Str_F_Lum_non-M_3.

6. Simulation results and discussion.

The annual demand by use for the different control strategies and alternative proposed models are shown in Table 7. The first results point to the negligible influence of humidity demand representing only 2.2% of the total demand under the climate conditions in Madrid. Consequently, no humidity considerations are included in results analysis.

Table 7. Summary of heating, cooling humidification and dehumidification energy demand for the different simulations of the control strategies. The reduction percentage is displayed for heating, cooling and total thermal energy with regard to the reference model (without shading devices).

Model	Demand	Heating		Cooling		Hum.	Dehum.	Total	
		[kWh]	%	[kWh]	%	[kWh]	[kWh]	[kWh]	%
Reference		3755	-	2424	-	141	0	6320	-
Str_A		3090	-17.7	2521	+4.0	144	0	5754	-8.9
Str_B		7743	+106	4	-99.8	61	7	7815	+23.7
Str_C		3676	-2.1	255	-89.5	141	7	4080	-35.4
Str_D		3663	-2.4	258	-89.4	141	8	4070	-35.6
Str_E		3505	-6.7	105	-95.7	132	4	3746	-40.7
Str_F		3497	-6.9	105	-95.7	132	4	3738	-40.8
Str_C_Lum		3185	-15.2	842	-65.3	142	0	4169	-34.0
Str_F_Lum		3284	-12.5	652	-73.1	134	0	4071	-35.6
Str_C_Lum_non-M		3919	+4.4	816	-66.3	138	0	4873	-22.9
Str_F_Lum_non-M		4040	+7.6	648	-73.3	131	0	4819	-23.8
Reference_3		3387	-9.8	902	-62.8	94	0	4383	-30.6
Str_C_Lum_3		2794	-25.6	396	-83.7	119	0	3309	-47.6
Str_C_Lum_non-M_3		2895	-22.9	393	-83.8	118	0	3406	-46.1
Str_F_Lum_3		2821	-24.9	347	-85.7	116	0	3285	-48.0
Str_F_Lum_non-M_3		2924	-22.1	348	-85.6	116	0	3387	-46.4

Thermal energy demand obtained without shutter inclusion in building model is used as reference to quantify the savings obtained with each shutter control strategy. This reference demand is displayed in Fig. 9 including monthly discretization by use (cooling, heating, humidification and dehumidification). The monthly break-down of the results shows the seasonal variations of the climatic conditions. Heating demand in the periods January-April, and November-December, while cooling demand between June and September all stand out. For May and October, both thermal uses display similar values. This differentiation is used to define the thermal use period input variable.

Fig. 9 Reference model: monthly thermal energy demand by use.

The monthly results of the thermal energy demand for the shutter position control strategies are presented in Fig. 10. On the one hand, shutter control strategy Str_A sets the output control variable as CLOSE at nighttime, which reduces thermal losses and generates heating savings in cold months. Conversely, a slight increase in heating is shown in the summer months compared to the reference model. The total energy saving obtained with strategy Str_A is 8.9%. On the other hand the shutter position control strategy Str_B defines the shutter as CLOSE during the daytime periods, to avoid solar gains. This position reduces the cooling demand in summer almost completely, but greatly increases the heating demand in winter, provoking an increase of 23.7% in total demand. Shutter position control strategy Str_C takes advantage of the benefits of previous strategies by the combination of the heating reductions in cold periods of the strategy Str_A, and the cooling reductions in hot period of Str_B, with a total demand reduction of 35.4%. Fig. 10 shows how shutter position control strategy Str_C fits with Str_A for cooling periods and with Str_B for heating periods. Thus, the inclusion of the thermal use period variable greatly improves the thermal energy savings, compared with those of a simple shutter control strategy based only on the incident radiation.

Shutter strategy Str_D, where heat conduction control is integrated as input variable, gives rise to an extra 0.2% of reduction in the thermal energy demand compared to the shutter control strategy Str_C, due to better use of the insulation properties of the shutters. The low additional thermal energy saving obtained by the addition of the heat conduction as an input control variable is remarkable.

Strategy Str_E includes real demand as an additional variable in the shutter control. It shows an extra thermal energy demand reduction of 5.3% compared with the strategy Str_C, reaching a total reduction of 40.7% with respect to the reference model. This decrease in energy demand mainly appears during the months of seasonal transition (May, June, September, and October), where both cooling and heating energy are demanded, and the dynamic behavior provided by the use of the real demand as input variable improves the results obtained with the thermal use periods variable. Alternatively, a slight increase in the total demand is observed compared to strategy Str_C for some months, such as November. This increase is due to variations in the thermal balance of the building generated by the prioritization of the real demand variable, rather than the thermal use period variable included in shutter control strategy Str_E. During September and October the use of real demand as an input variable leads to a significant decrease in cooling demand, which means that the average temperature of the building has decreased. This effect is accumulated by means of building thermal inertia, and in November, when heating energy is demanded, the temperature of the building is lower than that obtained with previous strategies and therefore the thermal energy demand increases.

Finally, the shutter position control strategy Str_F includes a combination of all the input variables of strategies Str_D and Str_E. The results show similar energy consumption compared to that of strategy Str_E, with a 40.8% of total saving. This result agrees with the conclusion obtained in Str_D where no significant reduction was appreciated when the heat conduction input variable was included. Therefore the thermal energy demand decrease generated by using strategy Str_F mainly appears during the months of seasonal change due to the integration of real demand as an input variable.

In summary, shutter position control strategy Str_C appears to be the optimum simple strategy, while strategy Str_F showed the highest thermal energy reduction for all complex strategies. The thermal energy savings obtained with the complex strategy were 5.4% higher than with the simple one.

The inclusion of the illuminance prioritization in the shutter position control strategies leads to an increase of the total energy demand of 1.9% and 5.3% for Str_C and Str_F, respectively, caused by the rise of the solar radiation gains in hot periods that leads to an intensification of

the cooling demand. Results are shown in Fig. 10. Despite this increment, the thermal energy reductions compared with those of the reference model exceed 35%. It is also noteworthy the reduction in heating demand observed in the autumn months. This is caused by the thermal inertia of the building. The HALF-OPEN position of the shutter increases the solar gains in summer compared with the CLOSE position. These solar gains increment the long-term average temperature of the building by means of its thermal inertia and they help to reduce heating demand at the beginning of the cold period.

Fig. 10. Simulated thermal energy demand for the different shutter control strategies.

Regarding alternative heat conduction conditions, the comparison between massive and non-massive shutters shows an additional thermal energy reduction of 11.1% and 12.8% for simple and complex strategies respectively, provided by the additional resistance of the massive shutters. Fig. 11 illustrates how these differences are mainly generated in heating demand (cold months), due to a better insulation that reduces conductive losses. On the contrary, the savings in hot months, due to the reduction of heat gains, are almost negligible. These results clearly illustrate the capability of massive shutters to reduce thermal energy demand and may be contrasted with the results yielded by strategy Str_D, where no great differences were appreciated by the inclusion of the heat conduction input variable in the control strategy. Consequently, the thermal energy savings achieved by the higher thermal insulation effect of the massive shutters were obtained without implementing a specific control strategy for that

variable. Likewise, this thermal energy demand is achieved by using shutter positioning control strategies that use as input variables only the solar radiation and the thermal use priority. Therefore, no additional meteorological information is needed to take advantage of the thermal insulation of massive shutters.

To analyze the effect of the triple-glazed windows a new reference model has been simulated (Reference_3) including triple-glazed windows without shutters. This reference model helps to differentiate the energy reduction obtained with the substitution of the windows and that obtained with the shutter control strategies. The results obtained using triple-glazed windows are illustrated in Fig. 11 and Table 7 for both simple and complex strategies, Str_C_Lum and Str_F_Lum. A thermal energy demand reduction of 30.6% in the Reference_3 model compared to the initial Reference model is obtained. This initial reduction without any shading device has a direct impact on the thermal energy saving potential achieved by the shutter positioning control strategy; that is, the additional thermal resistance of the high efficiency glazing overlaps the insulation effect of the massive shutters. For instance, the total thermal energy savings in triple-glazed windows with the Str_F_Lum control strategy decreases by only 17.4% compared to Reference_3, while the reduction for the double-glazed window in comparison with the Reference model was 35.6%. Additionally, the high efficiency of these triple-glazed windows greatly reduces the differences in the results obtained applying simple or complex control strategies, passing from 1.6% in double-glazed windows to only 0.3% in triple-glazed windows. Moreover, the thermal energy saving obtained with the massive shutters compared to non-massive blinds also fell from an average of 11.5% in the double-glazed windows to 1.5% in the triple-glazed ones. This result indicates that the effect caused by massive shutters in high efficiency triple-glazed windows is practically negligible.

The results also show how the use of a triple-glazed window for reducing heat conduction losses, in addition to non-massive blind control for optimizing solar radiation gains, is more effective (46.4% thermal energy reduction) than using massive shutter controls for optimizing both heat conduction transference and solar radiation gains in double-glazed windows (35.6% thermal energy reduction). However, shutter/double-glazed system reduces the thermal demand compared to triple-glazed windows without shadow devices. Moreover, triple-glazed

windows replacement has higher investment costs than the implementation of massive shutter optimally controlled in existing windows for building refurbishment (Pikas et al., 2014).

Fig. 11. Thermal energy demand for alternative heat conduction conditions, based on: (a) Simple strategies Str_C, (b) Complex strategy, Str_F.

7. Conclusions

Current work shows the great potential of shading positioning control strategies to reduce the thermal energy demand in buildings taking into account different control input variables. Results show how the main reduction is obtained by the optimization of the solar radiation gains. However, the selection of massive shutters, which supplements an additional active thermal resistance for the window, greatly improves the shutter performance for reducing the thermal energy demand. In contrast with other window refurbishment options such as the implementation of more efficient triple-glazed windows, the proposed system is characterized by its dynamic behavior, what allows adapting shutter behavior to building thermal requirements. This, coupled with its low investment costs, makes massive shutters appear to be an optimal thermal energy reduction system for both new and existing buildings.

The main conclusions from this study are as follows:

- Shutter positioning control strategies with solar radiation as the single input variable (Str_A and Str_B) give rise to a decrease in thermal energy demand, but only for a season. However, the inclusion of the thermal use periods as input variable generates a thermal energy reduction of 35% including both cooling and heating savings.
- Complex shutter position control strategies, where input variables includes temperature data, show a 5% additional reduction in the energy demand compared to those based only on radiation. This reduction is mainly caused by the inclusion of real demand as input variable, while low-energy savings are obtained including heat conduction as input variable on the shutter position control strategy. Therefore, only inner temperature is required to obtain the additional energy reduction with complex shutter position control strategies. This energy reduction is mainly produced during the months of seasonal change, where there is no predominant demand for either cooling or heating.
- For those cases where there is discrepancy between using natural illumination and optimizing the thermal demand two different criteria were analyzed to define the shutter position: 1) optimization of the thermal demand, defining the shutter position as CLOSE, and 2) prioritization of daylight illumination where the shutter is in a HALF-OPEN position. When the second criterion is used, thermal energy demand only increases by 2%-5%, compared to the initial energy demand optimization criterion. Therefore, no great increases in thermal energy demand were achieved including daylight illumination use prioritization.
- Massive shutters provide an additional energy reduction of 11-12% in comparison with non-massive blinds. However, the reduction is strongly influenced by the thermal characteristics of the window. The additional savings that massive shutters cause for a triple-glazed window compared to non-massive blinds is only 1.5%.
- Surprisingly, the thermal energy reduction caused by the increment in thermal insulation due to the massive shutters compared to non-massive blinds can be reached using simple radiation-based control strategies. The inclusion of heat conduction as a control variable only improves the results by 0.2%. Therefore, it is not necessary to increase the complexity of the massive shutter control strategies, including heat conduction as a

control variable, in comparison to non-massive blinds to take advantage of the thermal insulation.

- Energy reduction reached with the integration of an optimum shutter position control strategy of massive shutters in double-glazed windows is higher than the one obtained with the substitution of these windows ($U=2.46 \text{ W/Km}^2$) by a highly efficient triple-glazed window with no shading device ($U=0.59 \text{ W/Km}^2$).

Future work is devoted to experimentally contrast the simulation results obtained in present paper. To this aim a complete experimental protocol for computer controlled external massive shutters during a complete year is on process for the described building prototype. Strategy Str_C_Lum is selected to take advantage of maximum energy savings without increasing data acquisition complexity. Results and comparison with current work are considered for future publications.

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