Automated Control of Illumination and Climatization in Buildings

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Abstract

In recent years, there has been a substantial increase of the world energy consumption and one of the major contributors to this problematic is the building sector. In pursuance of reducing its contribution, efforts have been made in order to create automatic control programs capable of using electrical systems more efficiently especially in the field of home automation. These programs are expected to help reduce the electric consumption by HVAC systems without compromising people's needs under a specific environment.

The goal of this dissertation is to develop a numerical model capable of simulating the evolution of temperature and illuminance indoors and to study the occupant's comfort using scenarios of manual and automatic control. The study main focus is the automation of processes of natural ventilation and the evaluation of its benefits on the general comfort of people inside a room. In addition, it was also investigated the effect on indoor illumination and temperature, on the working plane, through the use of different control measures of shading devices.

It was concluded that the control algorithm developed is more efficient regarding energy usage, under simulated conditions, when compared to manual control scenarios, in spaces shared by several people. The presence of several people gives less control opportunities to each occupant to change the room's environment according to their own needs, which leads to adaption problems.

Moreover, it has been demonstrated that non-exhaustive manual control strategies can improve room conditions and, in the short-term, it might be a viable alternative to automatic control systems.

Keywords: Domotic, Energy management, Thermal comfort, Ventilation, Behavior modelling

1 Introduction

The International Energy Agency (IEA) predicts that the demand for electricity by 2040 will be 30% higher than in 2016, in an optimistic scenario - considering that member countries honor their commitments under the Paris agreement [1].

According to the United Nations Environment Program (UNEP), the buildings sector accounts for about 40% of global energy consumption and has a 30% contribution to the annual GHG release [2]. This sector is the one that offers the greatest potential to reduce GHG emission with reduced costs. It is possible to reduce the associated energy consumption by 30%, to 80%, using proven technologies that are commercially available [2].

The main purpose of this project is the development of a simplified model - able to estimate the luminosity and temperature in a closed space with solar exposure - and an algorithm of automated control. Using both model and the algorithm combined is possible to evaluate the effect of automated control on the occupant's comfort.

2 Bibliography review

2.1 Automated building energy management systems

In 2014 Maria Machado [3] developed a methodology capable of managing the energy demand of the HVAC systems. This model adjusted energy consumption to the comfort of users, the amount of energy produced by renewable sources and the electricity prices for different periods of the day [3].

A year later, in 2015, Bernardo Salvador [4] elaborated a simulation model of the illuminance on the work plane. According to [4], energy savings of 53% to 75% relative to lighting consumption are possible using an intelligent luminaire management model, depending on whether the light transmissivity through the windows is lower or higher.

Marchiori et al. [5] developed a system of energy management in buildings using sensors and actuators. The controllers read and process the data provided by the sensors and autonomously turn off appliances when unnecessary based on a decision algorithm. Despite its efficiency, this algorithm presents a great limitation since it is only applicable when rooms are unoccupied. Energy savings of 7.1% to 14.6% were possible with the application of this prototype [5].

In 2016, Rodrigo Leal [6] analyzed static strategies and strategies of automatic control of Venetian blinds. Each of these strategies was simulated for different conditions, such as: orientation of the façade (South, East, West and North), positions of the blinds in relation to the window (interior and exterior blinds), periods of the year (summer and winter), types of blinds (simple Venetian and double orientation) and climatic conditions (four European countries).

Despite existing several models to control electric lighting and manage blinds usage, Eric et al. [7]considers that an effort is needed to ensure that these models do not operate independently. According to [7], it is

important to use an integrated control system - sharing information such as air condition and occupancy level - to maximize energy efficiency and occupant comfort. In order to provide quantifiable comparisons between manual, independent and integrated strategies, it was necessary to develop a simulation platform — which uses: Building Controls Virtual Test Bed (BCVTB), EnergyPlus and Matlab.
The results of the study [7] were presented for three climatic zones (Baltimore, London, Abu-Dhabi), two types of blinds (interior and exterior) and different window areas. In most cases, integrated control is more effective than other strategies.

2.2 Thermal Comfort

The most common model used to predict thermal comfort is a numeric model named PMV-PPD, developed by Fanger [8]. The Predicted Mean Vote (PMV) index determines the average value of the thermal sensations felt by the occupants according to ASHRAE thermal scale. Related to it there is another index named Predicted Percent Dissatisfied (PPD) that accounts to the percentage of people feeling thermally uncomfortable. It can be estimated by the following equation:

$$\mathrm{PPD} = 100 - 95\exp[-(0.03353\mathrm{PMV}^4 + 0.2179\mathrm{PMV}^2)] \tag{1}$$

[26] considers this model an adequate tool to evaluate the occupant's satisfaction relative to environment conditions in HVAC buildings. However, [9] doesn't recommend its use in naturally ventilated buildings and advises to use adaptive models instead. In this type of buildings people tend to adapt themselves and generally tolerate higher temperatures than those predicted by the PMV model. Therefore, the range of comfort temperatures can be extended in infrastructures without HVAC systems.

3 Simplified model

One of the purposes of this project was to create a simplified model capable of evaluating the indoor temperature and illuminance on the work plane of a closed space, considering sun exposure. This model must simulate the evolution of interior conditions under several scenarios and allow a predictive control.
In order to validate the results obtained by the simplified model, a second model was developed with the same characteristics using the *EnergyPlus* software.

3.1 Illuminance

Two models were used to calculate the illuminance on the work plane, one for each component of light — natural and artificial. To account for the illuminance that entered through the window due to daylight the Lumen Method was used. The illuminance generated by the luminaires was estimated using a lighting design software – *DIALux*. In the end the two components (natural and artificial lights) were summed.

3.2 Temperature

The simplified model consists in an energy and mass balance to a control volume, in steady state conditions.

3.2.1 Heat Gains Through Opaque Surfaces

The heat gain through external and internal walls, which can't be considered as adiabatic, is mainly due to conduction heat transfer. This heat transfer was calculated by the Fourier Law:

$$\dot{q}_{\mathrm{cond}} = \sum \mathrm{U_i A_i}\,\Delta\mathrm{T}\ \ [\mathrm{W}] \tag{2}$$

$\dot{q}_{cond}$: conduction heat rate [W]; A_i: area of surface i [m^2]; ΔT: temperature diference [K]
U_i: coefficient of overall heat transfer between adjacent and conditioned space i [$W.K^{-1}.m^{-2}$] ;

3.2.2 Heat Gains Through Fenestration Areas

The calculation of solar heat gains through windows with shading devices can be made using the following equations:

$$\dot{q}_{\mathrm{sun,window}} = \mathrm{A_{window}}\times\mathrm{IAC}\times[\mathrm{E_D}(\theta)\times\mathrm{SHGC}(\theta) + (\mathrm{E_d}+\mathrm{E_r})_{\mathrm{Vertical}}\times(\mathrm{SHGC})_{\mathrm{D}}]\ \ [\mathrm{W}] \tag{3}$$

$$(\mathrm{E_d}+\mathrm{E_r})_{\mathrm{Vertical}} = \mathrm{CYE_{DN}} + \mathrm{E_{DN}}(\mathrm{C}\times\sin\alpha)\times 0.2/2\ \ [\mathrm{W/m^2}] \tag{4}$$

$$\mathrm{E_D} = \mathrm{E_{DN}}\cos\theta \text{ se} \cos\theta > 0 \qquad (\text{Otherwise } \mathrm{E_D} = 0) \tag{5}$$

$$\mathrm{E_{DN}} = \frac{\mathrm{G_{Horizontal}}}{\mathrm{C}+\sin\alpha}\ \ [\mathrm{W/m^2}] \tag{6}$$

$\dot{q}_{sun,window}$: solar heat rate [W]; E_D: surface direct irradiance [W/m^2]; θ: Incident angle [º];
E_r: diffuse ground-reflected irradiance [W/m^2]; IAC: inside shading attenuation coefficient;
$SHGC(\theta)$: direct solar heat gain coefficient as a function of incident angle θ; E_d: diffuse irradiance [W/m^2];
$(SHGC)_D$: diffusive solar heat gain coefficient; A_{window}: window area [m^2];
Y: ratio of sky diffuse on vertical surface to sky diffuse on horizontal surface; C: Sky diffuse factor;
$G_{Horizontal}$: Global horizontal irradiance [W/m^2]; α: Solar altitude [º]; E_{DN}: Direct normal irradiance [W/m^2]

The radiation that is exchanged between the room surfaces and the environment are also included in this model. This model applies the Stefan-Boltzmann Law, eq. (7), and a correlation for enclosures, eq. (8), to balance the energy emitted by this two sources.

$$\mathrm{E} = \varepsilon\, \mathrm{T}^4 \times 5.67\times10^{-8} [\mathrm{W/m^2}] \tag{7}$$

E: heat emitted per unit of surface [W/m^2]; ε: Emissivity; T: Temperature of the surface [K];

$$\dot{q}_{12} = \sigma(T_1^4 - T_2^4)/\left(\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}\right) \tag{8}$$

T_i: Temperature of the surf. i [K]; ε_i: Emissivity i ; F_{12}: View Factor; A_i: Surface area i [m^2];

The conductive heat transfer through fenestration areas is algo very significant due to single clear glass properties and it is estimated using the Fourier Law (2) once more.

3.2.3 Ventilation Heat Gains

The sensible heat gain due to air exchanges through doors and windows can be determined by the equation below:

$$\dot{q}_{vent} = Q\rho c_p \Delta T \ \ [W] \tag{9}$$

Q: air flow rate [m^3/s]; c_p: specific heat of air [J/(kg.K)]; ρ: air density [kg/m^3];
ΔT: temperature difference between indoors and outdoors [K]

The general form used to determine the airflow through a large intentional opening induced by wind and thermal forces is:

$$Q = C_D A_{ab} \sqrt{2\Delta p/\rho} \quad [m^3/s] \tag{10}$$

C_D: discharge coefficient for opening; A_{ab}: cross-sectional area of opening [m^2];
Δp: pressure difference across opening [Pa]

In case of an open window, it is necessary to account for the pressure difference induced by wind forces that can be determined by the following equations

$$U_H = U_{met}\left(\frac{\delta_{met}}{H_{met}}\right)^{\alpha_{met}}\left(\frac{H}{\delta_H}\right)^{\alpha_H} \tag{11}$$

$$\Delta p = s^2 C_p\, \rho \frac{U_H^2}{2} \tag{12}$$

U_H: approach wind speed at upwind wall height H [m^2/s]; δ_H: layer thickness [m]; ρ: air density [kg/m^3];
U_{met}: wind speed measured by the meteorological station [m^2/s];
H: height of the upwind wall [m]; H_{met}: height of the anemometer that recorded U_{met} [m];
δ_{met}: layer thickness at meteorological station [m]; α_{met}: exponent for the local building terrain;
α_H: exponent for the meteorological station; s: shelter factor;
C_p: pressure coefficient ; Δp: pressure difference across opening [Pa];

This model uses an average pressure coefficient based on data available on [10] for low-rise buildings considering the predominant wind direction in Lisbon and the presence of trees near the vicinity of external openings.

The general form used to determine the pressure difference by thermal forces is

$$\Delta p = \rho\left(\frac{T_o - T_i}{T_i}\right) g\, \Delta H_{NPL} \tag{13}$$

Δp: pressure difference across the opening [Pa]; ρ: Air density [kg/m^3]; g: gravity acceleration [m/s^2];
T_o: exterior temperature [°C]; T_i: interior temperature [°C];
ΔH_{NPL}: distance between the opening and the natural pressure level

ΔH_{NPL} is an important variable that permits the usage of the equation (13) in the case of a single opening (door or window) and in a case when door and window are open simultaneously while the other windows on the exterior wall of the building are open - resulting in an induced draft through every story of the building. A more detailed explanation of this variable and how it should be determined is given in [11].

The air flow is assumed to be bidirectional when there is only one single (door or window) opened and unidirectional in the case of two (doors or windows) opened on the opposite sides of the room.

3.2.4 Heat Balance

A thermal balance for a generic room can be represented by the equation. This balance is based on the first law of thermodynamics for a control volume and just accounts for variations of sensible energy, neglecting other forms of energy.

$$\frac{dU_{vc}}{dt} = \dot{q}_{vent} + \left(\dot{q}_{cond} + \dot{q}_{solar,janela} - \tau \times \dot{q}_{rad,\ emitida} + A_{janela}\sigma T_2^4\right)_{janela} + (\dot{q}_{cond} - \dot{q}_{12})_{parede\ ext} + (\dot{q}_{cond})_{parede\ int} + \dot{q}_{g\ int} \quad (14)$$

U_{vc}: Sensible energy [W]; $\dot{q}_{vent}$: heat gains through ventilation [W]; $\dot{q}_{solar,janela}$: solar heat gains [W]; $\dot{q}_{rad,\ emitida}$: Emited radiation from internal walls [W]; $\dot{q}_{cond}$: Ganhos térmicos por condução [W]; $\dot{q}_{g\ int}$: heat generated [W]; $\dot{q}_{12}$: balance of energy lost by radiation emition; T_2: sky temperature [K];

The variation of the room sensible energy $(dU_{vc}/dt\,0)$ is equal to the energy that enters due to solar radiation or to the existence of higher temperatures in the system surroundings, minus the energy that is lost to the exterior. In the systems where there is generation of energy within the own system, this term must also be included in the balance as a gain of the system, which in this case is represented by $\dot{E}_g$ (generated energy), in the equation (14). This term accounts for the sources of internal energy such as: lights, computer devices and the energy generated by the occupants in the room.

The system energy variations will influence directly the ambient temperature as can be seen here

$$\frac{dU_{vc}}{dt} = mc_p\frac{dT}{dt} \quad (15)$$

m: mass of control volume [Kg]; c_p: thermal capacity [J.Kg^{-1}.K $^{-1}$];

However, these variables are not linearly related, since the variation of temperature will depend on the thermal capacity of the medium, which changes according to the absolute humidity. The thermal capacities of the water vapour and the dry air are different and, for that reason, the contribution of each one of these components was separated in the following equation.

$$\frac{dE_{vc}}{dt} = (m_{H2O}c_{p\ ,H2O} + m_{ar\ seco}c_{p\ ,ar\ seco} + m_{parede\ exterior}c_{p\ ,parede\ exterior})\frac{dT_{in}}{dt} \quad (16)$$

This model assumes uniform temperature in the control volume and in the surrounding surfaces. Although this hypothesis might affect the results of PMV and PPD, it is the common approach used in air conditioning problems and it is believed to have low influence in the global energy balance.

3.3 Control algorithm

3.3.1 Manual

Manual control has already given proves of its inefficiency when used in spaces shared by several people, since it cannot offer the same control opportunities to every person in the room.

To develop an algorithm based on occupants' intervention on the indoor environment, both students' and professor's behaviors were observed.

The occupants have shown a passive attitude, choosing to adapt their clothing instead of adopting attitudes that could influence the thermal conditions and the comfort felt by every person in the room. Therefore, the manual model considers that occupants don't have an active role on the control of windows, doors and blinds. It assumes that doors and windows are always closed and the position of blinds does not vary during the period of occupation, although it can change from closed to opened in different days.

3.3.2 Automatic

There was developed an integrated control model of illumination and climatization management. Although illumination and climatization control algorithms are linked the algorithms were presented separately in Figure 1.

4 Case study description

This project represents a room model at Instituto Superior Técnico, in Lisbon, located on the 1st floor of the civil building. This room has one wall adjacent to the hallway, one external wall and a window that is facing east.

5 Results

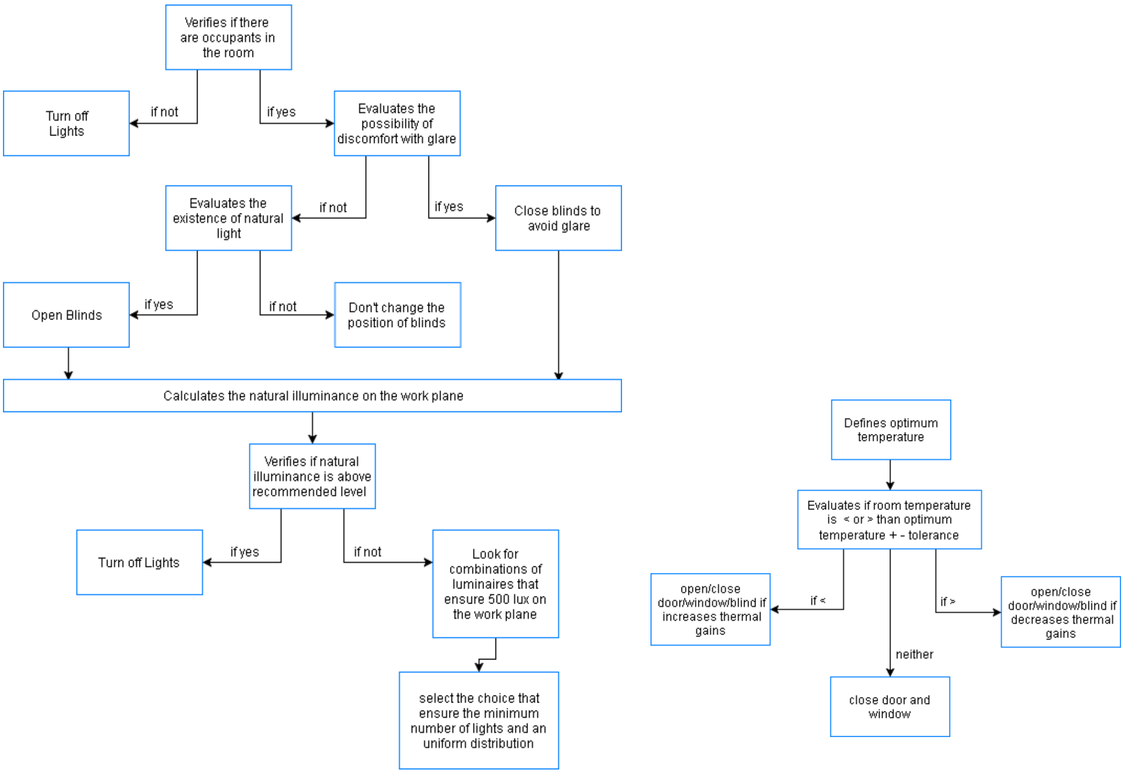
The climatic data used in the simulations were measured at Instituto Superior Técnico meteorological station, located at the top of the south tower, with a height of 50 m.

5.1 Comparison between simplified model and *EnergyPlus*

To validate the correct application of the theoretical models used in the simplified model, it was used another model - developed with the same characteristics established in *Energyplus.* Although the validation of the results from the *Energyplus* model depended on the correct information provided to the program through the idf file, it was assumed that there was no input error when everything ran as expected.

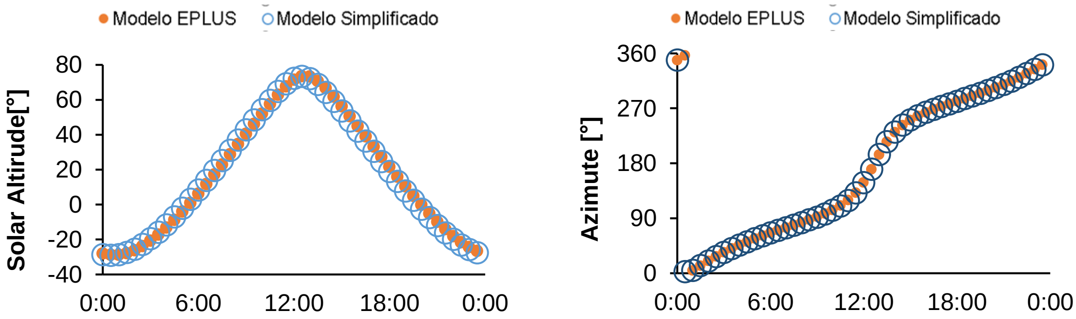
5.1.1 Solar model

According to the results, it was possible to conclude that the model that determines the solar position was well implemented. Figure 2 shows the results of solar altitude and solar azimuth for the two models. Since the angle of solar azimuth depends on the convention chosen, a simplified model was developed to use the same convention used by *EnergyPlus* - north convention.



(a) (b)

Figure 1. Algorithms of illumination and climate management



a) b)

Figure 2. Solar altitude (a) and Solar azimuth (b) variations calculated by the two models for the 9th of July

In Figure 3 the results of the application of the relations described by the equations (3) - (6) that determine the radiation on a vertical surface - are represented. The *EnergyPlus* model calculates the solar energy flux from the data in the climate file on the incident radiation on the earth's surface measured on July 9, 2005. This inconsistency in the reference conditions may justify the differences in the results obtained by the two models.

To compare the simulation models, a typical summer day was chosen and conditions were defined in the interior for the initial instant, so that both simulations could start from the same point.

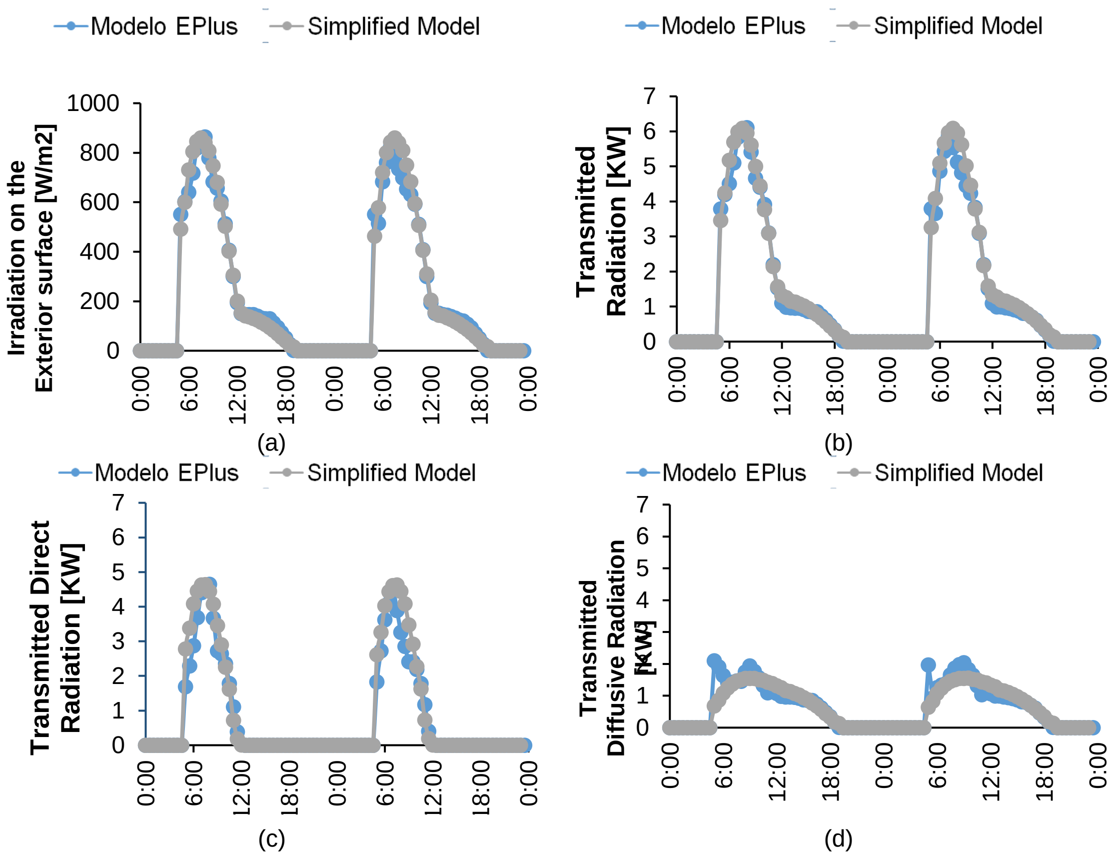


Figure 3. Solar model results

5.1.2 Average temperature indoors

The average temperature of the room undergoes very similar variations when calculated by each of the two models, as shown in Figure 4. This indicates that the variation of the thermal loads from positive to negative values match in time for the two models. Therefore, it is possible to concluded that simplified model is well designed.

In the situation illustrated in Figure 4, the room is insulated and is not ventilated at any point of time. These facts may explain the high temperatures, but it is important to notice that the initial temperature was imposed by the EnergyPlus. This software studies room evolution trends to determine the initial temperature. The simplified program, on the other hand, depends on the initial situation and, for that reason, to compare its results this program used the same initial temperature used by the EnergyPlus.

Other fact that can be related to the high temperatures is the lack of natural shading by the trees and buildings.

The difference between the two models reaches a maximum of 3ºC in the middle of the day.

Despite the differences, the simplified developed model fulfills well its role and reproduces satisfactorily the case under study.

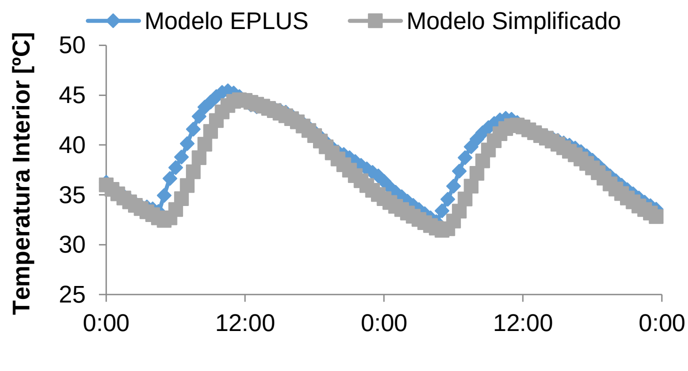


Figure 4. Indoor temperature calculated with both models (5th and 6th of july)

5.2 Manual control

The results of the simulations performed regarding an occupation of 26 people from 9 am to 8 pm on January 15 (Winter) and July 9 (Summer) are summarized in Table 1.

After comparing each of the scenarios, we can observe that in the hypothesis of the blinds always opened, the natural illuminance reaches a wider area of the work plane throughout more time, maintaining the 500 lux level with the help of exclusively natural means during more time (>140 h.m2) either in the summer or in the winter. Since this condition allows to increase the reach of the solar radiation within the room and since the artificial lights are turned on only when the illuminance provided by the sun is not enough to ensure the recommended level of 500 lux inside the room, in the points farther from the windows, the electrical power consumed shows savings of, approximately, 25% comparing to the opposite scenario – the blinds always closed.
The second scenario, despite requiring a prolonged used of the artificial illuminance systems, since the reach of the solar radiation is low relative to the first scenario and consequently increases the daily electrical power consumption, it helps reduce the thermal discomfort – the PPD values decrease – since it reduces the thermal loads from the solar source.

Table 1. Results for PPD, Luminaire consumption and level of illuminance from daylight at the work plane for different scenarios

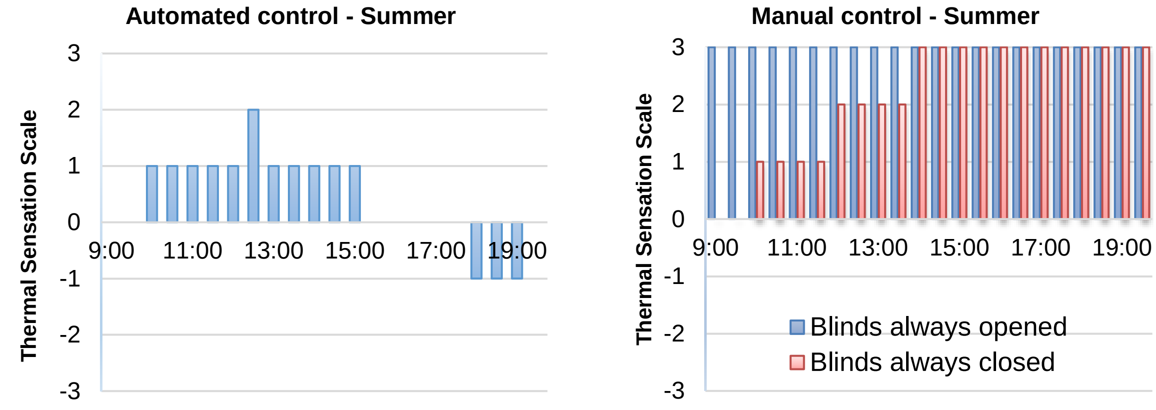
Scenario	Index	**Summer**	**Winter**
Open blinds	**PPD** > 50% [% horas]	100%	14%
	Luminaire's consumption [KWh/day]	15	16
	INPT* > 500 lux [h.m^2]	14 7 h.m^2	14 4 h.m^2
Closed blinds	**PPD** > 50% [% horas]	73%	0%
	Luminaire's consumption [KWh/day]	20,4	20,4
	INPT* > 500 lux [h.m^2]	58	15

*The luminaire's consumption is calculated based on the assumption that each luminaire has two fluorescent tubular lamps with 58 W; INPT: natural illuminance on the work plane

The analysed model does not consider the variation of the conditions in the room in the classroom breaks. As It is expected that these breaks decrease the thermal loads of the room, the percentage of the people discontent (PPD) represents a worst-case scenario in the summer period.
The door opening to increase the room ventilation is a regular strategy used in the hottest periods of the year in pursuance of reducing the thermal loads of the room. One complementary study considering doors opened when the temperature is too hot inside the room has shown no significant benefits to the thermal comfort.

5.3 Controlo automático

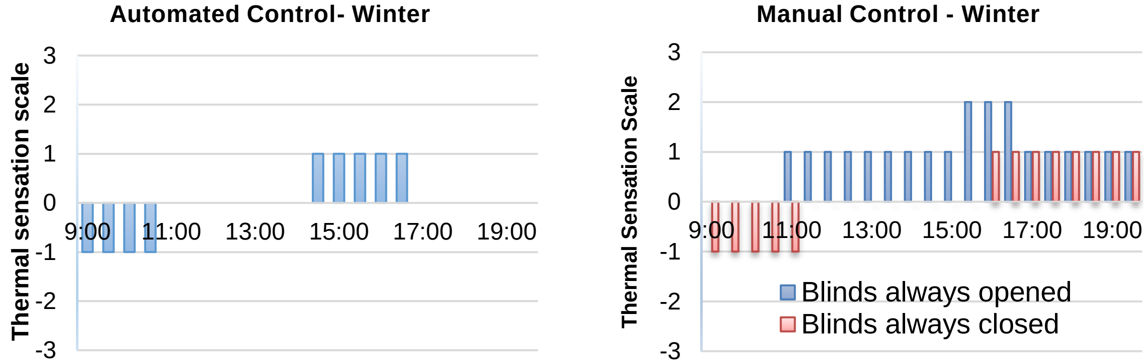
To evaluate the benefits of an algorithm of combined control of illuminance and air conditioning, the simplified numerical model was used and it was not considered the existence of any behaviours from the users that could influence the temperature in the internal medium.
The reference used by this algorithm to increase the thermal sensation of the occupants is the optimal temperature of comfort in the different seasons of the year – 24,5º in the summer and 22ºC in the winter.
The results obtained regarding the PMV index, either for the automatic and manual control situations are represented in Figure 5 e Figure 6 to the summer and winter periods. The results show forecasts for specific days, chosen based on historical weather data in order to approximate the external conditions to the nominal conditions of both seasons.
Based on the graphs of Figure 5 and Figure 6 it is possible to verify an improvement of the thermal sensations felt in general with the application of the control algorithm. The graphs represent the variation of the predicted mean vote (PMV) index based on the thermal sensation scale.
As stated in Table 1, most of the occupants feel discomfort when there are no shading periods throughout all day in the summer season. From the Figure 5 and Table 2, it is possible to verify that the control algorithm is capable of changing that state of discomfort (PPD = 100%), under extreme heat conditions (PMV = +3), to a state lower than 50%, under conditions much more acceptable in the sensation scales of the hottest months.



(a) (b)

Figure 5. Summer PMV indexes for automated control (a) and manual (b).

In the winter season, the algorithm also brings benefits, as expected. By comparing graphics (a) and (b) of Figure 6 it is observed that the automatic control allows an approximation of the neutral thermal sensations during all the occupancy time. The thermal sensations felt vary between -1 and 1, which constitute much better and acceptable conditions to the occupants as can be concluded in Table 7. Moreover, throughout the colder periods, people prefer slightly heated environments and vice-versa.



(a) (b)

Figure 6. Winter PMV indexes for automated control (a) and manual control (b).

Table 2. Results for PPD, Luminaire consumption and level of illuminance from daylight at the work plane for automated control

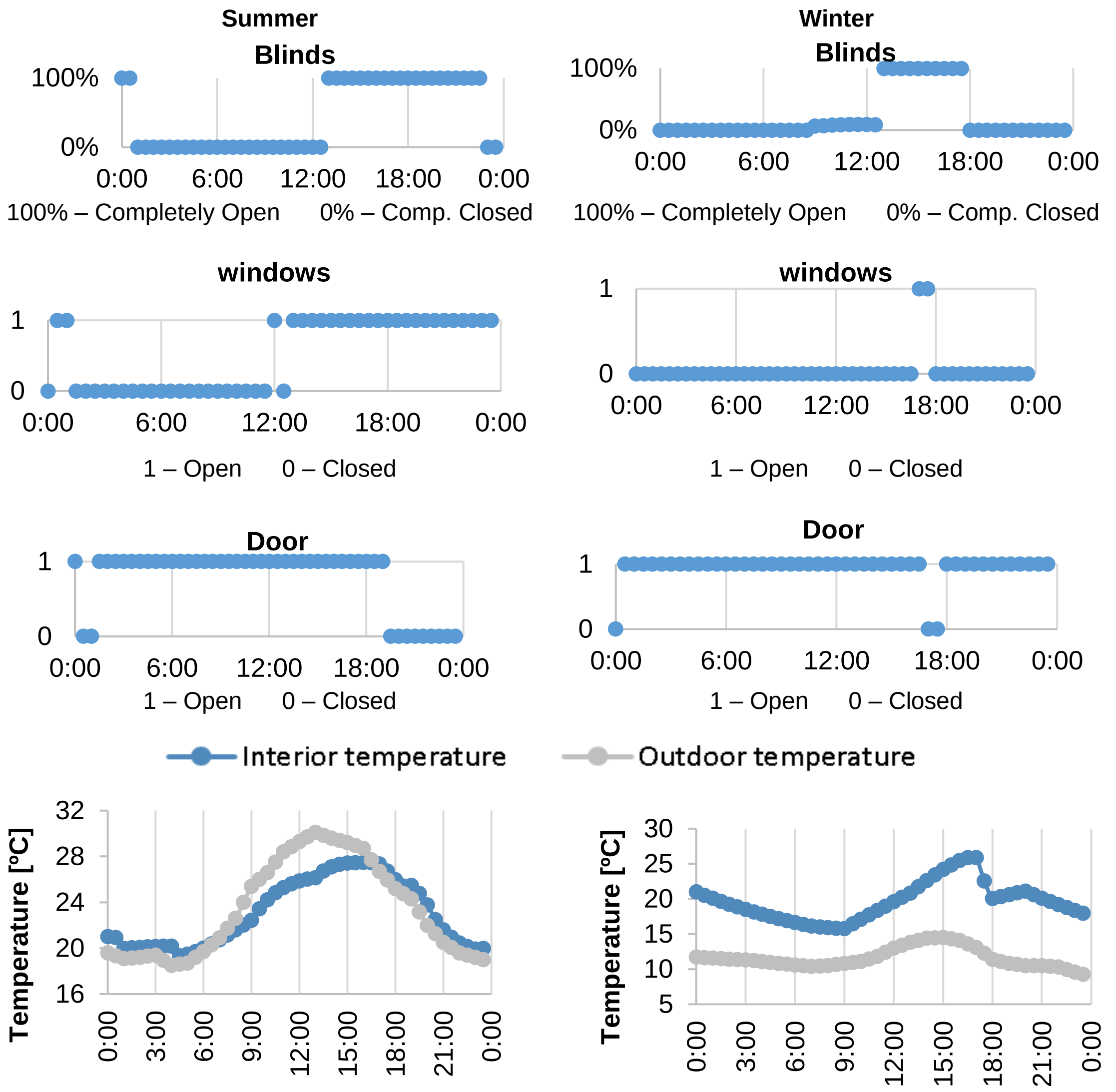
Indexes	**Summer**	**Winter**
PPD [%]	< 19%	< 25%
Luminaire's consumption [KWh/day]	15,5	17
INPT* > 500 lux [$h.m^2$]	58	15

*The luminaire's consumption is calculated based on the assumption that each luminaire has two fluorescent tubular lamps with 58 W; INPT: natural illuminance on the work plane

The graphics from Figure 7 represent the simulation of the interior temperature on the 9th of July, when the automatic control algorithm developed was implemented.

In the morning break, the blinds and windows were closed to reduce the thermal gains by solar radiation and increase the thermal losses by ventilation, respectively. The ventilation through the door allowed bigger thermal losses during this period. Considering the equation (3.17) it is clear that if the window was open (janela=1) and the door was closed (door=0), it would increase the thermal gains by ventilation, since the exterior air temperature is superior since 7:30 in the morning. Although, it is not so clear that if both elements

(door and window) were opened, the ventilation would increase the thermal gains since the existent temperature gains favour the exit of the air from the room – assuming that there is a similar distribution of openings in the superior half of the East façade of the building. Despite this, the wind could invert this trend. The ventilation does not depend solely of the exterior temperature as we first could think and because of that the decision factor to open the window is not the only difference between the exterior and interior temperatures, as we can observe in the graphs of Figure 7, in the period from 13h to 15h – the windows are opened despite the exterior temperature is higher than the interior temperature.
In the end of the day, when the conditions are uniform inside of the building, we should potentiate the losses from ventilation by opening the windows.
Around 1h in the morning, the window closes and the door opens which will allow the control of the temperature drop. The temperature in the corridor is assumed to be at 21ºc and is assumed to be invariable.
Similarly, a study was made to evaluate the performance of the algorithm in cold days. The graphs from Figure 7 represent the simulation of the interior temperature on the 15th of January, when the automatic control algorithm was implemented.
The blinds were closed during the night period to reduce the losses to the exterior and it remained closed during the morning to reduce solar chaining. It is worth noting that the solar altitude is lower in the winter than in the summer. The ventilation from the window is avoided to maintain the internal environment heated and it is given preference to the opening of doors since it allows the internal environment to be within lower thermal amplitudes.
It is possible to achieve the same results of automated control using a new manual strategy. In Figure 6Figure 7 the automated control has few interventions that can be easily taken by the occupants of the space.



(a) (b)

Figure 7. Control and resultant indoor temperature in summer (a) and winter (b)

6 Conclusions

Based on the results it can be concluded that the current strategies are very inefficient from the point of view of energy efficiency and thermal comfort. Under these conditions, the usage of an automated control has great chances to succeed. The control algorithm can reduce thermal discomfort and energy consumption by lighting systems up to 26% compared to the case of closed blinds.

It was observed that is very common to reach discomfort conditions under the two scenarios studied. However, a critical interpretation of PPD results is needed since people generally tolerate worse conditions than those predicted by the PMV-PPD model in naturally ventilated buildings.

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