Automatic Lighting Management System for IST Classrooms

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Sustainability and energy efficiency are issues that have been increasingly important recently. Since the highest energy consumption in society corresponds to buildings, and a significant part of that comes from lighting, taking advantage of natural light and reducing the consumption of artificial light is not only central to sustainability issues, but also visual comfort , since the human eye is more adapted to natural light. This dissertation has, therefore, the objective of designing an automatic control algorithm for the lighting of an IST classroom. This will be done by controlling the position of the blinds and the connected lighting fixtures, in order to use their configuration that corresponds to the lowest energy consumption, always maintaining visual comfort. In order to understand the effect that the various configurations of the blinds had on the illuminance inside the room, simulations were made, and later validated, using the *EnergyPlus* program. Similarly, the same was done for the luminaires, but using the *Dialux* program. Two control proposals are made. One is simply based on the time of day, but only gives information about the blinds. The other uses the simulations made previously so that, together with the day, time, and the illuminance of the room measured by a sensor, to predict which is the best option to take. The simple one always got good answers for the problem. The one that uses the simulations was able to always guarantee visual comfort with a mix o natural and artificial light.

Keywords: Sustainability, Automatic Control, Lighting, Blinds, Energy management

I. INTRODUCTION

In October 2014, the European Council agreed on a new 2030 framework for climate and energy, including EU-wide targets and targets for the period 2020 to 2030. This includes a 40% reduction in greenhouse gas emissions compared to 1990, that energy production comes from at least 27% from renewable sources and that there is an improvement of 32.5% (revised in 2018) in energy efficiency.

With these ambitious goals, new ways of achieving them are constantly needed. Almost 40% of the energy consumption in the world is related to buildings, and in non-residential buildings 12% to 23% of its consumption corresponds to expenses related to lighting([1, 2]), being the second largest source of consumption, especially in offices, behind of HVAC (30%-47%). In addition, savings in energy expenditure translate into savings at monetary levels. This presupposes a need to reduce these expenses, but without compromising visual comfort, as this is of the highest importance when it comes to productivity in the workplace.

This work aims to study the implementation in a classroom of the IST automatic control of blinds and luminaires in order to minimize energy consumption, while maintaining the comfort of its users. The system should let any user change the status of blinds or lights unimpeded.

The implementation in a real environment of this type of control will allow a reduction in energy consumption. In addition, the work done in the room in question can be replicated relatively easily to the other rooms in the same building.

II. BACKGROUND

A. Light Theory

The point-to-point method allows calculating the illuminance that a light source generates at a specific point, depending on the distance from the lamp to the point where it is intended to be calculated, the solid angle between them and the luminous intensity of the lamp, which in turn is the luminous flux (Φ), in *lumen* per unit of solid angle (Ω) (eq.1). This calculation is done using simply the inverse square law (eq. 2). Where E represents the illuminance in *lux*, θ the angle between the points, d the distance between the points and I the luminous intensity in *candela*.

$$I = \frac{\Phi}{\Omega} \tag{1}$$

$$E = \frac{I \times cos\theta}{d^2} \tag{2}$$

The EN 12464 standard ([3]) defines how lighting should be in different spaces or for different tasks. According to the standard, the recommended illuminance for each task/situation type is given by what is called *maintaned illuminance*, and the maximum UGR value by UGR_l. For this case, that is, an ordinary classroom, the illuminance should be 300 lux and the UGR_l 19, and the lighting must be controllable

The work of Yang and Jeon [4] focused on studying the effects of different Color Temperatures (CCT), making an extensive review of the existing literature on the subject. On certain themes there is consensus, on others not. It can be said with relative certainty that for higher illuminance levels users prefer higher CCT, and that with increasing CCT, for the same illuminance levels, the apparent brightness that users feel also increases. In terms of comfort or performance, there is no total agreement in the results.The conclusions varied from higher CCT being more discomfortable Yang and Jeon [4], low CCT having negative effects on performance [5], medium CCT having positive effects on concentration [6, 7] and even some that did not verify any significant difference Yang and Jeon [4].

To analyze the success of this type of control, it is necessary to compare it with the non-automatic alternative, ie the habits users have to manually control the lighting in a room. Among the works carried out to monitor people's behavior are [8–12], of where the following conclusions stand out.

- Occupants actively close blinds when there is glare, that is, glare or light that is too strong to the point of being uncomfortable. And they turn the lights on when there isn't enough natural light, however, they often don't turn the light off or open the shades after these uncomfortable conditions disappear.
- Actions on the Blinds
  - Users place blinds in a position that tends to be the result of a balance between positive and negative effects over a period of weeks or months, whereas daytime blind operations are rare.
  - Changes in the position of blinds tend to vary between never or daily for the same facade, and tend to occur at the extremes of the working period
  - People are more likely to accept a situation where the blinds are too open than too closed
- Actions on artificial lighting
  - The luminaires in a room tend to be all turned on/off simultaneously
  - Switching on/off happens mostly when entering or leaving a room

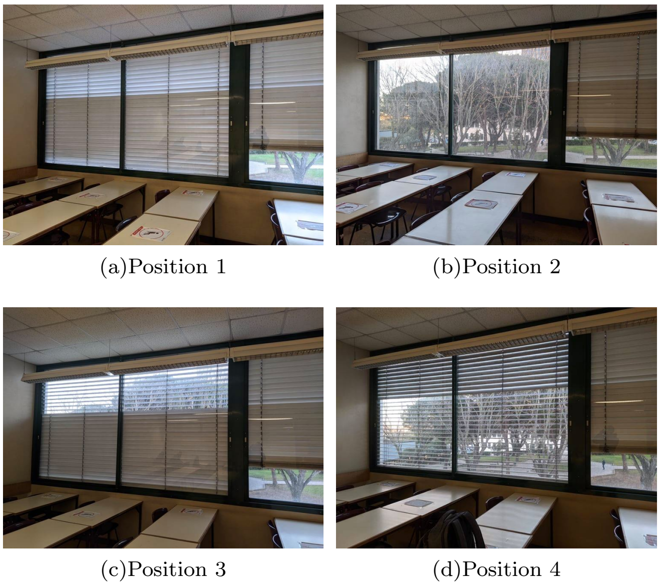
With a similar objective, Yun *et al.* [13] evaluated, in 4 offices, their users' habits and found that, on average, 58.1% of the time the offices have all the lights on. In the remaining time, either they would be all turned off (40.5%), or only half of the luminaires turned on (1.4%). This very little significant use of the use of only half of the luminaires is in line with what was verified, also in this study, that there is no significant relationship between available natural light and the use of artificial light in the studied offices.

B. Room

The room this dissertation is about is the V1.10 classroom of the Civil Pavilion of the *campus* of Alameda of IST. It's a square room with dimensions 7.4x7.4x3m, with several tables(2). On the wall facing west, that is, towards the interior of the pavilion, there is a door that gives access to the corridor and a glass area through which the light coming from the corridor lighting usually passes. On the east wall are two windows to the outside of the building. The south-facing wall separates the room from one of the adjoining rooms, and has a blackboard and a projection screen. The north wall separates the room from the other adjacent room and does not have any other characteristic elements.

Together, the two windows cover the entire length of the wall they meet, and range from 0.9m from floor to ceiling. Each window has some Venetian blinds that can be controlled through a manual switch, or through commands given by an API, since the blinds are connected to a Raspberry PI that allows it. Using the manual switch it is possible to raise or lower the blinds to any position, always being rotated so that no light passes through them when in an intermediate position. Using the commands there are 4 possible options, which are described below. However, regardless of whether you use the manual or automatic mode, there is no way to know the position of the blinds at a certain time, as this information cannot be retrieved directly and sent through the Raspberry PI, nor are there sensors in the room to carry out such verification, and, furthermore, it is also not possible to know directly whether they are in manual or automatic mode. As for luminaires, the room has 4 rows, each with 4 tubular LED lamps of 1500mm in length, and whose possible configurations to turn them on are in 2. These, unlike blinds, are not possible to control remotely. The room is also equipped with some sensors that allows to acquire some quantifiable data also through an API and Raspberry PI, namely temperature (ºC), illuminance (undefined unit), humidity (%), concentration of CO_2 (ppm) and volatile organic compounds (ppm). Of these, illuminance is naturally the most important, but unfortunately the sensor does not give this information in lux. These sensors are placed next to the room projector, which is located near the ceiling, approximately in the center of the room. The information that comes out of these can also be acquired through an API that gives values every 5 minutes. Its position turns out to be a problem, as the illuminance values change a lot from where it is placed to where you want to assess the illuminance, that is, in the work plane, which are the tables. Hence the need to create estimates or virtual sensors to know these values.

Each of the blinds (using the controls) has 4 possible configurations: All closed/lowered (Position 1), all open/raised (Position 2), all lowered with the lower part closed and the upper part rotated to pass light (Position 3), and all lowered with the top closed and the bottom rotated to pass light (Position 4). Each of them is in the figure 1. Taking into account that the room is not equipped with HVAC, the position of the blinds has a great influence on the temperature control of the room, especially to reduce its solar gains, which is in line with what is mentioned in [14].

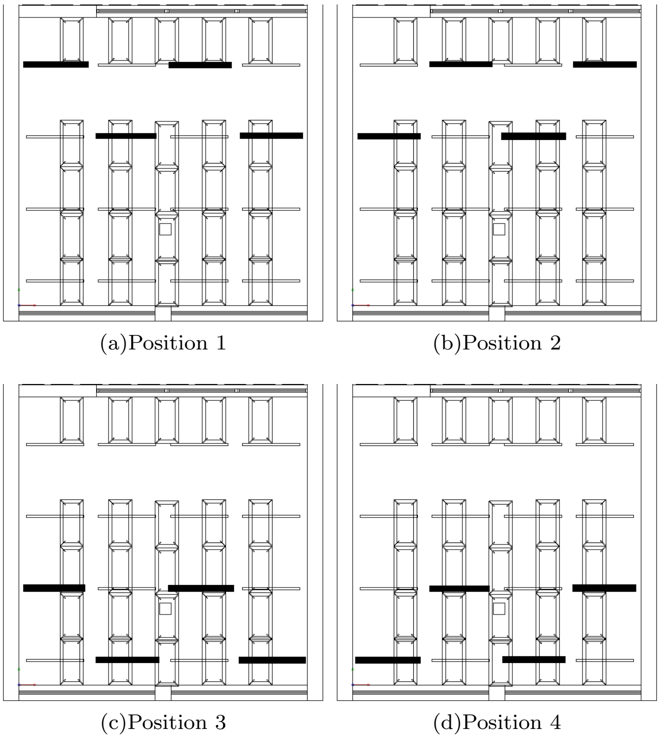


(a)Position 1 (b)Position 2

(c)Position 3 (d)Position 4

FIG. 1. Possible blind positions

There are 4 switches to turn the luminaires on/off. Each switch turns on 2 lamps of 2 rows each, in a criss-cross pattern. Two of the switches do this for the rows closest to the door, the other two for those closest to the window. Which lamps are turned on by each switch is shown in figure 2. In order to reference all these possible configurations between blinds and lamps, a nomenclature was created, which is expressed in the table I.



(a)Position 1 (b)Position 2

(c)Position 3 (d)Position 4

FIG. 2. Light Fixtures

C. Strategy

Many solutions work like the one presented in Matta and Mahmud [15], which has a sensor on the outside of the window to measure the radiation reaching the window, and shutters whose angle is manageable in order to control how much sunlight enters the room . Furthermore, they have a sensor on the ceiling to measure the room's illuminance, and lamps with dimming capability to provide the necessary lighting. de Bakker *et al.* [16] provided a detailed review of the state of the art regarding lighting control in open office spaces based on occupancy. In this review, it is stated that the control of the lighting service, which can represent up to 45% of energy consumption in service buildings (which includes educational buildings), can lead to savings of 60% in lighting, which can represent up to 27% savings in overall consumption. This work concluded that this approach is not yet followed in almost all buildings and that the use of model-based control strategies, such as predictive control, were important to implement this type of approach in the control of the lighting service.

Most lighting control methods control the degree of opening of shutters and also the dimming of artificial lighting, and achieve savings in lighting costs, designed through lighting software such as DAYSIM [17] or ENERGYPLUS [18], between 10 and 60% [19–21].

To model the effects of artificial ligthing in the room, the software chosen was Dialux evo 9.1, which is a free comercial software that allows the user to make a model of a room/area with a fair amount of detail including the luminaires. This sofware was chosen since it displayed good results in [22–25].

EnergyPlus 6 is an open source software made to model energy consumption (heating, cooling, ventilation, other electric spendings). It was designed by the US Department of Energy and is very commonly used with various purposes, including the calculation of natural light in a room [14, 20, 26–29], hence why it was chosen for that same purpose here.

As already mentioned, user comfort depends not only on the visual component, but also on other factors such as temperature, humidity and concentration of harmful particles or gases. Of these, the one that is most influenced by lighting is temperature. This is because solar gains have a significant effect on it, which does not happen with artificial lighting. Therefore, a lighting control strategy must take into account the effects that the taken control actions have on the temperature of the space. Furthermore, the energy costs of temperature control,

Nomenclature	Description
1/4 p	1 of the 4 light switches on, being it on the door side
1/4 j	1 of the 4 light switches on, being it on the window side
2/4 p	2 of the 4 light switches on, being both on the door side
2/4	2 of the 4 light switches on, 1 on the door and 1 on the window side
1/4p + 2/4j	1 switch on the door side and 2 on the window side on.
c1	Both blinds in position 1 (fully closed)
c2	Both blinds in position 2 (fully open)
c3	Both blinds in position 3 (upper part open)
c4	Both blinds in position 4 (lower part open)
c13+c24	Blind on the blackbord side in position 3, the other in position 4.

TABLE I. Examples of code names and respective meaning

such as HVAC, tend to be higher than that of lighting, which could make lighting control counterproductive in its energy efficiency goal. With all this in mind, what is proposed for a model control for this room follows approximately the following procedure:

- **Sensor value** This allows to measure the average illuminance inside the room
- **Day and time** Important because the height of the sun varies the illuminance in the room
- **Arrangement of blinds** This information is important to be able to correctly model the

  light distribution in the room. However, it is not available as there is no way to withdraw this value directly. To get around this problem:
  - **The blinds have been placed in manual mode** When returning to automatic mode, they have to be placed in a known position
  - **Remained in automatic mode** It is assumed that they are in the position of the last command
- **Active Fixtures** Same as the blind arrangement, but for the lighting fixtures.
- **Initial Modeling** The above 4 pieces of information are used, through a modeling program, in this case EnergyPlus for the natural lighting component and DIALUX for the artificial component, to simulate the distribution of illuminance by the work plane of the classroom.
- **Evaluation** First control step. Evaluates the comfort of the modeled result simply by checking that all points of the distribution created are within the defined limits for comfort. If it is and there are no active fixtures then the next step is not necessary. Otherwise, follow the next step
- **Settings test** Models are made for the distribution of illuminance in the room, using EnergyPlus for the natural component and DIALUX for the artificial component. This time, the hour, day and value on the sensor remain, but the settings for blinds and lighting are variable. The various cases are modeled and the solution is chosen that simultaneously checks the limits and has the lowest possible energy consumption (less lights on)
- **Optimal Solution Execution** Execute the decided solution

III. METHODOLOGY

A. Command Algorithm

For the automation of the lighting system, there are, among others, two possible strategies. One of them, usually referred to simply as control, requires some type of system modeling, and can be either an open loop or a closed loop, depending on whether it's used some measured/predicted output to use as feedback in calculating the action to take. On the other hand, when no modeling is used, and instead the algorithm that decides the control action follows only a system of rules, then it is typically called a command algorithm. The simplest way to automate the lighting system is simply to use a timetable so that the position of the blinds is best for the expected position of the sun. Thus, this form of automation qualifies as an algorithm of command. As long as the Sun is low (from 7 am), to avoid direct sunlight or reflected in the eyes, but to get in as much light as possible, the best position will be c3. At approximately mid-morning (9am), as the sun will already be higher, then you have to change this setting in order to cover the direct light, which now comes higher, that is, c4 or c1. Here, what will be used to decide which one to use is the sensor value. It was defined that up to and including 93, the algorithm chooses c4. Above that, choose c1. That's how they stay until noon, which is at around 12:30. After this, then there is no longer any problem of direct light in the user's vision and therefore the blinds can be opened completely to enter as much sunlight as possible. However, as this may mean too much light, one must choose between c4 or c2, which, once again, is done using the room sensor. This time, up to 86 c2 chosen, and above that c4. And it stays that way until the end of the day.

For choosing which luminaires to turn on, what was defined was simply that when the command algorithm decides the setting c1 then the configuration of the luminaires should be 2/4, since most likely artificial lighting will be needed throughout the room. If the position of the blinds defined is c2, c3 or c4, then the luminaires must have the 1/4p configuration, as for these positions the illuminance levels near the window tend to be sufficient, while next to the door it is not verified . As already mentioned, the position of blinds has a significant effect on temperature and, consequently, this effect must be considered. Usually, the air temperature range considered comfortable is approximately 19 to $24C$. Therefore, as the position c2 is the one that has a clear effect on the increase in temperature, then, if the internal temperature of the room, measured by the existing sensor, is equal to or greater than $24.0C$ then the algorithm must prevent this position be defined. To prevent the temperature from falling below the lower limit, it is not necessary to define any extra measures in the control of the blinds, as the algorithm already tries to maximize natural lighting, which generates heat.

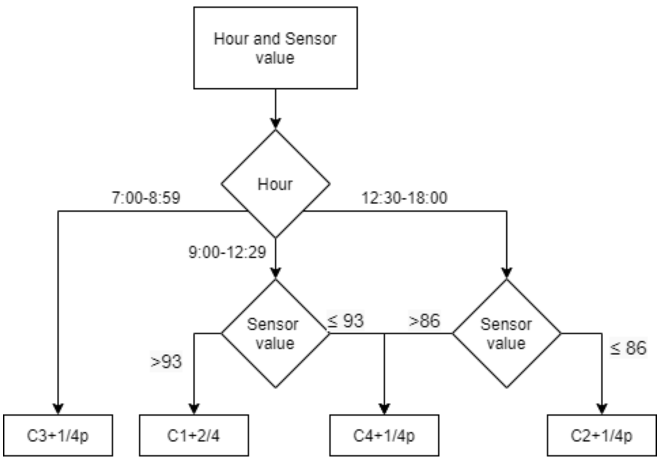


FIG. 3. Command Algorithm Flowchart

B. Predictive Control

Another control strategy consists of, in a situation that is considered not to be comfortable for the user, to predict the effects that certain changes would have and to choose a control action to be taken in accordance with these predictions. For this it is necessary to know the effects that each configuration of blinds and luminaires have on the illuminance in the room's work plan. To obtain this information, 2 simulation softwares were used, Dialux Evo 9 for calculating the artificial lighting effects, and EnergyPlus 6.0 for the blinds effect.

To get an idea of the effects that the various configurations of blinds and lighting have on illuminance and also to partially validate the results obtained by the software used, some measurements were made in the room. These measurements were taken at different times of the day, on nearby days and when the weather conditions were similar. Illuminance in the work plane (tables) was measured with the ISO-TECH ILM 1332A handheld illuminance sensor at six points in the room, the 4 corners, the center, and the place of the middle row next to the window. The seat next to the door in that row consistently measured the same values as the seat in the back row. This was done in several configurations that were considered likely to be used at that time.

To simulate the distribution of illuminance in the room's work plane, coming from sunlight, the EnergyPlus (EP) program, version 6, was used together with Google SketchUP 7 and OpenStudio. This distribution depends on 3 factors. The 1st is the position of the Sun, that is, the azimuth angle and the altitude, which in turn depends on the time and day of the year. The 2nd is the position of the blinds, whose various configurations were in 1. The third is the intensity of sunlight, which varies depending on the day and time, but also the state of the sky (cloudy or clear) at the time in question. The position of the sun and blinds varies the illuminance distribution in relative terms, while the intensity varies the illuminance values only in absolute terms. 1st and 2nd are defined in the EnergyPlus simulations, which are then used together with the information from the existing sensor in the room, in order to obtain results that better reflect the real situation at the moment. The output resulting from these simulations, as in Dialux, consists of a 7x7 matrix with the illuminance values in the work plane.

The control implementation was done in MATLAB. In general, the algorithm follows a similar structure to that of an MPC (predictive model control), as shown in 5. It starts by choosing a possible control action, predicts the result that such action would have, then assesses whether that response is valid/optimal, and depending on that assessment, performs that same control action or tests another, and so on. The way in which it evaluates the expected results and chooses which action to try next (if the evaluated one is not valid) follows the algorithm shown in figure 4. The program starts by placing the blinds in position c3, as it is a "safe" position, that is, it is usually a valid option. After that, with the hour (approximate to the units, since the simulations are hourly), day and value in the sensor, it simulates the distribution for that moment in the various blind configurations. Then check if all of these points are within the limits. The chosen limits were 200 lux for the minimum and 2000 for the maximum. From here it chooses the 1st (in order c1,c3,c4,c2) configuration that checks the criteria. If none check, then choose the last one that still checks the maximum threshold of 2000. After that, if there is, according to the simulated distribution, some point in the half closest to the door that is below the threshold, a lamp on that side is turned on and its contribution is accounted for in the expected distribution. The same is repeated later for the side of the window, and again for each side.

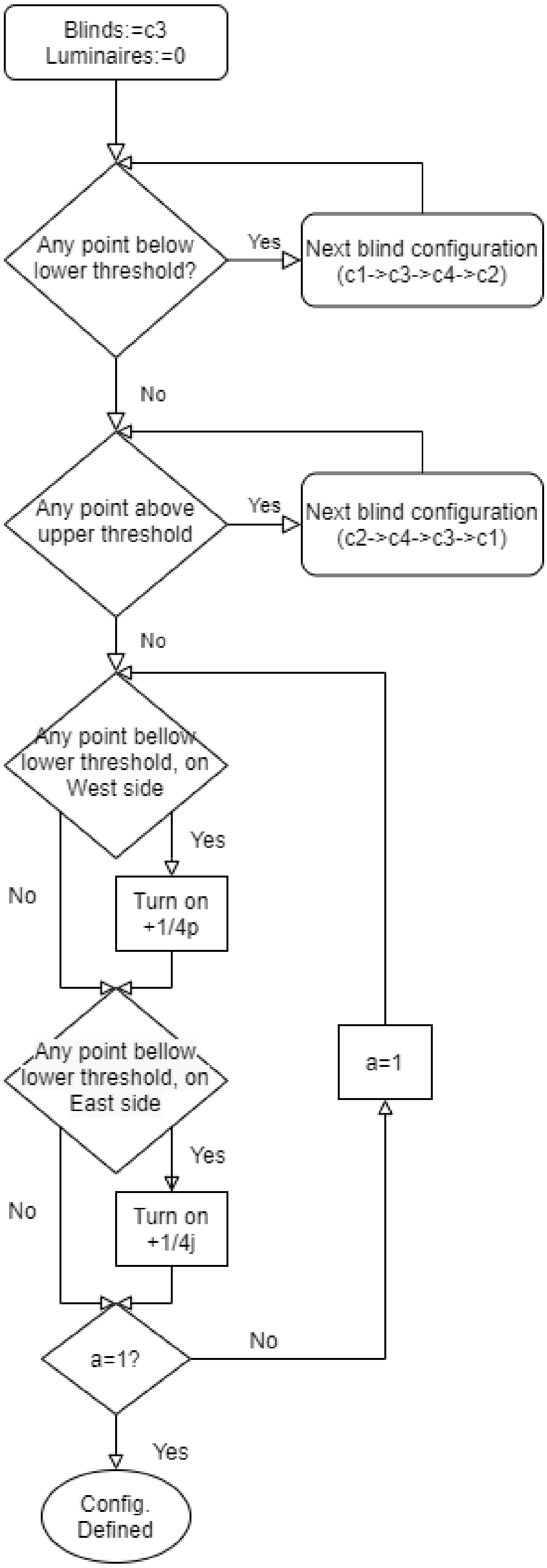


FIG. 4. Flowchart for choosing configuration

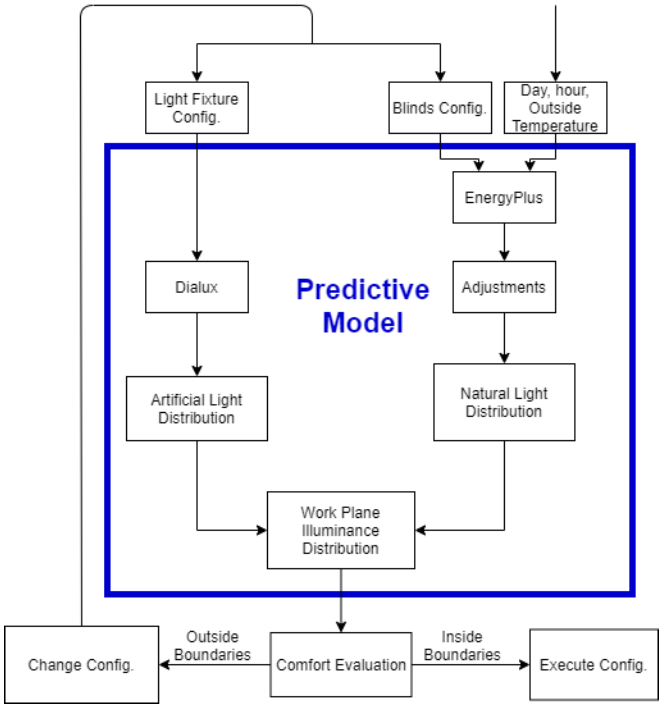


FIG. 5. Control Algorithm Flowchart

IV. RESULTS AND DISCUSSION

A. Validation of Simulations

To assess the accuracy of the simulations made in Dialux and EnergyPlus, the results predicted by the simulations for several different cases were compared with real measurements. And for this assessment, rather than seeing how large in absolute or relative terms the differences between the results are, we have to compare how far the simulated and experimental results are on the visual comfort scale. Once again, visual comfort is very subjective, yet the typically preferred range is 300-2000 lux ([30]), with lower values tending to be accepted or preferred when using computers ([31], [32]). For the purposes of how these values will be used, the important thing is whether both the forecast and the actual measurement fall within, below or above the comfort range. For example, if the measured value in a situation is 50 lux and the forecast is 150 lux, then despite being a relative error of 200%, both are below what is considered comfortable, and therefore it's a good result. The same applies if, for instance, if the actual value is 4000 lux and the predicted value is 8000 lux.

1. *Dialux*

In the table II are the comparisons between the measurements taken in the room, in 6 points of the room, in

4 cases with different light settings and closed shutters, and the predicted values using the Dialux results for the same cases. Looking at the results, there are some cases where the error exceeded 200 lux and 2 points where Dialux predicted the illuminance to be above 200 lux when the measurement was below, which could be a problem if the control thinks it is correct to close all blinds and lights on in some situation, but this is very unlikely to happen and to affect the success of the control. In addition, at the points near the window (1, 3 and 5) it is noted that there was a general underestimation by Dialux, which was also expected because in these areas, when the real illuminance values were measured, there was some light coming from the window that passed between the blinds. That said, the results are satisfactory, as most errors are close to 100 lux and these differences are not very noticeable by the human eye, therefore, the use of Dialux is validated.

Point	Dialux	Measure	Dialux	Measure
	2/4		2/4p	
1	265	535	82	120
2	250	240	384	330
3	467	540	122	120
4	564	600	590	400
5	332	500	88	120
6	336	360	562	330
	1/4p		2/4j+1/4p	
1	41	189	489	582
2	192	279	308	270
3	61	206	873	580
4	295	220	833	720
5	44	189	620	580
6	281	330	391	270

TABLE II. Results of Dialux Simulation Test. Values in lux

2. EnergyPlus

To validate the predictions made by EnergyPlus, tests were carried out as for Dialux, in the 4 configurations used, over the course of a day. The results are in the table III. Looking at the results, it can be said that the forecasts have, in general, an acceptable error considering how they will be used. However, it is possible to notice some frequent errors. Namely, the predictions for position c3 during the morning, and for position c4 during the afternoon.

B. Command Algorithm

To test the command algorithm, a test was carried out during one day, from 8:30 am to 6:00 pm, with answers about which blinds/light fixtures configuration should be performed every 30 minutes. The results are in the table IV, where "Sensor value" represents the value that the sensor presented at the respective moment, before the control action was executed. "Response" is the configuration that the algorithm asks to be executed, and below each number, corresponding once again to the measurement points, is the illuminance measured in the work plane at that point, after executing the requested "Response" by the algorithm. "Temperature" refers to the temperature inside the room in degrees Celsius.

The results of the command algorithm are quite positive, since at all times the option presented was translated into comfort. In addition, the options defined by it, for this day, were almost always the best option. The only time it can be said that this did not happen was at 8:30, when it was found that there was some direct light in the eyes, for whoever was sitting in some of the seats in the center. Something that would only not happen if the blinds were in position c1.

C. Predictive Control

To test the predictive control, a test was carried out during the same day as the command control, to get answers on what configuration of blinds/light fixtures should be performed every 30 minutes. The results are in the table V.

Looking at the results, it can be said that they were similar to those obtained by the command algorithm, especially during the afternoon, where the chosen option was always the same in both methods. However, these results cannot be considered as positive, since, during the morning, especially between 9:30 and 10:30, the option defined was not one that resulted in comfort for users. Overall, the results of both methods can be considered positive in that they translate into energy savings, as the estimated energy consumption, just for lighting, during this period would be 0.92 KWh and 0.72 KWh for the command and predictive control algorithm, respectively. These values are below the usual daily consumption of the room, which is around 1.2 kWh (from direct measurements of the electrical consumption of the room), which would represent savings in consumption associated with lighting of around 22 and 40%, respectively . These results are in line with what was obtained by similar works, mentioned in II C.

[1] U. Berardi, Procedia Engineering **118**, 128 (2015), defining the future of sustainability and resilience in design, engineering and construction.
[2] L. Pérez-Lombard, J. Ortiz, and C. Pout, Energy and

		Measure						Prediction					
		1	2	3	4	5	6	1	2	3	4	5	6
09:00	c1	640	100	640	280	520	75	156	52	185	127	213	52
	c2	5200	180	4300	980	3500	90	12105	263	13749	792	20046	233
	c3	1740	460	1840	1600	1550	380	51	9	62	16	62	9
	c4	1100	90	1200	520	1300	80	1215	144	1519	430	1681	144
10:00	c1	220	30	270	130	250	60	256	87	326	204	355	87
	c2	50000	800	50000	3400	50000	600	10090	525	8712	1220	14520	496
	c3	1400	250	1700	1200	1850	200	88	14	107	31	107	14
	c4	4600	460	4000	1700	4100	350	2674	259	3322	829	3686	259
11:00	c1	170	25	130	65	105	15	177	58	224	148	236	58
	c2	11000	260	10000	1440	20000	320	77834	489	10644	1177	39564	459
	c3	325	75	310	330	470	50	59	10	73	20	71	10
	c4	1950	105	1870	490	2000	85	2272	291	2784	822	3050	291
12:00	c1	325	40	300	130	255	30	131	29	170	118	183	29
	c2	11600	350	9900	1550	9100	260	8420	391	4247	1429	1009	374
	c3	330	80	360	390	400	70	291	75	342	346	342	75
	c4	1560	100	1630	500	2200	85	901	135	1105	580	1207	135
13:00	c1	270	40	330	140	275	25	115	32	144	104	158	32
	c2	6500	230	6300	1340	5600	170	2668	191	2523	721	580	180
	c3	500	125	610	600	800	120	224	64	280	235	280	64
	c4	2360	150	2420	670	2530	110	470	71	591	312	636	71
14:00	c1	175	25	185	75	127	30	59	21	74	45	81	21
	c2	5700	240	6000	940	5800	190	2655	204	2366	675	2525	191
	c3	460	105	490	420	610	85	163	76	191	192	191	76
	c4	1600	105	1600	450	1780	90	344	190	426	227	467	190
15:00	c1	100	15	105	50	115	15	64	20	71	43	78	20
	c2	6200	260	6550	1120	5100	210	2714	212	2634	720	2866	195
	c3	435	90	440	360	380	70	158	86	198	207	198	86
	c4	1250	130	1300	460	1520	100	381	209	462	244	503	209
16:00	c1	90	10	90	40	80	10	49	20	63	43	70	20
	c2	3000	150	2950	630	2730	100	1215	151	1329	495	1492	140
	c3	230	60	240	260	240	40	133	68	157	152	157	68
	c4	1230	90	1300	380	1365	80	280	164	346	184	373	164
17:00	c1	90	10	85	40	80	10	48	19	62	42	69	19
	c2	5100	190	5200	910	4800	110	1040	154	1206	491	1397	143
	c3	230	60	230	295	230	40	131	67	155	150	155	67
	c4	1120	90	1180	370	1250	70	277	162	329	182	369	162

TABLE III. Test Results of EnergyPlus Simulation

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Hour (UTC+1)	Sensor value	Response	Temperature	1	2	3	4	5	6
08:30	119	c3+1/4p	20.5	1710	830	1760	3300	1680	760
09:00	95	c4+1/4p	21.4	1140	280	1260	820	1340	360
09:29	96	c1+2/4	21.7	470	280	680	660	530	360
10:00	89	c1+2/4	21.6	490	280	740	690	580	400
10:30	86	c1+2/4	22.3	490	280	740	690	580	400
11:00	96	c4+1/4p	22.1	1990	300	1930	790	2040	370
11:30	102	c4+1/4p	22.5	2570	340	2400	930	2540	420
12:00	92	c4+1/4p	22.3	3140	390	2860	1070	3040	470
12:30	94	c4+1/4p	22.6	1500	250	1500	670	1650	350
13:00	95	c4+1/4p	22.5	1520	400	1500	620	1500	300
13:30	97	c4+1/4p	22.5	1750	300	1650	730	1640	380
14:00	97	c4+1/4p	22.5	800	430	960	600	1100	290
14:30	101	c4+1/4p	22.5	830	400	950	550	1000	280
15:00	96	c4+1/4p	22.6	750	380	830	480	830	230
15:30	91	c4+1/4p	22.6	1050	300	1150	600	1200	340
16:00	91	c4+1/4p	22.5	800	400	900	500	960	230
16:30	94	c4+1/4p	22.5	880	230	880	500	890	320
17:00	90	c4+1/4p	22.4	400	240	430	390	400	330
17:30	89	c4+1/4p	22.4	430	275	485	370	410	300
18:00	86	c2+1/4p	22.3	430	570	460	690	420	500

TABLE IV. Command Algorithm test Results

Hour (UTC+1)	Sensor value	Response	Temperature	1	2	3	4	5	6
08:30	119	c1	20.5	700	200	700	315	90	400
09:00	95	c1	21.4	640	100	640	280	520	75
09:29	96	c2+1/4p	21.7	3000	220	3000	670	2500	330
10:00	89	c2+1/4p	21.6	50000	800	50000	3400	50000	600
10:30	86	c2+1/4p	22.3	4600	460	4000	1700	4100	350
11:00	96	c1	22.1	520	70	570	230	70	520
11:30	102	c1+2/4	22.5	740	260	900	1000	760	400
12:00	92	c2+1/4p	22.3	5000	520	4650	1390	3650	310
12:30	94	c4+1/4p	22.6	1500	250	1500	670	1650	350
13:00	95	c4+1/4p	22.5	1520	400	1500	620	1500	300
13:30	97	c4+1/4p	22.5	1750	300	1650	730	1640	380
14:00	97	c4+1/4p	22.5	800	430	960	600	1100	290
14:30	101	c4+1/4p	22.5	830	400	950	550	1000	280
15:00	96	c4+1/4p	22.6	750	380	830	480	830	230
15:30	91	c4+1/4p	22.6	1050	300	1150	600	1200	340
16:00	91	c4+1/4p	22.5	800	400	900	500	960	230
16:30	94	c4+1/4p	22.5	880	230	880	500	890	320
17:00	90	c4+1/4p	22.4	400	240	430	390	400	330
17:30	89	c4+1/4p	22.4	430	275	485	370	410	300
18:00	86	c4+1/4p	22.3	390	380	400	390	380	220

TABLE V. Predictive Control Test Results

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