Sensitivity analysis of visual and thermal parameters for energy savings: combining illuminance and temperature set-points for possible trade-offs

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Abstract

This study presents a methodology for evaluating the effects of simultaneous temperature and illuminance set-point variations on energy consumption. Different illuminance levels are achieved with an innovative dynamic shading control algorithm that allows keeping constant values of maximum workplane illuminance. Findings from applying the methodology to a specific office-like workplace located in Switzerland show that the new shading control algorithm leads to lower cooling energy consumption in comparison with a standard shading control system (i.e., based on maximum irradiance) for constant 300 and 500 lux indoor illuminance thresholds. Moreover, multiple combinations of temperature and illuminance levels result in similar cooling consumption values, implying that trade-offs between those two parameters are possible to achieve energy savings.

Introduction and goals

Energy within buildings is mainly spent to guarantee users' comfort in terms of light, temperature, ventilation and humidity levels. Changing the settings related to these parameters represents an opportunity for substantial energy savings as far as comfort is preserved. Currently recommended thresholds for indoor environmental factors, as found in standards, come from studies investigating the effect on comfort of one factor at a time, neglecting the fact that the human sensory system is not modular but integrates and responds to environmental factors simultaneously (Bluyssen, 2013). The awareness of the interactive combinations of different indoor stimuli has led to a renewed interest in the study of the effects of *interactions* between multiple environmental parameters on users' comfort (e.g., how thermal parameters affect visual conditions and visual parameters affect thermal conditions as in Chinazzo at al. (2016)), and synergistic interactions between indoor parameters and comfort perception have already been demonstrated in selected conditions (Fang et al., 1998; Huizenga at al., 2006; Tiller et al., 2010). Such studies clearly indicate potential energy savings from the possible extension of standardized comfort ranges, thanks to changes in comfort perception through particular combinations of indoor environmental factors. This potential is notable in research relating light with temperature, as their operation is responsible for the largest share of the energy used in buildings (Huebner et al., 2016; te Kulve et al., 2015).

Even though the comfort perception of humans related to particular combinations of light and temperature levels is still under investigation, it is already possible to study the energy consumption associated to different combinations of these two parameters with the help of energy simulations. In other words, it is possible to study how energy consumption is affected by the simultaneous change of illuminance and temperature set-points and if trade-offs between the setting of these two parameters are possible to achieve energy savings.

In energy simulation studies, indoor illuminance and temperature set-points have been listed as determinant elements affecting the thermal and lighting energy consumption of a building (Lee et al., 2016). The positive impact of extended air temperature set-points on energy consumption has been demonstrated through building simulations (Freire, Oliveira, & Mendes, 2008; Hoyt, Arens, & Zhang, 2015; Konis & Zhang, 2016; Yonezawa, 2000), while temperature variation acceptability in terms of subjective thermal comfort is already well known as adaptive comfort (Nicol & Humphreys, 2002) or as a trade-off for energy savings (Hwang et al., 2009). Changes in indoor illuminance levels and their impact on energy consumption has been connected only to shading control studies, with indoor horizontal illuminance used as the control algorithm for shading automation (Athienitis & Tzempelikos, 2002; Carletti et al., 2016; Lee et al., 1998). Nevertheless, shading control systems usually operate with algorithms based on other parameters than indoor illuminance, even if workplane illuminance has been shown to be the principal parameter that prompts occupants to interact with shading devices and electric lighting (da Silva, Leal, & Andersen, 2012). The most common control algorithms are based on maximum direct or transmitted irradiance , and indoor temperature (van Moeseke et al., 2007). When indoor illuminance is used as a a a trigger in the control algorithm, it only prompts the blinds to close when a threshold is exceeded, or it sets particular slat angles for predefined lux ranges (Yun, Park, & Kim, 2016), not allowing to have a constant indoor illuminance. Nevertheless, future findings on the effects of indoor factor interaction on comfort might indicate as comfortable particular combinations of constant temperature and illuminance values. To our knowledge, no studies have investigated the use of a dynamic shading control to reach and keep constant different values of maximum workplane illuminance. As a consequence, no studies on the energy consumption

induced by combinations of temperature and constant maximum indoor illuminance levels are available.

The goal of this study is to investigate, through sensitivity analysis (Saltelli, 2008; Tian, 2013), the effect of simultaneous variations of constant maximum indoor illuminance and temperature setpoints on the energy consumption of a simple workplace model with the use of a new dynamic shading control. To do so, we simulate the energy performance (at different temperature set-points) of a 3D office-like room with a dynamic "illuminance" shading control that allows to keep (almost) constant different workplane illuminance levels. We call this model "DYNILL". Results of the DYNILL are compared with the ones calculated with a reference case model (REF, with a "standard" shading control algorithm, i.e., based on a maximum irradiance threshold), a "no shading option" (NOSHAD), and a "no windows option" (NOWIN).

We chose to change the indoor illuminance levels with a shading system as, with this particular control algorithm, it allows to keep (almost) constant different values of maximum workplane illuminance. Moreover, its operation influences the amount of solar gains and subsequently the indoor temperatures. To reach accurate results, it is therefore necessary to integrate climate-based thermal and daylighting simulations as already done in previous research on shading control strategies (Goia, Haase, & Perino, 2013; Jakubiec & Reinhart, 2011; Konstantoglou & Tsangrassoulis, 2016; Shen & Tzempelikos, 2012, 2013; Tzempelikos & Shen, 2013), but with an innovative control algorithm. The simulation workflow to reach this goal and the analysis of the results define a *methodology* to quantify the potential energy savings for existing or designed buildings due to temperature and illuminance set-point combinations during their operation. The methodology is applied to a specific case (office-like room in a Western Swiss climate) with particular temperature and illuminance set-points, although the chosen approach can be applied to any building model or location and the set-points tailored to the particular preferences of occupants.

In the following paragraphs, we first describe the simulation workflow, then the modelled office-like room, the temperature and illuminance set-point variations, the DYNILL model and the three comparison ones. Finally, we analyse and discuss the results.

Simulation workflow

Simulations are conducted with the following dynamic energy and daylighting simulation software: EnergyPlus v. 8.0 (UIUC, 2004) and DIVA-for-Rhino v. 4.0., a Rhino 3D plugin used to interface with Radiance and Daysim (Jakubiec & Reinhart, 2011). EnergyPlus allows to set different set-point values for indoor temperature and to choose control strategies for dynamic shading devices (such as maximum irradiance). Nevertheless, it has two main limitations:

1. Indoor illuminance cannot be used as trigger in the for the operation of the external blinds;
2. The shading position applied to an opening can only be "fully on" or "fully off", although slat angle variations are possible.

For these reasons, to simulate a dynamic shading control based on illuminance thresholds (our DYNILL model), it is necessary to combine the daylight simulation tool with the energy simulation software. The simulation integration workflow consists of four steps (figure 1):

Step 1: A 3D model is defined within both the daylight (DIVA) and EnergyPlus modelling platforms.

Step 2: Several combinations of shading positions and slat angles are modelled in DIVA. For each combination, the workplace illuminance at a single point (in this case 1.3 m from the north façade and at 0.8 m height) is calculated with detailed daylight simulations, resulting in an annual hourly file with illuminance values for each combination.

Step 3: Combining the hourly files with illuminance values, a "blind schedule" for each illuminance set-point is generated to keep the indoor illuminance constant. The blind schedule is an hourly file containing the shading configuration and represents the control algorithm to input into EnergyPlus for the external blinds.

Step 4: Energy simulations for each temperature set-point and illuminance level (associated with a particular shading operation schedule) are conducted.

Steps 1 (EnergyPlus model only) and 4 are also executed for the other three models (REF, NOSHAD, NOWIN).
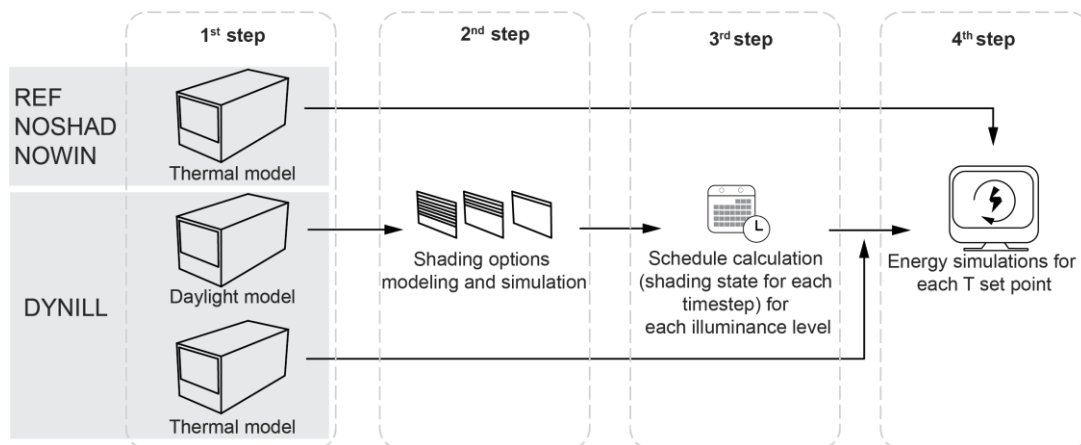

Figure 1: Simulation workflow for the four models (REF, NOSHAD, NOWIN and DYNILL)

Model setup

In the following sections, we define in detail all the modeling parameters, assumptions and specifications for the energy calculations according to the recommended format of the European standard 15265 (CEN, 2007).

Climatic data

Simulations have been carried out for a typical year in a single climate. The IWEC weather file (source: U.S Department of Energy's website) used as input data in the simulations corresponds to the Geneva weather station.

Model description

The modelled shoe-box (figure 2) represents a simplified version of a real test room in which comfort experiments are ongoing to test users' perception and acceptability of temperature and illuminance combinations. The model is simplified as it does not reproduce the complex heating, cooling and ventilation system present in the real space.

The shoe-box has a floor area of 20 m^2 and a height of 3.05 m. It has two windows, one for each of the two smaller walls, facing North and South respectively. Each window, with an external and internal clear glass pane of 3 mm and an air gap of 13 mm, has a total dimension of 5.6 m^2 (height of 1.90 m and width of 2.95 m, representing 60% of the wall area), a U-value of 1.96 W/(m^{2}K), a g-factor equal to 0.69, and a visual transmittance of 0.74. The opaque envelope has been modelled to satisfy the minimum required value of U=0.2 W/(m^{2}K) for the thermal transmission coefficient of an external envelope according to the SIA 380/1 standard in force in Switzerland (SIA, 2009). The walls are made of concrete, mineral wool, and plaster. Table 1 illustrates the material specifications in terms of reflectance values. An external shading device is present only on the south opening and is characterized by movable slats of 10 cm width and a between-slat distance of 8 cm. The reflectance factor of the blinds is 0.80.

Table 1: model component properties.

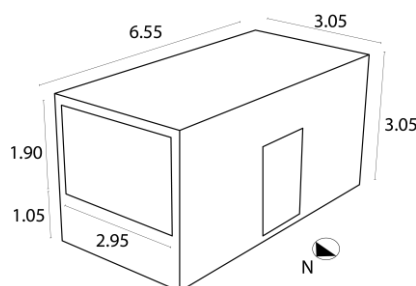| Component	Material	Reflectance[-]
Wall and ceiling	White plaster	0.70
Floor	Grey opaque finishing	0.20
Window frame	White aluminium	0.70

Figure 2: Geometry and principal internal dimensions (m) of the modelled room.

Internal gains

Internal gains are assumed to be at maximum 35 W/m^2. They account for three people (120 W each) and for a lighting load of 17 W/m^2 for an illuminance requirement of 500 lux and of 10 W/m^2 for an illuminance requirement of 300 lux. All simulations are performed with a dimming strategy to control electric lighting. This means that the light power is continuously adjusted by a real-time dimming system, which reduces the electric power proportionally to the amount of incoming daylight to guarantee a minimum predifined illuminance on the workplane. The room is assumed to be occupied Monday to Friday, from 8:00 to 18:00. Saturday and Sunday are free days and 20 days of holidays are accounted for. No office equipment is modelled.

Illuminance and temperature set-point values

According to EN 15251 (CEN, 2007) and to the Swiss norm SIA 180 (2014), heating is required for operative temperatures below 21 °C and cooling is required for operative temperatures above 24 °C. Those values are used to define our model in terms of thermal control, complemented with set-back temperatures of 16 °C in winter and 28 °C in summer outside the occupied hours. Regarding lighting control, the standards define a minimum illuminance threshold for a specific task, provided with daylight and/or electric light, i.e., the minimum value below which electric lighting is required. In the case of an office building, this minimum value ranges from 300 to 500 lux according to the type of task as specified in EN 12464-1 and in the Swiss norm (SIA, 2006; CEN, 2011). In user assessments studies in real situations, the value of 300 lux is indicated as the maximum threshold for manually switching on the artificial lighting (Reinhart & Voss, 2003) and the levels of daylight are considered sufficient even when they are below recommended thresholds (Konis, 2013). Nevertheless, we considered both 300 and 500 lux as the minimum values for electric lighting control, to be coherent with the standards. The upper limits for illuminance usually refer to glare avoidance or to maximum levels of preferred daylight (Wienold, 2010). According to Wienold (2010), users asked to interact with the shading system to achieve a comfortable workplace lighting environment chose on average a horizontal illuminance level of 3000 lux, by adjusting (opening or closing) the shading system when the illuminance deviated (was below or above) that value. The only way to set a maximum illuminance value is to use the dynamic shading control with horizontal illuminance as a trigger in the control algorithm, or another type of shading control. Hence, in all the EnergyPlus models, the illuminance set-point refers only to electric lighting.

Heating, cooling and ventilation settings

The EnergyPlus software calculates the energy needed for keeping the room temperature within the set-point values in both summer and winter, assuming a perfectly efficient HVAC system (ideal loads). The space is provided with mechanical ventilation including heat recovery to guarantee a minimum airflow per person of 10 l/(s person) (CEN, 2007). An infiltration rate of 0.7 air change per hour (ACH) is considered. Heating, cooling, ventilation and lighting schedules are defined according to the occupation time described earlier.

Temperature and illuminance set-point variations

Building upon the set-point values described in the previous paragraph, we here define the set-point variations for temperature and illuminance levels in order to study their effect on energy consumption.

The analysis is mainly focused on cooling energy demand as the type of control algorithm used is more efficient in the summer season (as explained in the next paragraphs). Nevertheless, also annual simulations are conducted for being able to compare changes in cooling and heating set-points. In case of annual simulations, heating and cooling set-points are never changed in combination, meaning that when cooling set-points are varied (from 24 °C to 23 °C, 25 °C, 26 °C, 27 °C and 28°C), the heating set-point is kept constant at 21 °C. On the other hand, when the heating set-points are changed (from 21 °C to 18 °C and 23 °C), the cooling set-point is constant at 24 °C. When focusing on cooling energy demand, the same levels of temperature as in the annual simulations are considered.

The temperature set-point variations occur in the DYNILL model as well as in the three comparison ones. For the illuminance set-point variations, it is necessary to distinguish between (i) the minimum threshold under which the electric light is turned on and (ii) the maximum daylight threshold accepted in the room. Regarding the electric light, only two values, i.e., 300 lux and 500 lux, are simulated for all four models. The maximum daylight illuminance threshold is varied only for the DYNILL model, following the methodology described in detail in the next paragraph, between 300 lux and 3000 lux. Within that range, users' comfort and acceptability is high as long as glare and reflections are avoided. The simulated illuminance threshold levels are: 300 lux, 500 lux, 1000 lux, 2000 lux and 3000 lux. For the 300 lux and 500 lux cases, the electric lighting set-point in EnergyPlus is changed accordingly. Figure 3 illustrates this aspect by showing the illuminance set-point variations for electric lighting (all models) and daylighting (DYNILL).
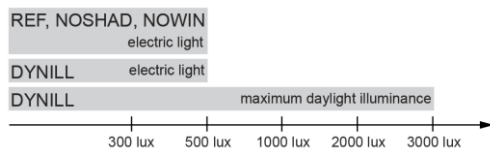

Figure 3: Illuminance set-point variations for electric light (minimum threshold) and daylight (maximum threshold) for the four models.

The DYNILL and the comparison models

In the following sections, we describe in detail the DYNILL model and the other three comparison models. The energy performance values associated with the DYNILL model for all combinations of illuminance and temperature set-points represent the core results of this study. The results of the "common" dynamic shading control model (REF) and the other two models (extreme cases NOSHAD and NOWIN) are used as a comparison to understand the energy impact of the dynamic illuminance control strategy in combination with different temperature set-points.

Dynamic illuminance shading control model (DYNILL)

The dynamic illuminance shading control model uses the constant maximum horizontal workplane illuminance within the control algorithm for the external blinds. To simulate the energy performance of the dynamic movement of the slat angles and height positions, the four-steps integrated simulation workflow between the daylight and energy tool is followed (figure 1). Within step 2, several combinations of shading positions and slat angles are simulated in DIVA. In particular, we discretize the shading operation in four height positions in combination with two main slat angles, plus two additional slat angles for just one height position. Figure 4 illustrates the simulated 10 height and slat angle combinations. The blind heights refer to a shading position at 1/4, 1/2, 3/4 and 4/4 of the window starting from the top. This shading division is modelled as four separate openings (window-stripes) in the thermal model, each of them with a specific schedule for the control of the slat angles. This is necessary to overcome to problem of the energy tool in which the shading position applied to an opening can only be "fully on" or "fully off", and only the slat angle can be changed. The slat angles between the glazing outward normal and the slat outward normal are modelled to be 90° and 45°, plus two additional angles (67.5° and 22.5°) for only the 3/4 height. For each of the 10 combinations, plus an extra one in which blinds are completely open, a climate-based daylight simulation is performed for a single point in the room, resulting in hourly values of indoor illuminance for the whole year. From these results an hourly dynamic schedule combining blind heights and slat angles is created for each illuminance threshold, in order to guarantee the closest illuminance value to the desired threshold and the maximum view to the outside (in case of equal results for two combinations). Each schedule is then converted into another four indicating the slat angle for each height (hence, for each of the four window-stripes in EnergyPlus).
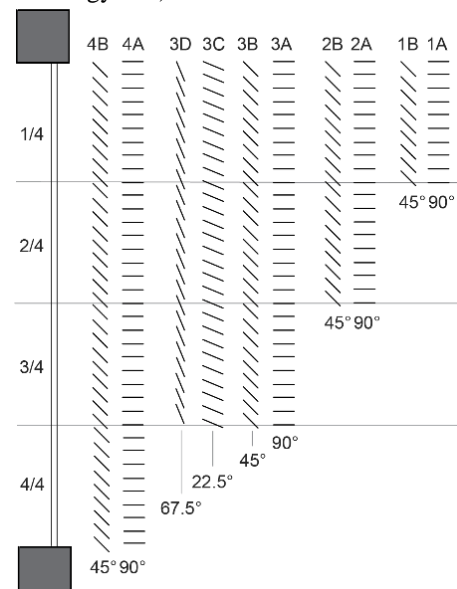

Figure 4: Shading height and slat angle combinations.

Figure 5 illustrates the results of the dynamic schedule operation for different illuminance levels and over two specific days of the year: the 4th of March (cloudy sky) and the 22th of July (clear sky). Figures 5a and 5b show the variations of slat combinations during the occupied hours for different illuminance scenarios. Figure 5c and 5d illustrate the illuminance values resulting from the dynamic schedules operation. It is possible to see that the illuminance control is more accurate at lower levels of illuminance as the shading control discretization has more slat angle values when the blind is at 3/4 of the window, resulting in more control options. It is clear that the more increments simulated in slat angles and heights, the more accurate the dynamic shading control is in terms of maximum indoor illuminance control.

When computing the annual energy performance, the dynamic illuminance shading control is applied in two ways, i.e., over the whole year (DYNILL$_{allyear}$) and only in summer (DYNILL$_{summer}$). In the latter case, an internal glare control screen is assumed during wintertime.

Dynamic irradiance shading control model (REF)

The dynamic irradiance shading control model is considered as the reference case (REF) as it presents a "more common" dynamic shading control based on maximum irradiance (150 W/m^2 on the external vertical surface). This type of control is directly set in EnergyPlus, without the need for integrating daylight and energy simulation platforms as in the DYNILL case.

No shading control model (NOSHAD)

This model is equal to the REF and the DYNILL except for the shading system. It does not have external blinds in

any of the two windows. Therefore, it represents an extreme case that is not realistic but that is useful for comparison with the other models. It is modelled and simulated only with EnergyPlus.

No window model (NOWIN)

This model represents the other unrealistic but extreme case, where the shoe-box does not have any window. The two windows (and hence the blinds) are deleted from the model, resulting in a room without any opening to the exterior except for the door. As the REF and NOSHAD models, it is modelled and simulated only with EnergyPlus.

Evaluation criteria

Two evaluations are conducted:

1. The cooling energy consumption for the summer period (from April 30th to September 30th) according to EN ISO 13790. The dynamic illuminance shading control strategy is considered more suitable for the summer case, as in winter time the solar gains cannot be exploited when using the blinds.

2. The energy use for the entire year. The energy use is computed in the form of electricity, assuming that the heating and cooling are provided by a reversible heat pump system with an average seasonal COP of 2 and a EER of 2.5, respectively.
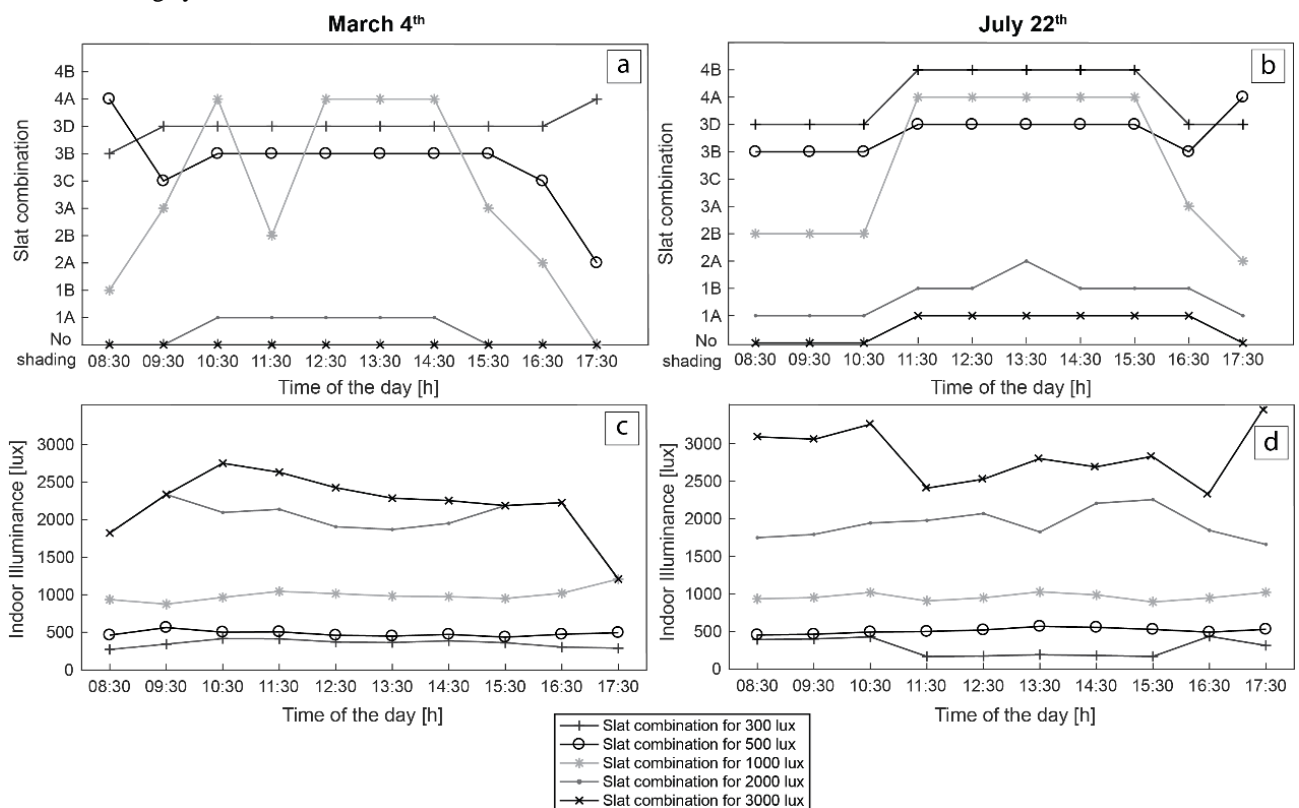
Figure 5: Dynamic control of slat angles and heights for different illuminance levels.

Results and discussion

Cooling energy consumption

Figure 6 illustrates the cooling energy consumption at various cooling temperature set-points for the illuminance levels of the DYNILL model and for the REF, NOSHAD and NOWIN models. The (a) 300 lux and (b) 500 lux results refer to a change of the electric light threshold in all models, and a simultaneous change of the daylight illuminance set-point for the DYNILL model.

As expected, all results for the two dynamic shading control cases (REF and DYNILL) lay in between those of the two extreme cases, i.e., NOSHAD and NOWIN. Figure 6b shows that results from DYNILL_3000 are almost comparable to the ones for the NOSHAD_500 case, as the dynamic operation of the shading led to a configuration of the blinds almost always open. The same conclusions can be drawn for DYNILL_2000 even if a slightly lower cooling consumption is attributable to a more closed configuration of the blinds. Both graphs show that energy consumptions for both DYNILL_300 and DYNILL_500 are lower compared to the REF (at 300 and 500 lux), where the shading is triggered by external irradiation on the façade. This result illustrates that the innovative dynamic illuminance shading control algorithm, when operated for 300 and 500 lux illuminance thresholds, leads to better results in terms of energy than a more common shading control algorithm (i.e., based on maximum irradiance). The cooling energy consumption of the DYNILL_1000 model is lower than the one of REF_500 only at 23 °C. Results from the two models are the same at 24 °C, but for higher temperature levels, REF_500 leads to slightly lower cooling energy consumptions. In any case, we can conclude that DYNILL_1000 and REF_500 lead to comparable results. For DYNILL_300 and DYNILL_500, the maximum daylight illuminance and the electric light thresholds are changed at the same time. Nevertheless, the difference between their results is mainly due to the change of the daylight illuminance set-point. In fact, it is clear from the small difference between REF_300 and REF_500, as well as between NOSHAD_300 and NOSHAD_500, that the effect of the electric light on the cooling energy consumption is rather small. The explanation is the occupation schedule used for the cooling energy calculation that, in summer, mainly includes daylit hours when no electric lighting is needed. By looking at the difference between NOWIN_300 and NOWIN_500, the gap is rather big due to the continuous usage of electric lighting and hence a big influence of the change in internal gains.

Graphs 6a and 6b provide valuable information for possible trade-offs between temperature and illuminance set-points: it effectively illustrates how to achieve similar energy consumption values by choosing different set-points combinations. As an example, if the preferred illuminance value is 2000 lux, it is necessary to increase the cooling set-point by 1 °C to limit the cooling energy consumption to the one of the REF_500 model at 24 °C. This type of comparison can be done between different illuminance levels (among the DYNILL cases) and between different solar control strategies (among the DYNILL, REF and NOSHAD models). Table 2 quantifies the relative difference of the cooling energy consumption (ΔE_c) of the REF_500 model at 24 °C (comparable to REF_300 and DYNILL_1000) with the ones of the same model at different temperature levels and of the DYNILL cases at various illuminance levels and temperature set-points. The results show that, for our particular simulation model and location, the maximum energy saving is reached with DYNILL_300 at 28 °C ($\Delta E_c = 62\%$), obviously a theoretical temperature value since definitely outside the comfort range. Always in comparison to REF_500 at 24 °C, higher cooling set-points are necessary for obtaining a similar cooling energy consumption with higher illuminance thresholds. In any case, lower energy savings will be reached if high illuminance values are considered (at maximum $\Delta E_c = 39\%$ with DYNILL_3000 at 28 °C).
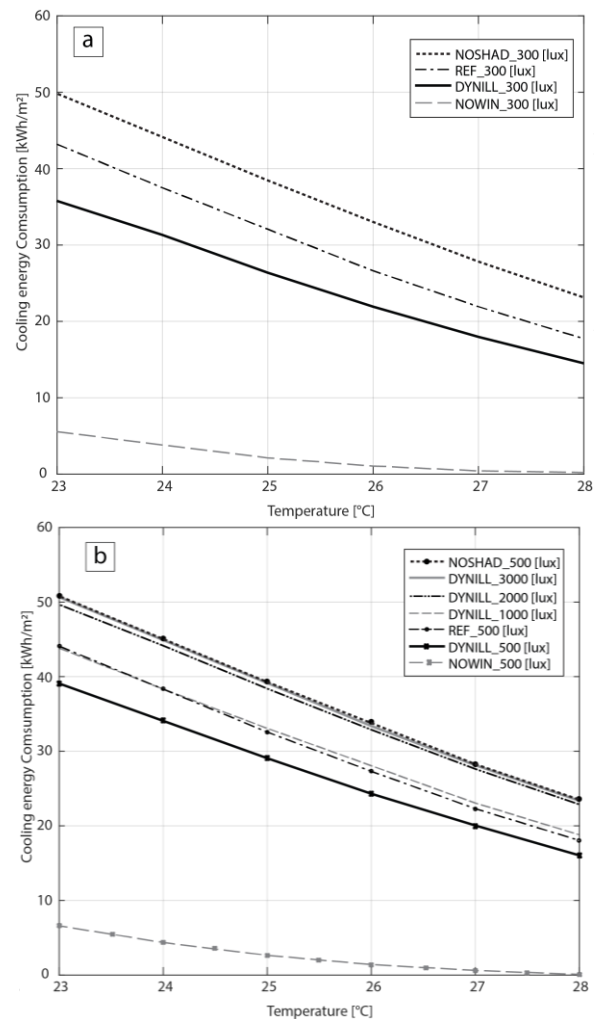

Figure 6: Cooling energy consumption for different temperature and illuminance set-points for DYNILL, REF, NOSHAD and NOWIN models. Figure (a): electric light (and daylight illuminance only for DYNILL) set-point at 300 lux. Figure (b): electric light (and daylight illuminance only for DYNILL) set-point at 500 lux, together with other illuminance levels for DYNILL.

Table 2: Cooling energy consumption comparison with REF_500 at 24 °C as a reference case (in red and bold).

	REF_500		DYNILL_300		DYNILL_500		DYNILL_1000		DYNILL_2000		DYNILL_3000	
Top [°C]	Ec [kWh/m2]	ΔEc [%]	Ec [kWh/m2]	ΔEc [%]	Ec [kWh/m2]	ΔEc [%]	Ec [kWh/m2]	ΔEc [%]	Ec [kWh/m2]	ΔEc [%]	Ec [kWh/m2]	ΔEc [%]
23	44.1	-15	36.1	6	39.0	-2	43.7	-14	49.9	-30	50.7	-33
24	**38.2**	**0**	31.4	18	34.1	11	38.4	0	44.1	-15	44.9	-18
25	32.5	15	26.6	30	29.1	24	33.1	14	38.4	-1	39.2	-2
26	27.2	29	22.0	42	24.3	37	27.9	27	32.9	14	33.6	12
27	22.3	42	18.0	53	19.9	48	23.1	40	27.7	28	28.3	26
28	18.1	53	14.4	62	16.1	58	18.8	51	22.9	40	23.5	39

Annual energy use

After a deep analysis of the cooling energy consumption, it is necessary to look at the results for all models in terms of annual energy use. Figure 7 shows the energy use for REF, DYNILL$_{allyear}$, DYNILL$_{summer}$, NOSHAD, and NOWIN for two cooling set-points (23 °C and 28 °C, with a constant heating set-point of 21 °C) and two heating set-points (18 °C and 23 °C, with a constant cooling set-point at 24 °C) at 500 lux. The difference between DYNILL$_{summer}$ and DYNILL$_{allyear}$ is in the dynamic shading control operational time, as described earlier. For the other models, the shading control is always on (the irradiance threshold of 150 W/m^2 is always achieved for REF), the shading is never present (NOSHAD), or the windows are not modelled (NOWIN). The two temperatures for the cooling and for the heating set-point displayed represent the extremes of the calculated ranges. All other values lay in between these results.

At a first glance, we can see that – excluding the results for the no window case – the energy use is more sensitive to changes of temperature set-point rather than changes in the visual control strategy. In addition, energy use results are higher for the highest temperature set-point in winter (23 °C, with 24 °C in summer) compared to the lowest temperature set-point in summer (23°, with 21 °C in winter). It confirms that for this type of climate, the energy for heating is greater than the one for cooling. Moreover, as the relative difference between the results of the two temperature set-points in winter is bigger than the relative difference between the results of the two temperature set-points in summer, we argue that variations in heating set-points lead to higher energy savings compared to variations in cooling set-points.

Figure 7 shows that the energy consumed by the electric light operation is almost always constant through the different set-points and models, except for the NOWIN model. This result can be explained by the fact that in the REF, DYNILL and NOSHAD models, the operation of the blinds is different during daytime only and it is not affecting the operation of the electric light during the occupied hours. The lighting energy use for the NOWIN model is higher as the lighting is always on during the occupied hours. Consequently, the NOWIN cooling energy use is very low due to the absence of solar gains (almost zero for the cooling set-point of 28 °C), but its heating energy use is comparable with the ones of the other models as the lack of solar gains is compensated by the lack of heat losses due to the absence of windows. Despite the constant lighting energy use, the DYNILL

models (both all year and only summer operation) represent the best ones in terms of energy saving as they present the lowest total annual energy use for the sum of lighting, cooling, and heating energy use. The principal factor influencing this result is the cooling energy use. Heating energy use for the DYNILL model in fact sometimes leads to higher results in comparison with the ones of the REF model. This only happens for the DYNILL$_{allyear}$ model (at 500 lux) where the operation of the dynamic illuminance shading control system during the entire year leads to higher heating energy use due to the lack of winter solar gains because of blinds operation.

Figure 8 illustrates the annual energy use for the REF model at two illuminance thresholds (300 lux and 500 lux) and the DYNILL$_{allyear}$ model at all the illuminance thresholds for two temperature set-points (with heating set-point set at 21 °C). At the lowest temperature (23 °C) the DYNILL$_{allyear}$ at 300 lux is the solution that leads to the lowest energy use, due to its low cooling and lighting energy use. The lighting energy use of this model is comparable to the one of REF_300, while its heating energy use is slightly higher. What makes a substantial difference is the cooling energy use. The DYNILL$_{allyear}$ at 500 lux results in higher total energy use compared to REF_300 only due to the difference in lighting energy use, as the cooling consumption (and hence energy use) is lower for the DYNILL$_{allyear}$ at 500 lux as illustrated in figure 6. Figure 8 illustrates results for the DYNILL$_{allyear}$ model only. The DYNILL$_{summer}$ case presents even better
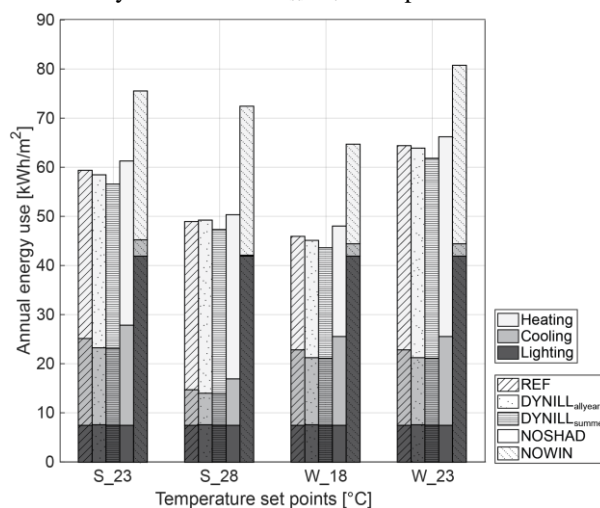

Figure 7: Energy use for the four models (plus one) at two cooling set-points (S_23 °C and S_28 °C) and two heating set-points (W_18 °C and W_23 °C) at 500 lux.

results as its shading control set only in summer allows more heat gains in winter, resulting in a lower energy use for heating. Nevertheless, this difference is minor, as seen in figure 9 showing the energy use for all illuminance thresholds of the DYNILL model for both DYNILL$_{allyear}$ and DYNILL$_{summer}$ control. The displayed results apply for the winter temperature set-point of 21 °C and summer temperature set-point of 24 °C. It is possible to see that the DYNILL$_{summer}$ control has lower energy use for heating at lower illuminance thresholds because, as pointed out before, the precocious closing of the shading device in winter cuts out some heat gains that, with the internal glare control of the DYNILL$_{summer}$ case, are contributing to a reduction of the heating energy. At higher illuminance thresholds, the energy use for heating for the DYNILL$_{allyear}$ case levels out with the one for the DYNILL$_{summer}$ case as the blinds are increasingly open, both in summer and winter. The energy use of the DYNILL$_{allyear}$ case at 500 lux is almost the same as the one of the DYNILL$_{allyear}$ case at 1000 lux only because the decrease in the energy use for heating is compensated by the increase in the energy use for cooling. The small differences between the two operation modes of the DYNILL model are due to the fact that the heat gains from solar penetration in winter are likely less significant compared to the losses of the shoe-box (high infiltration rates). In any case, it is suggested to apply the dynamic control for illuminance thresholds only in summer rather than during the whole year. These results are in agreement with the ones of Wienold et al. (2011) about different shading control systems, where they explain that a combination of external shading and internal glare protection can reduce the overall energy consumption significantly compared to only external or internal mounted shadings.
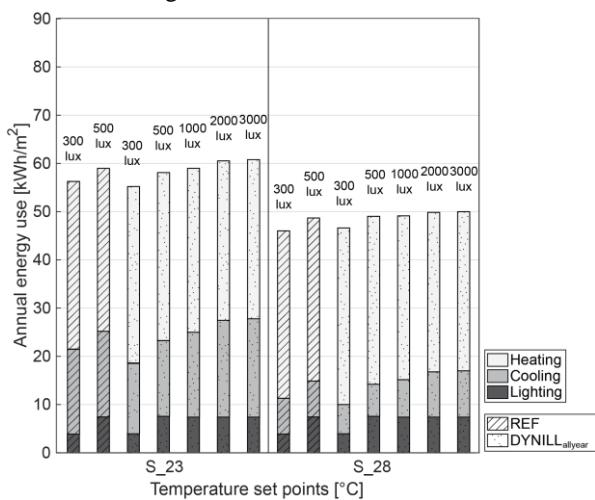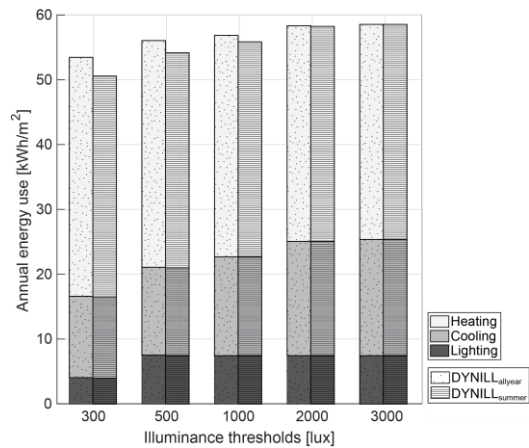

Figure 9: Energy use for DYNILL$_{summer}$ and DYNILL$_{allyear}$ at different illuminance thresholds (heating set-point at 21 °C and cooling set-point at 24 °C).

Conclusions

This study introduces and applies a methodology for the evaluation of the effects of the combined variation of temperature and constant indoor illuminance set-points on cooling energy consumption and annual energy use. The calculation of the energy consumptions resulting from different set-points of constant indoor illuminance is made possible thanks to the use of an innovative shading control algorithm based on constant maximum indoor illuminance, simulated with the integration of thermal and daylighting software.

The application of the methodology to an office-like case study in Switzerland illustrates that the dynamic illuminance shading control algorithm allows reaching significantly lower cooling energy consumption in comparison with a dynamic reference shading control based on maximum irradiance, when 300 lux or 500 lux are used as a threshold value for the control algorithm. In particular, at 24 °C, a reduction of 18% of energy use is observed when the dynamic illuminance shading control algorithm is used with a threshold value of 300 lux or of 11% with a threshold value of 500 lux. Results with a 1000 lux value are comparable to the ones of the reference model, meaning that with the same energy consumption higher levels of indoor illuminance are achievable with the new control algorithm.

In case higher indoor illuminance values are desired by the users or more energy savings are foreseen, it is necessary to increase the cooling set-point in summer (the thermal comfort implications that would consequently follow are not tackled in this study). Results show that different combinations of illuminance and temperature set-points lead to similar cooling energy consumption, making possible trade-offs between those two parameters to achieve energy savings.

When looking at the total annual energy use, two main conclusions can be drawn. First, the dynamic illuminance shading control leads to better results when used only in summer in combination with an internal glare control during winter time, in comparison with an "all year" operation (up to 7% energy savings when using 300 lux as a threshold value). Finally, the percentage of energy

Figure 8: Energy use for REF (at 300 lux and 500 lux) and DYNILL$_{allyear}$ at different illuminance thresholds at two cooling set-points (S_23 °C and S_28 °C, with heating set-point set at 21 °C).

saving increases more with changes in temperature set-point (e.g., from 23 °C to 18 °C in winter or from 23 °C to 28 °C in summer) than with changes in illuminance levels (e.g., from 3000 lux to 300 lux). Moreover, within temperature set-point changes, winter set-point variations lead to higher energy savings (28-29% for the DYNILL and the REF at 500 lux) compared to summer set-points variations (15-17% for the REF and DYNILL at 500 lux). These results refer to the particular case study analysed, but the same methodology can be applied to other building typologies and climates for gaining insights on the effects of temperature and illuminance set-point variations on energy consumption.

Acknowledgements

Nomenclature

REF = Reference Case

DYNILL = Dynamic Illuminance control strategy

NOSHAD = No Shadings

NOWIN = No Window

T_{op} = operative temperature

ΔE_c = relative energy difference for cooling consumption

E_c = cooling energy consumption

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