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IMPACT OF OCCUPANT BEHAVIOUR ON LIGHTING ENERGY USE

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ABSTRACT

Artificial lighting contributes for a large part to the primary energy use of an office building. Lighting control systems can help reduce the lighting energy use. When calculating the potential energy savings, neglecting the occupant behaviour leads to an overestimation. This research shows that the energy saving performance of a daylight dimming system in an individual office decreases by about 10% when user behaviour is accounted for. A parameter analysis shows that this result is fairly independent of boundary conditions.

INTRODUCTION

In industrialized countries, the building stock is typically responsible for about 40% of the total energy use (IEA, 2008). In Flanders, the northern part of Belgium, its share was 35% in 2007. Office buildings account for about a third of this total building energy use (Flemish Government, 2008). Consequently, the focus of policy makers is largely on the building sector in their attempts to reduce energy use and the emission of greenhouse gases. In this perspective, the EU voted the Energy Performance of Buildings Directive in 2002. Within that framework, Flanders put its Energy Performance Regulation (EPR) into force in 2006. The EPR demands an evaluation of the energy performance of the building *as a whole* and sets, amongst others, a legal standard for maximum primary energy use.

According to (Best Practice Programme, 2000), artificial lighting contributes for about 20% in the total primary energy use of a standard cellular office building. Possibilities to reduce that lighting energy use exist at three different levels. Firstly, the *demand* for artificial lighting can be decreased by thoughtful design to increase the daylight availability. Secondly, the *control* of artificial lighting can be optimized to only provide light when necessary and as much as necessary. The latter is off course in strong relation with the first level. At a third level, the *emission efficiency* of the lighting installation – lamp, gear, luminaire- needs to be maximized. Although this three-level approach seems straightforward, some important remarks need to be made. For instance, the possible influence of the increase of daylight availability on the thermal environment, e.g. higher solar, must be taken into consideration. Another aspect to be considered, is the impact of the occupant and his behaviour. To exclude glare risks, direct solar radiation into the office space must be avoided. This influences the blind control and thus the daylight availability. Further on, inconsiderate use of the artificial lighting by the occupant may compromise any efforts to provide sufficient daylight in the office space. These and other occupant impacts need to be taken into account when evaluating measures to increase lighting energy efficiency.

The energy saving potential of the use of daylight has been the subject of several earlier studies. Results from calculations vary from 20% to 80% (Bodart et al., 2002). Of particular interest is the research of (Opdal et al., 1995), where calculated energy savings are compared with measurements. The latter resulted in a saving potential of about 30%, whereas the simulations, without accounting for occupant behaviour, predicted a potential of 40%.

SIMULATION

Objectives

The purpose of the research is to evaluate various light control and blind control systems (see tables 1 and 2) in combination with different types of user behaviour. For each combination, the hourly lighting energy use is calculated for a whole year, so comparison between the control systems can be made. Furthermore, the impact of the occupant behaviour on the performance of a control system is assessed. Evidently, the results depend significantly on the boundary conditions (orientation, blind type, window size, glazing type, etc.). A sensitivity analysis is performed to analyze the dependency on these parameters.

Methodology

The simulations are performed with the Daysim software (Reinhart, 2006). Daysim calculates the illuminance in certain points due to daylight based on the daylight coefficient (DC) approach (Tregenza et al., 1983), combined with the Perez all-weather sky luminance model (Perez et al., 1993). The DC's are calculated by backward ray-tracing with the Radiance algorithm (Ward et al. 1998). As a result of this simulation, illuminances at every point of interest are obtained for every time step for a whole reference year. By using the DC method, the amount of very time consuming ray-tracing procedures is limited, while maintaining a good accuracy (Reinhart et al., 2000).

Table 1
Considered blind control systems, from (Reinhart 2006)

BLIND CONTROL SYSTEMS	
Name	*Description*
Manual	Blinds lowered when 50 W/m^2 direct solar radiation on workplane
Automated*	Blinds lower when 50 W/m^2 direct solar radiation on workplane and pull up otherwise**

*This does not necessarily mean that the blinds are controlled automatically, but could also be considered as an idealized type of user behaviour.

**This is an idealized control strategy, that could lead to control instability in real life.

Table 2
Considered light control systems, from (Reinhart 2006)

LIGHT CONTROL SYSTEMS	
Name	*Description*
Manual	Manually controlled on/off switch by the door (reference system)
Switch-off	Absence detection (delay time 15 minutes), combined with manual on/off switch by the door
Switch on/off	Presence detection (delay time 15 minutes)
Dimming	Photosensor controlled dimmed lighting (ideal adjustment of lighting output to available daylight)
Switch-off + dimming	Photosensor controlled dimmed lighting, combined with presence detection (delay time 15 minutes)

Daysim couples this daylight calculations with a stochastic behavioral model, called Lightswitch. Four user types are proposed (see table 3). However, the distribution of the occupants over the different types is unknown for an existing office building. The occupant decisions of the 'active lighting control' user types are based on probability functions, derived from statistical research (Reinhart et al. 2003). These functions can be found in figure 11. The lighting switch-off decision relates to the expected time of absence. The lighting switch-on decision at arrival has a strong relation with the available amount of daylight on the workplane. The intermediate switch-on decision however, shows a much weaker correlation with the ambient daylight. It is also a relation that has not been validated by other studies. Therefore, a sensitivity analysis is performed (see further). It is important to remark that the functions described are derived for individual offices, where the occupant has personal control over lighting and blinds. It is safe to assume that the functions will also be valid in two-person offices. In landscape offices though, the situation is completely different and can not be described with the Lightswitch behavioral model. Because of the stochastic nature of the behavioral model, the results of simulation runs with identical inputs will be different. A test with 20 runs revealed however that the standard deviation is 5% at maximum. It is therefore decided that it is not necessary to take the average of several runs of the same simulation to interpret the results.

Since this research requires a great amount of simulations, special attention has gone to the simulation settings that influence the calculation time, i.e. the Radiance parameters, the number of daylight sensor points and the simulation time step. Based on (Ward et al. 1998), the Radiance parameter set shown in table 4 has been used for the simulations. The number of diffuse interreflections (ambient bounces, -ab) is very important, as the sky contribution is calculated with the diffuse interreflection algorithm. The combination of ambient accuracy (-aa) and ambient resolution (-ar) is chosen to be able to model details as small as 5 cm, which is sufficient for the scene geometry (see further). For every daylight sensor point, an entire set of daylight coefficients must be calculated, by far the most time consuming part of the calculation. Therefore, only two daylight sensor points are selected (see figure 1 for their location). Finally, a time step of 5 minutes was chosen after a thorough analysis. This time step is small enough to model the weather dynamics and the control dynamics (e.g. delay time of switch-off occupancy sensor).

Model description: base case

The simulations are performed for the moderate climate of Uccle, Belgium. The model geometry is this of an individual office space, with an external façade facing south. The height is 2.8 m and the floor area is 10.2 m^2, based on the assumption of 10 m^2 per person in an individual office in EN 15251. The glazing-to-wall ratio is 41% and the glazing-to-floor ratio is 38%. An internal screen is used as a shading device, with two different settings: up and down. The screen is placed at a 5 cm distance from the glazing. The daylight sensor points are at workplane height (0.75 m) and in the middle of the width of the office space. One is located at 1 m of the window, the other at 2 m.

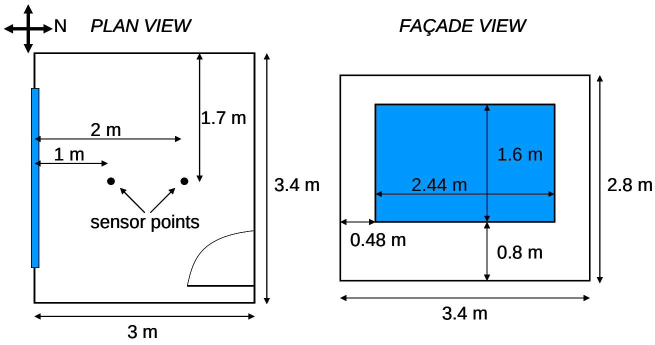

Figure 1 Office geometry

The interior ceiling, walls and floor are considered perfect diffusers, with a reflectance of respectively 70%, 50% and 30%. The glazing is clear, thermally improved double glazing with a visual transmittance of 65%. The internal screen scatters all incoming light, of which 30% is transmitted. The front reflectance is 30%, the back reflectance 36%.

The target workplane illuminance value for an office space is 500 lux (EN 15251). It is obtained by 4 Philips Master TL5 High Efficiency lamps of 28 W, assuming a lamp efficiency of 93 lm/W, a gear efficiency of 95%, a luminaire output ratio (LOR) of 90%, a maintenance factor of 0.75 and a utilance of 72%. This results in an installed lighting power of 11 W/m^2 or a normalized power density (NPD) of 2.2 W/100 lm. According to (Hanselaer et al. 2008), the artificial lighting of an office space of this size should have a NPD lower then 4.1 W/100 lm to be categorized as 'energy efficient', so this requirement is met. In (Roisin et al. 2008), the stand by power consumption of an occupancy sensor and DALI controller was found to be about 2.5 W, whereas this is about 2 W for a photosensor and DALI controller. These hidden consumptions are taken into account in the simulations.

Parameter variation

A stated before, the influence of a few boundary conditions on the results is analyzed. The parameters are varied one by one, to assess their individual impacts. The adjusted parameters are:

- The glazing material: the visual transmittance is decreased to 35%.
- The screen material: the internal screen is assumed perfectly opaque.
- The window size: the glazing-to-floor area is varied 10%-17%-27%-38%-52%-67%.
- The shading device: instead of an internal screen, internal venetian blinds are used as shading device. Two positions -horizontal slats and tilted slats- are considered. See figure 2 for the geometry. The slat material is assumed an opaque perfect diffuser with a reflectance of 50%. Since the venetian blinds add detail to the scene geometry, the radiance parameters are changed. The number of ambient bounces is set to 7 and the ambient accuracy and ambient resolution are increased to be able to model details as small as 5 mm.
- The office geometry: the floor area of the office space is doubled, to simulate a two person office. The area of the façade is unaltered, so the depth of the room is increased tot 6 m. A glazing-to-floor ratio of 26% is achieved by a glazed area of 5.26 m^2. Sensor points are at 1 m, 3 m and 5 m distance of the window.
- The orientation: the orientation of the external façade is varied from south to west, east and north.

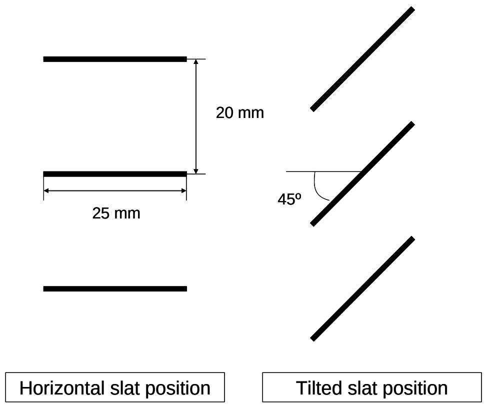

Figure 2 Internal venetian blind geometry

ANALYSIS OF THE RESULTS

Base case

Tables 5 and 6 give an overview of the results of the simulations. In figure 12, the cumulative lighting energy use for a whole year is given for user type 1 and user type 2. Figure 13 gives the average daily profiles of lighting energy use for user type 1 and user type 2. The difference in energy use between manual control and switch on/off control for user types 2 and 4 is due to the energy consumption of the occupancy sensor.

By comparing graph 12-A with 12-B, the impact of active occupant lighting control on the energy use can be assessed. Apart from the on/off occupancy controlled lighting –obviously-, the lighting energy use decreases significantly when the occupant makes a switch-on decision depending on the available daylight.

This behavioral impact is especially important when attempting to predict energy savings of certain measures. From table 6, when comparing user types 1 with 2 and 3 with 4, it can be concluded that neglecting the occupant behaviour leads to an overestimation of the energy savings of efficient control systems. For this case, the maximum overestimation of the energy saving potential -corresponding with a distribution of 100% of type 1 users- of a daylight dimming system is about 10%. As shown in figure 3, this difference of 10% is not dependent on the considered blind control.

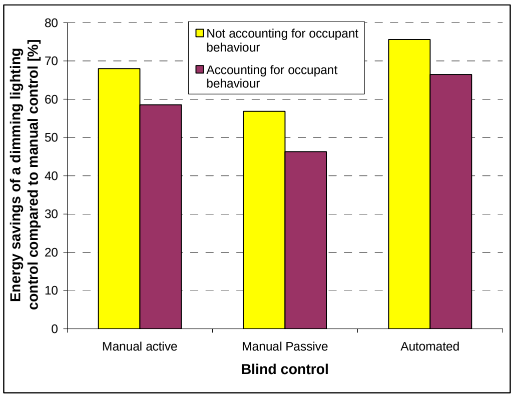

Figure 3 Energy savings of daylight dimming compared to manual control for different blind control systems, with or without accounting for occupant behaviour

It is a very common practice when comparing energy use of different lighting control systems to take an absence detection (switch on-off) system as a reference system. However, this is in most cases not in compliance with reality. In most individual office spaces, the lighting control is simply manual and this system should then be taken as a reference system. Figure 4 shows the importance of the correct reference system when calculating lighting energy savings. For this case, the maximum difference in calculated energy savings -corresponding with a distribution of 100% of type 1 users- is about 20% for a daylight dimming light control.

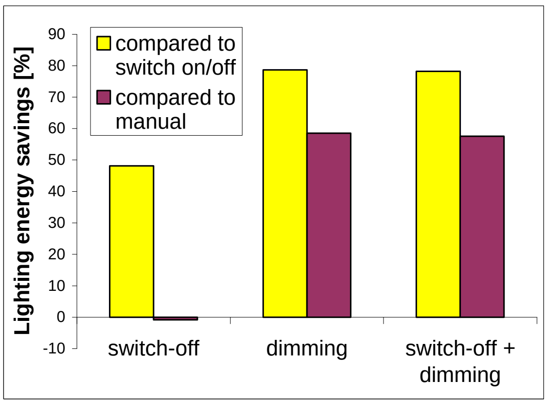

Figure 4 Energy savings compared to different reference systems

Sensitivity analysis on intermediate switch-on decision

The probability function for the intermediate switch-on decision has not been validated. Furthermore, this probability is defined as a function of the available daylight, although a weak correlation was found. In order to estimate the sensitivity of the results on this function, a number of simulations is done with the probability divided by 2 and multiplied by 2 (see figure 10). Off course only simulations with active user behaviour are influenced by this function. Figure 5 gives the results of this analysis for user type 1, automated blind control and manual lighting control. A relative difference of about 10% on the yearly lighting energy use is found. For this sensitivity analysis, the average result of 10 runs of each simulation has been used, to smoothen the effect of the stochastic behavioral model.

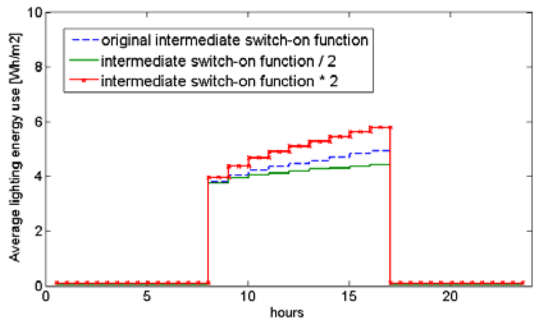

Figure 5 Average daily profile of lighting energy use for user type 1, automated blind control and manual light control. Sensitivity on intermediate switch-on probability

Parameter analysis

Figure 11 gives an overview of the parameter analysis. For all parameter variations, the impact of accounting occupant behaviour in the calculation of energy savings by daylight dimming is shown. An maximum overestimation of about 10% by neglecting occupant behaviour is found, more or less independent of any parameter changes.

In the following, some interesting results of the individual parameter variations are discussed.

Decreasing the glazing visual transmittance to 35% results in less daylight entering the office space. Changing the shading material to opaque has the same effect, but only when the shading device is lowered. Both parameter variations can be expected to lead to higher lighting energy use for dimming systems. Furthermore, the energy use of systems with manual switch-on and daylight dependent user light control will increase. Figure 6 shows the influence of both parameter variations on the resulting energy use. It is obvious that possible energy savings of a dimming system compared to a manual system are much lower when less daylight enters the room. This effect however is more pronounced for the opaque screen than for the decreased glazing transmittance. This is due to the choice of material properties variation.

For dimming systems, the increase in energy use is largest for the opaque screen, whereas a lower glazing transmittance has the largest effect for manual systems. The reason for this is that, contrary to the glazing transmittance, the opacity of the screen has no influence on the lighting switch-on decision at arrival, because the screen is never closed when the occupant arrives. The latter is off course a consequence of the façade oriented to the south.

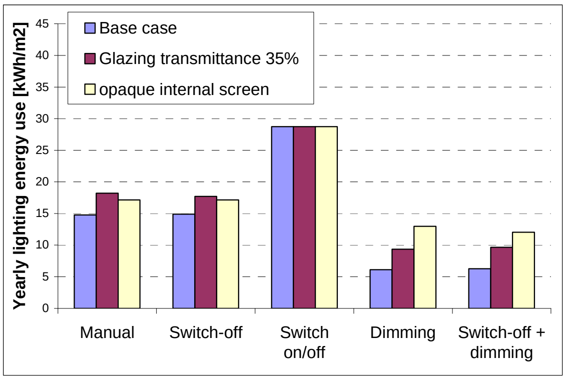

Figure 6 Comparison of the lighting energy use for user type 1, automated blinds for different glazing visual transmittance and screen visual transmittance

Figure 7 shows the yearly lighting energy use as a function of the glazing-to-floor ratio of the office space, for user type 1 and automated blinds. The marginal efficiency of enlarging the window size decreases. The fact that the lines in figure 7 are not very smooth is due to the stochastic effect as discussed in the section on the methodology.

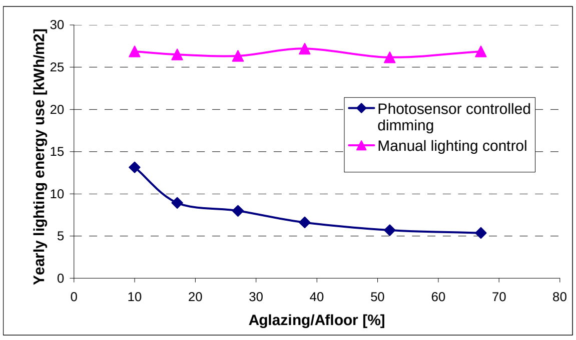

Figure 7 Yearly lighting energy use of manual and dimming light control systems for user type 1, automated blinds, as a function of glazing-to-floor ratio

At least for the base geometry and material properties, the orientation shows to be a parameter that doesn't influence the lighting energy use very much. Thus, the energy savings due to daylight dimming are not very orientation dependent (see figure 8). This might seem strange at first, because the daylight availability during office hours shows a strong correlation with the façade orientation. It can however be explained by the use of the shading device.

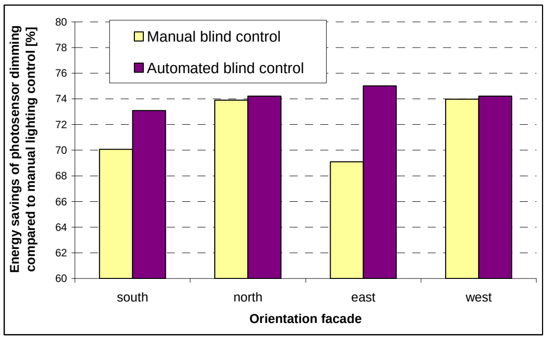

Figure 8 Energy savings of daylight dimming compared to manual control for different orientations and different blind control systems

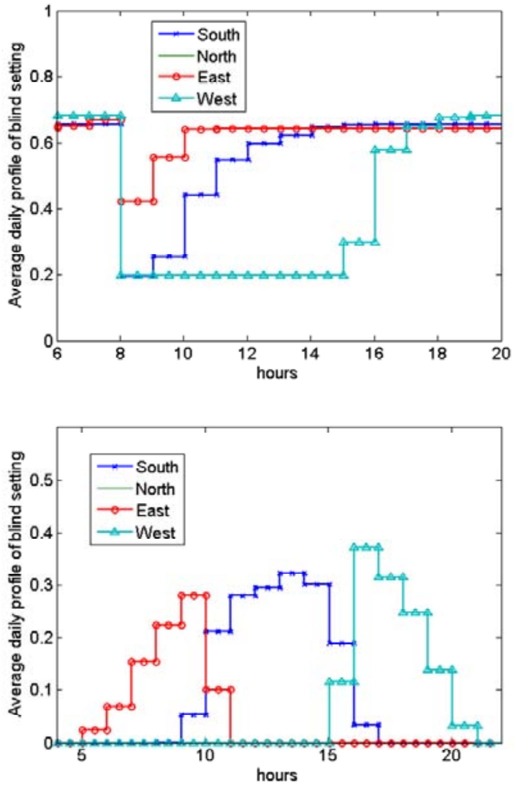

Figure 9 Average daily profile of the blind setting (1=closed, 0=open) for manual blind control (top) and automated blind control (bottom) for different orientations (note different scales)

When the blinds are manually controlled, it is assumed they are closed when direct sunlight hits the workplane and kept closed until arrival the next day. Off course, the blinds will be closed during a greater part of the day for the east orientation, followed by south and west (see figure 9). For the north orientation, blinds are never closed. This even results in more energy savings by daylight dimming for the north orientation than for the south orientation (see figure 8). When the blinds are automatically controlled, they are lowered during the largest part of the day for the south orientation, followed by east and west (see figure 9, bottom). This compensates for the differences in daylight for the orientations, resulting in lighting energy uses that are more or less orientation independent (see figure 8).

CONCLUSION

The lighting energy use is responsible for a large part of the primary energy use of an office building. It is therefore important that the energy efficiency of artificial lighting is increased. When calculating the energy saving potential however, the occupant behaviour can not be neglected. This study shows that the potential of daylight dimming systems is overestimated when not taking the user behaviour in account. The magnitude of this overestimation depends on the distribution of user types in the building and is at maximum about 10%. This result has prooved to be fairly independent of boundary conditions, such as the blind type, the orientation or the blind control.

Of equal importance, is the choice of the reference system. Calculating energy savings by comparing systems to a continously switched-on lighting, is in most cases not correct. When the lighting is manually controlled in an office, this system should be held as a reference.

The properties and control of the shading device is an important factor in assessing lighting energy use (see figure 3). This must be included in research for energy efficient lighting control systems.

FURTHER RESEARCH

In this research, only single shading devices are considered. The combination with an external shading device, e.g. solar gain controlled, is not included. This step is however necessary in order to assess the influence of lighting control on the energy demand for heating and cooling demand.

ACKNOWLEDGEMENT

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REFERENCES

Best Practice Programme 2000. Energy use in offices, Energy consumption guide 19.

Bodart M., De Herde A. 2002. Global energy savings in office buildings by the use of daylighting, Energy and Buildings 34, pp. 421-429.

EN 15251-2007. Indoor environmental parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, CEN.

Flemish Government 2008. Energy Policy 2009 (in Dutch), www.vlaanderen.be.

Hanselaer P., Lootens C., Ryckaert W.R., Deconinck G., Rombauts P. 2007. Power density targets for efficient lighting of interior task areas, Lighting Res. Technol. 39, pp. 171-184.

IEA 2008. Worldwide trends in energy use and efficiency, www.iea.org.

Opdal K., Brekke B. 1995. Energy saving in lighting by utilization of daylight, Proceedings of Right Light 3, pp. 67-74.

Perez R., Seals R., Michalsky J. 1993. All-weather model for sky luminance distribution – preliminary configuration and validation, Solar Energy 50, pp. 235-245.

Reinhart C.F. 2004. Lightswitch-2002: a model for manual and automated control of electric lighting and blinds, Solar Energy 77, pp. 15-28.

Reinhart C.F. 2006. Tutorial on the use of Daysim simulations for sustainable design.

Reinhart C.F., Andersen M. 2006. Development and validation of a Radiance model for a translucent panel, Energy and Buildings 38, pp.890-904.

Reinhart C.F., Herkel S. 2000. The simulation of annual daylight illuminance distributions – a state-of-the-art comparison of six RADIANCE-based methods, Energy and Buildings 32, pp. 167-187.

Reinhart C.F., Voss K. 2003. Monitoring manual control of electric lighting and blinds, Lighting Res. Technol. 35, pp. 243-260.

Roisin B., Bodart M., Deneyer A., D'Herdt P. 2008. Lighting energy savings in offices using different control systems and their real consumption, Energy and Buildings 40, pp. 514-523.

Tregenza P.R., Waters I.M. 1983. Daylight coefficients, Lighting Res. Technol. 15, pp. 65-71.

Ward G., Shakespeare R. 1998. Rendering with Radiance, Morgan Kaufmann Publishers.

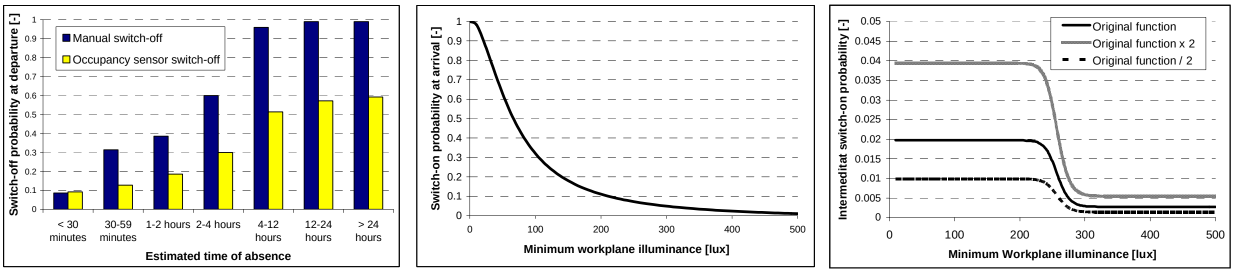

Figure 10 Lightswitch probability functions, from (Reinhart, 2004)

Table 3
4 User types in Lightswitch algorithm, from (Reinhart 2006).

USER TYPE	LIGHTING CONTROL	BLIND CONTROL	DESCRIPTION OF USER BEHAVIOUR TYPE
1	active	active	A user whose electric lighting switch-on decision is in relation to ambient daylight conditions (figure 10, left), and who opens the blinds in the morning and closes them during the day when necessary to avoid direct sunlight.
2	passive	active	A user who keeps the electric lighting on throughout the working day, and who opens the blinds in the morning and closes them during the day when necessary to avoid direct sunlight.
3	active	passive	A user whose electric lighting switch-on decision is in relation to ambient daylight conditions (figure 10, left), and keeps the blinds closed throughout the year to avoid direct sunlight.
4	passive	passive	A user who keeps the electric lighting on throughout the working day and keeps the blinds closed throughout the year to avoid direct sunlight.

Table 4
Radiance parameter set

-ab	-ad	-as	-ar	-aa	-lr	-st	-sj	-lw	-dj	-ds	-dr	-dp
5	1000	100	30	0.1	6	0.15	1	0.004	0	0.2	2	512

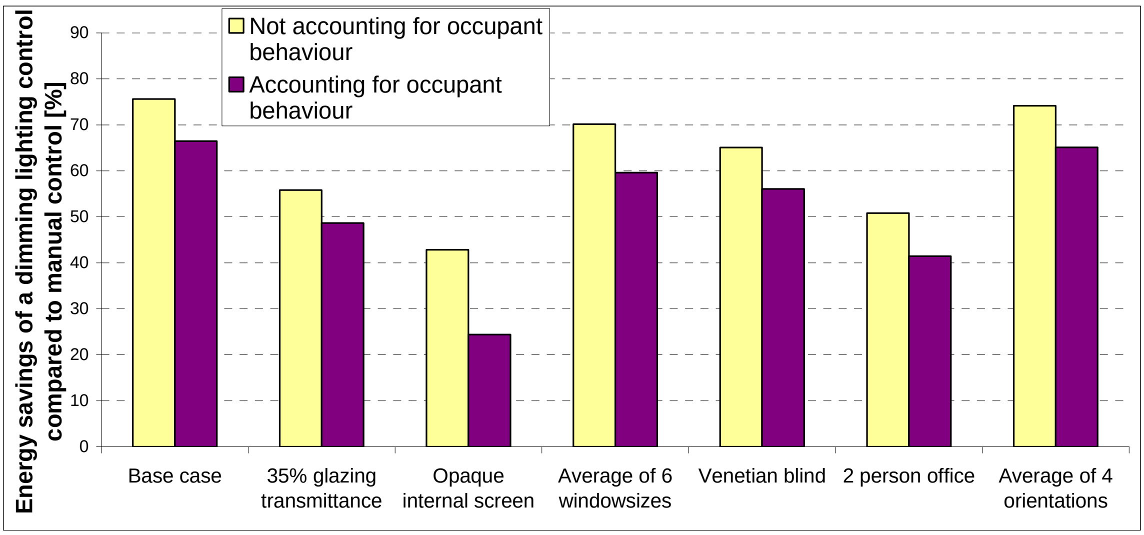

Figure 11 Overview of parameter analysis on the energy savings potential of daylight dimming lighting control compared to manual control, with or without accounting for occupant behaviour

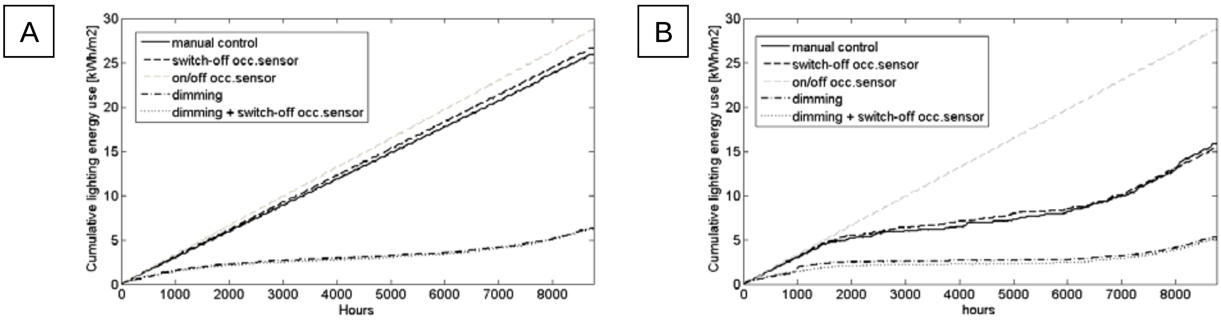

Figure 12 Plots of cumulative lighting energy use for different control types and user types of the base case (A – user type 2, automated blinds; B - user type 1, automated blinds)

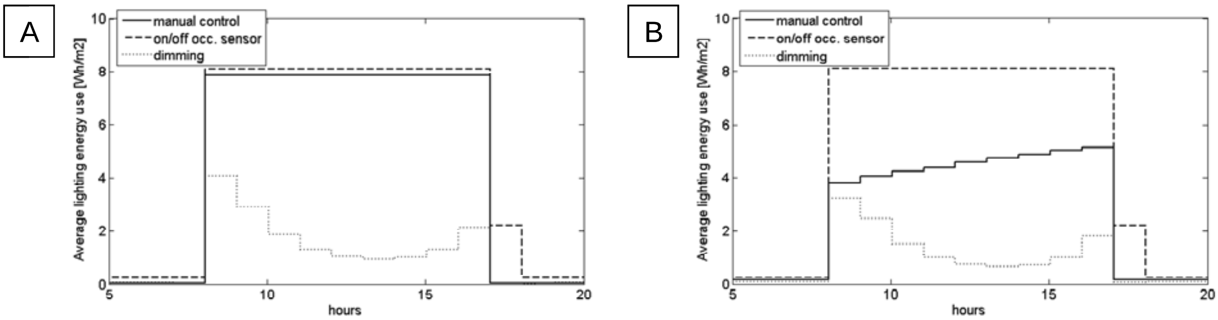

Figure 13 Average daily profile of lighting energy use for different control types (A – user type 2, automated blinds; B - user type 1, automated blinds)

Table 5
Total yearly lighting energy use for base case scenarios [kWh/m^2]

User type	Blind control	Manual	Switch 0n/off	Switch-off	Dimming	Switch-off + dimming
1 (active-active)	manual	14.8	28.8	14.9	6.1	6.3
	automated	15.9	28.8	15.4	5.3	5.1
2 (passive-active)	manual	25.8	28.8	26.8	8.3	7.6
	automated	26.0	28.8	26.7	6.3	6.3
3 (active-passive)	manual	19.2	28.8	19.5	10.3	9.7
4 (passive-passive)	manual	26.2	28.8	26.8	11.3	11.2

Table 6
Total yearly energy use for base case scenarios, relative to manual light control [%]

User type	Blind control	Manual	Switch 0n/off	Switch-off	Dimming	Switch-off + dimming
1 (active-active)	manual	100	195	101	41	42
	automated	100	181	97	34	32
2 (passive-active)	manual	100	111	104	32	29
	automated	100	111	103	24	24
3 (active-passive)	manual	100	150	101	54	51
4 (passive-passive)	manual	100	110	102	43	43