Solar Shading and Daylight Redirection

Demonstration project for a system of motorised daylight redirecting venetian blinds and light controlled luminaire

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Lund University
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The group's goal is to help energy-efficient systems and products to be brought to market more quickly. The development projects are aimed at making the use of energy more efficient while also improving functionality and comfort.

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The report has a traditional structure with separate chapters covering background, methodology, result and a discussion. However, because the report discusses a number of different part-studies, certain aspects of the methodology and points in the discussion are included with the result in order to make the report easier to read and the result easier to understand.

Summary

This report is an evaluation of a demonstration study of an innovative venetian blind with a newly developed control system combined with a daylight controlled office luminaire. The demonstration study was a follow-up to the technology competition "Daylight and solar shading" which was held in 2004 and financed by BELOK and the Swedish Energy Agency (STEM).

The general premise of the technology competition was that BELOK wanted to find solutions capable of improving the indoor climate and reducing energy use in office buildings. One specific objective of the competition was to develop new products that could improve efficiency in existing offices. During the summer months in particular, daylight can supply high illuminances indoors, potentially replacing electric lighting. The most interesting technologies are those that are able to balance the conflicting demands of daylight/views and anti-glare/solar shading.

From a purely technical point of view, the evaluated system using a motorised venetian blind and a light controlled fitting performed very well. The type of motor selected for the venetian blind allows very precise control, and even after many control sequences, the venetian blind is always in the "correct" position – in other words at the angled determined by the control system.

A prerequisite to avoid glare is to avoid direct solar radiation. This is the fundamental concept of the evaluated solar protection control: control based on the altitude of the sun and so called cut-off angles (sun tracking). Because the sun is high in the sky during summer, the venetian blind slats are kept very open, allowing views of the surrounding outside. However, it is our conclusion that the angles during summer are not large enough. i.e. the venetian blind is too open to prevent solar glare from the sky or from the venetian blind itself. This is mainly the case at times of high solar intensity which, generally, coincides with the times having the highest illuminances. If the control system is changed to prioritise greater slat angles (the venetian blind is more closed) this would also provide more effective solar shading because the g-value (the total solar energy transmittance) would fall. Unfortunately, this limits opportunities to see outside.

An alternative control system could be based on the luminance of the inside of the window, but both seating positions (in the field of vision) and individual preferences need to be taken into account here. It would therefore be valuable to continue studies using test subjects in order to find suitable control algorithms. The sensor location is also critical here, and the main consideration must be the luminance occurring in the user's field of vision.

The electricity savings for the evaluated system were significantly greater in May than in November, because obviously it is lighter and the sun is higher in May than in November. The electricity saving for lighting was 77 % in May and 5 % in November. These figures are based on working hours of 08:00 to 17:00. On an annual basis, the saving was calculated as approx. 50 %. The annual saving for a whole office, with around half the desks farther away from the window it can be expected to be about half the above percentage, approx. 25 %, compared to this test office with the desks located very close to the window.

It is very easy to create a light redirecting section – an area that is more open than the rest – in a venetian blind. It is sufficient to shorten the cords on the room side of the venetian blind. In the evaluated system, this was done by winding the cord a single turn around a simple plastic clip. This allows more daylight to enter the room, usually through the top of the venetian blind, which is normally higher than the central field of vision. There are

problems working with two slat angles if direct solar radiation is to be avoided throughout the year. Our research indicates that the difference in angle between the upper and lower parts of the venetian blind must be limited to approx 20-23 degrees in order to avoid problems with direct solar radiation in winter. This is much smaller than the difference in angle normally offered with these systems. For example, the evaluated system came with a clip to create an angle difference of 45 degrees, which was modified during the study.

To prevent glare, the dividing line between the upper and lower sections must be kept well above eye level and the central field of vision. This is because a more open venetian blind is open to the bright sky and the blind slats themselves become lighter meaning that ”normally” located windows – i.e. with top about 2.1 m above the floor – enables only limited daylight redirection opportunities. In our experimental room, the indoor illuminance was estimated to increase by around 10 % with the light redirecting section at the top of the venetian blind. Computer Radiance simulations for similar rooms would give comparable results. Our conclusion is that for offices where windows occupy a moderate proportion of the facade wall and the windows are also "normally" situated (upper edge about 2.1 m above floor level), light redirection only produces a negligible increase in illuminance, while probably increasing the risk of glare. The benefit of light redirection is therefore doubtful in these situations. On the other hand, the entire venetian blind can be seen as a light redirector, as it channels light up to the ceiling.

There were no real differences between the measured indoor climate and the values calculated in ParaSol, so ParaSol seems to be a reliable program for assessing indoor temperatures and energy use in room modules with venetian blinds.

If the proposed solar protection control system is used with external venetian blinds, there is a very good opportunity to limit excess temperatures inside and minimise cooling requirements. A between-panes venetian blind performs rather worse, but is still significantly better than an internal venetian blind. If the venetian blind control system is changed so it closes slightly more in the strong summer sun, the proposed 25 mm controlled venetian blind is able to perform a solar shading function as well as an anti-glare function. The light redirecting top can probably be omitted for normally situated windows, as it only creates a very small increase in the amount of light. This makes the venetian blind much easier to handle and control.

Contents

1 Background

This report evaluates a demonstration study of an innovative venetian blind with an advanced control system combined with a daylight controlled office fitting. The demonstration study was a follow-up to the technology procurement program ”Daylight and Solar Shading” which was held in 2004 and financed by BELOK and the Swedish Energy Agency (STEM).

The general premise of the technology competition was that BELOK wanted to find solutions capable of improving the indoor climate and reducing energy use in office buildings. One specific objective of the competition was to develop new products that could improve efficiency in existing offices. Because the building industry is split into a large number of separate branches, one of our objectives was to establish cooperation between companies representing different niches that do not normally work together. In this case, the industries are solar protection, lighting and, to an extent, HVAC.

Problems of high temperatures and low comfort, combined with higher expectations of the indoor climate, has led to a wide-spread use of comfort cooling in Swedish offices. According to a piece on Swedish National Radio on 17 July 2006, the only European countries with a greater cooled surface area per inhabitant are Spain, Greece and Italy. This is an alarming statistic, considering how different our climate is. However, comfort cooling should be kept as a last resort when it gets too warm indoors. The energy balance of the entire building must be studied, as there is significant interaction between the design of the building and its activities. The elements to be reviewed include the solar shading, the ventilation system and its operating strategies (for example supply air temperatures, air flows, operating hours, night cooling etc.) and the heat load generated by the activities inside the building. Once this is done, the most energy- and cost efficient solutions can be identified.

One of the largest causes of high indoor temperatures of modern office buildings is the rise in the use of computers and other office machines, causing a significant increase of heat load inside offices. On the other hand, the recent switch to flat screens shows that progress can be made, because these screens only use a fraction of the energy demand of CRT monitors. Modern laptops are also much more energy efficient than desktop computers. An old computer plus monitor could generate between 150-300 W, whereas a modern laptop with docking station and a separate flat screen only generates something like 50-80 W. Lighting also has become significantly more efficient in the last 10-15 years, with around half or even a third of the installed power that was normal in the 1970s. This is also confirmed in the detailed inventory of some offices in the technology competition. The tendency to fit more and more people into the same surface area also increases the heat load in offices. Many managers confirm a general tendency to convert individual offices into open plan arrangements, which has an effect on staffing densities.

In the last ten years, it has become fashionable to use large glass surfaces in architecture, and although this is most common in prestigious office buildings, the trend is also apparent in residential buildings. As the proportion of glass in the facade increases, so too does the solar gains which directly influences the size of the cooling and ventilation systems. To restrict the use of artificial cooling in offices, while still taking advantage of glass surfaces, solar radiation must be limited. This can be achieved with solar protection glass and/or different types of fixed and retractable solar protection.

1.1 Previous research in the field of solar shading and daylight

The current architectural trend with highly glazed facades triggered wide-ranging studies of different solar protection in the Solar Shading Project at Lund University, Energy and Building Design. The project was financed primarily by Formas and STEM, with a contribution from the Swedish Solar Shading Association (Wall & Bülow-Hübe, 2001 & 2003). The ParaSol program was developed as part of the Solar Shading Project. ParaSol is now freely available on the Internet (www.parasol.se) and is intended as a tool allowing consultants to compare different solar protection and glass systems and their influence on energy use, power requirements and indoor temperatures.

In the second stage, the scope of the project was widened to include the effect of daylight in adjacent rooms. In 2001, the luminance distribution, contrasts and illuminances were studied in rooms with different solar protection, partly using the Radiance program (Dubois, 2001a) and partly through full-scale trials at Byg og Byg in Hørsholm, Denmark (Dubois, 2001b). However, these studies did not take account of the perceptions of test subjects.

With a high proportion of glass in the facade, there is a greater risk of low thermal and visual comfort. Office work these days largely consists of looking at a screen, so the line of sight has been raised from the desktop to more or less horizontal. This often places the window in the central field of vision, creating high background luminance values with associated glare issues, unless the window is fitted with adequate solar protection. The screen contrast also deteriorates, and solar radiation often causes disturbing reflections. Meanwhile, 70 % of office personnel want to sit close to the window. (Christoffersen et al, 1999, Dubois, 2001a).

The illuminance and especially the luminance distribution in the room are probably the most important factors determining visual comfort. Looking more closely at earlier research around light quality and visual comfort, for example glare in daylight environments, it is clear that we still do not know exactly which parameters, at which levels, generate visual comfort (Veitch & Newsham, 1996; Osterhaus, 2001). Dubois' (2001a) evaluation of light measurements in full-scale rooms (for example to establish a desirable luminance distribution) was therefore based on lighting recommendations and rules of thumb developed for artificially lit environments. A pilot study carried out in stage 2 also indicates that it is difficult to relate the perceived daylight comfort either to the illuminance at the workplace or to the sky luminance (Bülow-Hübe, 2000). However, it is likely that the visual factor is what first prompts a user to lower a solar protection, and not thermal requirements. Where offices have large glass facades, and especially in open plan arrangements, the problems of glare and the loss of individual control are accentuated. All too often, this creates a situation in which the solar protection is completely closed, restricting view out and seriously limiting access to daylight. This in turn can cause an increase in demand for electricity for artificial lighting.

A further interesting area of research investigates various links between daylight and so-called non-visual effects of lighting, in fields such as environmental psychology (Küller, 1981). This research has attracted a lot of attention in recent years – especially the discovery of what is called the third receptor in the retina. This explains the mechanisms between light exposure and the suppression of melatonin, which in turn controls the biological clock. In particular, light with wavelengths corresponding to blue light was found to be effective in inhibiting the production of the sleep hormone melatonin. (Brainard et al., 2001). Because the spectrum of daylight is continuous, i.e. it contains all wavelengths, and is also much more intense than artificial light, daylight is regarded as particularly valuable in controlling our biological clock and also for our health in general.

In early 2005, a new laboratory for energy and comfort measurements was completed at Energy and Building Design, LTH. The laboratory was financed by the Delegation for Energy Supply in Southern Sweden, DESS. The building contains two pairs of identical rooms. Two rooms are intended primarily for thermal and visual studies, and the other two are designed for measurements of energy balance through facade systems, see figure 1.1-2.

All four rooms have interchangeable south-facing facades, and have the same dimensions. (2.7 x 4 m with 3 m ceiling height). The two daylight rooms have some thermal inertia, modern office ventilation with flow-controlled supply units and daylight controlled lighting. The laboratory is unique in Sweden, offering unparalleled opportunities for studying different systems for solar protection and daylight redirection from thermal and visual perspectives in a real-life climate (Bülow-Hübe et al, 2005).

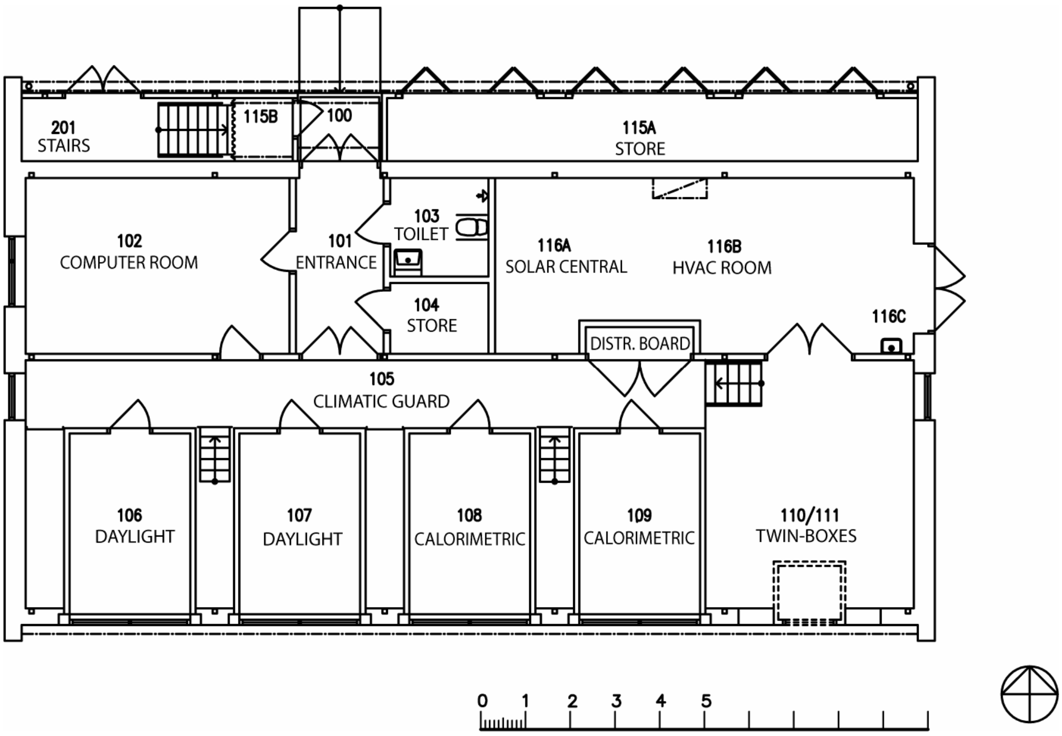


Figure 1.1 Plan of EBD's new energy laboratory.

Figure 1.2 EBD's new energy laboratory: exterior and interior of "daylight room" before the experiment.

2 Objectives and purpose

The overriding purpose of the demonstration project is to identify optimum solutions to the conflicting demand for solar shading and daylight. The project-specific purpose is to demonstrate and document the function of a new daylight redirection system for office buildings, integrating the control of artificial lighting, daylight and solar shading. The project is a demonstration project that follows up on the recently completed technological procurement program for solar shading and daylight redirection, financed by the BELOK consumer group and the Swedish Energy Agency (STEM).

The objectives of the project are as follows:

- to evaluate the function of the proposed system
- to evaluate the potential of the proposed system for saving electricity use for lighting
- to study the illuminance and luminance distribution associated with daylight redirection
- to identify appropriate luminance sensors and their positions, and to identify control strategies to obtain "good" daylight, in other words plenty of daylight without glare
- to "verify" Parasol and Radiance simulations against measurements.

3 Methods

The evaluated solar protection system was a motorised version of a traditional venetian blind with 25 mm slats, designed for internal use or, preferably, between the panes of glass in coupled units. The venetian blind was fitted with small 24V motors hidden in the top of the venetian blind, and was equipped with a newly developed control system, see section 3.1. The upper part of the venetian blind also had a light redirecting function with the slats held slightly more open by clips shortening the cords, see figure 3.1. The venetian blind was manufactured by NIMEX and was fitted with a motor and control system developed by SOMFY.

In addition to the venetian blind there was a luminaire with built-in sensor for constant light adjustment, see figure 3.2. The luminaire came from Ateljé Lyktan and the light control system was provided by Wennerström Ljuskontroll.

Figure 3.1 Picture of venetian blind with light redirection using clips. (Photograph: Thore Sonesson).

The study was carried out in the two daylight rooms in the new energy and comfort laboratory at LTH. The facade of the rooms originally consisted of one aluminium window with 6 sections or lights. The glazing was insulated double glazing with a clear low-emission glass in the outer pane, creating high daylight transmittance.

The glass surfaces were reduced to a single row of windows by covering the two upper and lower sections internally and externally, and insulating them. This means that glass accounted for 33 % of the facade surface area viewed from inside. To imitate the dimensions of older office spaces, a white suspended ceiling was added 2.6 m above floor level. Both rooms were furnished very simply, with two tables placed at an angle, see figure 3.2. The walls were made of panels painted white and the floor was made of untreated concrete.

One daylight room was designated the “test room” (room 107) and equipped with the new motorised venetian blind, which is controlled according to outdoor illuminance using a light sensor fitted outdoors on the facade close to the window. The second room (room 106) was the reference room and was equipped with a venetian blind of the same colour, but without a control system and light redirection. The venetian blind was fitted internally for cost reasons, to avoid the need to rebuild the facade to create coupled units. The light redirecting capacity was not considered to differ significantly whether the venetian blind was installed between panes or internally.

Because the outdoor climate and the solar altitude change constantly, the measurements were concentrated in one period in May and one period in November. Measurements were also taken between these periods, but mainly for partial testing of individual system parameters as described below. In this way, data was collected for fine days with different solar altitudes, and also for cloudy days.

Figure 3.2 *Exterior and interior of test room. The light sensor for controlling the venetian blind was placed on the facade between the rooms. The more open part of the venetian blind can be seen as a darker strip at the top of the windows in the room on the right.*

3.1 Description of tested system

The system evaluated in our test room was a motorised indoor venetian blind with 25 mm slats in white, combined with a daylight controlled luminaire. The motors for the venetian blind were capable of extremely precise positioning, known as encoder motors.

The venetian blind control system is a product developed by SOMFY, who provided all control equipment and associated software (animeo). The venetian blind control system had various functions – for example the blind can be lowered at night to save energy. However, this study only examined daytime operation, i.e. when the light controlling function was active. The control principle means that the venetian blind is lowered when the vertical illuminance at the window exceeds 20 kilolux for more than one minute. If the illuminance remains below 15 kilolux for an extended period, a signal is issued to raise the venetian blind, but with a delay of 30 minutes. If the illuminance stays low during this delay, the slats will be rotated to a horizontal position after approximately 3 minutes. But if the illuminance increases, the venetian blind will be returned to the correct slat angle. All times and set point values can be adjusted by the user. Figure 3.3 shows a screen from the menu system displaying these settings. The principles governing the venetian blind control system as a whole are illustrated in figure 3.4.

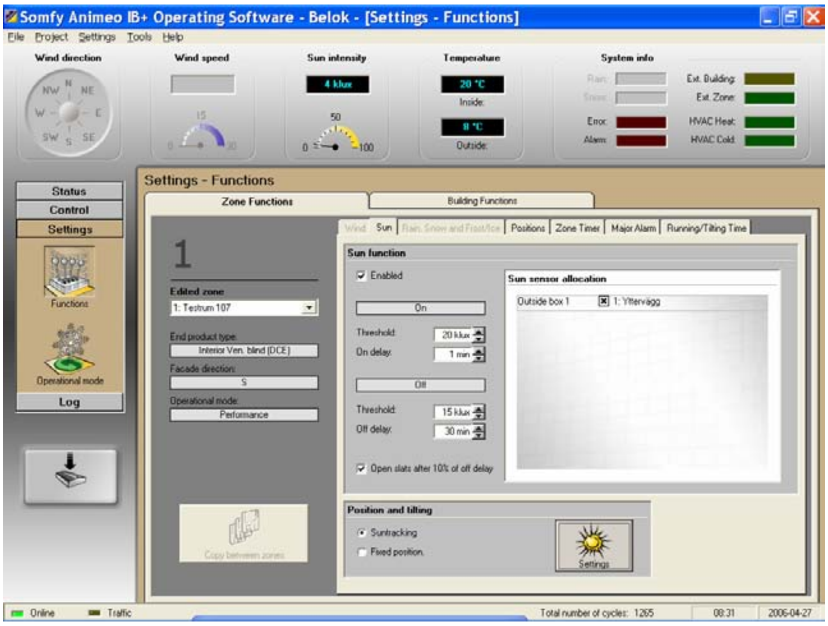


Figure 3.3 *Screenshot of menu controlling solar protection.*

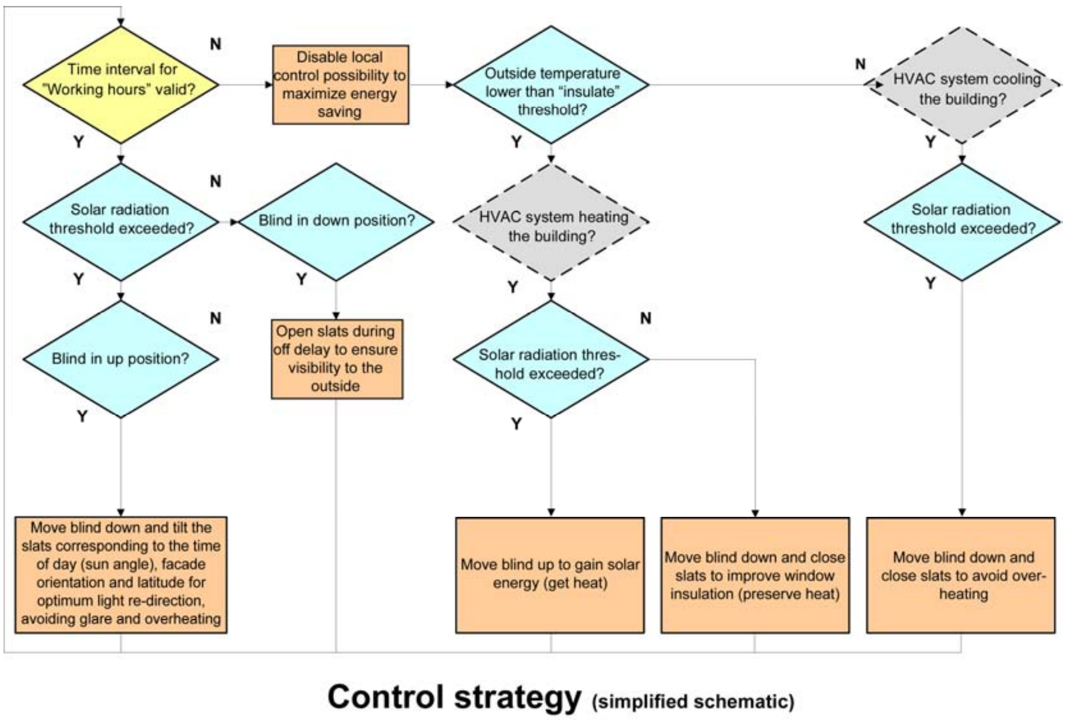


Figure 3.4 *Flowchart of solar protection control strategy. (Source: SOMFY)*

To take account of the constantly changing solar altitude angles, it was decided to configure the control system for three different slat angles during the day: one for the morning, one between mid-morning and the afternoon, with the morning angle returning in the later afternoon/evening. During the same month, the angles are similar each day. The angles calculated in this way are set out in a table, and can be adjusted if necessary by the user. The desired slat angle is at least the cut-off angle, i.e. the precise angle at which direct solar radiation is prevented. With the installed venetian blind, when the sun is higher than 41 degrees, the cut-off angle is actually negative, see figure 3.5. However, because a negative angle allows a direct view of the sky, and with it a large amount of light (risk of glare), the control system does not allow negative angles – the venetian blind instead remains horizontal or close to horizontal.

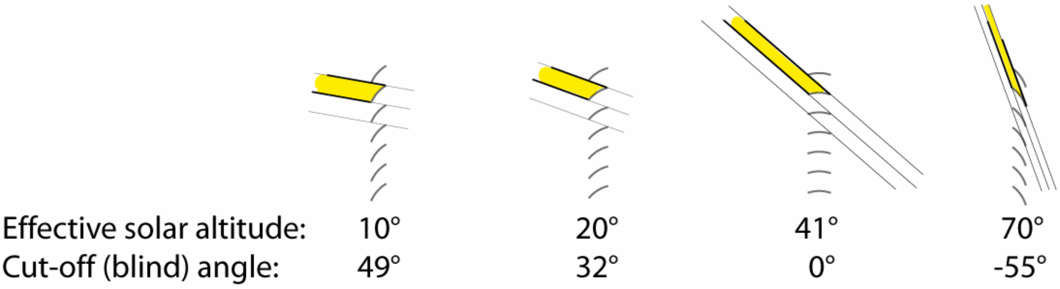


Figure 3.5 Examples of cut-off angles for different projected solar altitudes.

Sun-tracking is the name given by SOMFY to the control principle described above, in which account is taken of the current solar altitude angle. A calculation of the cut-off angle as a function of the projected or effective solar altitude against the facade was carried out by Bengt Hellström for our blind geometry, and the result appears in figure 3.6. The applicable slat angles must always be calculated in advance by the control system on the basis of the latitude and orientation of the building. In other words, the effective solar altitude against the window must be calculated and not just the solar altitude. Further, the cut-off angles must also be established for the shading device in question. Examples of solar altitudes and effective solar altitudes for a south facing and east facing window are shown in figures 3.7 and 3.8.

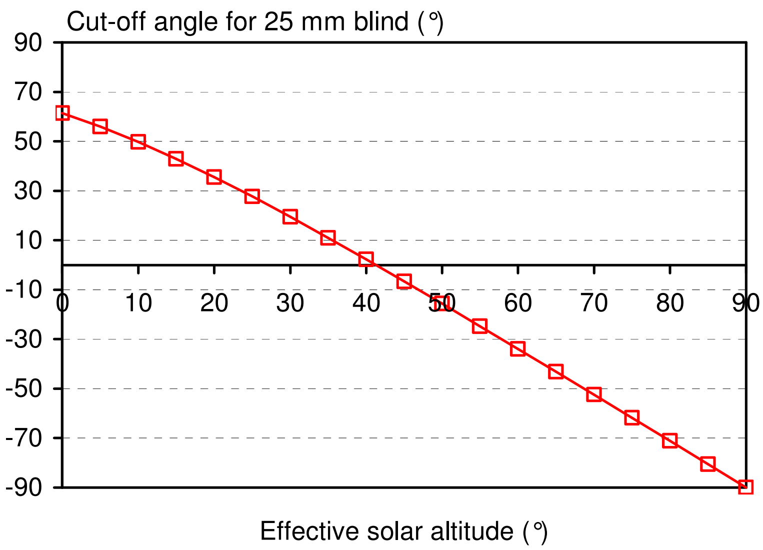


Figure 3.6 Calculated cut-off angles for a standard 25 mm venetian blind with 21.5 mm slat spacing.

It is essential to understand the concept of the effective solar altitude and not just the solar altitude itself. This is because the effective solar altitude is higher in the morning and in the afternoon than at noon between the equinoxes in spring and autumn. It this is not understood, sunlight may otherwise unexpectedly enter the room in the summer, when the effective solar altitude actually varies between the solar altitude and 90 degrees for a south facing window and between 0 and 90 degrees for a window facing east or west. For example, at 10:00 in Lund, the effective solar altitude for a south facing window has already reached 41 degrees by the beginning of April, which means that the venetian blind must be set to at least a horizontal position to avoid direct solar radiation from entering the room.

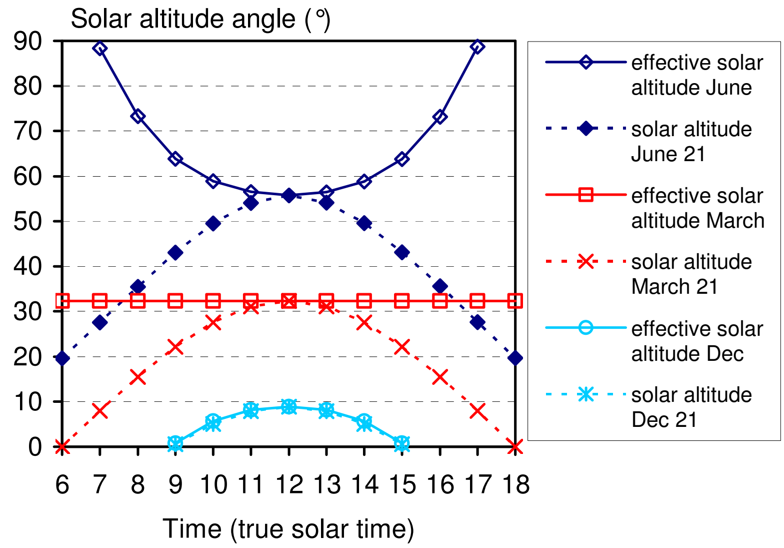


Figure 3.7 *Solar altitudes and projected solar altitudes calculated for a south facing window in Lund at the summer and winter solstice, and at the autumn and spring equinox.*

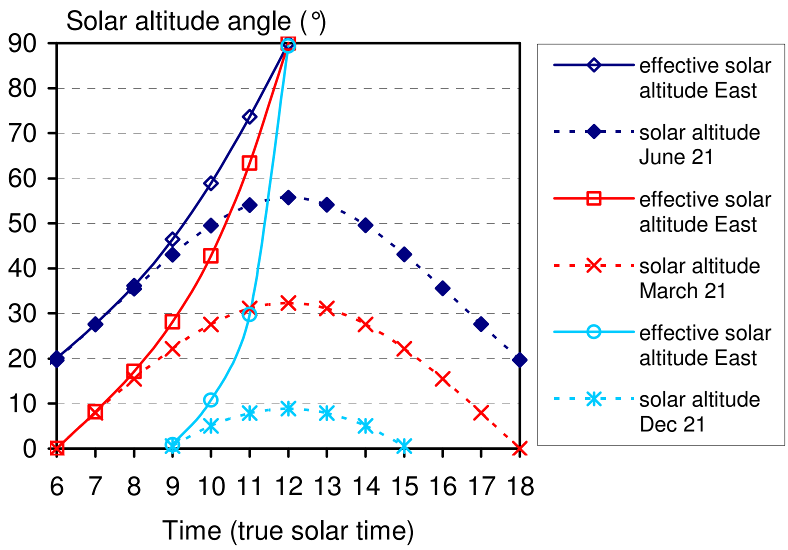


Figure 3.8 *Solar altitudes and projected solar altitudes calculated for an east facing window in Lund at the summer and winter solstice, and at the autumn and spring equinox.*

The venetian blind was supplied with separate sensors for outside vertical illuminance, inside temperature and outside temperature. A wind speed sensor can also be connected to the system, but this is not relevant for an internal venetian blind. It was difficult to save and extract these values afterwards, so the evaluation used measured radiation or daylight values from the climate station of the laboratory. However, the actual control of the venetian blind was based mainly on the vertically installed light sensor, see figure 3.2.

Only the venetian blind in the test room was controlled in this way. For the measurements, the venetian blind in the reference room was lowered and set to a fixed angle of +34 degrees from the horizontal (blocking the view to the sky but not to ground level).

A luminaire from Ateljé Lyktan was installed in each room. The light was kept on between 08:00 -17:00 using a simple timer. In the reference room, the luminaire was turned on throughout the day, whereas the one in the test room was light controlled with regard to the light level in the room. This control was fully automatic and integrated into the fitting, i.e. the control was based only on the light entering the room, without any direct link with the venetian blind control system. The luminaire had two 36 W T5 fluorescent tubes, i.e. the installed power was 80 W or around 7 W/m² including ballast losses. The integrated sensor points down to the work surface and the light output can be adjusted to supply the desired illuminance, to a maximum of around 500 lux. The luminaire could also be fitted with an external sensor, for example a ceiling mounted sensor.

3.2 Measuring light and outdoor climate

The illuminance outside and inside both rooms was measured continuously. Inside each room, three light sensors were placed at table height (B) 80 cm above floor level, and two light sensors were placed in the ceiling (T). Sensor B1 was placed approx. 1 m from the window, B2 in the middle of the room and B3 approx. 1 m from the rear wall. Sensor T1 was placed closest to the window in the middle of the first half of the ceiling, with sensor T2 in the middle of the second half of the ceiling. See figure 3.9-10. The inside sensors were Hagner SD2 light detectors. They were connected to a test computer via a Hagner MCA-1600 amplifier and a CR1000 logger. All sensors were new and calibrated when the tests started. The sensors at points B1 and T1 were calibrated for 0-10,000 lux, and the other indoor sensors were calibrated for 0-5,000 lux. This means that in absolute numbers, the measuring error (stated as better than +/- 3%) at low light levels is slightly greater for the sensors at points B1 and T1.

A climate station on the roof was also used to measure the outside temperature, global illuminance and global diffuse solar radiation (all to the horizontal), figure 3.11. The light sensor was a Hagner ELV 741 and the global radiation sensor was a 2nd class pyranometer from Hukseflux (LP02). The diffuse radiation sensor was a Kipp and Zonen CM5, equipped with a shading ring.

The outside temperature was measured using a thermistor installed with radiation protection and fan. Measured values were obtained every 30 seconds and saved to the log file as six-minute average values. By analysing the difference between the illuminance in the two rooms, the effectiveness of the system as a whole can be studied, but most measurements included light from the luminaries. In specific test series in the summer, the lights were switched off in order to study the effectiveness of the venetian blind itself.

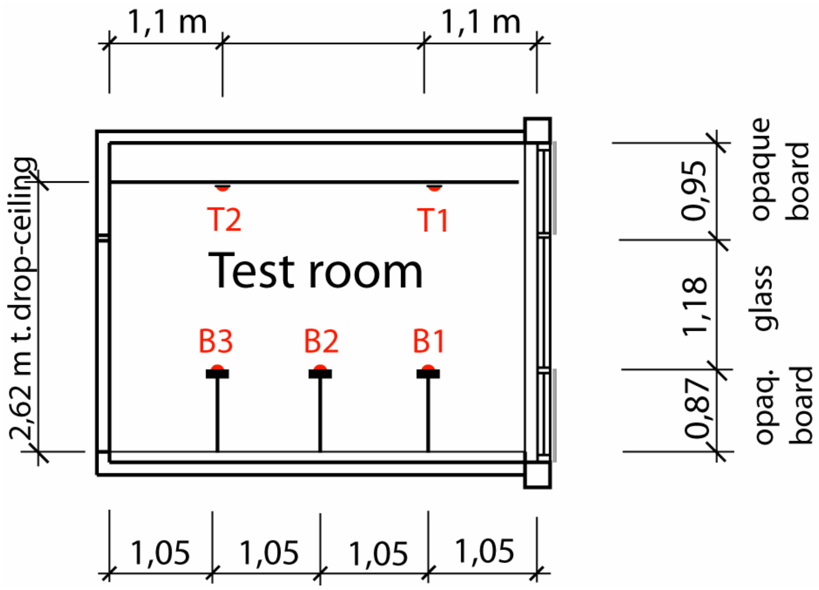


Figure 3.9 *Section through rooms 106 and 107 with sensor locations.*

Figure 3.10 *Ceiling mounted light sensor/sensors at table height (right).*

Figure 3.11 *Outside sensor for global illuminance and luminance camera (right).*

At certain times during the test period with specific weather conditions (for example overcast or sunny days), the luminance distribution was also measured with a calibrated CCD camera (luminance camera) of type IQcam Model III, figure 3.11. The camera was placed at the back of the room on a frame, and could be moved relatively quickly between rooms. The range of the test camera was limited to 3000 cd/m², which was likely to be sufficient as glare was considered to occur for surfaces with a luminance of around 1500 cd/m². A filter could also be used to measure higher luminances.

3.3 Measuring electricity use for lighting

The control and monitoring system of the building was used to continuously measure and log the electricity use of each of the rooms. Because the luminaire was the only device using electricity, this meant that the electricity use for each of the luminaries could be easily measured. The electricity meters were single phase meters, ABB Mini, and were programmed to one pulse per Wh, in other words with a very high resolution. The results show the accumulated electricity use for selected days with either sunny or cloudy weather, as well as the daily savings compared to using constant lighting over a longer period of changing weather.

3.4 Measuring and simulating indoor climate

The laboratory's own control and monitoring system continuously measured and logged the supply air flow, the supply air temperature, the room temperature and the extract air temperature, see figure 3.12. The inlet air diffuser can be set to supply between 5-50 l/s at a temperature down to approx. 14 °C without comfort problems, which provides a certain cooling capacity. During the tests the VAV-function was disabled and a constant supply air flow of 20 l/s was used, a more standard value for older offices.

The set point value for the supply air temperature was 17°C, but because the controlling sensor is located immediately after the heat exchanger, the air in the duct is heated as it moves to the room. The supply air temperature was therefore around 18 degrees, unless there was a heating requirement (the room is heated with a heating coil in the air supply unit). With this low flow, the capacity was insufficient to completely remove the solar gains when the facade was fully glazed (double glazing with LE coating, LT approx. 80%, g-value 0.59). When the window surface area was reduced, however, the solar radiation into the room dropped significantly, and the cooling capacity was considered to be sufficient. The temperature of the surrounding climate chamber was kept stable and logged. The results show the measured temperature inside the room with the two different internal venetian blind systems – the fixed venetian blind (34 degrees) and constant lighting in reference room 106, and the controlled venetian blind and controlled lighting in test room 107.

A comparison between the measurements and the ParaSol ver 3.0 simulation was carried out for selected periods. Because the location of the venetian blinds (inside) was not ideal in terms of limiting the air temperature, alternative calculations of the indoor climate were carried out assuming that the facade had had coupled windows (1+2) and it had been possible to place the venetian blinds in the outer gap. These calculations were performed with a climate file created on the basis of measured climate data. This means that the direct radiation on a horizontal surface was calculated from the global and diffuse radiation and then converted to the normal direction towards the sun. In addition, hourly average values were created from the six-minute values in the log file.

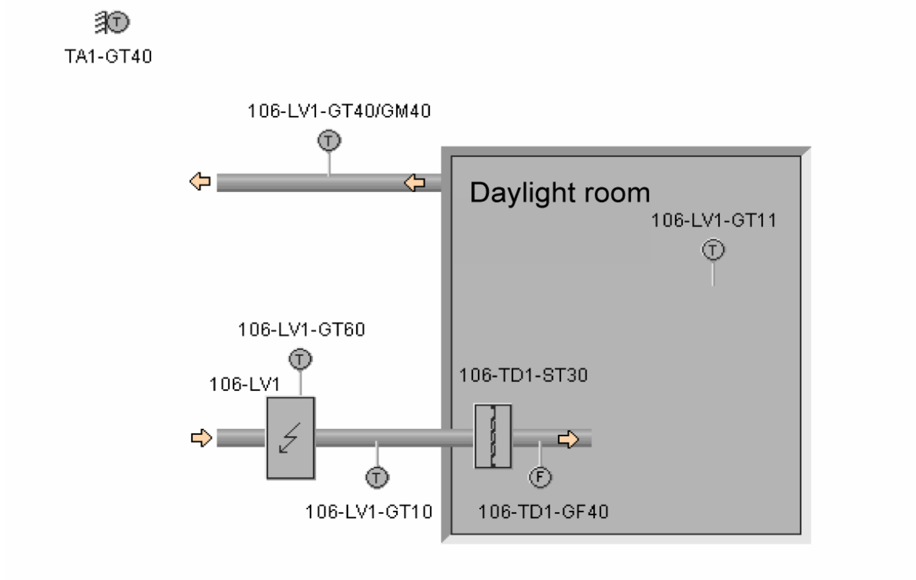


Figure 3.12 *Screenshot from the building automation system, with measuring points for temperature, air flow and air humidity (air humidity only in the extracted air).*

3.5 Test of the light redirecting section of the venetian blind

To assess whether the light redirecting section, i.e. the more open upper section, had a significant effect on the amount of light in the room, certain measurements were carried out. First, the light level in the room was measured with the venetian blinds in both rooms adjusted in the same way (in the lower section in the test room). The control system was disabled and electric lighting was switched off. In addition to these measurements, the light distribution was studied using simulations in Radiance for a typical office room with 30 % window surface area for one hour of high sun. This simulation allowed the effect of two separate angle differences between the upper and lower sections to be studied (20 and 45 degrees difference), as well as two different heights for the break-point or dividing line. A sunny day in July was selected for the simulation – i.e. the same solar altitude as the measurements. The angle of the venetian blinds was also about the same as in the measurements, 35°. In this way, it was possible to compute four different cases (15° top/35° bottom and -10° top/35° bottom) and different heights for the dividing line (1.6 and 1.8 m above floor level.), see figure 3.13. The simulated room is the same as the reference office room studied in the project "Office buildings in glass", for example see (Poirazis, 2005 and Bülow-Hübe, 2008). The proportion of glass was somewhat lower than in the measurements, but the difference was not so great as to make the comparison meaningless.

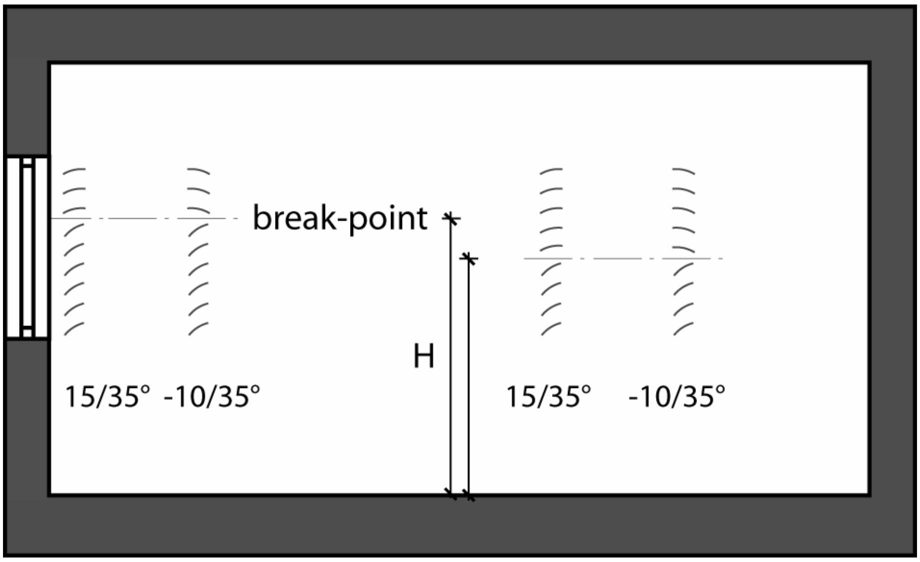


Figure 3.13 *Diagram illustrating the simulated light redirecting venetian blinds: two different heights for the dividing line was studied as well as two different angles for the top part of the blind.*

3.6 Test of sensor location

In the first stage of the evaluation (May, June) a ceiling mounted light sensor was used, pointing down towards the window at an angle. At one stage during the measurements, this sensor was compared with an integrated sensor pointing down to the table, see figure 3.14. For these comparisons, the venetian blinds were either raised in both rooms or fixed venetian blinds with the same angle were used, because the purpose was simply to study the effect of the sensor position and not the effect of the controlled and light redirecting venetian blind. In the November measurements, the integrated sensor was used.

Figure 3.14 *Ceiling mounted sensor (left) and integrated sensor (right).*

4 Results

4.1 General function of venetian blind

4.1.1 Commissioning and control

The venetian blind control system worked perfectly throughout the test period. The settings for the pre-programmed angles proved to be extremely precise, and the venetian blind always returned to the correct position even after a large number of adjustments. When the venetian blind was first put into use, however, it was necessary to teach it its current angle. This was done by manually measuring the slat angle using an angle gauge (a kind of spirit level). This method can produce small errors, and the slat angle was assumed to be subject to a reading error of +/- 2-3 degrees.

During commissioning it emerged that the control system was adjusted for a standard venetian blind without light redirection. The problem was unexpected but entirely logical: When the light redirecting clips were attached, the cords on the room side were shortened. The consequence of this was that the slats below the clips were closed, while the angle above the clips stayed the same. If it was then attempted to move the lower section of the venetian blind to the cut-off angle, the programmed angle differed from the actual angle by a relatively constant value (varying slightly according to the venetian blind position). When the blind was put into use, the set point angles were therefore changed to compensate for the angle error.

Creating a light redirecting venetian blind by shortening the cord with a clip is a very simple and ingenious solution. However, the question is how much more open the top section of the venetian blind can be while still maintaining visual comfort. To allow more light in, the clip should be attached as low down as possible, and the angle difference made as great as possible. This can easily conflict with the need to prevent direct solar radiation to avoid glare. Shortening the cord restricts the freedom of movement of the venetian blind: it is not possible to adjust the slats further than fully closed in the bottom section, which means that the upper section can never be fully closed. This is a problem if large angle differences between the upper and lower sections are allowed. In Sweden's very northern latitudes, e.g. Lund lat 55° N and Stockholm lat 59° N this is a particular problem because of the low solar altitudes in winter.

During the initial phase of the project it was decided that angle differences exceeding 20 degrees are impractical if direct sunlight in winter is to be avoided. The clip supplied with the venetian blind created an angle difference of around 45 degrees. It became obvious in March that this difference was too great, as the venetian blind allowed direct light onto the work surface through the upper section, see figure 4.1. The clip was therefore removed and the cords were shortened manually with needle and thread. At the end of the project a prototype clip creating a smaller angle difference was supplied, but this still requires further development.

The control system combined with the manually shortened cord meant that in June, the venetian blind was set to about 33 degrees in the lower section and 12 degrees in the upper section when the blind was down. On sunny days, the venetian blind was lowered automatically at about 09:00 (daylight saving time).

Figure 4.1 *During the set-up phase, it became obvious that the angle difference between the upper and lower sections was too great, allowing direct solar radiation onto the work surface. This was corrected before the measurements started. (Photograph: Thore Sonesson).*

4.1.2 Luminance of window wall

As it is usually the window that produces the highest luminance levels in the room – and consequently causes perceived glare problems – it is interesting to study how the venetian blind setting affects the luminance against the window. In some cases, the luminance of the window wall in the test room was measured using a CCD camera. Because the camera did not have a wide angle lens, it was decided to take an image showing one window and part of the room – the window on the right as viewed from the interior, plus the front part of the side wall and ceiling. The view out of the window consisted of shrubs, grass and trees, and a road turning to the left. The horizon line defined by the green vegetation can be seen through the venetian blinds in figure 4.2.

Figure 4.2 Image of the room taken by the luminance camera.

As experiment leader I found that the there was often a large amount of light in the test room during the summer measurements. The reason is that the control system was designed to avoid direct solar radiation into the room. Because the sun is high in the summer, the slats are adjusted to a very open angle. Although this provides a good view through the slats, the window surface is also very bright, which is often experienced as glare. To illustrate this, a series of images from June 19 appears below, taken between 14:01 and 14:18 with varying slat angles. The day provided stable sunny weather, but it was also quite hazy. The illuminance outside (horizontal) varied only slightly, between 77 – 81 kilolux during the period the images were taken. This variation was not considered to be large enough to affect the analysis of the individual images. The vertical illuminance on the facade was estimated at around 53 kilolux. The luminance image with the venetian blind up is shown in figure 4.3. The colours vary between green, white and red. Red indicates the measuring range maximum of 3100 cd/m², and all white areas are beyond the measuring range of the camera. At one selected point on the wall, approximately in the middle of the light green area, the luminance was 1200 cd/m². The sky was white, i.e. over 3100 cd/m².

By adding a filter to the camera with approx. 12% transmittance, the luminance of the sky could be estimated at around 12,000 cd/m² maximum, figure 4.4. The vegetation mostly appeared in the green shades, with a luminance that varied between around 500 – 2000 cd/m². The white area in the middle of the window in figure 4.3 is the road, with light coloured old asphalt that reflects more light than the vegetation and a luminance of approx. 5000 cd/m².

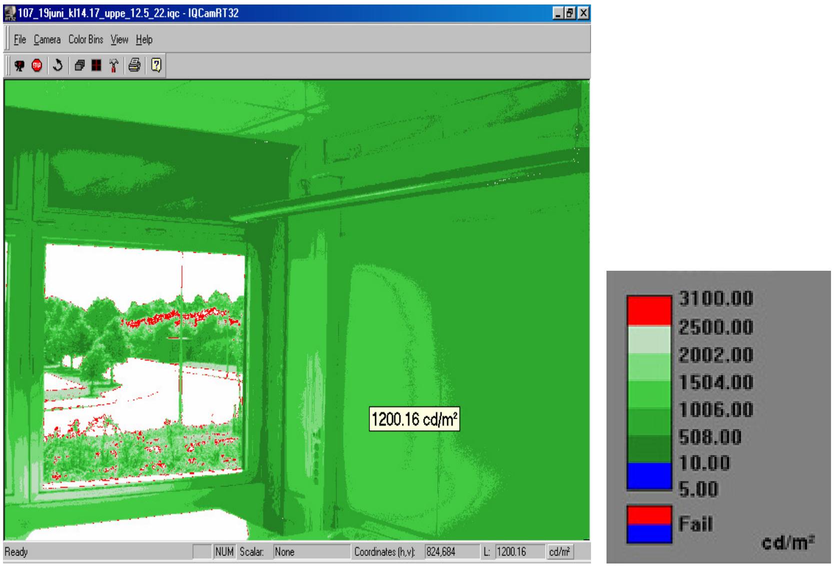


Figure 4.3 *Luminance image on 19 June with venetian blind fully up. The colour scale appears on the right.*

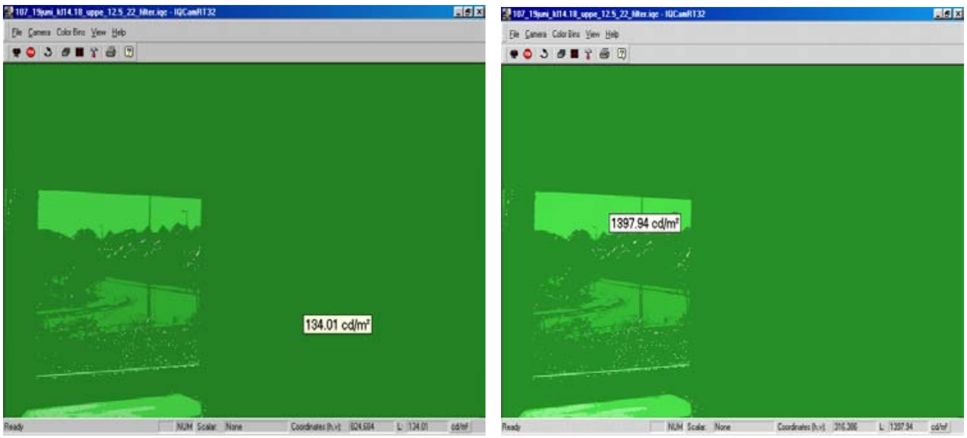


Figure 4.4 *Luminance image from 19 June taken with filter T12%, control system's initial setting of venetian blind (33 degrees in bottom section).*

Figure 4.5 shows a series of images with the venetian blind down but adjusted to various angles. The first image (far left) shows the venetian blind with the slats fully open (lower slats inclined to approx. 14 degrees). The luminance at the selected wall point is 850 cd/m², which corresponds to a 70 % light transmittance through the venetian blind system. The luminance of the sky was normally around 10,000 cd/m² (average with 1 degree viewing angle). In the next image (top right) the venetian blind was closed to an angle of 20 degrees, i.e. to around 34 degrees in the lower section of the venetian blind. The wall luminance is now around 760 cd/m² and the sky luminance is generally around 6500 cd/m² for a one degree viewing angle, and up to around 8500 cd/m² for an individual pixel in the image between two slats.

The third image in figure 4.5 shows the effect of closing the venetian blind even more, to around 65°. This resulted in 420 cd/m² at the selected point on the wall and around 3400 cd/m² for the sky viewed through the window (bottom left). Fully closing the venetian blind reduces the luminance at the same point on the wall to 200 cd/m², and reduces the luminance of the sky to approx 900 cd/m² (bottom right). The fully closed light redirecting venetian blind is therefore capable of reducing the luminance on the wall by a factor of 6, while the sky luminance is 13 times lower when viewed from the camera position. This corresponds to a maximum light transmittance through the entire system of 20 %.

The series of images clearly shows that if the slats are too open, the view outside is relatively unobstructed, and the window surface is very bright, with an evident risk of glare. The more open, light redirecting section at the top of the venetian blind is clearly visible in the two lower images. In the image on the left, the sky luminance varies depending on whether the measurement is taken on a slat or between slats. Even though the venetian blind is relatively closed, some areas still have a high luminance, exceeding 3100 cd/m². The risk of glare is significantly lower than in the first two images, but a small risk may still be present if the top section is within the employee's field of vision.

Below the dividing line, the almost horizontal venetian blind only reduces the luminance of the road and the vegetation by a small amount. When the venetian blind is set to an angle of around 30°, the view outside can still be seen. The window surface is slightly darker, but there are still many red and white areas when the luminance is 3100 cd/m² or higher. For people who are sensitive to glare, there is an evident risk of glare. When the venetian blind is closed to 65°, the view is completely obstructed. The slats shade each other and the venetian blind becomes significantly darker, between 1200 cd/m² and 1800 cd/m² in the bottom section. This ought to be sufficient to prevent any glare.

The fully closed venetian blind is very dark, between 1000 cd/m² at the top and 300 cd/m² at the bottom, which also means that even less light is allowed into the room, making it unnecessarily dark inside.

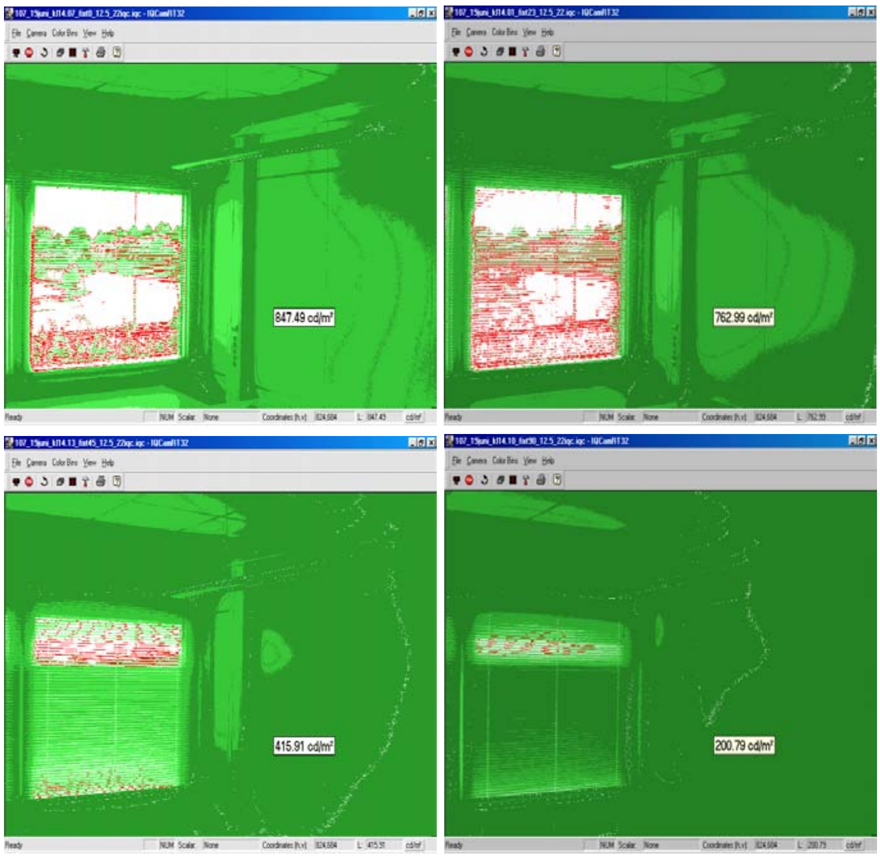


Figure 4.5 *Luminance images from 19 June, top left with slats set to almost horizontal (approx. 14°), top right set to approx. 34° incline, bottom left relatively closed (65°) and bottom right fully closed (75-80°).*

4.2 Measured electricity use, illuminance and indoor climate

4.2.1 Electricity use and lighting in May/June

The daily accumulated electricity use of the lighting during the summer period May/June was measured and compared with the average outside global illuminance on the roof, see figure 4.6. In the reference room, the venetian blind was down (slat angle 34 degrees) and the lighting was kept on all day (08:00-17:00), so the electricity use is the same every day, around 0.7 kWh/day.

In the test room, the position of the venetian blind was adjusted according to the solar altitude and illuminance, and the luminaire was in turn adjusted according to the amount of light in the test room. These combined factors significantly reduced the electricity use all day, and on very bright days the luminaire was used much less, and was switched off for much of the day. During this period, the system was controlled by the ceiling mounted sensor.

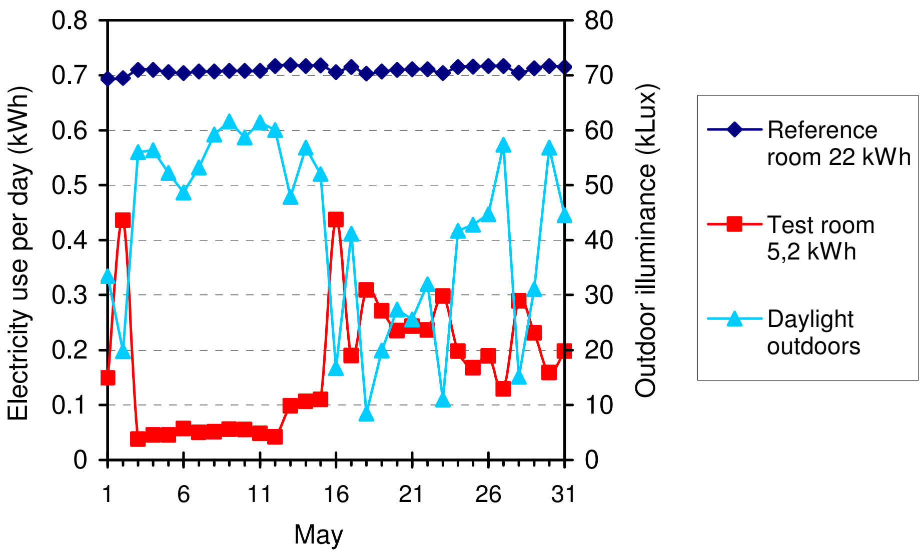


Figure 4.6 Daily electricity use in May for test room and reference room, and average outside illuminance (global, horizontal).

Figure 4.7 shows the savings compared to the constant lighting and fixed venetian blind. In total, the saving was 77 % during the month of May. It is clear that there is a strong correlation between the saving and the outside illuminance.

Because the illuminance is measured globally on the roof, these were the first values used in the evaluation. However, the system used a vertical mounted light sensor that was not satisfactorily logged. Therefore, in order to estimate the vertical illuminance, a vertical solarimeter belonging to the climate station (situated on the south facade above the room) was used as follows: The luminous efficacy was calculated from the horizontal light sensor and sun sensors on the ceiling. The luminous efficacy is the number of lumens per watt produced by the solar radiation, and is calculated from the ratio of illuminance to global radiation, and the unit is lm/W. The luminous efficacy varies slightly with different weather and solar altitude, but remains relatively constant – between 86 and 113 lm/W – for the days in May (average daily values, 08:00-17:00), and the average value for all days in May was 95 lm/W. The vertical illuminance could then be calculated as the product of the luminous efficacy and solar radiation measured on the vertical.

Figure 4.8 shows the electricity saving plotted against the measured illuminance on the horizontal and against the illuminance on the vertical estimated as described above. Both the "sensors" performed acceptably, but the saving did not fall to zero when the outside illuminance outside fell to zero, as would be expected. Note that the values are average values during the day (08:00-17:00) and the rapid changes in the daylight are not included.

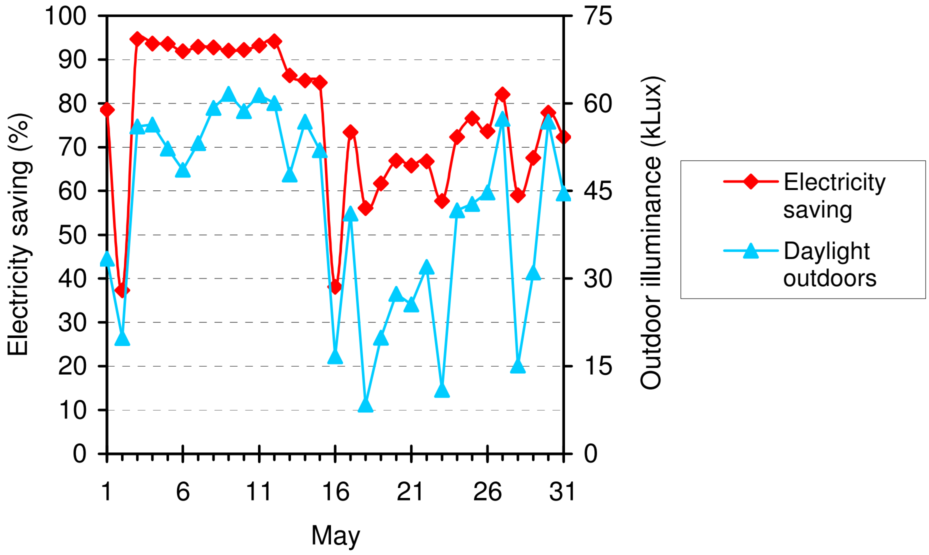


Figure 4.7 *Daily electricity saving in May for test room compared to reference room, and average outside illuminance (global).*

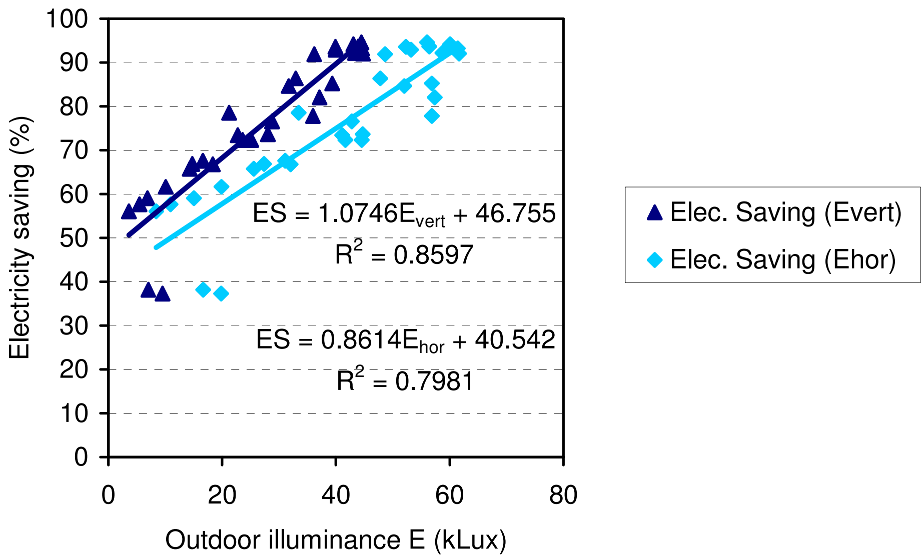


Figure 4.8 *Daily electricity saving for lighting (percentage) in May for the test room compared to the reference room, as a function of the outside illuminance (kilolux) measured horizontally (light blue points) or estimated vertically to the facade (dark blue points). Regression lines are also shown.*

Measurements of outside illuminance and the electricity use on three selected days appear in figure 4.9-10. One interesting feature of the luminaire is evident here: it is switched off completely after a period at the minimum adjustment. This is a good idea because the luminaire continues to consume around 20 W or 25% of full power even when it is fully dimmed (giving around 10 % of light) because of ballast losses and poor luminous efficacy in the fluorescent tubes while dimmered.

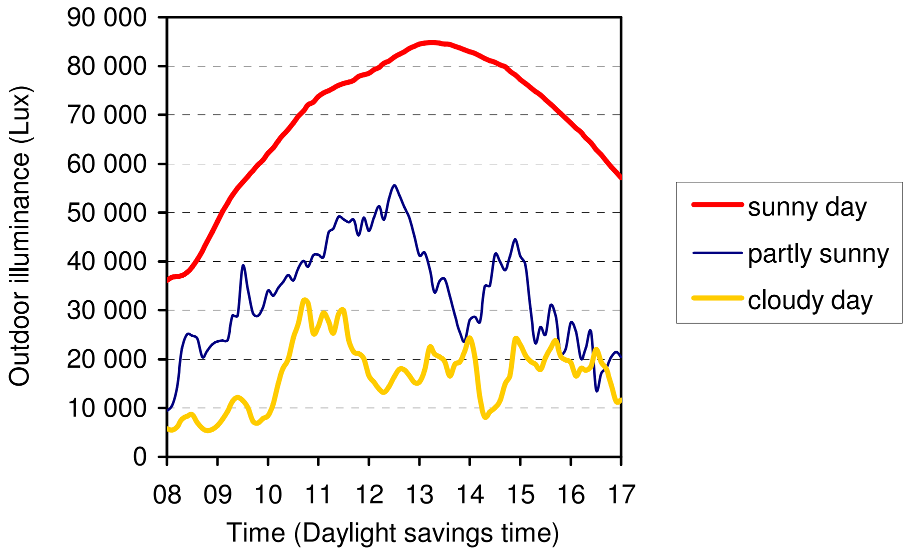


Figure 4.9 *Illuminance (lux) outside (horizontal) for three selected days. One bright sunny day (June 11), one partly sunny day on May 1, and one overcast and relatively dark day (May 16).*

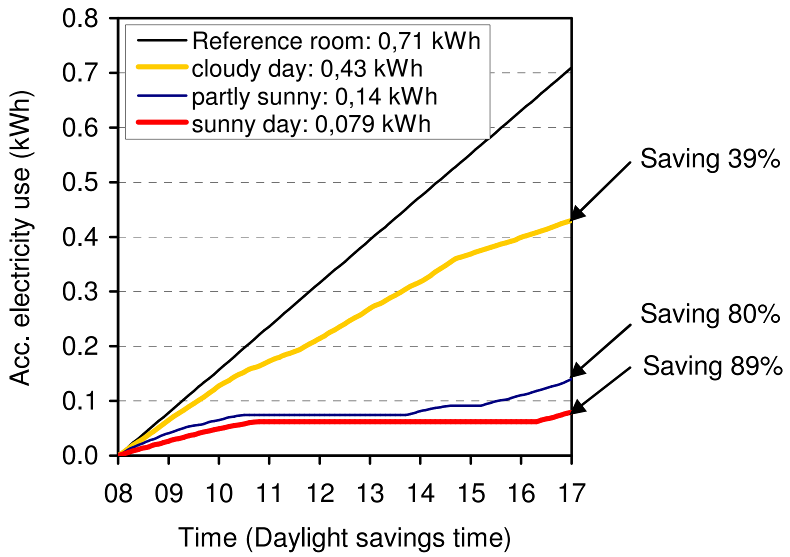


Figure 4.10 *Accumulated electricity use and total saving for the day on one sunny day, one partly sunny day and one dark overcast day in May and June compared to constant lighting in the reference room.*

Figures 4.11-12 go into more detail with the lighting in two selected points in the room on these three days. The figures show the illuminance at the centre of the room (measuring point B2), and in the middle of the front half of the ceiling (measuring point T1). The illuminance on the facade, estimated as described above, is also shown. In order to relate these measurements of the total illuminance (daylight + artificial light), the illuminance from the luminaries themselves at full luminous flux is included for comparison, measured at night in April, see table 4.1. This shows that the addition of electrical light at point B2 is approximately 400 lux in the reference room and approximately 470 lux in the test room. At T1 on the ceiling, the illuminance was around 180 lux in the reference room and 220 lux in the test room. The apparent difference between the two luminaries may be because the adjustment of the light control system was not perfect. Other sources of error (apart from a calibration error in the light sensors) are the installation of the light sensors (lateral position, possibly at an angle), and poor balancing of the luminaries, which were difficult to fully rectify.

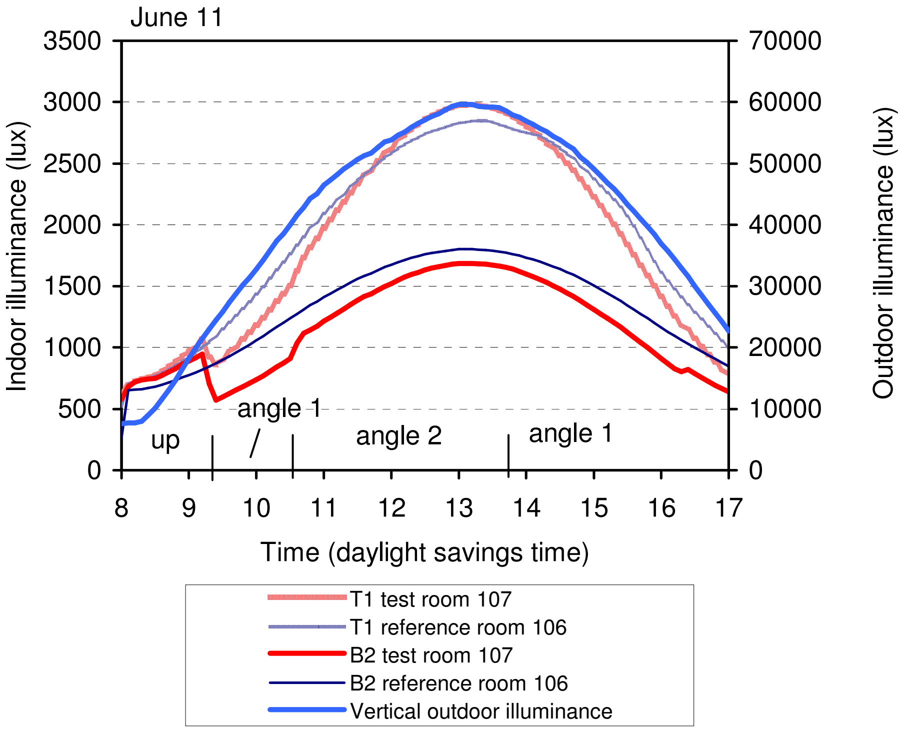
Table 4.1 Measured illuminance (lux) from the luminaries at full luminous flux during night measurements in April. Precision approx. +15/-5 lux.

Measuring point	Test room 107	Reference room 106
B1	314	317
B2	468	405
B3	224	201
T1	220	177
T2	154	134

During the sunny day on June 11, something happened just after 09:00 – the venetian blind in the test room was lowered, see figure 4.11. The illuminance at B2 fell by at least 400 lux and at T1 by around 200 lux. The lighting had nothing to do with this – it was switched on at 08:00 but was dimmed immediately, consuming just 25 W up to 10:45 when it was switched off completely. This means that the luminous flux was approx. 18 % of the full flux. The light was switched on again at 16:25, but remained fully dimmed until it was switched off just after 17:00. In the reference room, the lighting was left on full, consuming 78-79 W.

At around 10:30, there is a sharp bend in the curve for B2 in the test room. This is because the venetian blind was opened by 13 degrees at that time. At 13:45 the venetian blind was programmed to return to the same angle as the morning, but this is more difficult to see in the chart. The slight bend at 16:25 is when the lighting was switched on.

On the partly cloudy day on May 1, it is also evident that the venetian blind was lowered at around 9 (09:16 according to the log file). Between 13:45 and 16:55 the venetian blind stayed down and alternated between its set point value and horizontal slats (i.e. in the waiting position ready to be raised). But because of the changing luminous intensity, the venetian blind is not raised until 16:55, which appears as a sharp rise in the curve. The lighting is dimmed in the morning, almost as much as on 11th June, and is switched off for two periods during the day, figure 4.11.



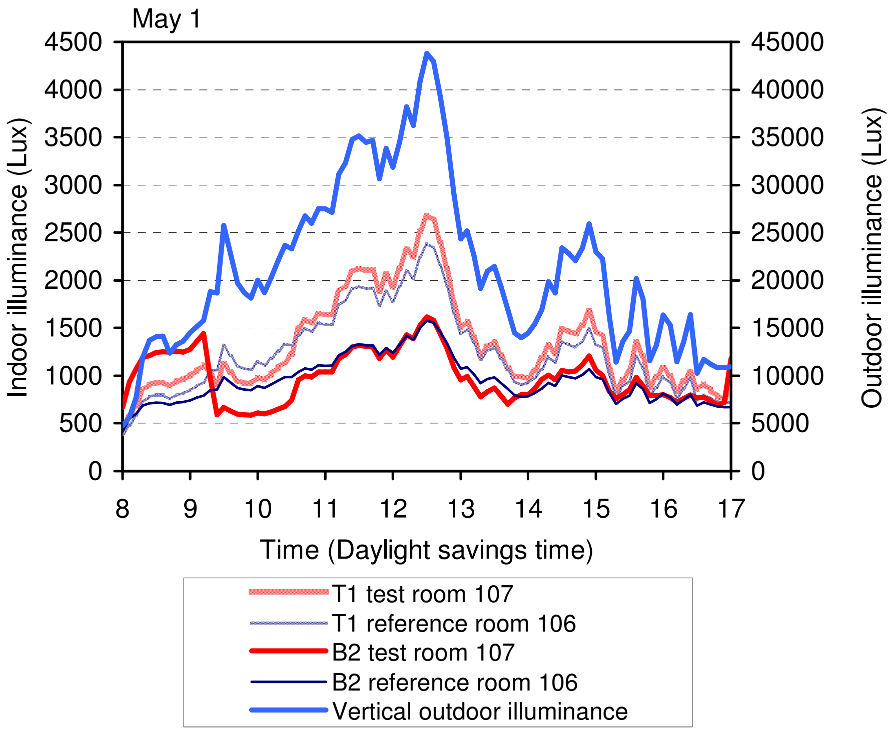


Figure 4.11 *Illuminance at the centre of the room (point B2) and in the front part of the ceiling (point T1) in the test room and reference room. Estimated illuminance on the facade is also shown. Top: Sunny day on 11th June, bottom: Partly cloudy day on 1st May.*

The overcast day on 16th May is shown in figure 4.12. The illuminance outside is significantly lower on that day. Judging by the curves, the venetian blind appears to have been up or fully open on this day. The lighting appears to have performed very well in relation to the varying luminous intensities outside. It may be relevant to stress that the illuminances inside are significantly higher with daylight on all days studied than at night with electrical lighting alone. In the ceiling the luminaire only produces 150-200 lux, but the measurements were 300-3000 lux in daylight for the three days in question. At the centre of the room, the lighting produced 400-500 lux, compared with values of 1000 lux or more in daylight. All measured illuminance values in May are set out in Appendix 1.

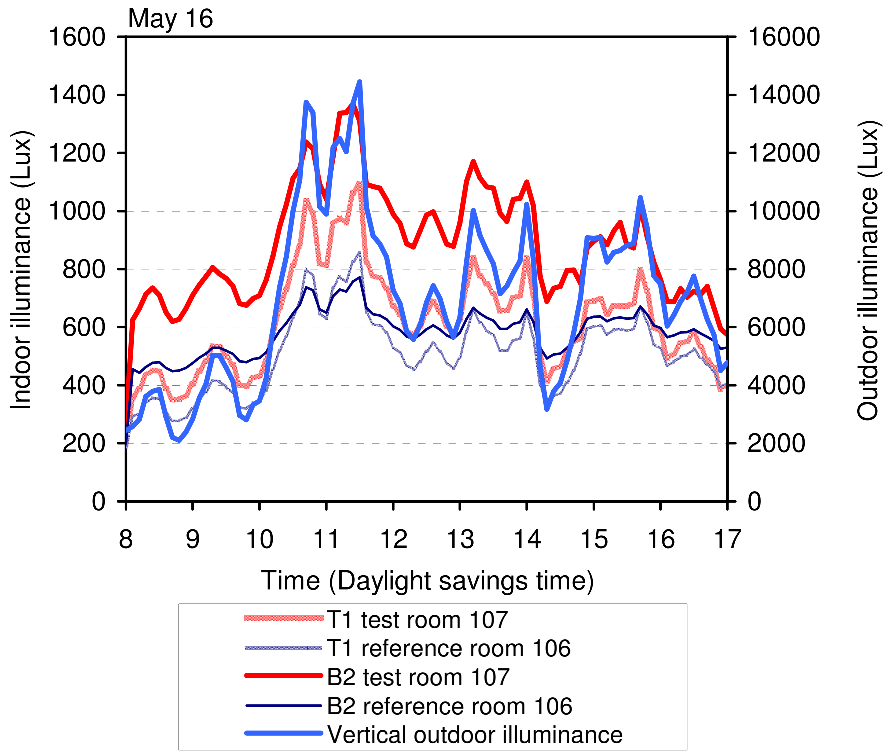


Figure 4.12 *Illuminance at the centre of the room (point B2) and in the front part of the ceiling (point T1) in the test room and reference room. Estimated illuminance on the facade is also shown. Overcast day on 16th May.*

4.2.2 Resulting indoor climate on a sunny day in June

The temperature in the two rooms during the sunny day on 11th June is shown in figure 4.13. When the first measurements are taken in the morning, the temperature in the rooms is more or less the same. The average supply air temperature at night was 18.9 degrees, rising to an average 20.1 degrees in the middle of the day. This was caused by operating problems in the cooling system. The supply air flow was 20 l/s on average. The introduced air cooling is calculated as the product of the air flow and the temperature difference between the extracted air and the supply air, times the air density and specific heat of air. Because of the strong radiation this day (see figure 4.9) the temperature rises during the day. The curves show that the air cooling effect increases slightly during the day as a result of the increasing difference between extract and inlet air temperatures, but the effect is the same in both rooms. The temperature in the reference room is slightly higher than in the test room. The difference in room temperature is greatest in the afternoon, when it reaches around 1.4 degrees. During this measurement, the venetian blind was more closed in the reference room than in the test room, reducing the solar radiation in the reference room. The lighting in the reference room was switched on between 08:00 and 17:00, with a constant rated power of 78-79 W. In the test room, the lighting was fully dimmed up to 10:50 and after 16:20, and was switched off completely in between these times (see figure 4.10). The higher temperature in the reference room can therefore be attributed to the lighting, which gives off much more heat in the reference room.

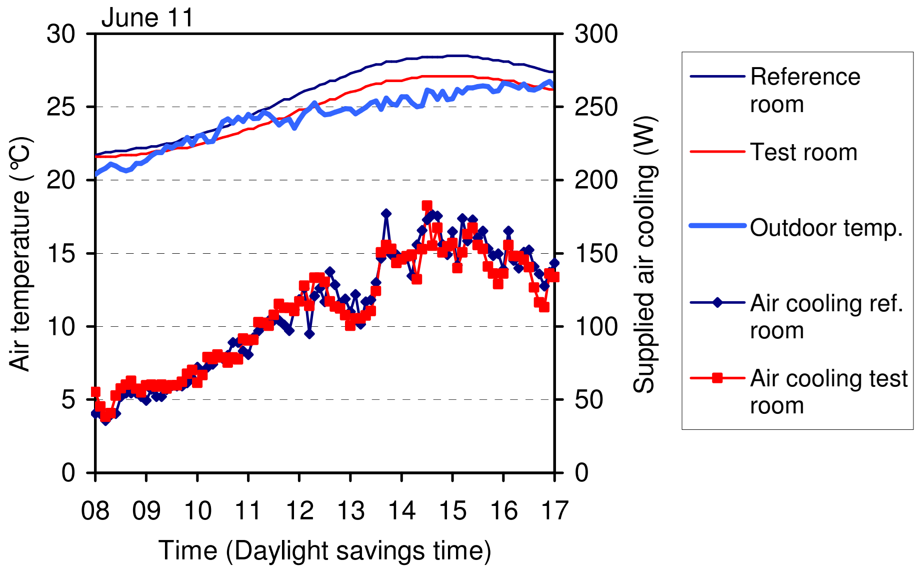


Figure 4.13 *Measured outside temperature and inside temperature in reference and test room on a sunny summer day (11th June). Introduced air cooling (right axis).*

4.2.3 Effect of sensor location

The location of the light sensor clearly has a significant influence on potential savings for lighting energy. For example, a sensor that detects light a long way into the room will receive less daylight than a sensor near the window. The sensor location obviously must be adapted to the workplace and to the surface the luminaire is intended to light. During a short period in August/September, a straightforward comparison was carried out between a sensor pointing down to the table, integrated at one end of the luminaire (the end nearest the window), and a sensor installed on the ceiling and pointing at an angle down towards the window. The idea behind the ceiling mounted sensor was to be able to detect when the venetian blind was strongly lit, and so dim the light. The following comparison was carried out both with raised venetian blinds, and with fixed venetian blinds in the same position with no adjustment in either room. The electricity saving was calculated by comparison with the use of lighting that was switched on full. The analysis did not take account of the illuminance resulting of the luminaire, because the daylight itself frequently produced more than 500 lux and the measured illuminance was the total illuminance (daylight + artificial light).

The electricity saving between 8:30 and 17:00 on a relatively sunny day (28/8) with raised venetian blinds was 62 % with the ceiling mounted sensor and 89 % with the integrated sensor. The illuminance outside averaged 49 kilolux, see figure 4.14.

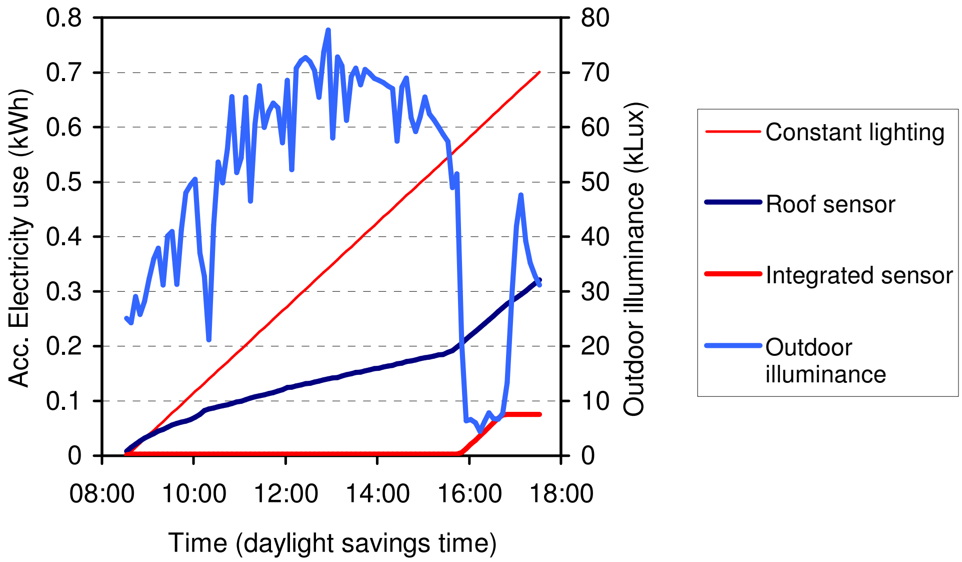


Figure 4.14 *Electricity saving on a sunny day (28/8) without venetian blinds 8:30 -17:00*

On another sunny day (11/9) the venetian blinds were adjusted with a slat angle of 40 degrees. The electricity saving between 08:00 and 17:00 totalled 64 % with the ceiling mounted sensor and 88 % with the integrated sensor. Outside, the average illuminance was 45 kilolux. Figure 4.15.

Another day is also shown (7/9), which started quite dark and overcast but which became brighter in the afternoon, see figure 4.16. On this day the venetian blinds were down and were adjusted to an angle of 40 degrees. Both luminaries were on full until 14:00. When the outside illuminance reached around 30 kilolux, both luminaries started to adjust, and the saving for the day as a whole (08:00-17:00) was around 17% for the ceiling mounted sensor and 25 % for the integrated sensor.

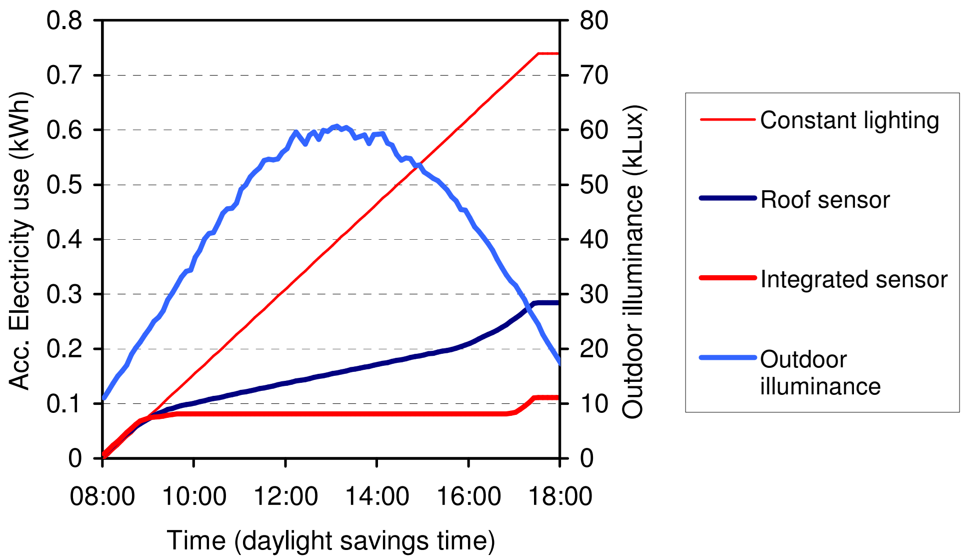


Figure 4.15 *Electricity saving on a sunny day (11/9) with venetian blinds at 40°. The lights were switched off at 17:30*

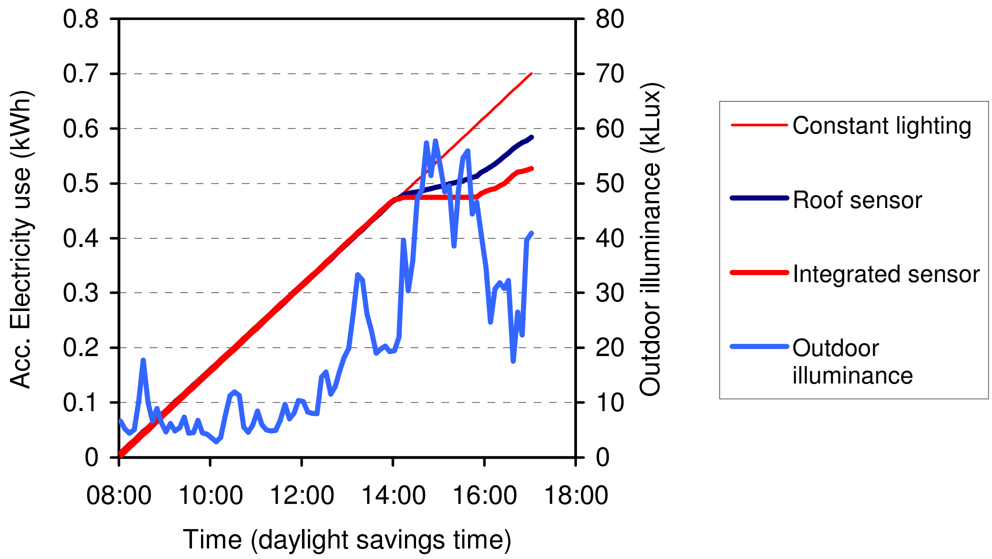


Figure 4.16 Electricity saving on one day that started overcast then became changeable (7/9) with venetian blinds at 40°.

4.2.4 Electricity use and lighting in November

Measurements of electricity use for lighting were also carried out during part of November – the period 8-30 November is shown here. The period was characterised by a large number of overcast days with low illuminance. The saving of electricity for lighting was therefore only a modest 5 %. During this period the luminaire in the test room was controlled by the integrated sensor and not by the ceiling mounted sensor, to ensure that the electricity saving was not underestimated (cf. section 4.2.3 above). Figure 4.17 shows the daily saving and the average illuminance outside. The chart shows the measured horizontal illuminance on the roof as well as the estimated vertical illuminance against the facade. The chart clearly shows that when the sun shines in November, the illuminance is much higher on the vertical window than to the horizontal, because of the low solar altitude. (The solar altitude at 12:00 falls from 18 degrees on November 8 to 12 degrees on November 30).

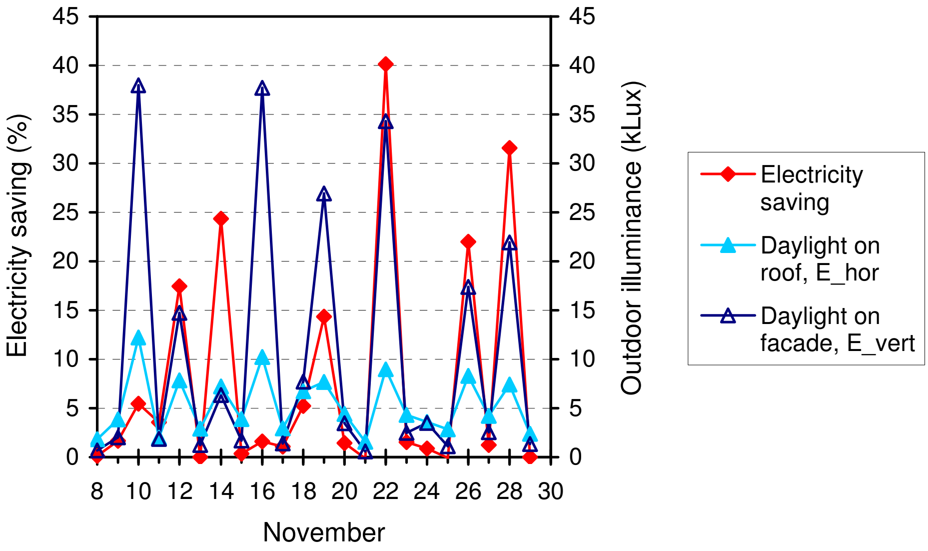


Figure 4.17 *Daily electricity saving in November for test room compared to reference room, and average outside illuminance (global).*

The correlation between the percentage saving and the outside illuminance is shown in figure 4.18. The vertical illuminance is estimated as described in section 4.3. The luminous efficacy varied between 91 and 115 lm/W, averaging 103 lm/W (the average over daylight hours, i.e. approx. 08:00 -15:30). The relationship between the saving and the illuminance is not as close as in May. The result above shows a very complicated relationship between the controlled venetian blind and the electricity saving. The luminaire is controlled entirely by the daylight falling on the table, so in a sense it follows the venetian blind. This probably explains the weaker correlation compared with the measurements taken in May.

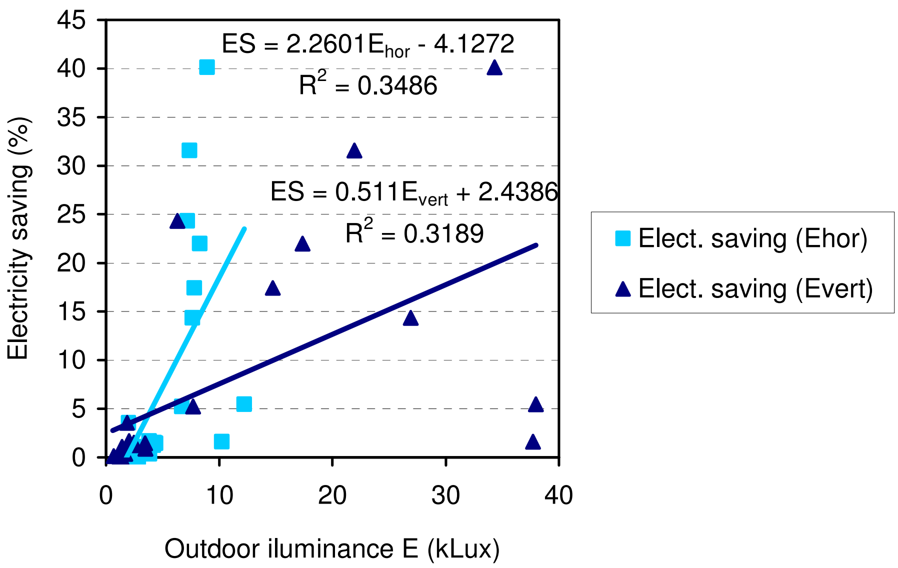


Figure 4.18 *Daily electricity saving for lighting (percentage) in November for the test room compared to the reference room, as a function of the outside illuminance (kilolux) measured horizontally (blue points) or estimated vertically to the facade (orange points). Regression lines are also shown.*

The inside illuminance during measurements in November is shown in Appendix 2. Figure 4.19 shows the correlation between illuminances in the five pairs of identically positioned measuring points. The values for the reference room are shown on the x axis and the corresponding points in the test room appear on the y axis. On the days when the levels in the two rooms are the same the points coincide with the line. On a total of seven days, it is on average darker in the test room, and the points appear below the line. On other days it was lighter in the test room (points above the line). This wide variation is due to the interaction between the controlled venetian blind and the controlled luminaire. The chart is rather difficult to interpret, but it does show that on about half the days in the studied period, it is considerably lighter inside in November than would be provided by electrical lighting alone. On other days, the contribution is small because it is very dark outside. When it is completely dark outside, the illuminances at the 10 measuring points in the room vary between 135 and 440 lux, see table 4.2. During the day, this is the maximum contribution than the measured illuminances can receive from the electric lighting – the rest must come from the daylight.

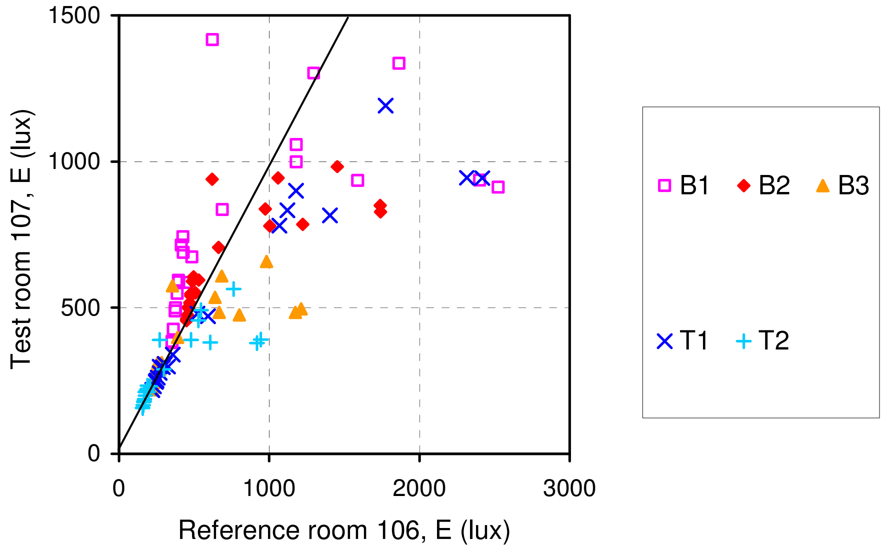


Figure 4.19 *Measured illuminance (lux) in the reference room compared to the corresponding points in the test room for table mounted sensors (B1-B3) and two ceiling mounted sensors (T1-T2). Average values between 08:00 and 17:00*

Table 4.2 *Measured illuminance (lux) from the luminaries at full luminous flux during night measurements in November. Precision approx. +15/-5 lux.*

Measuring point	Test room 107	Reference room 106
B1	277	335
B2	417	437
B3	195	213
T1	190	198
T2	135	148

Figure 4.20 shows the ratio of the measured illuminances in figure 4.18 in the five pairs of identical points B1-B3 and T1 and T2. The daylight outside is also shown. The chart shows

that it was sunny on 10th, 16th, 19th and 22nd of November. There was also some sun on 12th, 26th and 28th of November. On all these days, apart from 28th of November, the illuminance in the test room is slightly or significantly lower than in room 106. On the very sunny days on 10th and 16th of November, the difference is particularly clear. This must mean that the venetian blind was lowered and the slats were fairly closed. This explains why there was no electricity saving on these two days. At the times at which the venetian blind in the test room is lowered, the slats are very closed, whereas the fixed venetian blind in 106 are much more open. This explains why the illuminance is sometimes so much lower in the test room.

The 14th of November departs slightly from the pattern in another direction, because there is an unexpectedly high electricity saving despite relatively small amounts of daylight outside, cf. figure 4.17. Looking at the inside lighting, it is clear that the illuminance at B1 and B2 is highest on this day. There was some direct radiation during the day and the diffuse radiation was relatively high, but probably not high enough to lower the venetian blind, allowing the luminaire to be dimmed.

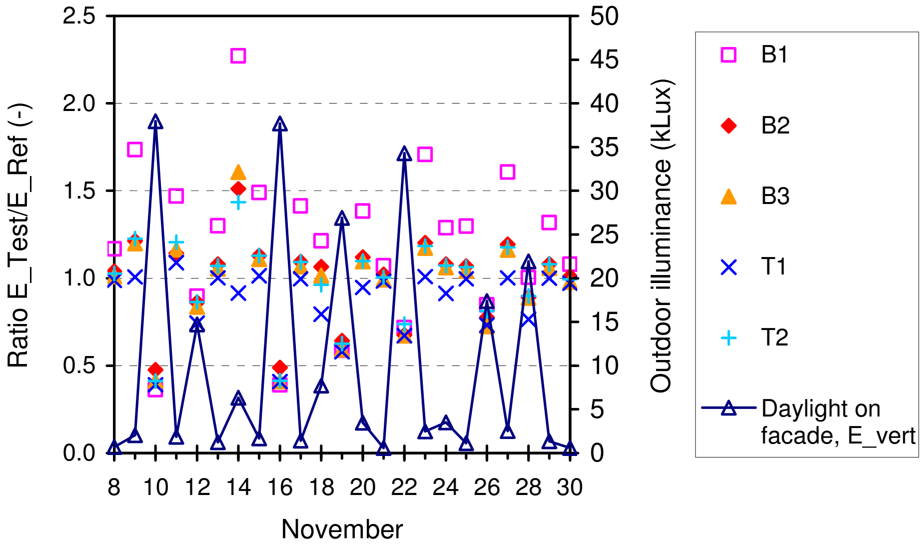


Figure 4.20 *Measured illuminance (lux) in test room and reference room for measuring points B1-B3 at table height and T1-T2 on ceiling.*

4.2.5 Estimate of annual electricity savings

Measurements were carried out in May and November in order to produce a rough estimate of the electricity saving that can be expected on an annual basis. The estimate was calculated using the regression lines in figures 4.8 and 4.20 and by applying these equations to a climate file for a normal year. The equation for May was used for the six months around summer (21/3-21/9) and the November equation was used for the winter. A synthetically generated climate file from the Meteonorm program was used, for Lund and with hourly values for the global solar radiation. The luminous efficacy was set to 95 lm/W for the summer and 103 lm/W for the winter. All these factors taken together mean that the estimate is very approximate. The calculated electricity saving was around 50 %, counting all hours between 08:00 -17:00 (when the lighting is assumed to be switched on).

4.3 Effect of light redirecting section of venetian blind

4.3.1 Measurements without electric lighting

A comparison of venetian blind designs with and without a light redirecting section was carried out over two weeks in June/July. The venetian blinds where fixed and the measurements were taken without electric lighting. The venetian blinds were adjusted as follows:

- Test room: Slats in top section 14°/in bottom section 34°
- Reference room: Slats 34°

We will first illustrate the relationships on an overcast day. 27[th] June was selected as an ideal evenly overcast day. This is confirmed by the ratio of the global radiation to the diffuse, which was 1.0 throughout the day. The average of the outside measurements during the day was 13 kilolux. The outside illuminance and the table sensor closest to the window (B1) and farthest into the room (B3) in the test and reference rooms are shown in figure 4.21. Even though the day is overcast, the illuminance fluctuates widely during the day, in other words a typical situation. The inside illuminance follows the outside illuminance, and the chart shows that the difference between the two rooms is relatively small. The daylight factor is estimated by dividing the measured inside illuminance with the outside illuminance, figure 4.22. This chart also includes the measurements taken with ceiling sensor T1. This figure shows slightly more clearly than the previous figure that it is somewhat brighter in the test room equipped with the daylight redirecting venetian blind. The difference is illustrated again when the ratio of the illuminance measured in the two rooms is calculated instead, see figure 4.23. At table height, the illuminance increases on average by around 10 % at the sensor closest to the window (B1) and 15 % at the sensor farthest into the room, (B3), whereas the light at the ceiling is more or less the same in both rooms. The difference remains relatively constant throughout the day, which would be expected for an overcast day. The reason is that the light distribution from the sky does not depend on the sun position. The daylight factor, i.e. the ratio of the illuminance inside to outside, is relatively constant throughout the day. In addition, the daylight factor is not dependent on the orientation of the room.

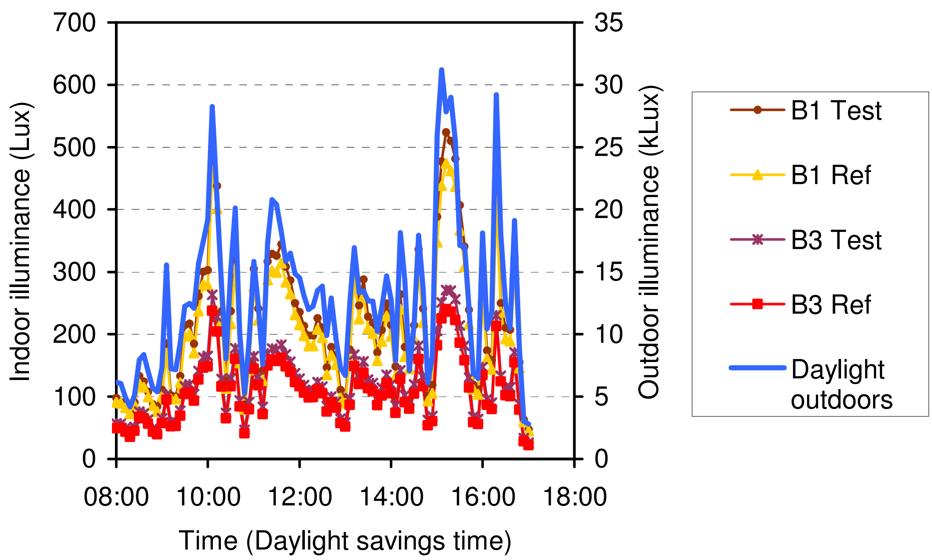


Figure 4.21 Illuminance inside (lux) at table sensors B1 and B3 in the test and reference room, and illuminance outside (right axis) in kilolux. Overcast day the 27[th] of June.

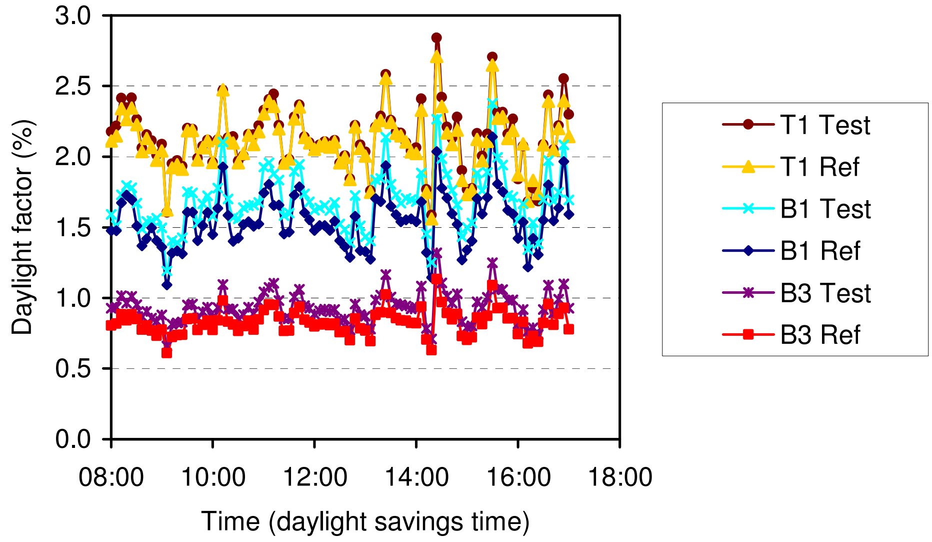


Figure 4.22 *Daylight factor at table sensors B1 and B3 and ceiling sensor T1 the test room and reference room. Overcast day the 27th of June.*

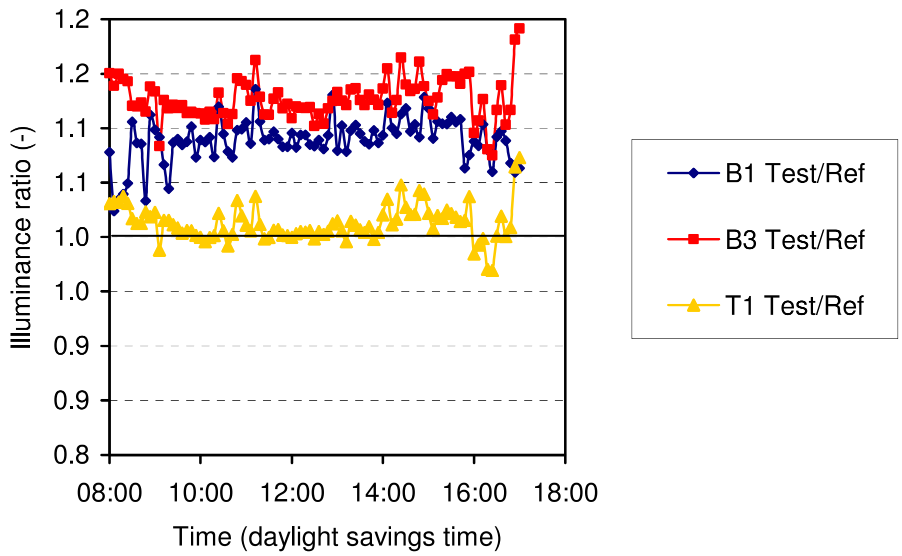


Figure 4.23 *Ratio of illuminance in test room to reference room at table sensors B1 and B3 and ceiling sensor T1. Overcast day the 27th of June.*

The measurements from a clear sunny day appear in figure 4.24. Here, the outside illuminance is considerably higher, averaging 67 kilolux for the period 07:00-17:00 (winter time). The difference between the two rooms is still small, but a difference does emerge at the ceiling sensor during the afternoon that is difficult to explain. The trend is slightly different compared to the overcast day: the illuminance increases somewhat at table height, but decreases at the ceiling. The sun can be calculated as being at its highest on that day around 12.10 winter time, and this agrees with the measurements which reach their maximum precisely at that time.

Even though calculating the daylight factor for a sunny day is inappropriate because the daylight factor is defined for overcast weather, this has been done anyway, see figure 4.25. The ceiling sensor in the test room shows slightly raised values just before 12:00 and slightly lowered values in the afternoon. This may be due to measuring errors, for example the meter may not be perfectly horizontal and may be affected differently by reflected light when the sun is low in the east or low in the west. However, it is more likely that the venetian blind was adjusted and changed slat angle at these times. The curve for T1 in figure 4.25 is therefore quite difficult to interpret.

At point B3 (farthest into the room) it is clear that the illuminance increases in the morning and the evening (by up to 10 %) with daylight redirecting venetian blinds, while there is virtually no difference between the rooms in the middle of the day. See figure 4.26. It is also worth noting that the illuminance in B3 reaches as much as 1000 lux in the middle of the day even though the venetian blind is set to 34 degrees. In other words there is twice as much light at this point as the normal design value for work surfaces in offices (500 lux), and close to the window (B1) it is four times lighter.

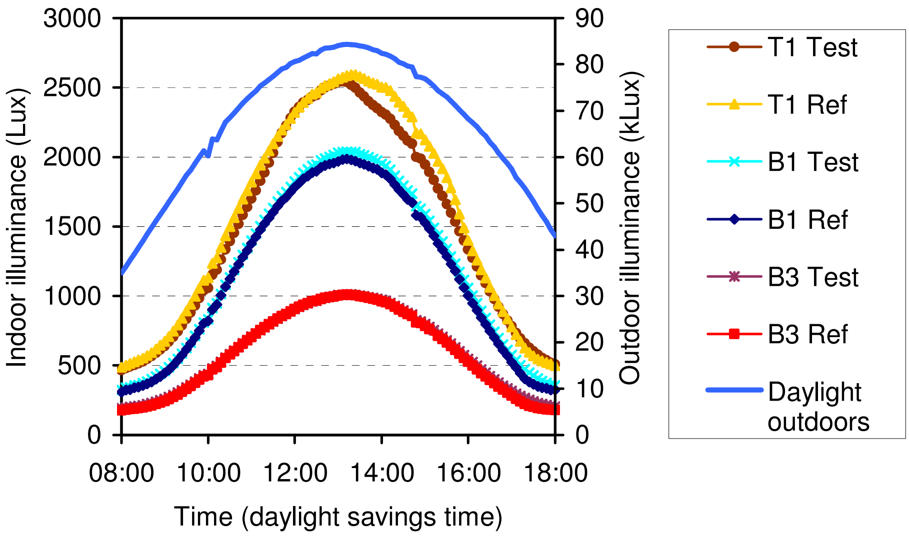


Figure 4.24 *Illuminance inside (lux) at roof sensor T1 and table sensors B1 and B3 in the test and reference room, and illuminance outside (right axis) in kilolux. Sunny day the 2nd of July.*

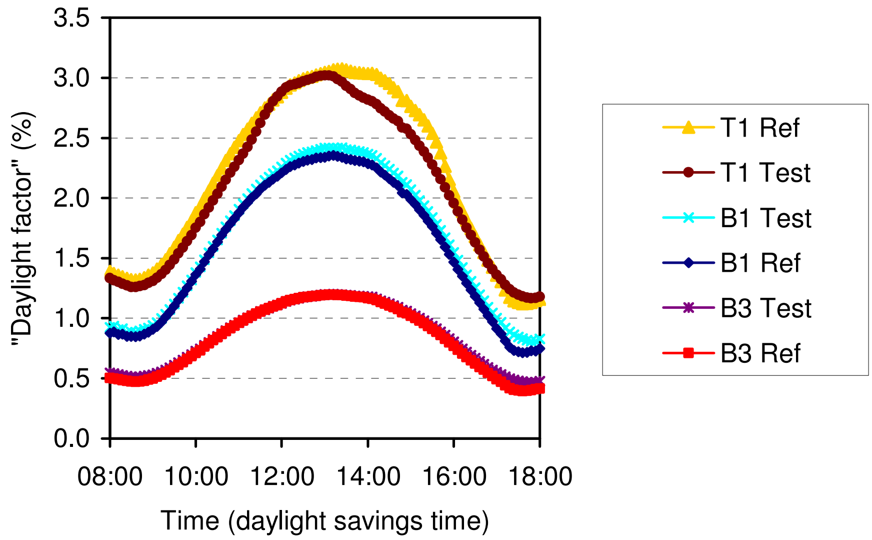


Figure 4.25 *Daylight factor at table sensors B1 and B3 and ceiling sensor T1 the test room and reference room. Sunny day the 2nd of July.*

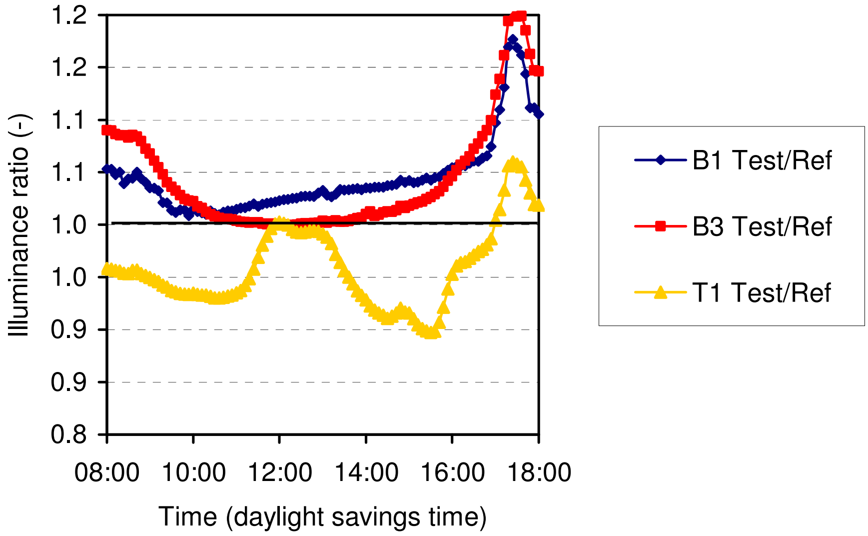


Figure 4.26 *Ratio of illuminance in test room to reference room at table sensors B1 and B3 and ceiling sensor T1. Sunny day the 2nd of July.*

4.3.2 Simulation in typical office without electric lighting

The effect of light redirecting venetian blinds was also investigated by means of light simulations in Radiance. Here a model was created of a typical office room with a modular dimension of 2.4 m, i.e. slightly narrower than the room in the lab, but around the same depth and height. Instead of a row of windows, the model had two windows in the facade with a coupled triple glazed window (1+2) and a venetian blind between the outer two panes. The outside window surface area (with a hypothetical storey height of 3.5 metres) is around 30 %. The reflectance of the surfaces inside the room was 85 % for the roof, 65 % for the walls, 35 % for the floor and 50 % for the furniture. These figures correspond to the recommendations for energy-efficient offices issued by NUTEK (NUTEK, 1994). Figure 4.27 shows an image from the door to the facade.

Figure 4.27 Image simulated in Radiance for the solar altitude in June at 12.00 true solar time

The illuminance at the centre line of the room in June with a sunny sky is shown in figure 4.28 for four versions of light redirecting venetian blinds and for a standard venetian blind with the same angle from top to bottom. (The dividing line between the upper and lower sections was varied as well as the angle difference between the upper and lower sections, see section 3.5). The venetian blinds were named as follows: “slat angle top/bottom section, height of dividing line”. The light redirecting venetian blinds allow more daylight to enter, but the difference is small in absolute terms and difficult to perceive with the naked eye.

The percentage difference is illustrated more clearly in figure 4.29, in which the relative increase compared with the standard venetian blind has been calculated. This figure shows that lowering the dividing line is more important than having the slats more open at the top of the venetian blind. With an angle difference of 45 degrees and the dividing line at 1.6 metres above floor level, the illuminance increases by at least 20%, but with an angle difference of just 20 degrees and the dividing line at 1.8 metres, the increase is only approx 5 %. In practice, in Sweden an angle difference as high as 45 degrees is problematic if we are to prevent direct sunlight in winter, because shortening the cords limits the movement in the lower section of the venetian blind. (More southern latitudes do not have the same problem with low solar altitudes, so 45 degrees may be acceptable). Lowering the dividing line may also be difficult, because a more open venetian blind is brighter and therefore causes more glare. This is why the more open section should be placed above the central field of vision.

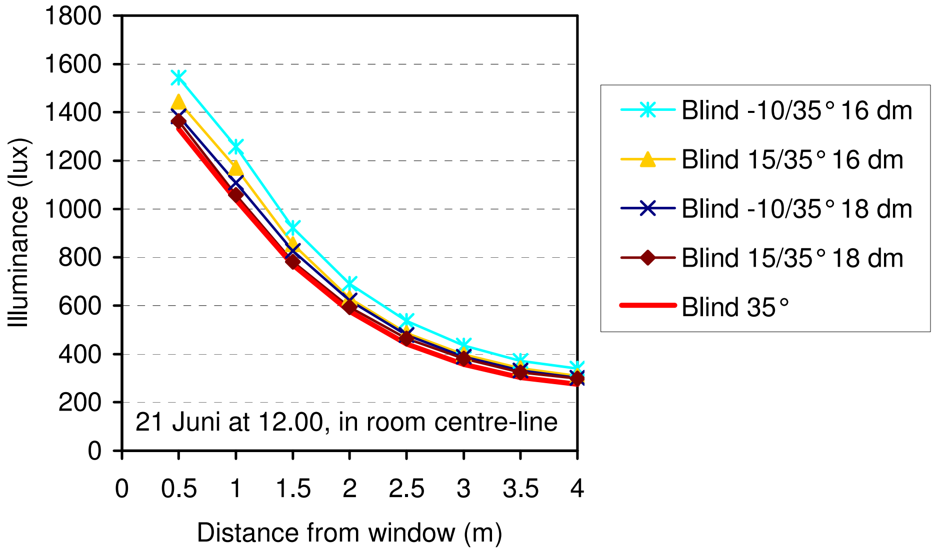


Figure 4.28 *Illuminance (lux) at various distances from the window for a standard venetian blind with 35 degree slat angle and four versions of daylight redirecting venetian blinds. Calculated in Radiance for the solar altitude in June at 12.00 true solar time.*

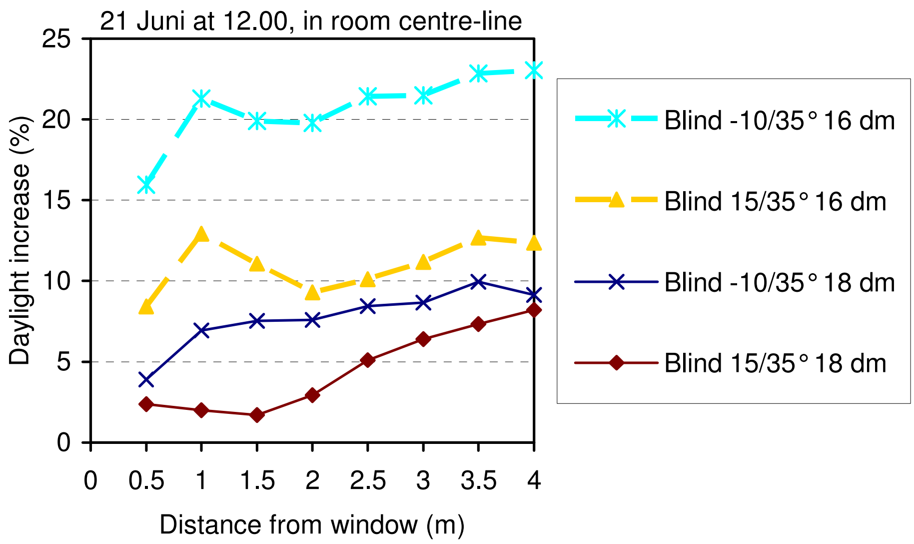


Figure 4.29 *Relative increase in illuminance (%) at various distances from the window for four versions of daylight redirecting venetian blinds compared with a standard venetian blind with a 35 degree slat angle. Calculated in Radiance for the solar altitude in June at 12.00 true solar time.*

4.4 Temperature comparisons between measurements and ParaSol simulation

To allow a comparison between the measured and calculated values for inside temperature and heating requirement, a geometric model of the laboratory room was created in ParaSol v 3.0. However, the ability of ParaSol to vary certain parameters within and between individual days is limited. For example changing slat angles and changing internal loads resulting from variations in the dimming of the luminaire cannot be modelled. To obtain a meaningful comparison, the measurements from the reference room were taken, since conditions there are more constant. A special climate file for May and June 06 was created from measurements of outside temperature and solar radiation. The internal load was set to the measured power requirements for the luminaire (which was switched on every day between 08:00 and 17:00). The supply air temperature and flow were set to the average for the evaluated periods (different values for day and night). Because the room has very light-weight enclosing surfaces on the ceiling, outer walls and inner walls, light-weight walls were selected in the simulation. However, the thermal inertia of the slabs (floor/ceiling) where varied in the simulation among the three alternatives light, medium and. The input data for the ParaSol simulation is summarised in table 4.3.

Table 4.3 Input data for ParaSol room dimensions and solar protection.

Room dimensions (w x h x d)	2.7 x 3.1 x 4.1 m
Double glazing with LE coating and argon	
(From the outside: 4 mm Optitherm SN – 16 Ar – 4 mm Optifloat)	
Glass surface area	2.7 m²
U value of glass area	1.21 W/m²K
g-value of glass area	0.57
Frame surface area	1.3 m²
Outer wall	0.63 W/m²K, light
Inner wall	light
Floor and ceiling	3 alternatives: heavy/medium/light
Solar protection	white venetian blind inside, slats 34°, no control system

4.4.1 Period in May with heating requirement

The first period evaluated was a period in May (12th -19th) that started with sunny weather followed by a few overcast or partly cloudy days, see figure 4.30. The input data used for the energy balance in ParaSol is set out in table 4.4.

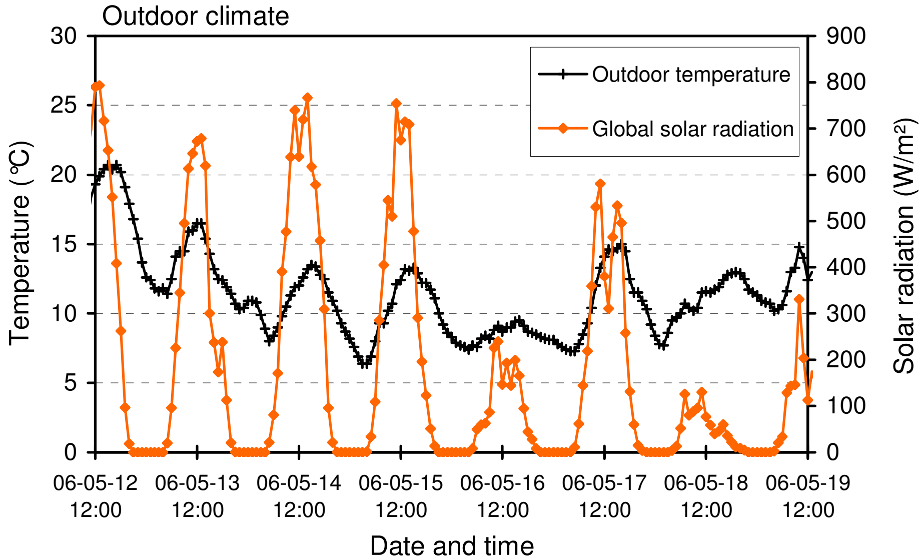


Figure 4.30 Measured outside climate (air temperature and global solar radiation on horizontal surface) for the period 12-19 May 2006.

Table 4.4 Input data for the energy balance of the ParaSol room 12th-19th May.

Thermostat setting heating/cooling	20/30 °C
Internal load day/night	7/0 W/m²
Supply air temperature day/night	18/18 °C
Supply air flow (constant)	20 l/s

The results from the ParaSol simulation and the measurements are shown in figure 4.31. At the end of the period, the room was heated at night with pulses of warm air, explaining the high peaks for the supply air temperature (the maximum temperature was 50-55 degrees). (The control system was adjusted on the basis of a room sensor).

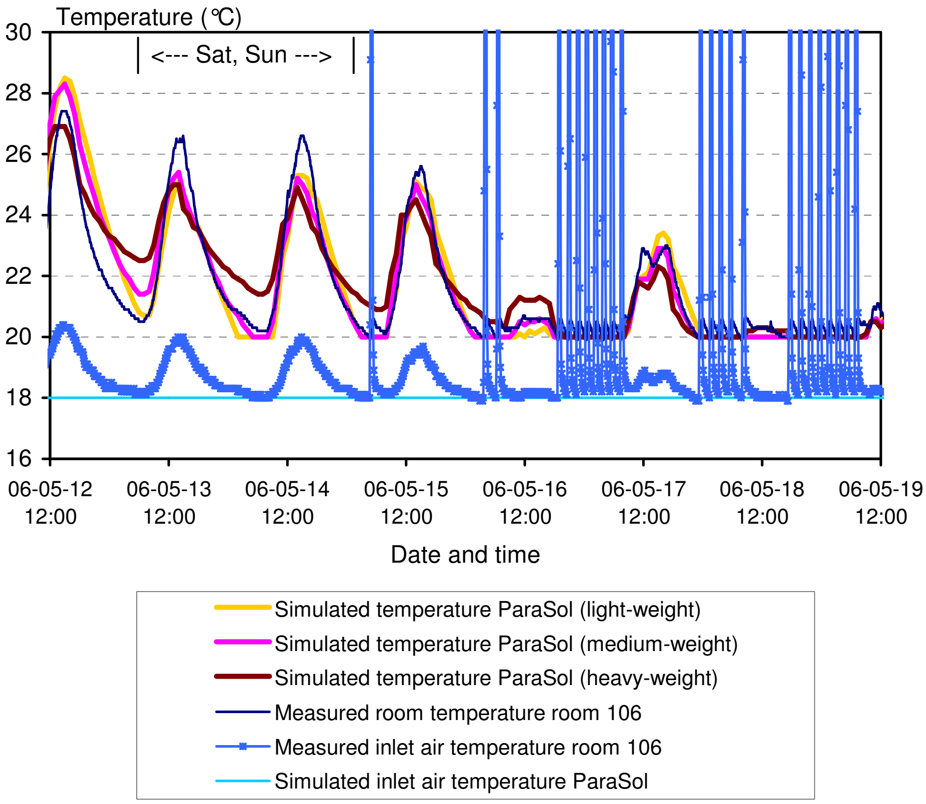


Figure 4.31 Measured and simulated room temperature and measured and simulated supply air temperature for the period 12th-19th May 2006.

The case with the heavy floor and ceiling is very different from the light-weight and medium cases, which are similar to each other. The measured temperature is quite similar to the lightweight and medium cases. This is discussed in more detail in section 4.4.2. It should be noted that 13th and 14th May were a weekend. Because Parasol's input data menus treat nights and weekends in the same way, no internal load was put in during the weekend. For the measurements, however, the lights were on all day during the day. In the sunny period, this is evident from the simulated inside temperature for the lightweight and medium cases, which exceeds the measured values during the week, but is lower at the weekend.

The heating events during the last three nights can be studied further by comparing the simulated heating requirement in ParaSol and the supplied heating energy in the room. This heat is calculated from the available temperature and flow measurements, which are shown in figure 4.31. It is clear from these measurements that part of the supply air appears to pass directly out against in the exhaust unit, because the temperature there is clearly affected by the heating events. This short circuit may also explain why the measured extracted air temperature is always lower than the room temperature when there is no heating requirement. Of course, another possible explanation is a measuring error in one of the sensors, but this was not investigated further.

Despite the above, the actual heating requirement of the room was estimated from the measured supply air flow and the difference between the supply air temperature and the exhaust air temperature. This assumes that the room is completely air tight and that the extracted air flow is identical to the supply air flow. The room is certainly well sealed, but there was an unsealed round hole of approx. 10 cm in diameter during the tests. In addition, the heat transfer through the inner walls to the climate chamber was neglected.

The heating coil in the supply air has a very high capacity while the heating requirement is small. This means that the heating coil runs for a short time and then switches off, as is evident in figure 4.32. The period between events during the evaluated period was just under two hours. The heating requirement was therefore first calculated from the logged 6-minute values and then integrated to form 2-hour values.

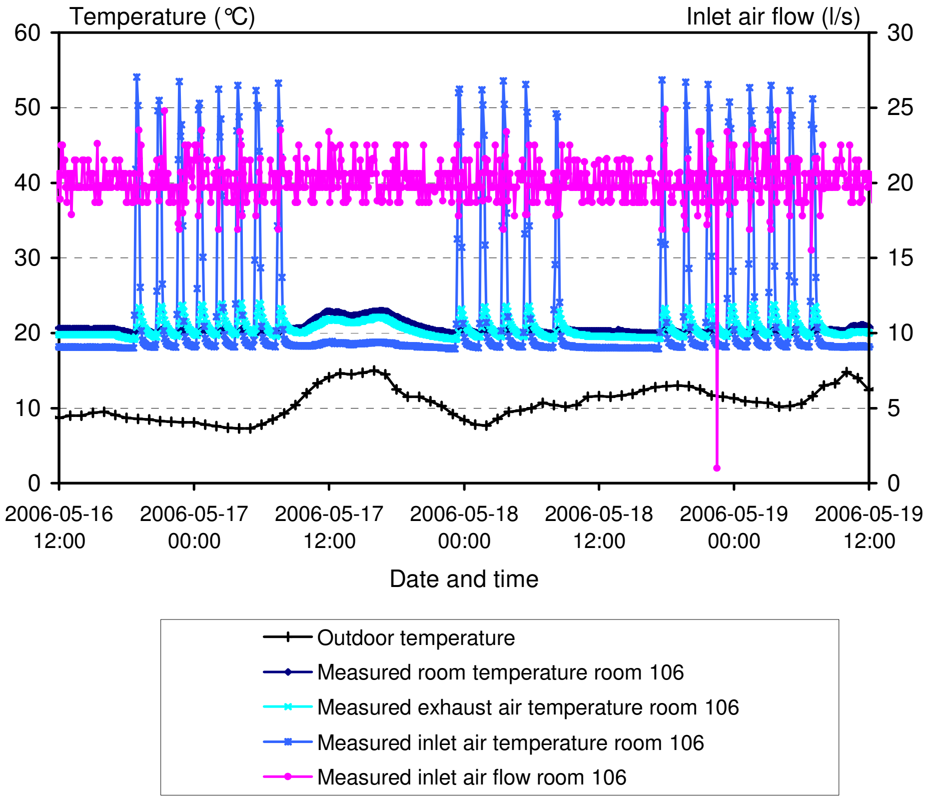


Figure 4.32 Measured temperatures and air flows for the period 16th-19th May.

The room was then simulated in ParaSol with heavy, medium and light-weight slabs (floor and ceiling). The heating requirement calculated in this way is the heat that must be introduced into the room in order to maintain the desired room temperature, assuming the supply air temperatures and flows set out in table 4.4. Because the assumptions included low-temperature supply air with a constant temperature and flow, the calculated heating requirements were adjusted as follows:

$$Q_{adj} = Q_{sim} \cdot (T_{\sup ply} - T_{room}) \cdot q_{\sup ply} \cdot \rho \cdot c_p$$

Where Q_{adj} is the adjusted heating requirement, Q_{sim} is the heating requirement simulated in ParaSol, T_{supply} is the supply air temperature (constant, 18°C), T_{room} is the simulated room temperature, q_{supply} is the supply air flow (constant, 20 l/s), ρ is the air density and c_p is the specific heat of the air. In the simulation, the supply air flow is identical to the exhaust air flow, and perfect mixing is assumed for the air in the room. The extracted air temperature can therefore be assumed to be identical to the room temperature. Figure 4.33 shows a comparison between the heating requirement measured and calculated in this way, adjusted to take account of the low-temperature supply air. (Because the simulation was carried out on an hourly basis, the figure shows the hourly values). The correspondence is good, but the simulated heating requirement tends to be slightly lower than the measured values. This may be due to measuring uncertainties. However, one uncertain factor in the simulation is the actual U value of the outer wall. In the three basic cases in ParaSol, the outer wall (incl. window) is assumed to have a U value of 1.05 W/m²K. The sensitivity was studied in a fourth simulation case, in which the case with the lightweight slab was given an inferior outer wall. The effect was to bring the U value to 1.31 W/m²K. This causes the heating requirement to increase at night. The difference is greater than between the lightweight and medium cases, so this parameter is important.

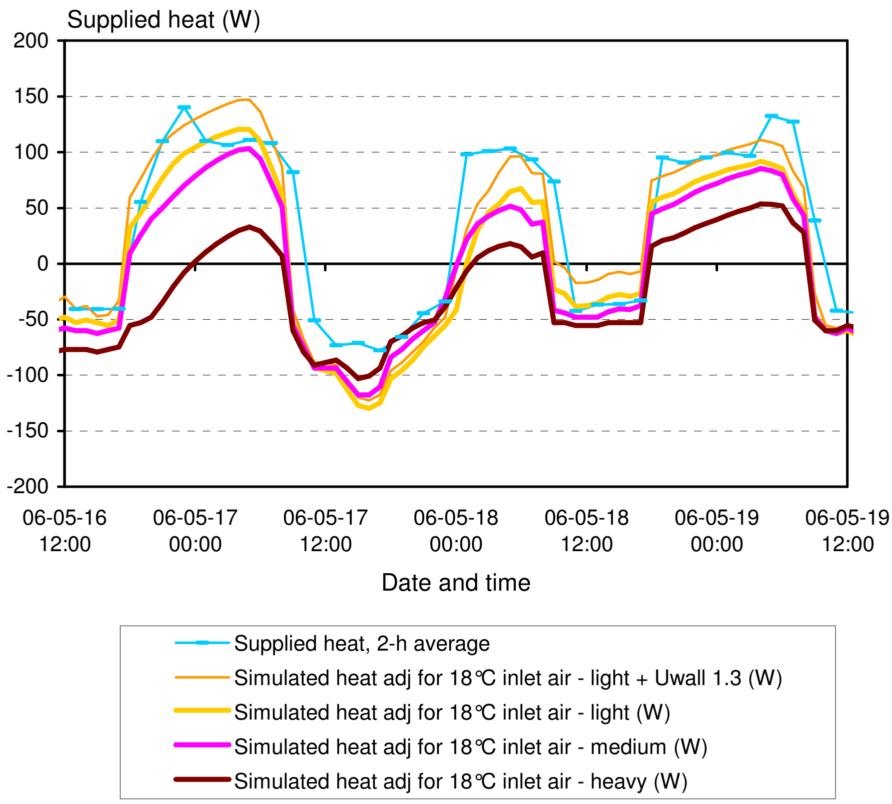


Figure 4.33 Comparison of measured and calculated heating requirement for the period 16th-19th May.

4.4.2 Sunny period in June

The second period to be evaluated was a sunny period studied above, 10th-11th June, when there was no heating requirement and the sky was blue. The input data used for the energy balance in ParaSol is set out in table 4.5.

Table 4.4 Input data for the energy balance of the ParaSol room 10-11 June.

Thermostat setting heating/cooling	20/30 °C
Internal load day/night	7.14/0 W/m²
Supply air temperature day/night	20.1/18.9 °C
Supply air flow (constant)	19.8 l/s

The temperatures obtained with these assumptions are shown in figure 4.34. It is evident that the various assumptions for the thermal inertia of the floor and ceiling have a significant influence on the calculated maximum temperature in the room – the heavy case is particularly different. The medium case has a maximum temperature that is very similar to the measured values, but the lightweight case has a slightly higher maximum temperature. The minimum temperature for the lightweight and medium cases corresponds closely to the measured values. The correspondence between calculations and measurements is therefore relatively close between both the *medium* and *light-we*ight cases.

However, it is not so easy to establish which case corresponds more closely to reality. There are uncertainties in several parameters, which all affect the absolute level of the temperature in the room. Errors in the venetian blind's measured slat angle of +/- 5 degrees produce minor differences in temperature, and minor variations in the estimated total U value. For example, the variation in supply air temperature between day and night is regarded as a source of major error, and especially as the cause of the mismatch between simulation and measurement that is evident in the chart. This probably explains why the temperature in the simulation rises more quickly in the mornings than in the measurement. In the simulation, the losses through the five inner surfaces of the room are assumed to be zero, whereas in fact there was a temperature difference between the room and the climate chamber that produced some heat loss even though the room was well insulated.

The reason why the supply air temperature could not be maintained at 18 degrees was a malfunctioning of the cooling system in the building during the test period. The simulation is also based on integrated hourly values for temperature and radiation, whereas the measured values were averaged over 6-minute periods. However, the internal load of the simulation and measurements coincided fully during the period (08:00-17:00). Bearing this in mind, the result in ParaSol appears to be entirely reasonable and acceptable.

A further source of error was the total thermal inertia of the room in reality compared to the simulations. The simulated inertia that corresponds most closely could be guessed from the speed at which the temperature falls in the evening/night, and the medium case looks as if it matches the measurements very well. However, the temperature drop is quite closely related to the supply air temperature, making it difficult to draw clear conclusions from a measurement, so even the lightweight case may be applicable. Because ParaSol only allows the user to choose between these predefined structures, it may be useful to know what these structures look like and how they differ from the actual structures used in the measurements. In the case of light outer and inner walls, for example, the simulation assumes walls with 26 mm of plaster on the inside, whereas the inner walls in the lab consist of 0.5 mm sheet steel and 4 mm of plywood, which is even “lighter”. In principle, the outer wall consists only of 4+4 mm glass, which is also lighter than simulated. Furthermore, during the measurements the two lower sections of glass were covered by 30 mm of cellular plastic, which means that the inertia of the glass cannot be used. The ceiling in the lab is built in the same way as the inner walls, which means it is very light. The floor consists of 100 mm of concrete on top of

100 mm insulation, making it the only structure in the room in which thermal inertia plays an important role.

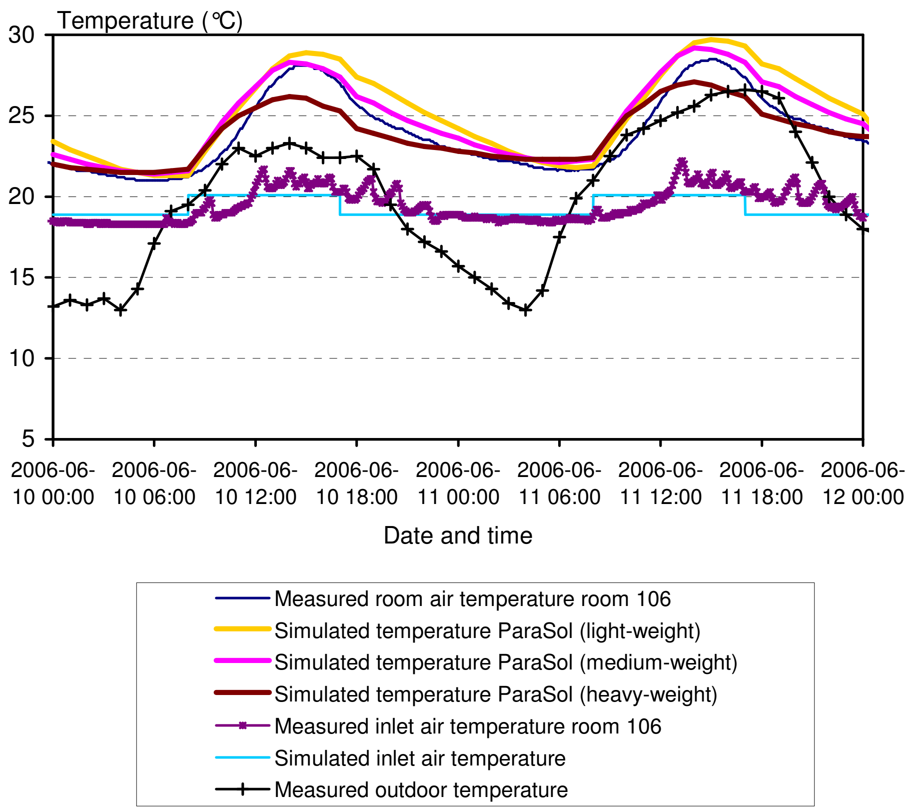


Figure 4.34 Comparison of simulated and measured room temperatures, supply air temperatures and the outside temperature for two sunny days in June.

In the ParaSol simulation, the floor and roof structure are the same, consisting of 30 mm of wood in the light-weight case. A medium slab consists of 125 mm of lightweight concrete and a heavy slab consists of 100 mm of concrete.

Note that the sunny days on 10th-11th of June fell on a weekend, and because the internal load was set to zero for the evenings, ParaSol also sets the entire 24-hour period to zero at weekends. To avoid this source of error, the climate file was faked so that the values for the 10th-11th of June were copied to the 8th-9th of June, which were weekdays, and the calculations shown are actually for these days.

4.4.3 Parameter study of venetian blind location

Because the tested venetian blind was designed to allow use between two panes of glass in existing offices with older coupled windows, a simple parameter study of the venetian blind location was carried out with a window of this type. A slightly more modern triple glazed window of the 1+2 type was selected, which was very common in 1990s office buildings (single glazed on outside, insulated double glazing on inside). The slab is set to heavy; otherwise the same input data as in table 4.5 was used.

Three blind positions were studied: (1) An external fixed, light-coloured 80 mm wide venetian blind (2) an intermediate (between-panes) 25 mm venetian blind placed in the outer gap (3) an interior 25 mm venetian blind. The slat angle was the same for all three cases: –34°.

The resulting inside temperatures for the sunny period between 12th-15th May are shown in figure 4.35. The interior venetian blind provides some benefit compared with no solar protection at all, but the temperature is still uncomfortably high during the day, over 28 degrees. The intermediate venetian blind, on the other hand, creates a very good indoor climate, with the temperature rising to a fully acceptable 24 degrees. The outside venetian blind blocks the solar radiation so effectively that the temperature only climbs to around 21.5 degrees.

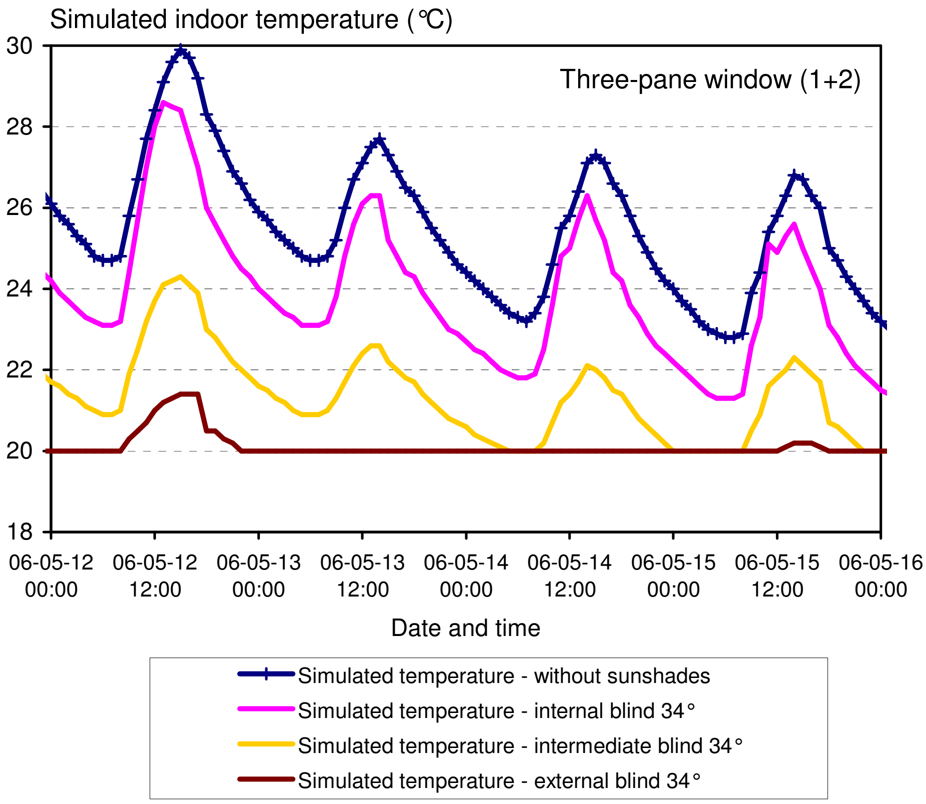


Figure 4.35 *Simulated inside temperature in an office room during a sunny period in May (Thu-Sun) with an external venetian blind, between glass panes venetian blind and internal venetian blind with coupled triple glazed window (1+2). Heavy construction.*

Although the actual temperature will vary according to internal loads, supply air temperatures and air flow, this calculation clearly shows that a between-panes venetian blind combined with a 1+2 solution constitutes highly effective solar shading. Unfortunately, this window type is often neglected in modern offices, where insulated double glazing is used almost exclusively, often in combination with large, fixed glass panels. However, something similar to the 1+2 window is being built today in high prestige projects, where an extra glass layer is placed outside the normal glass facade – known as double skin facades or double shell facades (the name varies). Finally therefore, some g-values are shown for a venetian blind in the three positions discussed above, alongside this triple glazed window, with two different slat angles (g_{system}). The values are simulated in ParaSol ver 3. See figure 4.36.

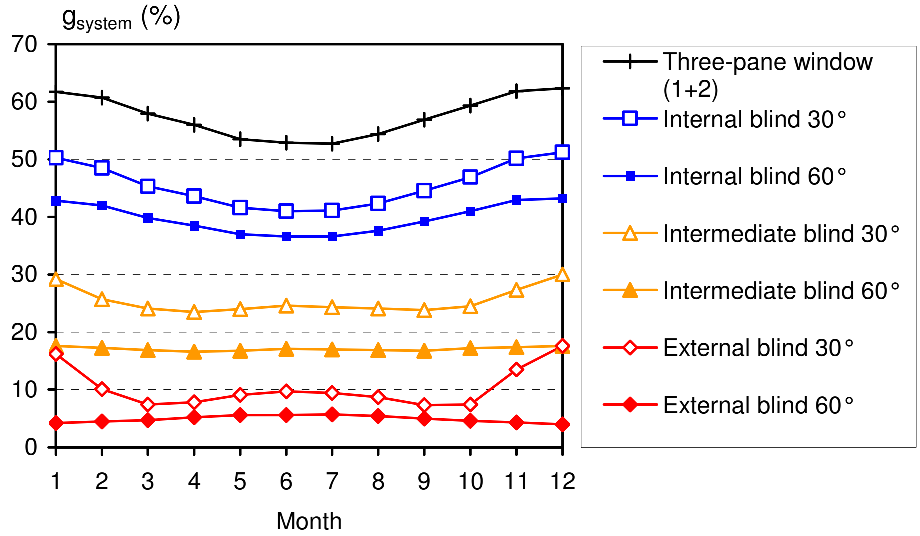


Figure 4.36 *Simulated g-values for coupled triple glazed window with different positions for the venetian blind. The g-value of the window itself is also shown. Calculated as monthly averages for a south facing window in the Lund climate zone.*

5 Discussion

Daylight generally introduces considerably more light into a room than artificial light alone. If the work surface is correctly positioned in relation to the window, daylight can therefore be a good source of light for perimeter offices. Research into our biological clock and the non-visual effects of light indicate that plenty of daylight has additional positive effects on our health. So it should also be healthy to have a lot of daylight at the place that many people spend most of their day – at work. Earlier studies have also shown that when employees are allowed to choose their position, they prefer to sit near the window. This could be interpreted as meaning that they prefer this brighter position, but the preference could of course also be based on the better views outside. At the same time, glare must be avoided. This requirement often comes into conflict with the desire to allow daylight to enter.

Effective solar shading becomes more and more important as the proportion of glass in the facade increases, in order to prevent excessive temperatures and to avoid or limit the need for comfort cooling. External solar shading is generally more effective than internal systems. But all types of solar shading restrict access to daylight. Because solar shading is only required when it is sunny, fixed solar protection can block daylight when we would like to use it to light up rooms. Adjustable solar shading is much more flexible, and is more useful for screening the sun all year round – the altitude of the sun varies a great deal through the year. Facility managers are usually very cautious when they select motorized solar shading, because they are not sure how long the products will last and because maintenance costs are expected to be higher. And apart from the wind, in our northern climate, we have to take snow and ice into account. A solution that can be placed within coupled windows is therefore potentially highly effective, as this position is good for blocking the heat of the sun, while remaining protected from wind and precipitation.

No other solar protection is as flexible as a venetian blind, bearing in mind its infinitely variable positioning to control incoming light and glare. That is why it was so interesting to study the effectiveness of a standard venetian blind equipped with a newly developed motor and control system. As well as the control system, the effect of a light redirecting venetian blind was studied – in this case a version of a standard venetian blind with white slats, whose slats in the upper section were about 20 degrees more open than in the lower section.

It is relatively easy to create a light redirecting venetian blind. In order to open the slats in the top section it is sufficient to shorten the cords on the room side of the venetian blind. This can be done by winding the cord around a cheap and simple clip. The more the cord is shortened, the greater the difference between the slat angles in the upper and lower sections. This technique presents a benefit as well as a risk: the benefit is that the lower section can be closed quite a lot while the top section still lets in light. This means that the lower section can be made dark enough to avoid glare from the venetian blind. The risk is that the venetian blind remains too open at the top, making it impossible to block direct sunlight when the sun is low, for example in winter for a south facing window or the morning for an east facing window. So in our northern latitudes, where the sun is low in the sky, the angle difference needs to be kept quite small. This of course limits the amount of daylight that can be let in. The dividing line must also be placed slightly above eye height in order to avoid glare. The result is that the effect is very limited in standard offices with windows whose top edges are at 2.1-2.2 metres. This is shown in the measurements and also in the Radiance simulation.

Daylight through windows in walls can be regarded as a vector pointing primarily diagonally down, which lights the room in a different way than artificial light does. The venetian blind slats direct the daylight to the ceiling throughout its surface area. The entire venetian blind should therefore be regarded as a light redirector. The sensor location in the ceiling did not always seem to work as intended. The problem is that the daylight comes down from the sky at an angle, lighting up the table quite strongly with the venetian blind slats relatively open. Yet the roof sensor did not see this light because it was pointing in the other direction, down between the slats: instead, it could see a dark asphalt surface below the window. When compared with a sensor integrated in the luminaire, the latter produced a somewhat greater saving in the electricity used for lighting.

The studied solar protection control system is mainly based on a measurement of the daylight against the window combined with the calculated solar angles against the window and the calculated cut-off angle of the venetian blind. The cut-off angles had a certain safety margin. However, it is the luminance on the inside of the window that determines the risk of glare, and this is determined by the sky luminance in combination with the light transmission of the glazing and solar protection. The luminance is much more difficult to measure, and even today we are not sure exactly what luminance values can be tolerated. This partly depends on how the room is furnished and therefore where people are sitting: what can they see in their central and peripheral fields of vision? What we do know is that we are more sensitive to high luminances in the central field of vision – yet high luminances in the peripheral field of vision can also cause subtle glare problems.

Past research also shows that there are large differences between individuals in terms of their sensitivity to glare. A great deal more research is required before we can make specific proposals for alternative control strategies.

6 Conclusions

6.1 General function of venetian blind

From a purely technical point of view, the evaluated system using a motorised venetian blind and a light controlled fitting performed very well. The type of motor selected for the venetian blind allows very precise control, and even after many control sequences, the venetian blind is always in the "correct" position – in other words at the angled determined by the control system.

6.2 Resulting light environment

In the summer especially, daylight has the capacity to create very high light levels inside, and daylight also lights the room in an entirely different way than electric light installations do. In particular, the ceiling receives significantly more light with daylight, but table surfaces are also strongly lit. A venetian blind or other form of anti-glare device is therefore essential in work situations like offices. Even with the venetian blinds down and partly closed, the illuminance and especially the luminance inside can be problematic.

To avoid glare problems, a pre-requisite is that direct solar radiation is avoided in the office. This is the fundamental concept of the evaluated solar protection control: control based on the altitude of the sun and so-called cut-off angles. Because the sun is high in the sky in summer, the venetian blind slats are left fully open, allowing views of the surroundings. However, it is our conclusion that the angles during summer are not large enough, i.e. the venetian blind is too open to prevent glare from the sky or from the venetian blind itself. This is mainly the case at times of high solar intensity, which of course coincides with the times when there is the highest illuminance. If the control system is changed to prioritise greater slat angles (the venetian blind is more closed) this would also provide more effective solar shading because the g-value (the total solar energy transmittance) would fall. Unfortunately, this limits opportunities to see outside. An alternative control system could be based on the luminance of the inside of the window, but the seating position (or the field of vision) and individual preferences need to be taken into account here. It would therefore be valuable to continue studies using test subjects in order to find suitable algorithms.

6.3 Electricity saving for lighting

The electricity saving for the evaluated system was significantly greater in May than in November, because obviously it is lighter and the sun is higher in May than in November. The electricity saving for lighting was 77 % in May and 5 % in November. These figures are based on working hours of 08:00 -17:00. On an annual basis, the saving was calculated as approx. 50 %. These savings were calculated by comparison with a reference case with an identical room with lighting permanently switched on to 100% between 08:00 and 17:00, and with a fixed venetian blind with a slat angle of 34 degrees. The annual saving for a whole office with around half the desks far away from the window can be expected to be about half the above percentage, i.e. 25 %, compared to this office in which the desks were situated close to the window.

The control of the luminaries was based on the light allowed in by the venetian blind. Because the venetian blind was in turn controlled on the basis of the daylight outside, it was not possible to determine the saving that would have been obtained if the venetian blind had been fixed in the test room too, i.e. not controlled.

6.4 Effect of sensor location

In the study, a ceiling mounted sensor pointing at an angle down towards the window was compared with a sensor integrated in the luminaire, detecting directly down to the table surface. Here, the integrated sensor produced a slightly greater saving in the electricity used for lighting, because the sensor sees a medium bright table surface placed close to the window, which was often fairly bright. The intention of the ceiling mounted sensor was to be able to detect when the window was brightly lit, in other words when it had a high luminance, but this is not how it turned out: the sensor is unable to detect the solar radiation passing diagonally down through the window. With the venetian blind up, the sensor sees part of the ground in front of the window and with the venetian blind down, it sees some of the ground between the slats. The ground was made with rather new asphalt, making it very dark – in other words very little light was reflected up to the ceiling sensor. Nor is this a suitable location for a sensor controlling the actual venetian blind by measuring luminance. To find a suitable location for a sensor measuring luminance, we must instead take the point of view of users and their central and peripheral field of vision. An ideal sensor might be placed on the user's forehead – or at least pointing diagonally out/up to the bright sky.

6.5 Effect of light redirecting section of venetian blind

It is very easy to create a light redirecting element – an area that is more open than the rest – in a venetian blind. It is sufficient to shorten the cords on the room side of the venetian blind. In the evaluated system, this was done by winding the cord a single turn around a simple plastic clip. This allows more daylight to enter the room through the top of the venetian blind, which is normally higher than the central field of vision. There are problems working with two slat angles if direct solar radiation is to be avoided throughout the year.

Our research indicates that the difference in angle between the upper and lower parts of the venetian blind must be limited to around 20 degrees in order to avoid problems with direct solar radiation in winter. This is much smaller than the difference in angle normally offered with these systems. For example, the evaluated system came with a clip to create an angle difference of 45 degrees, so we used a modified clip that did not seem to be fully developed.

To prevent glare, the dividing line between the upper and lower sections must be kept well above eye level and the central field of vision, because a more open venetian blind is more open to the bright sky and the blind itself is lighter when it is more open. This means that "normally" situated windows – i.e. whose top is about 2.1 m above the floor – present limited daylight redirection opportunities. In our experimental room, the indoor illuminance was estimated to increase by around 10 % with the light redirecting section at the top of the venetian blind. Computer simulations of similar rooms using Radiance produced similar results.

To be able to use the evaluated control system with this type of light redirection, the menu system need to be adapted in order to continue to control the lower section of the venetian blind. This is because the shorter cords close the venetian blind below the clip, so the angles no longer correspond to the angles indicated in the control system. The freedom of the venetian blind to rotate is also limited – the upper section can never be fully closed. If the control system will be used for this type of venetian blind, thought should be given to what happens when the cords are shortened by various amounts and how the angles should be entered in the system, and the necessary changes should then be made. Our conclusion is that for offices where windows occupy a moderate proportion of the facade wall and the windows are also "normally" situated (upper edge about 2.1 m above floor level), light redirection only produces a negligible increase in illuminance, while probably increasing the risk of glare.

6.6 Indoor climate and cooling requirement

There were no real differences between the measured indoor climate and the values calculated in ParaSol, so ParaSol seems to be a reliable program for assessing indoor temperatures and energy use in room modules with venetian blinds.

If the proposed solar protection control system is used with external venetian blinds, there is a very good opportunity to limit excess temperatures inside and minimise cooling requirements. An intermediate venetian blind is slightly less effective, but is still significantly better than an internal venetian blind. If the venetian blind control system is changed so it closes slightly more in the strong summer sun, the proposed 25 mm controlled venetian blind is able to perform a solar shading function as well as an anti-glare function. The light redirecting section at the top can probably be omitted for normally situated windows, as it only creates a very small increase in the amount of light. This makes the venetian blind much easier to handle and control.

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Appendix 1 – Illuminances in May

Measured illuminance inside and outside in the period 1–31 May are shown in figure A1.1–6. Values are averages for 08:00–17:00 and night values for electric lighting. During the period, a fixed venetian blind was used with 34 degree slat angle and constant lighting in room 106. In room 107, a controlled venetian blind was used with daylight controlled lighting. When the venetian blind was lowered, it was closed less than in 106. Figure A1.7–8 shows the ratio of the measured inside illuminance to the outside global illuminance on a horizontal surface (E_{hor}). However, this includes the contribution of the artificial lighting to the inside values, so it is not entirely correct to call these values the daylight factor.

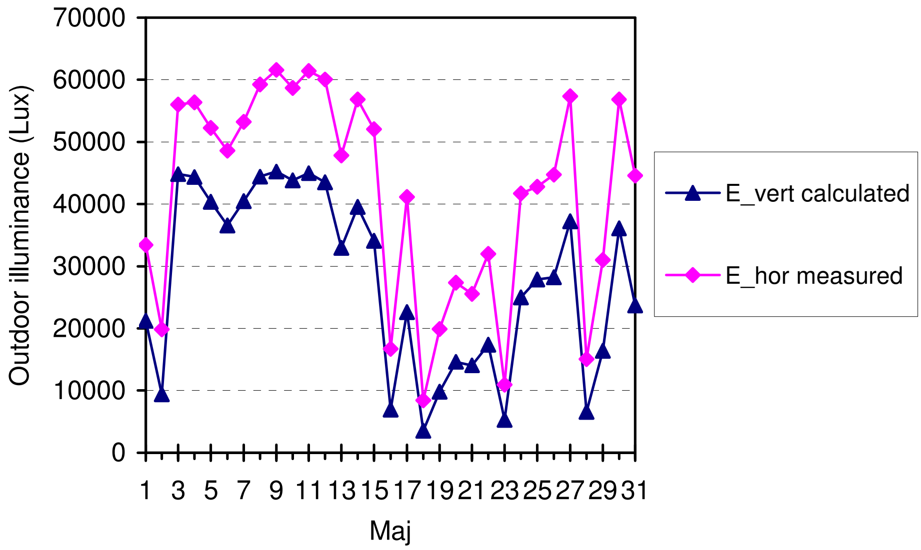

Figure A1.1 *Measured illuminance on a horizontal surface (roof) and calculated vertical illuminance on the facade.*

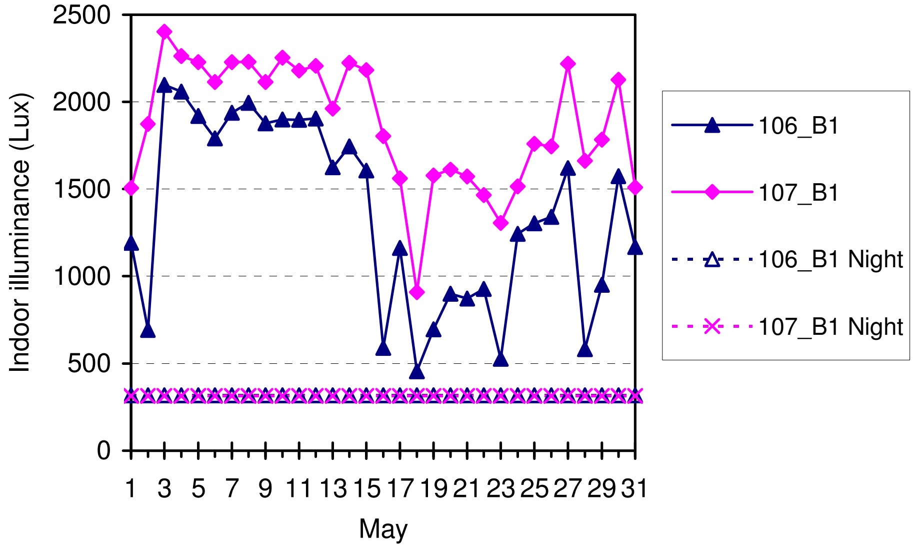

Figure A1.2 *Measured illuminance at table height at point B1, 1.05 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

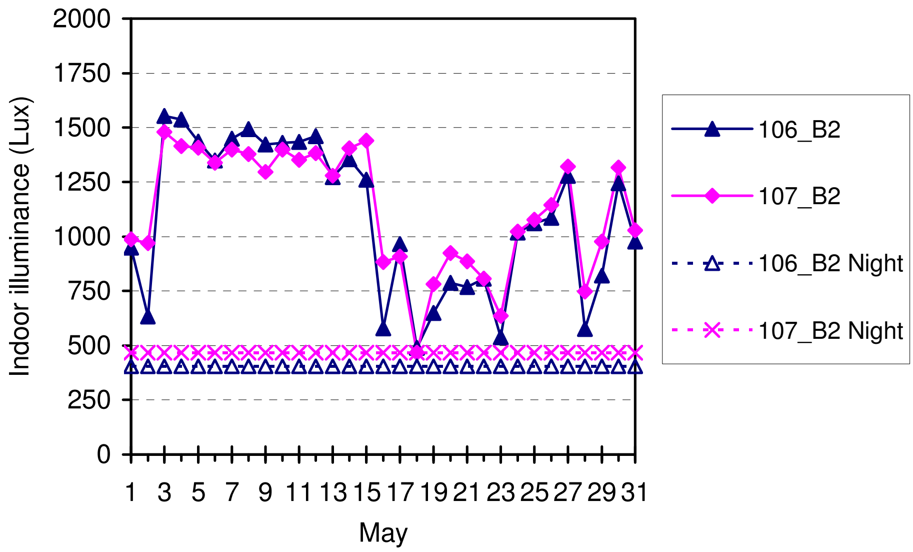

Figure A1.3 *Measured illuminance at table height at point B2, 2.1 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

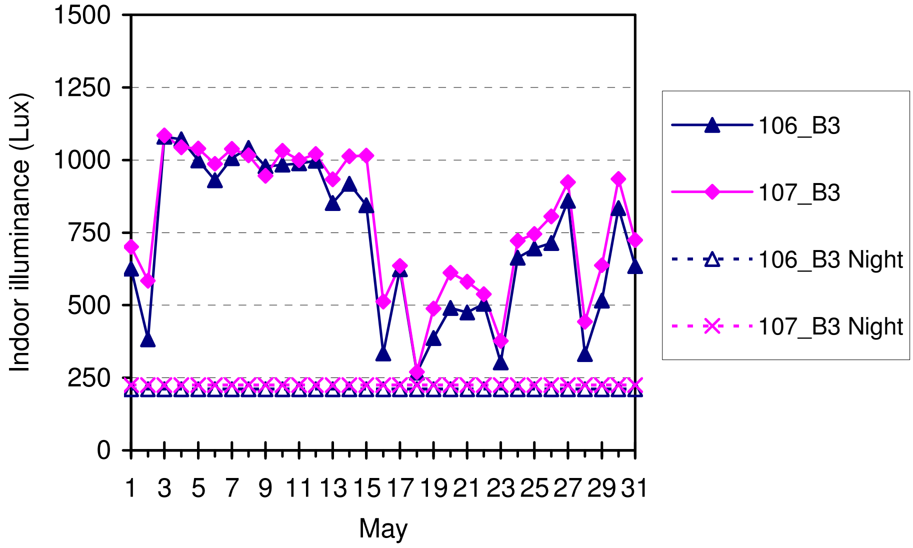

Figure A1.4 *Measured illuminance at table height at point B3, 3.15 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

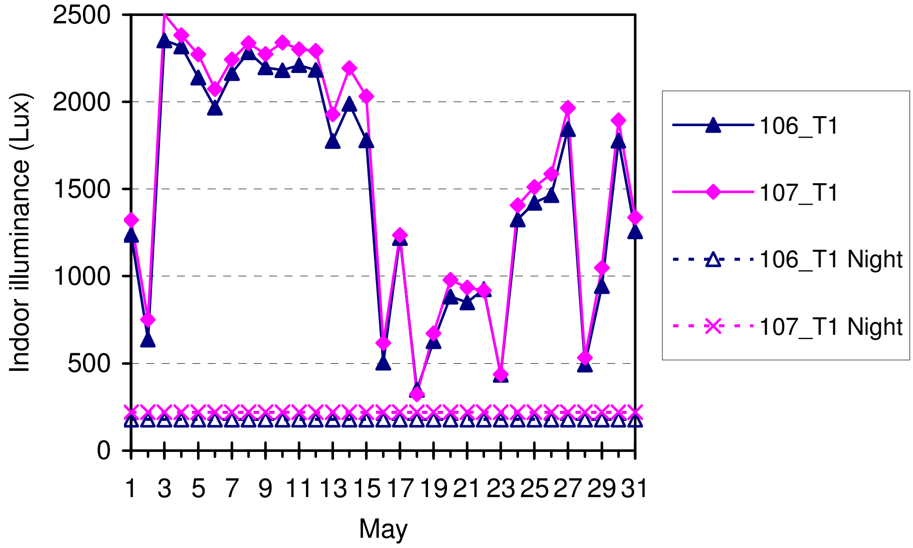

Figure A1.5 *Measured illuminance at ceiling at point T1, 1.1 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

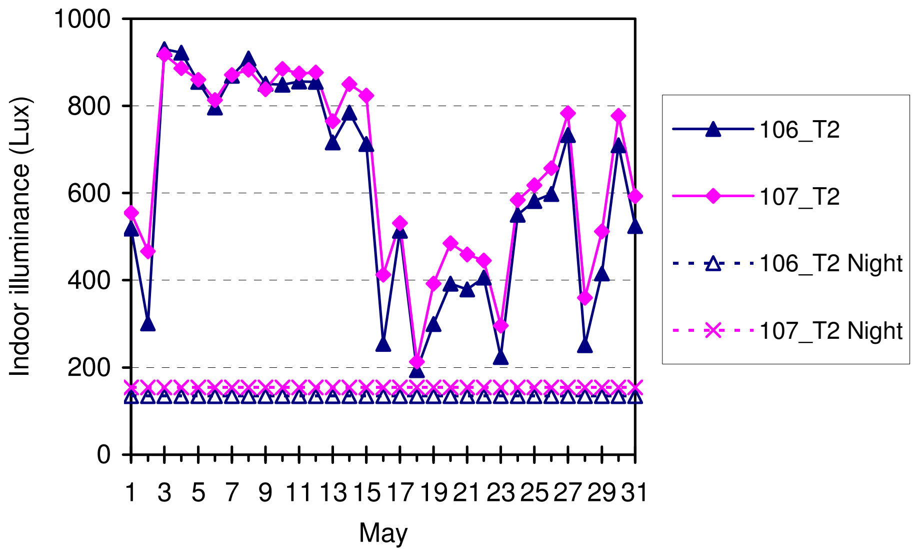

Figure A1.6 *Measured illuminance at ceiling at point T2, 3.1 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

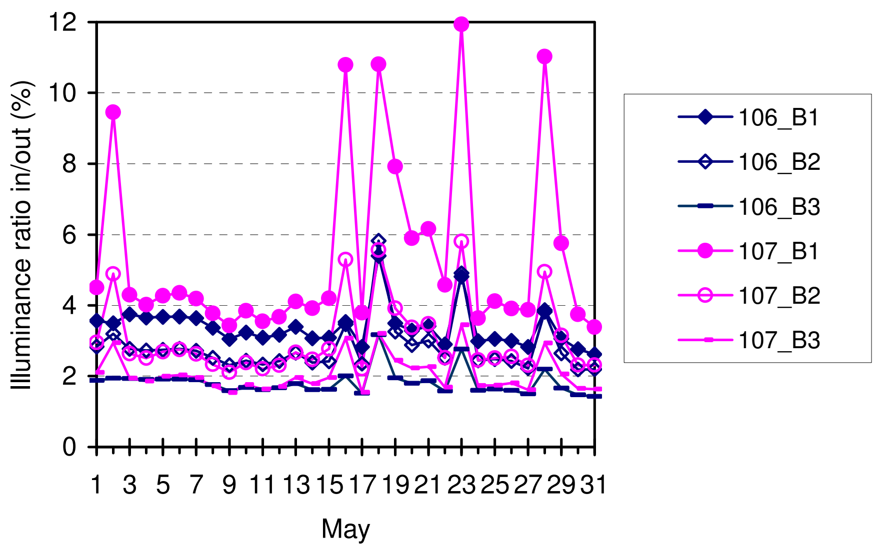

Figure A1.7 *Ratio of measured illuminance outside (horizontal) to inside at table height (points B1-B3) in test and reference rooms.*

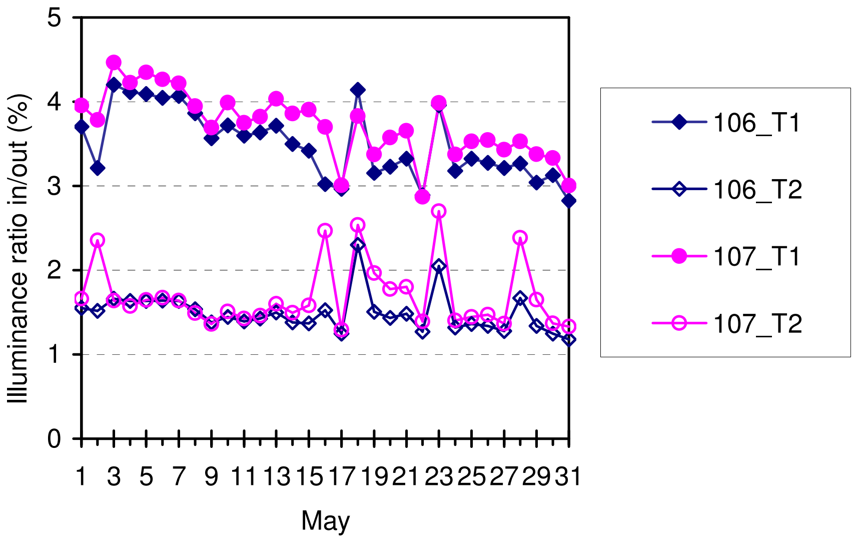

Figure A1.8 *Ratio of measured illuminance outside (horizontal) to inside at ceiling (points T1-T2) in test and reference rooms.*

Appendix 2 – Illuminances in November

Measured illuminances inside and outside in the period 8–30 November are shown in figure A2.1–8. Values are averages for 08:00–17:00 and night values for electric lighting. During the period, a fixed venetian blind was used with 34 degree slat angle and constant lighting in room 106. In room 107, a controlled venetian blind was used with daylight controlled lighting. When the venetian blind was lowered, it was closed more than in 106. Figure A2.7–8 shows the ratio of the measured inside illuminance to the outside global illuminance on a horizontal surface (E_{hor}). However, this includes the contribution of the artificial lighting to the inside values, so it is not entirely correct to call these values the daylight factor.

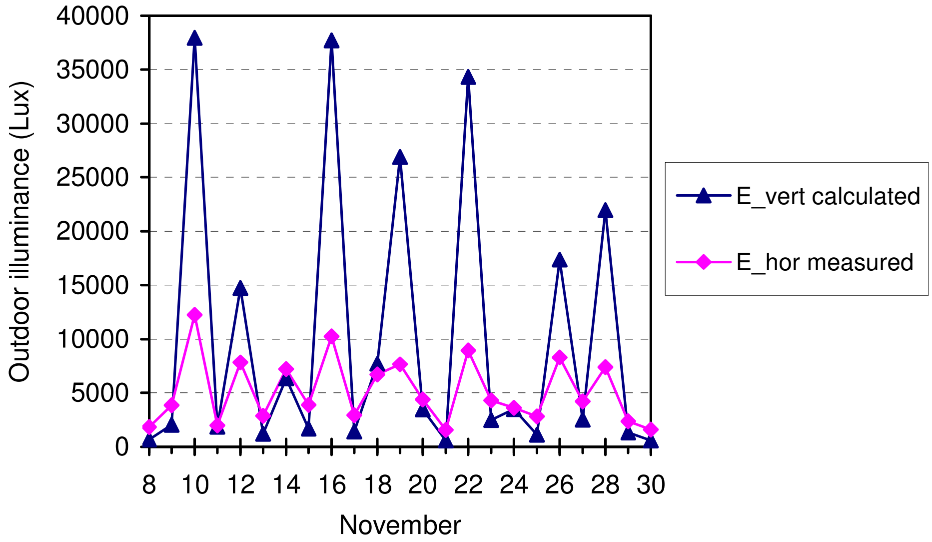

Figure A2.1 *Measured illuminance on a horizontal surface (roof) and calculated vertical illuminance on the facade.*

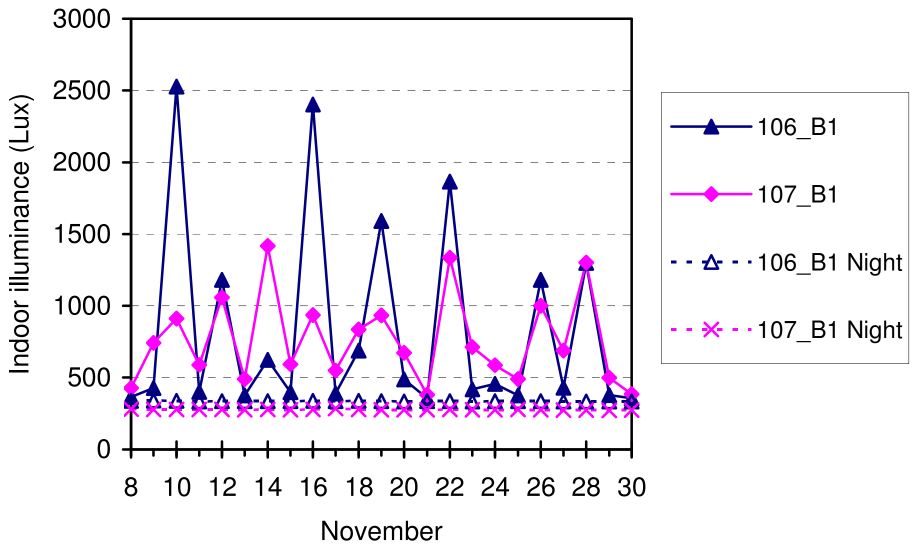

Figure A2.2 *Measured illuminance at table height at point B1, 1.05 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

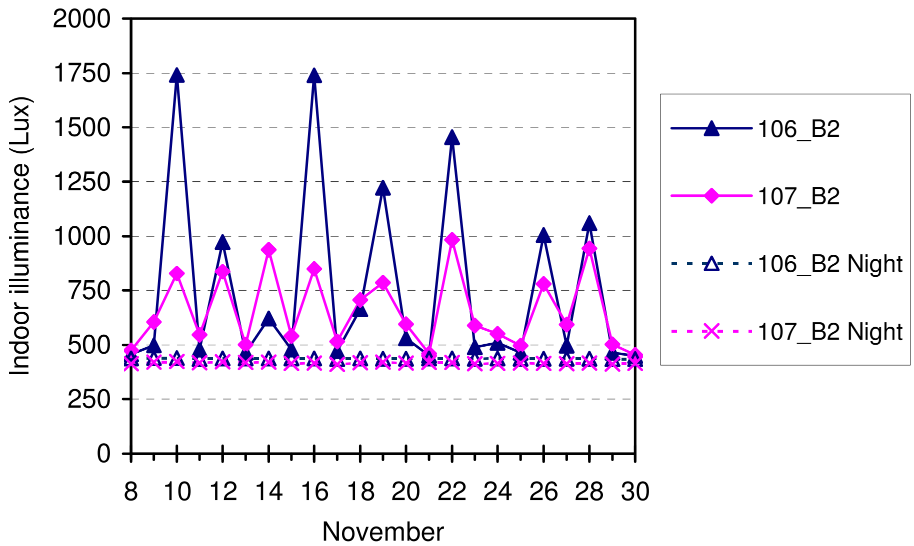

Figure A2.3 *Measured illuminance at table height at point B2, 2.1 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

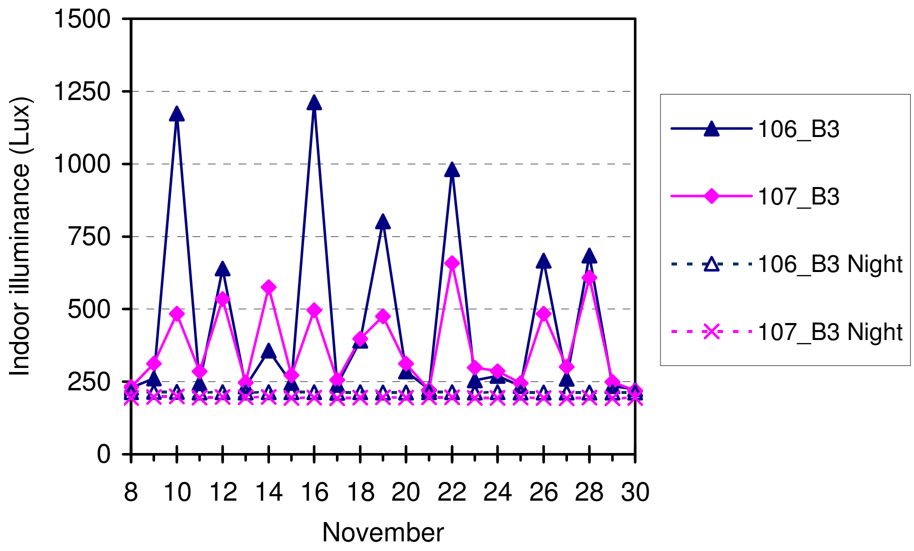

Figure A2.4 *Measured illuminance at table height at point B3, 3.15 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

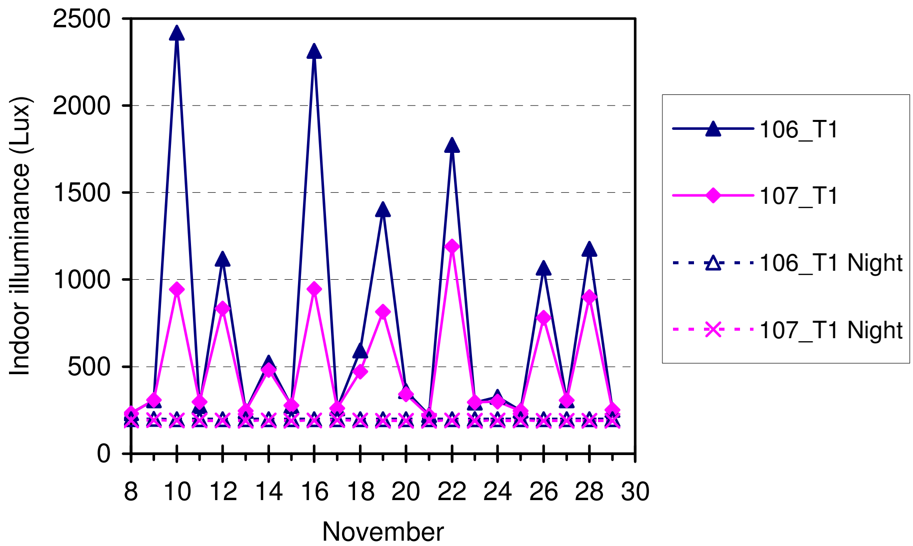

Figure A2.5 *Measured illuminance at ceiling at point T1, 1.1 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

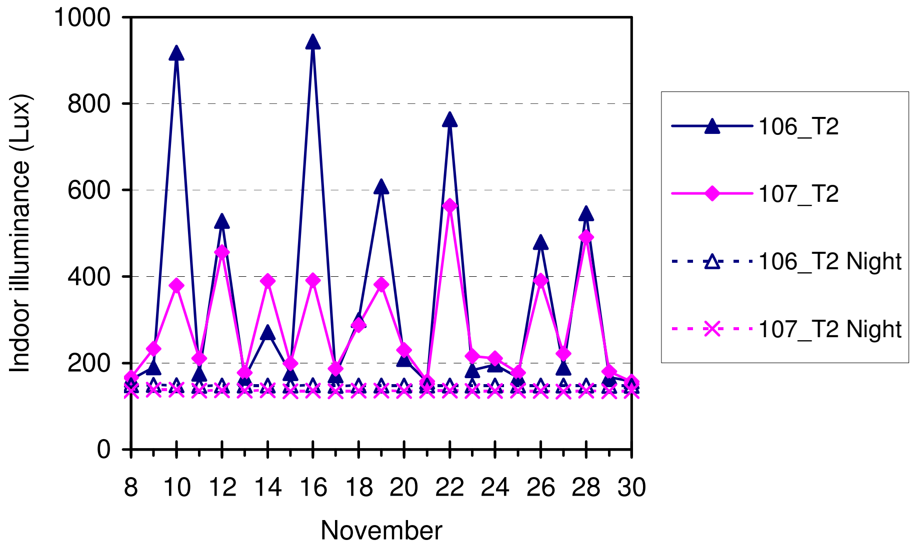

Figure A2.6 *Measured illuminance at ceiling at point T2, 3.1 m from the window in room 106 (reference room) and room 107 (test room). Night measurements from the lighting are also shown (when there was no daylight).*

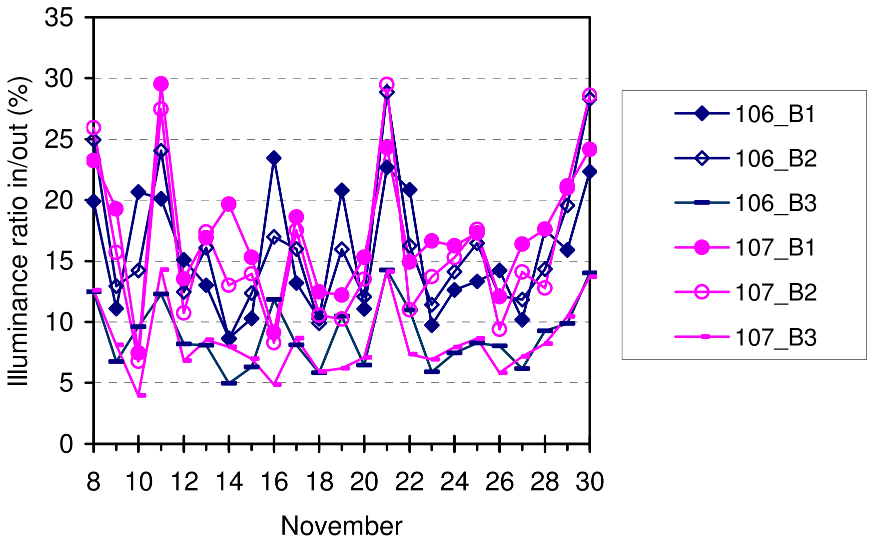

Figure A2.7 *Ratio of measured illuminance outside (horizontal) to inside at table height (points B1-B3) in test and reference rooms.*

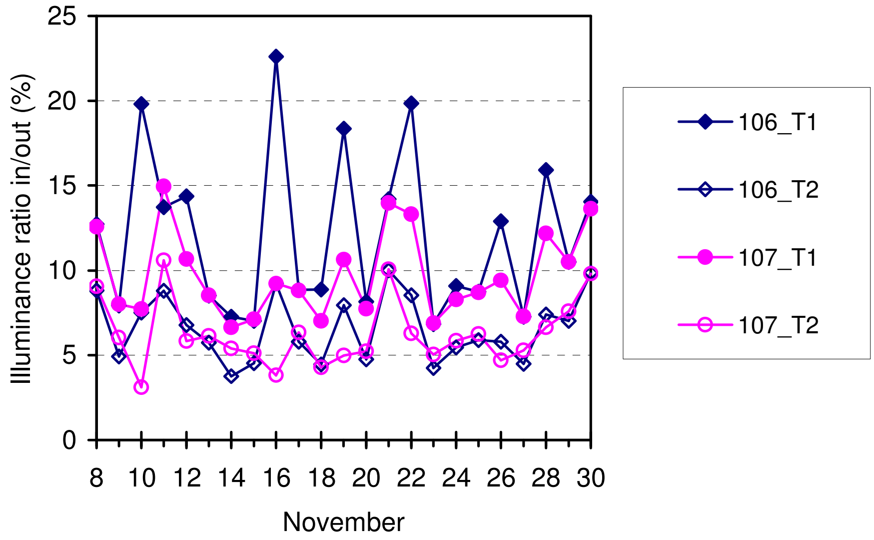

Figure A2.8 *Ratio of measured illuminance outside (horizontal) to inside at ceiling (points T1-T2) in test and reference rooms.*