Thermal comfort of a new university building in Luxembourg with passive cooling

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ABSTRACT

The new Luxembourgish university buildings should comply with a low energy standard, which was defined for typical offices and smaller lecture rooms by a thermal end-energy lower than 14 kWh/m^3a and an electricity use for HVAC and lighting of max. 6 kWh/m^3a. Consequently it was necessary to find ways to avoid the need for mechanical ventilation and air-conditioning. The heat consumption was minimized by an air-tight and well insulated building envelope.

A difficulty was posed by special outside façade elements which were set-up as a grid over the complete outer surface as an architectural element. To prevent the risk of overheating during summer, it is necessary to reduce the solar gains by optimizing the window sizes and the glazing types, as well as through the installation of movable indoor shading elements. Nevertheless enough daylight should enter the rooms to limit the consumption of electricity for artificial lighting. Hence detailed dynamic simulations were performed using TRNSYS and TRNFLOW to ensure thermal comfort without active cooling.

The effective electricity consumption of a newly installed state-of-the-art lighting system, including presence detectors and daylight controllers for dimming, was measured in a test installation to determine the internal loads by lighting. Radiation and illuminance measurements were performed on sample elements of the façade grid. The results were used to verify the daylight simulations and to analyze the benefits of daylight controllers. Several iterative steps were taken to gradually improve the building by introducing different modifications, e.g. reduction of the window sizes, installation of a lighting control system, improving the night ventilation and effective use of the thermal inertia of the building.

1. INTRODUCTION

In the coming years, the University of Luxembourg will move from the city of Luxemburg to the new campus site in Esch/Belval. The development of low energy buildings with a high thermal comfort played a decisive role during the planning of the buildings.

In March of 2009 the groundbreaking ceremony for the first building „La Maison du Savoir“ took place. This building was simulated using dynamic thermal simulation software TRNSYS including TRNFLOW. Several iterative steps were made to avoid a mechanical ventilation and air-conditioning. This methodology allowed to reduce the simulated energy consumption of the building and to improve thermal comfort.

The software RELUX, a daylight simulation tool, was also used in order to define the optimal window size. On the one hand, the room should be illuminated by enough daylight, but on the other hand overheating by solar gains should be avoided as far as possible. A sample element of the special outer grid façade of 50 m^2 was installed for measurements and verifications of its shading effect.

2. BUILDING DESCRIPTION

"La Maison du Savoir", the new main building of the University of Luxembourg (Fig.1) will include auditoriums, seminar rooms and office rooms. The special aluminum grid elements are suspended outside and thus constitute fixed solar shading elements. They are planned as single- or double-layer elements to create a special façade design.

Figure 1: Main building "La Maison du Savoir" of University of Luxembourg, Architect: Baumschlager – Eberle.

In the lower floors of the building, seminar rooms and auditoriums with more than 50 seats are planned. For these kinds of rooms mechanical ventilation cannot be avoided. The tower will content mainly office spaces. To evaluate the possibility of passive cooling in the office rooms, a standard floor of the tower was simulated using TRNSYS. This floor (40,50 m x 25,65 m) was divided in 9 zones according to the orientation of the facade (Fig. 1).

2.1 Building construction

The exterior wall of the building has a thickness of 50 cm. The different layers are from outside to inside are plaster, insulation and fair faced concrete. The U-value of the wall is approximate 0,30 W/m^{2}K. The ceiling should also be built with a main layer of fair faced concrete and a raised floor system above (Fig. 2).

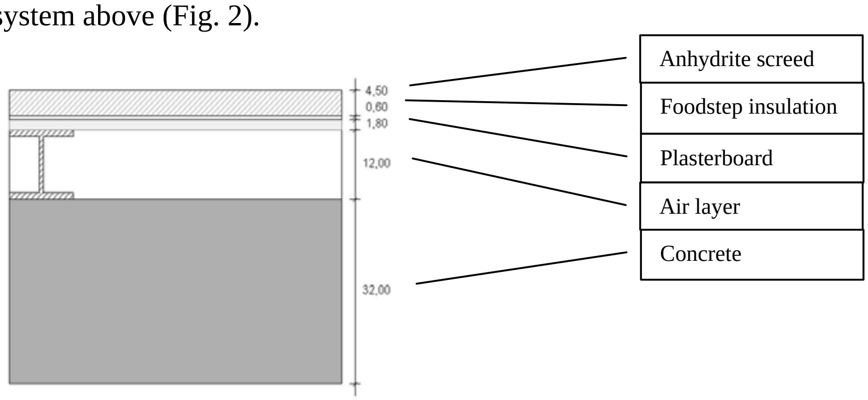


Figure 2: Fair faced concrete ceiling and raised floor system

The planned window size was 2,10 m x 3,27 m. Therefore the window area of the building envelope was more than 60 %. The U-value of the glazing should be 1,0 W/m^{2}K and the g-value 0,5.

The special aluminum grid elements (Fig. 3) were planned as a fixed external shading device. The elements measure 1,25 m x 1,25 m, separated by a distance of 10 cm and are mounted with a distance of 58 cm to the exterior wall. Any further external shading device will be installed.

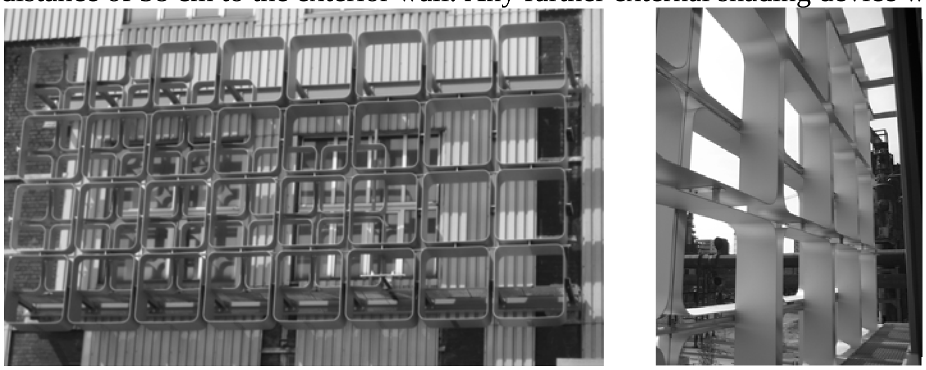


Figure 3: Mock-up of the fixed external façade element in front of an existing test room

An additional internal sunblind is planned but not further specified at this time. A high transmission and absorption factor of 50 % and 35 % respectively were assumed. Furthermore it was assumed, for simulation purposes, that the occupants will only use the additional shading device, if the shading effect of the static external grid elements is lower than 50 %.

2.2 Internal loads

Internal loads are divided into three groups according to the heat source:

- Lighting of a standard office room
    - Fluorescent tubes including electronic ballasts of approximately 10 W/m^2
    - Artificial light between 8:00 a.m. to 6:00 p.m. (Monday to Friday)
      → Maximum service time of 2610 h per year
    - Daylight dimming system and presence detectors are not considered
- Persons and office equipment
    - Standard office room of 20 m² is planned for two employees
      → 1 person per 10 m^2 according to European standard DIN EN 13779 (2005)
    - Standard occupancy rate is 50% between 8:00 a.m. to 6:00 p.m. (Monday to Friday)
      Heat emission of an employee is 100 W
      → Internal gains by persons are estimated to be 5 W/m^2
    - Internal gains by office equipment are estimated to be 8 W/m^2

→Total internal gains without lighting are estimated to be 13 W/m^2 from 8:00 a.m. to 6:00 p.m. (Monday to Friday)

2.3 Ventilation strategies

The ventilation rates are the most sensitive parameters. Due to the building height of 80 m, an infiltration rate of 0,3 h^{-1} was assumed. The natural ventilation rate by use of the building is estimated to be 1,0 h^{-1}. Rijal (2007) analyzed in a field survey the user behavior in naturally ventilated office buildings. The opening time of the window depends on how long the room needs to cool down before the user feels uncomfortable. Furthermore, the results show that people most often open windows, when both the indoor and outdoor temperatures are high.

Hence it was assumed that there is an additional ventilation rate of 2,0 h^{-1} if the room temperature rises above 24,0 °C and the windows will be closed again as soon as the room temperature is lower than 23,0 °C.

3. PARAMETERS INFLUENCING THERMAL COMFORT

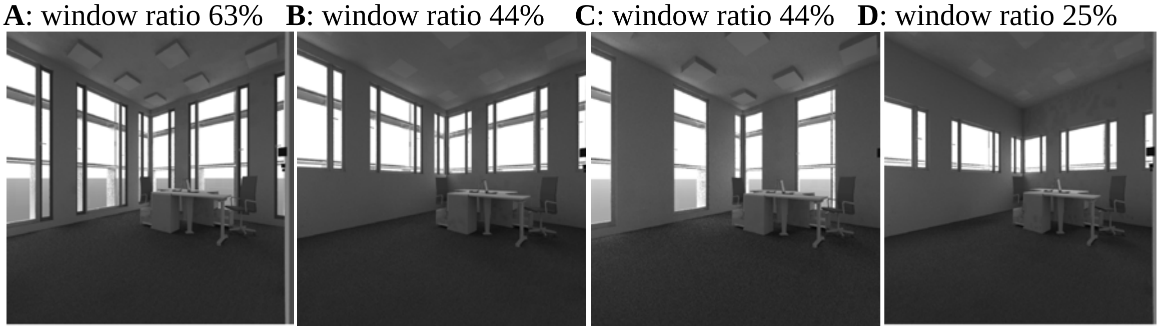
Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment (ASHRAE Standard, 2004). Ensuring thermal comfort in this kind of building during the winter months is much easier than in summer. In fact, the efficient use of passive cooling by night ventilation was chosen to prevent the overheating risk. Thus an air-conditioning system in all office rooms could be avoided.

The solar gains should be reduced by smaller window sizes and lower g-values. As the internal loads have a great influence in office buildings, it is particularly necessary to develop a perfect interaction between the window size and the use of artificial light.

3.1 Window sizes

The window size of a standard element was defined to 2,10 m x 3,27 m (Fig. 4 – type A) at the beginning of the planning. The planned g-value was 0,5 and the light transmission factor 0,68. Comparative calculations using the daylight simulation software Relux, which is based on the Raytracing method, could prove that the sunlight illuminates the working area in an office room with smaller windows (window ratio 44 % - Type B) just as well as in a room with standard window size. Figure 4 shows the results of a southeast orientated office room, with four different window sizes. The width of the windows was determined by the raster of the grid elements. Therefore three different window ratios were analyzed with different window heights. Type C shows an alternative to type B. This variant is preferred by the architects, because of the free panoramic view.

A: window ratio 63% **B**: window ratio 44% **C**: window ratio 44% **D**: window ratio 25%



Need for artificial light (full load hours):

A: 1143 h/a **B**: 1203 h/a **C**: 1516 h/a **D**: 1618 h/a

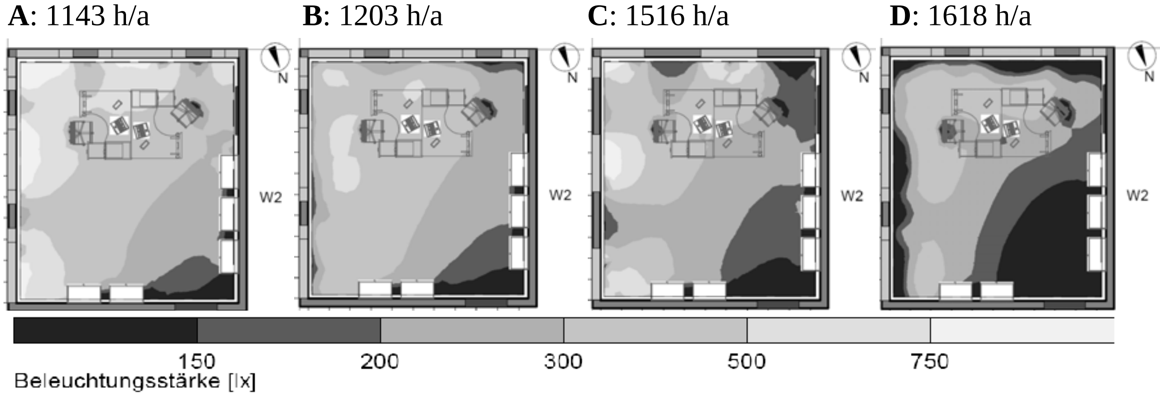


Figure 4: Daylight simulations with Relux – Southeast office room – overcast sky – 21st September

In addition, a lower g-value was checked with regard to its influence on thermal comfort. If a glazing type with a lower g-value is selected it should be made sure that the light transmission (τ-factor) is still greater than 60%. Otherwise the glazing will not transmit enough daylight to illuminate the room and the need for artificial light will increase. Higher energy consumption and higher internal gains will therefore lead to higher room temperatures.

Figure 5 shows the influence of the different window sizes and g-values on the thermal comfort. The light transmission factor was set to 68%. If the window area increases from 44% to 63% there will be 39 overheating hours per year in the southeast office instead of 3 hours. If the g-value increases in addition from 0,34 to 0,5 the overheating hours will increase by a factor of 5. These results show the significance of an optimized window.

Furthermore the correlation between the window ratio and the electricity consumption by lighting was analyzed. Thus a window ratio of 44% (Fig.4) was suggested with a g-value of 0,34 and a light transmission factor of 68%.

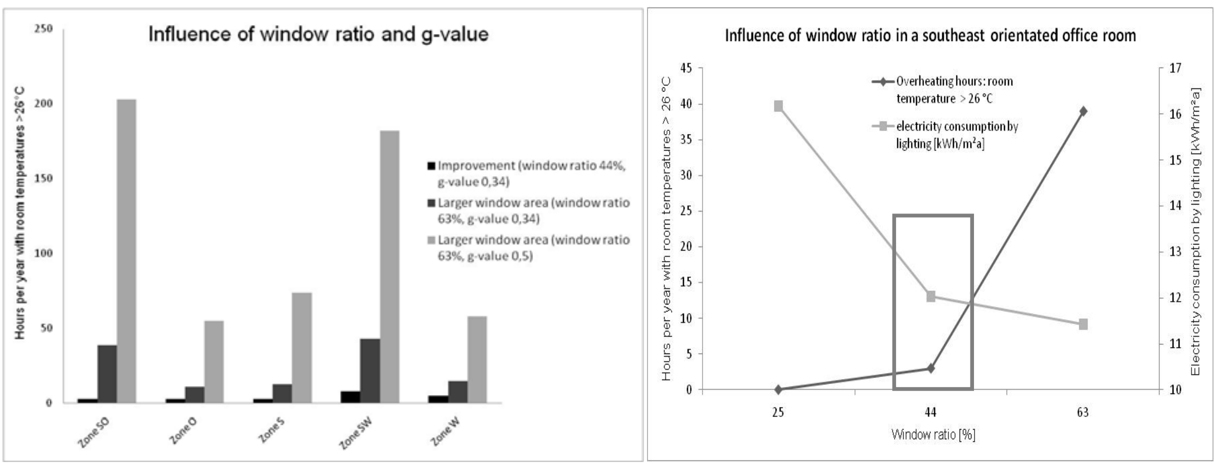


Figure 5: Overheating hours in the southeast office room with different glazing types and areas

Relux calculated also the daylight coefficients, which are only calculated for uniformly overcast sky. These coefficients are independent of time of day and time of year and were the basis for further calculations and allowed an estimation of energy efficiency of daylight dimming fluorescent lamps also during hours with clear sky. Therefore it was possible to estimate the hours without artificial light for one year.

To confirm that enough daylight will transmit through the facade elements and that the smaller windows with the daylight dimming system will work efficiently in the office rooms, a sample facade was installed (Fig. 3) and measured over a longer period. The measured radiation in front of the grid elements and the illuminance inside the room were used to calculate the daylight coefficient [%] and the results were compared with the Relux simulations (Fig. 6).

A: simulation B: real photo

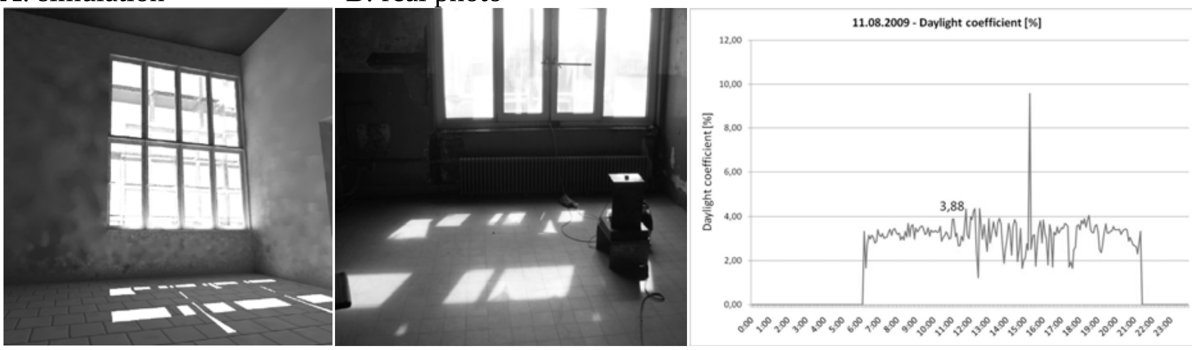


Figure 6: Relux vs. reality – measured daylight coefficients 11.08.2009

At August 11, 2009 the measured daylight coefficient with overcast sky was 3,88 % (Fig. 6), equivalent to a measured indoor illuminance of 516 Lux and outdoor of 13.290 Lux. The calculated illuminance for the same day and the same position in room was 515 Lux with an outside illuminance of 14.500 Lux. The result of the calculated values gives a daylight coefficient of 3,53 %. The measurement validated the simulations of the grid elements.

3.2 Lighting

The required illuminance in single offices is 500 Lux according to DIN V 18599-10 (DIN standard, 2007). If this limit is reached by daylight there is no need for additional artificial light.

To have a perfect interaction between artificial light and daylight, it is necessary to use daylight dimming sensors, which measure the illuminance in the room and ensure 500 Lux at the workplaces at any time. The daylight sensors allow an automatic controlled dimming of the fluorescent lamps to save energy. The optimized window size in chapter 3.1 (Fig.4 – type B) ensures enough daylight in the room and reduced solar gains. The daylight simulations with Relux result in totally 1150 hours per year with artificial light based on the calculated daylight coefficients. That means a saving effect of 56 % only by dimming in comparison to a continuous operation during the working time (2610 hours). The type C which was preferred by the architects reduces the hours with artificial light to 1525. This produces a saving effect of 42 %.

A new high performance artificial lighting system was installed for test purposes in an office room (2 persons) and in a seminar room (15 seats) at the University of Luxembourg, to verify the real energy savings by a daylight dimming system. The new fluorescent tubes with a very high efficiency factor can be dimmed by daylight sensors (Fig. 7). In the seminar room an additional presence detector was installed to stop the waste of energy during vacancy time. The old lighting system, 58 W fluorescent tubes including conventional ballast, was not reconstructed (Fig. 7), but together with the new system controlled by an EI-bus-system. A dimming of the old tubes was not possible. There was only a standard ON/OFF switch.

The EI-bus-controlling system allows a weekly switching between the old and the new lighting system. Therefore it is possible to measure the time of use and the energy consumptions of both systems in both rooms.

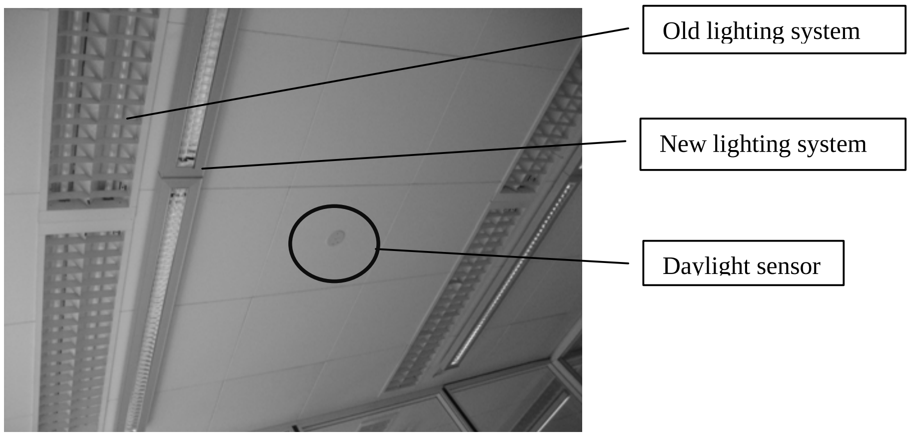


Figure 7: Test installation at University of Luxembourg – old and new lighting system

Figure 8 shows the utilization factor of the old and new lighting system for two different days in the office room. The graph of the old system shows clearly the ON/OFF switching. The utilization factor of the old lighting system is always 100% or 0% whereas the installed daylight dimming system regulates the performance of the new fluorescent tubes in 5% steps to reach always the 500 Lux thresholds in the work areas.

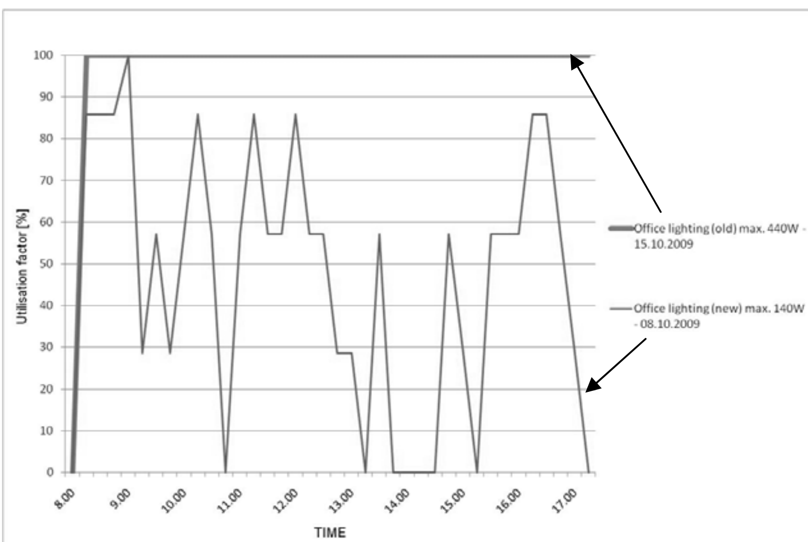


Figure 8: Utilization factor of new and old lighting system in an office room of University of Luxembourg

The weekly alternating measurements were done for a period of 9 months to reduce the influence of seasonal weather factors or changes in the number of users. Based on the measurements the average hours with artificial light per week were calculated for the new and old lighting system. The weekly consumed energy of the new lighting system was converted in full load hours with a performance of 100 %. Hereby the effect of the daylight dimming sensors could be considered and the full load hours of both systems could be compared. The results in both rooms show a saving effect of 45% for the full load hours in both rooms. Additionally, considering the lower installed maximum power of the new system (8 W/m^2 versus 24 W/m^2), at the same illuminance in the room, a result of 82 % energy saving was reached.

Table 1: Energy saving effect of a new state-of-the-art lighting system including daylight dimming sensors

Office room (40h/w)	Average full load hours per week	Savings
Old lighting	22h	
New lighting	12h	45%

Literature shows different energy savings by artificial lighting dimming depending on daylight availability. Bodart and De Herde (2002) gave an overview of these values and calculated by themselves an energy saving effect of 50 – 80% from using daylight dimming systems. Li et al. (2006) measured an effect of 33%, whereas Ihm et al. (2009) measured 60% energy saving through daylight dimming sensors. Older measured energy saving effects of Rutten (1991), Zeguers (1993), Zonneveldt and Rutten (1993), Opdal and Brekke (1995), Embrechts and Van Bellegem (1997) ranged always between 20% and 46%. This is approximately the same dimension as the self-measured values of the University of Luxembourg.

3.3 Passive cooling by night ventilation

A second important parameter to achieve thermal comfort without active cooling is to use passive night ventilation in case of overheating risk. During heat periods the employees shall open the windows in their offices at the end of the working day so, that their offices are able to cool down during the night. Thus all users are responsible for the thermal comfort in their offices, but active information by email, in case of heat wave, was supposed.

In the simulations an air change rate of 4,0 h^{-1} was considered for the night ventilation during the night time (6:00 p.m. to 8:00 a.m.) if the room temperature at the end of the working day is too high. This air change rate is necessary to adequately cool the room.

The rooms were simulated using TRNFLOW to verify that this air change rate is reached. As a result, with the real ventilation openings the average of air change rates per night could be verified with a minimum of 8,0 h^{-1}. Thus the planned cross-section area of the opening allows cooling down of the offices using night ventilation.

3.4 Internal shading device

The high saving effects from daylight dimming systems (Chapter 3.2) are only possible, in combination with the given external façade elements, if a good internal shading device allows the use of diffuse daylight using a light redirection system. Otherwise there will not be enough daylight to light the room. With such a system the diffuse light can be used to illuminate the room and direct light can be reflected. A high reflection factor of the direct light is requested to reduce the solar gains in the room. Such a shading device is assumed in chapter 4 for the improved suggestion.

3.5 Massive ceilings vs. suspended ceilings

The massive ceiling (Fig.2) with fair faced concrete is the last parameter which was simulated to analyze its effect on the thermal comfort. The fair faced concrete stores the heat during the day and releases it back during the night. This case is compared with office rooms which have suspended ceilings where the heat cannot be absorbed during the day and the room temperatures will increase as a result.

4. SIMULATION RESULTS AND THERMAL COMFORT

The University of Luxembourg defined a maximum room temperature of 26 °C as the limit for thermal comfort in summer, which should not be exceeded. This limit value is also indicated in the DIN EN ISO standard 7730 (2006) and the future Luxembourgish regulation for non-residential buildings.

The improvements which are described in chapter 3 were considered to have proven this required comfort limit. In the next step only one parameter was respectively modified to determine its influence on thermal comfort. The graph in Figure 9 shows the results for the southeast orientated office room. The night ventilation obviously has the greatest influence on the room temperature. Furthermore the importance of analyzing the optimized window size and glazing type could be ascertained. The influence of the suspended ceilings is not as significant as assumed, because there are still the exterior concrete walls.

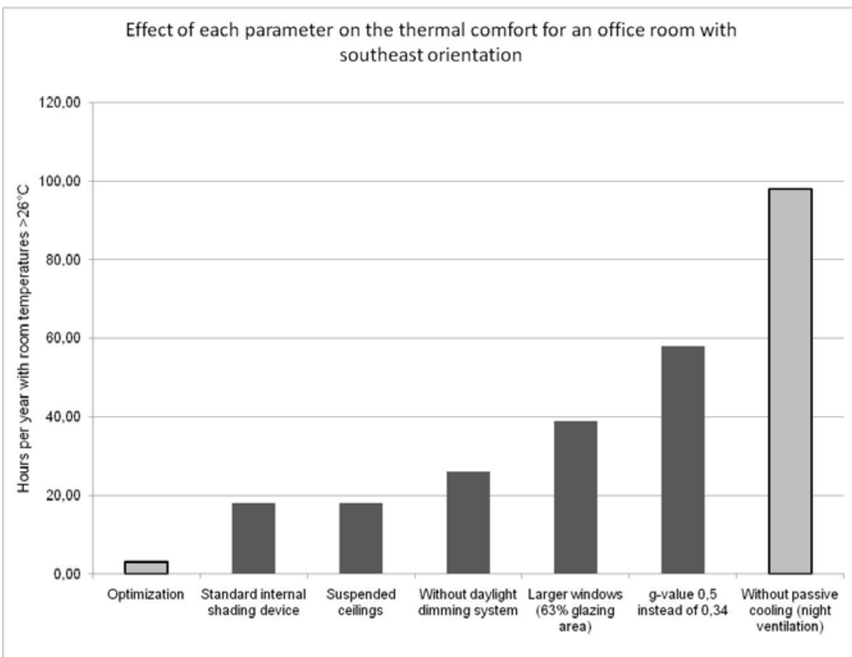


Figure 9: Effect of each parameter on the thermal comfort of an office room with southeast orientation

The relation between the room and outside temperatures for every working hour is illustrated in Figure 10. The limit values are defined according to DIN standard 1946-2 (1946). There is practically no overheating in the optimized scenario and the limits of the acceptable room temperatures are approximately respected.

In the case without natural night ventilation there will be overheating hours starting at outside temperatures from 21 °C on. During the year, the maximum room temperature is 27 °C during working hours, what seems unacceptable according to DIN EN ISO 7730 (2006) or DIN standard 1946-2 (1994).

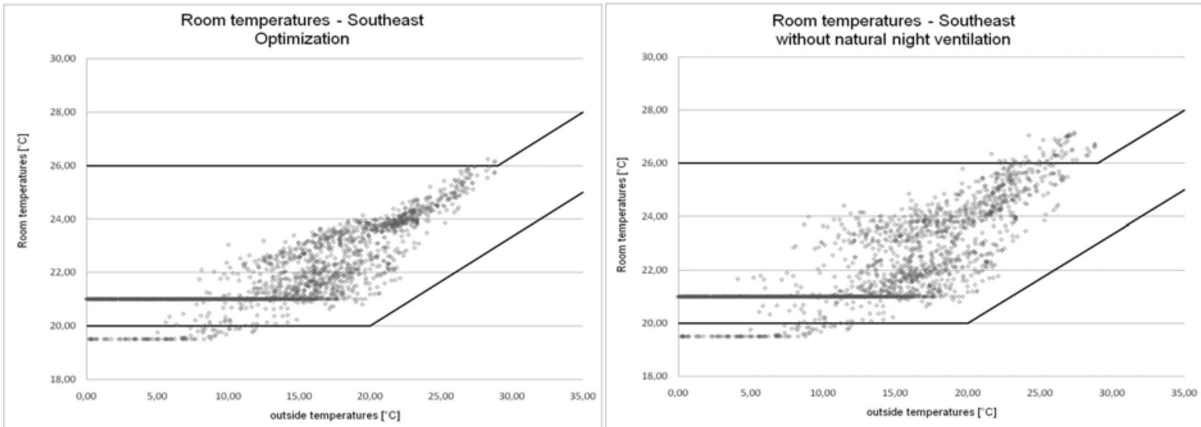


Figure 10: Room temperatures versus outside temperatures simulated for one year – DIN standard 1946-2

Moujalled et al. (2008) compared different comfort criteria in natural ventilated office buildings and came to the conclusion, that the adaptive comfort criteria of DIN EN standard 15251 (2007) and ASHRAE Standard 55 (2004) are in close agreement with the measured comfort votes. Therefore we compared the simulation results with these both standards.
The DIN EN standard 15251 (2007) classifies the limit values in three different categories according to the expectations placed on the thermal room comfort (e.g. category I – PMV -0,2 to +0,2). All limit values are based on thermal comfort measurements in office rooms without active cooling systems. The calculated room temperatures are related to the running mean of outside temperatures.

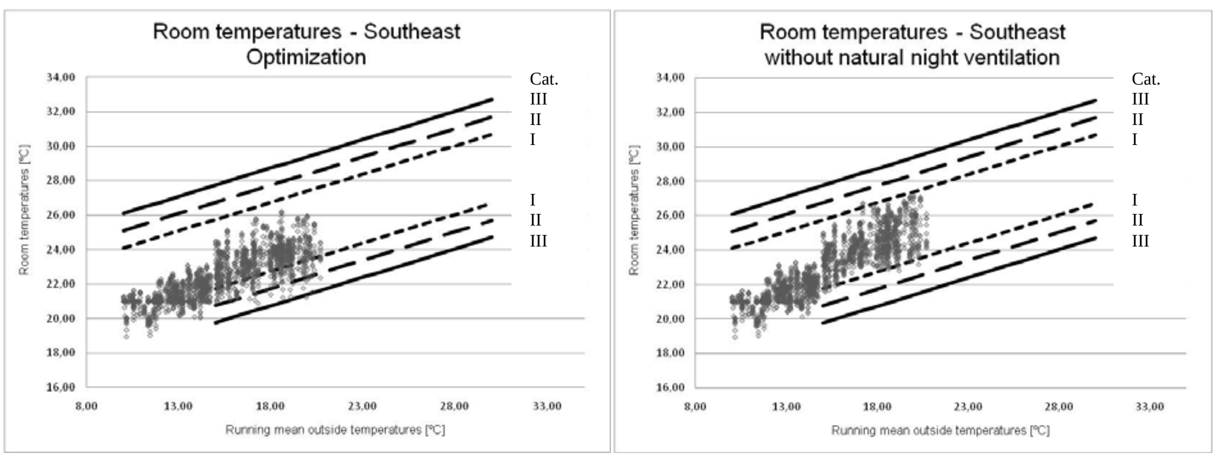


Figure 11: Room temperatures versus running mean outside temperatures – DIN EN standard 15251

In Figure 11 the results of the optimized room are compared with those of the case where no night ventilation was used. Surprisingly all simulated room temperatures in the case without night ventilation are within the limits of category I, which is the category with the highest expectations. However in the optimized solution the lower limits are often exceeded as a result of the night ventilation after warm summer days due to the fact that the room cools down too much during the course of the night.

The acceptable upper limit temperatures in the naturally ventilated offices are higher than the limits defined by DIN standard 1946-2 (1994), which is valid for rooms with mechanical ventilation systems. This effect, that the acceptable room temperatures in naturally ventilated offices are higher, was already described by Hellwig (2005) and de Dear et al. (1997).

De Dear and Brager (2002) published a revision to ASHRAE Standard 55. The 90% and 80% thermal acceptability were applied with a band of 5 K (90%) respectively 7 K (80%). The calculated room temperatures were analyzed in reference to the mean monthly outside temperatures, if the mean value is greater than 10°C. The analysis of the case without night ventilation shows that the majority of overheating problems were expected in June and September, according to Figure 12. Some values cross the 80%-limit, which is worse than category III in Figure 11.

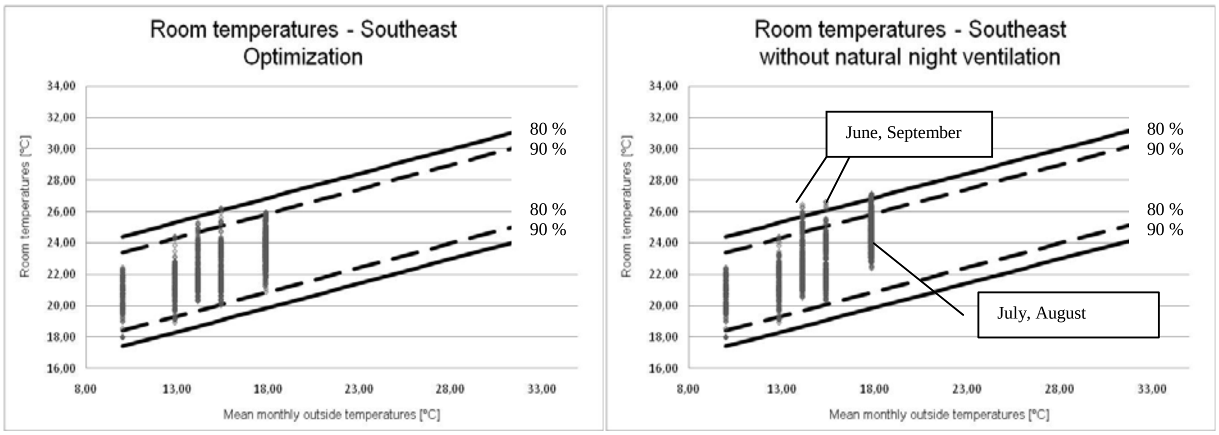


Figure 12: Room temperatures related to mean monthly outside temperatures – ASHRAE standard 55

If, in contrast to Figure 9, all suggested parameters are set to standard values step-by-step (cumulated effects), it can be seen, that the sum of the effects lead to the fact, that the building in its initial planned state could not be used without an air-conditioning system. More than 1000 hours per year with temperatures of more than 26 °C are unacceptable in the working environment (Fig. 13). The greatest influences are once again the impact of night ventilation and the increase of internal gains by removal of a daylight dimming system.

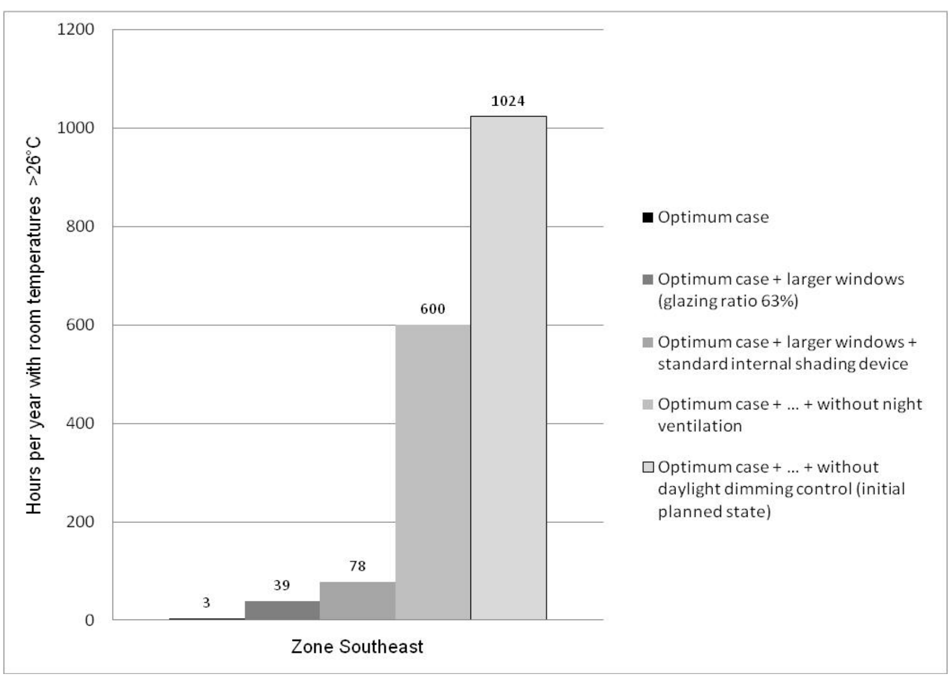


Figure 13: Overheating risk in a southeast orientated office for different cases – cumulated effects

5. SUMMARY

Researchers of the University of Luxembourg have the aim to develop a building concept for their new university buildings with low energy consumption and a high thermal comfort. To achieve these objectives it was necessary to develop a concept ensuring tolerable room temperatures without mechanical ventilation and air-conditioning based on low electricity consumption for lighting and office equipment.

The new main building "La Maison du Savoir" of the University of Luxembourg was simulated dynamically by means of the software tools TRNSYS and TRNFLOW. Furthermore, daylight simulations were performed, because special façade elements were imposed by the architects, and measurements of test installations were done to optimize the internal loads from lighting. Through this optimization of the windows considering the effects of daylight and solar radiation in the summer period, energy saving effects by the lighting of 50% are realistic.

The night ventilation reaches the highest cooling effect of all analyzed means. As the opening of windows is not mechanically controlled, a heightened awareness on the part of the user is assumed for an effective realization.

Separate calculations of the annual heating demand were done and result in a theoretical heat energy consumption of 12 kWh/m^3a (48 kWh/m^2a). The optimized electricity consumption of lighting, domestic hot water and auxiliary energy is approximately 4,5 kWh/m^3a (18 kWh/m^2a) in the office part of the building. These values comply with the limit values according to the internal guidelines of the University (Maas et al., 2008). But in case mechanical ventilation and air-conditioning were used, these limits could not be respected anymore.

The thermal comfort in the office rooms of the "La Maison du Savoir" is ensured according to the future regulation of Luxembourg for non-residential buildings, if all suggestions are going to be realized. The analysis of temperatures in the office rooms according to ASHRAE standard 55 (2004) or DIN EN 15251 (DIN EN standard, 2007) show the same result.

In the analyzed case without passive cooling, the DIN EN 15251 seems to give the lowest requirements. The limit values of the highest expectations category would be respected during all working hours. Whereas an analysis according to DIN 1946-2 (DIN standard, 1994) shows a result of 62 overheating hours per year with room temperatures higher than 26°C during working hours. Only the room temperatures of two of the six "cooling months" are completely within the 90%-satisfaction limits subject to ASHRAE standard 55 (2004). In June and September the room temperatures even exceed the upper limit of the 80 % satisfaction level.

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