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Dynamic simulations to develop a natural ventilation concept for an office building

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Abstract:	The Sustainability Group of the University of Luxembourg defined for their new buildings a maximum thermal end-energy of 14 kWh/(m3a) and an electricity consumption for HVAC and lighting below 6 kWh/(m3a). Therefore it was necessary to avoid active cooling loads and mechanical ventilation in the offices and small lecture rooms. The well insulated and air-tight façade, including special outside shading elements which were designed as a grid over the complete building envelope, was an essential given architectural element of the building. Therefore further external shading devices were not applicable. The only possibility to have an influence on solar gains was to optimize the window size, the glazing type and potentially an internal shading device. Furthermore, to prevent the risk of overheating during the summer period, it was necessary to reduce the internal gains from lighting and IT-equipment. Hence detailed dynamic simulations using TRNSYS and TRNFLOW were done to evaluate the thermal comfort without air-conditioning and mechanical ventilation. The effects of optimizations like a state-of-the-art lighting control system or a window-based night ventilation, as well as the influence of the effective thermal inertia of the building were analyzed. The assumed natural ventilation rates were calculated by combining TRNFLOW and TRNSYS simulations and by the software LESOCOOL.
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1. ABSTRACT

The Sustainability Group of the University of Luxembourg defined for their new buildings a maximum thermal end-energy of 14 kWh/(m^3a) and an electricity consumption for HVAC and lighting below 6 kWh/(m^3a). Therefore it was necessary to avoid active cooling loads and mechanical ventilation in the offices and small lecture rooms.

The well insulated and air-tight façade, including special outside shading elements which were designed as a grid over the complete building envelope, was an essential given architectural element of the building. Therefore further external shading devices were not applicable. The only possibility to have an influence on solar gains was to optimize the window size, the glazing type and potentially an internal shading device. Furthermore, to prevent the risk of overheating during the summer period, it was necessary to reduce the internal gains from lighting and IT-equipment.

Hence detailed dynamic simulations using TRNSYS and TRNFLOW were done to evaluate the thermal comfort without air-conditioning and mechanical ventilation. The effects of optimizations like a state-of-the-art lighting control system or a window-based night ventilation, as well as the influence of the effective thermal inertia of the building were analyzed. The assumed natural ventilation rates were calculated by combining TRNFLOW and TRNSYS simulations and by the software LESOCOOL.

Keywords: Thermal comfort, natural ventilation, night ventilation, lighting

NOMENCLATURE

Q = Air flow rate [m^3/s]

m = Mass flow rate [kg/s]

C_d = Discharge coefficient [-]

ρ = Air density [kg/m^3]

$w(z)$ = Width of the opening at the height z [m]

$\Delta p(z)$ = pressure difference at the height z [Pa]

C_w = Drag coefficient [-]

A = Cross section area of the opening [m^2]

g = Gravitational acceleration = 9,81 m/s^2

H = Height of the opening [m]

ΔT = Temperature difference between inside and outside temperature [K]

T = Maximum temperature [K] (inside or outside temperature)

Re = Reynold number = $(v_0 \cdot D_r)/\boldsymbol{\nu}$

Gr = Grashof number = $(g \cdot \Delta T \cdot H^3)/(T_m \cdot \boldsymbol{\nu})$

D_r = Depth of the room (distance from the opening to the opposite wall) [m]

$\boldsymbol{\nu}$ = Kinematic viscosity of air [m^2/s]

T_i = Abolute room temperature [K]

T_e = Absolute outside temperature [K]

T_m = Mean temperature of inside and outside temperature [K]

n = Air change rate [h^{-1}]

v_0 = Wind velocity [m/s]

2. INTRODUCTION

The University of Luxembourg is going to 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 software TRNSYS including TRNFLOW and daylight software RELUX. Several iterative steps were taken 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 most important concept to ensure thermal comfort in the building is the efficient use of natural ventilation during the night, which requires a reduction of heat sources. A Swiss handbook on passive cooling (Zimmermann, 1999) defines boundary conditions for night ventilation. The total required heat removal should not exceed 150 Wh/(m²d) if the temperature difference between day and night is less than 5 K and 250 Wh/(m²d) if the difference is higher than 10 K. Zeidler (2001) gives a limit for heat sources of 30 W/m² in an office room with typical use and a free cooling concept.

Therefore it was necessary to reduce the internal and solar loads in the office rooms. The software RELUX, a daylight simulation tool, was 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 loads should be avoided. The possible energy saving effects by daylight dimming systems were analysed by means of measurements on a test installation. By the way, the simulation results of RELUX could be validated.

The software tool TRNSYS was used to verify the overheating risk in the office rooms during the summer months. A constant natural ventilation rate during the night hours was assumed for the thermal simulation. The air changes were estimated so that the thermal comfort was ensured and an additional active cooling could be avoided.

Comparative calculations using TRNFLOW as well LESOCOOL were done to verify the estimated air change rates with the planned cross sections of the window openings and the mean climate conditions.

3. 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 aluminium 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.

In the lower floors of the building, seminar rooms and auditoriums are envisaged with more than 50 seats, where mechanical ventilation cannot be avoided. To evaluate the possibility of passive cooling in the office rooms, a standard floor of the tower was simulated using TRNFLOW and LESOCOOL. This floor (40.50 m x 25.65 m) was simulated as Multi-zone model and was divided in 9 zones according to the orientation of the facade (Fig. 1).

3.1 Building construction

The exterior wall of the building has a thickness of approximate 50 cm. The different layers (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).

The U-value of the glazing is planned to be 1.0 W/(m^{2}K) and the g-value 0.5.

Special aluminium 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. No further external shading device will be installed.

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 %.

3.2 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 were considered (s. Chapter 4.1)

    →Minimum service time of 1150 h per year using the daylight dimming system

- 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 from 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)

→Total internal gains assuming stand-by mode of office equipment are estimated to be 2 W/m² during non-working time

3.3 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 through use of the building is estimated to be 1.0 h^{-1}. This air change rate agrees with measured air changes by Pfafferott et al. (2003) of 0.3 to 1.7 h^{-1} for natural ventilation during working hours for similar climatic environmental conditions.

Furthermore the minimum ventilation rate in natural ventilated office rooms has to be ensured in order to fulfill hygienic requirements. Different standards specify such limits. The German DIN standard 18599-2 (2007) defines a requirement for office rooms of 40 m^3/(h*pers) which implies for a standard office in „La Maison du Savoir“ a required minimum ventilation rate of 0.6 – 1.3 h^{-1}. The European DIN EN standard 15251 (2007) requires that for low-pollutant office buildings with standard expectations a fresh supply air of 7 l/(s*pers) and 0.7 l/(s*m^2). This results in a minimum ventilation rate of 1.2 – 1.6 h^{-1}. The estimated ventilation rates (infiltration + natural ventilation) in the office rooms comply with these regulations.

To ensure the required air change rate during working hours is it necessary to open or tilt the windows at periodical intervals. Measurements in an existent, randomly chosen office room at the University shows that such user behavior is realistic during a summer period (Chapter 4.2).

Existent research analysis of the user behavior in naturally ventilated office buildings, based on field studies, were summarized, validated and extended by Herkel et al. (2008). The studies confirmed that the percentage of open windows increases rapidly until a percentage of 100 is reached when indoor temperature exceeds a certain value.

Rijal et al. (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 cold discomfort. 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.

The night ventilation rate was assumed to be 4.0 h^{-1} if the room temperature exceeds 24.0 °C at 6:00 p.m. This describes a passive summer cooling concept, whereby the user has to manually open the windows in his office at the end of his working day. At 8:00 a.m., when the next working day begins, it is assumed that the windows will be closed again.

This range of values for air change rates by natural night ventilation are realistic and often reported in literature documenting analysis based on measurements. The air change rates depend on the cross section of the window opening and the outside temperatures. A low energy building was monitored and analyzed by Eicker et al. (2006). The user had also to manually open the upper section of the windows and the room doors in this building. The cross section of the opening for two windows is 4000 cm^2 in a standard office with a surface of 20 m^2. The measured average air change rates during 170 night hours in summer 2003 was 9.3 h^{-1} at an average wind speed of 1.1 m/s. Furthermore, Eicker et al. (2006) found a linear correlation between wind speed (v_0) and air change rate (n) with a very weak correlation coefficient:

$$n = 1.8173 \cdot v_0 + 7.2544 \quad (1)$$

That means an air change rate of a minimum of 7.25 h^{-1} during the night hours without wind.

The average size of the window openings in a standard office room in the new university building in Luxembourg is approximately 7400 cm^2. Therefore, an estimation of an air change rate of 4.0 h^{-1} during the night time seems pessimistic rather than optimistic. Simulations with TRNFLOW and LESOCOOL as described in Chapter 5 verify this thesis.

4. EXPERIMENTS

Some measurements were made to verify some assumptions, before thermal simulations were used to optimize the new University building from an energetic point of view.

4.1 Saving effects from the use of daylight

A requirement of the low energy concept with natural ventilation strategy is the decrease of the internal gains. Therefore a main focus is on the development of an energy efficient lighting system. An interaction between the window size and the use of artificial light is particularly necessary.

The required illuminance in single offices is 500 Lux according to DIN standard 18599-10 (2005). If this threshold is reached through the use of daylight there is no need for additional artificial light. Therefore, use of daylight dimming sensors, which measure the illuminance in the room and ensure 500 Lux at the workplaces at any time, allow through a controlled dimming of the fluorescent lamps, a high energy saving effect and a reduction of the internal gains.

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 arising from the use of a daylight dimming system. The new fluorescent tubes with a very high efficiency factor can be dimmed by daylight sensors. The old lighting system, 58 W fluorescent tubes including conventional ballast, was not removed (Fig. 4), but was used 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 allowed a weekly switch between the old and the new lighting systems. Therefore, the usage periods and the energy consumptions of both systems in both rooms could be measured and compared.

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 into 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. 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.

4.2 Night ventilation and thermal comfort

During a heat wave in August and September 2009, thermal comfort measurements in a southeast-orientated single office at the University of Luxembourg were taken.

The internal loads were ascertained based on:

- 1 employee, Monday to Friday between 8:00 a.m. and 5:00 p.m.

  → Effective occupancy rate only 4 hours per day
- 2 computers each with 140 W
  - 1 PC runs 24 hours per day
  - 1 PC between 8:00 a.m. and 5 p.m. from Monday to Friday
- Artificial light (4 x 55W), 4 hours per day (Monday to Friday)

One window was tilted during the working hours. Natural night ventilation was not possible, because the cleaning staff closed the window in the evening. The external shading device was closed during the course of the measurement exercise.

The measuring system allows a recording of all the physical parameters which are needed for assessing and evaluating the thermal comfort. That means the external and room temperature, relative humidity, as well as air velocity and the CO_2 concentration in the room. The height of the sensors was installed at the same height as that of a seated person (approx. 1.10m).

Over a longer period, outside temperatures of more than 20 °C with a peak of 34 °C during working hours (Fig. 5) were measured. Significantly lower temperatures during the night time are typical for the central European climate. Hence, temperatures less than 10 °C were measured.

Further, it could be revealed that acceptable room temperatures are not attainable using window ventilation during the course of the working day. Such ventilation behavior complies with typical user behavior during summer period according to Herkel et al. (2008). Also the room did not cool down significantly during the night time, though the outside temperature decreased to 10 °C in some cases. This is due to reduced air exchange by infiltration which is a consequence of new airtight buildings.

The measured temperatures in the office room were compared with the dynamic simulation results of TRNSYS to estimate the real air change rate (Fig. 5). The outside temperatures were applied in TRNSYS according to measurements. The solar radiation was not measured but was assumed based on weather files from the Meteonorm library in TRNSYS. The global radiation values from the library were compared with measured values from a meteorological station close to the site over a period of three weeks. It could be identified a good correlation. The differences of the calculated sums of the radiations over the period are approximately 10 %. Only during the last three days the real global radiation values were significant higher than the values from the library.

The input values such as surface area, volume, glazing type and wall layers were defined on the basis of architectural drawings. The internal loads were estimated based on an interview with the user. The external shading device in front of the windows was assumed to have a shading factor of $F_c = 0.25$ according to DIN standard 4108-2 (2007).

The exact air change rate as a result of the tilted window could not be measured with the available measurement system. Therefore a parameter study helped to identify this value as accurately as possible. Comparison of the measured room temperatures with the simulated temperatures of TRNSYS shows a good congruence for a total ventilation rate of 1.3 h^{-1} during the working hours (1.0 h^{-1} by natural window ventilation and 0.3 h^{-1} by infiltration) and 0.3 h^{-1} for the hours during vacancy time. A comparative simulation with TRNFLOW calculates approximately the same air exchange rate of 1.0 h^{-1} for a tilted window with the real cross-section and hence resulting in a C_d value of 0.41.

During the night from 27.08.2009 to 28.08.2009 a significant difference is noticeable between actual measurements and simulations. This is the result of passive cooling by night ventilation, because the cleaning staff did not close the window. The room temperatures decreased by 8 K due to the higher air change rate and the low outside temperature. In contrast TRNSYS simulated only with an infiltration rate of 0.3 h^{-1} during this night. Thus the positive effect of night ventilation could be visualized. This positive effect with lower room temperatures is noticeable during the subsequent two days, although the analyzed building is a lightweight construction with a low thermal inertia. Without night ventilation the room temperatures increased to 31 °C during the working hours of the following day. As a result of the passive cooling the room temperatures did not exceed 27 °C.

5. SIMULATIONS

This paper focuses on the use of different simulation tools to develop a low energy concept for the new University main building. A high thermal comfort shall be ensured without the use of mechanical ventilation and air conditioning in the office rooms.

5.1 Daylight simulations

Daylight simulations with the software RELUX were done to analyze the possible saving effects of a dimming system based on the previously described measurements (Chapter 4.1). The simulations should confirm that enough daylight transmits through the smaller windows taking account of the special façade elements and the daylight dimming system working efficiently in the office rooms. A sample facade was installed (Fig. 3) and results 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. Hence, the verification of the Relux simulations allowed the definition of the optimal window size.

At the beginning of the planning process the glazing was defined with a g-value of 0.5 and a light transmission factor of more than 60 %. The window ratio was 63 %. After several simulations the optimized window ratio was defined to 44 % (Fig. 6) and the g-value reduced to 0.34 but still with a high light transmission factor of more 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 would therefore lead to higher room temperatures.

The need of artificial light could be calculated after the definition of the optimal window ratio and the resulting daylight coefficient. This output value of full load hours in RELUX was implemented with an ON/OFF controller in the TRNSYS simulation. Hence with the calculated quantity of full load hours and the optimal window ratio, the thermal comfort in the office rooms could be verified.

5.2 Thermal comfort

The University of Luxembourg defined a maximum room air temperature of 26 °C as the limit for thermal comfort in summer, which should not be exceeded regularly. A temperature of 26 °C is also indicated without further specification, if room air or operative temperature, in the future Luxembourg regulation for non-residential buildings, which will come into effect at 1st January 2011. In Figure 7 were analyzed the room air temperatures as worse case and not the operative temperatures, which are used as reference value in the most common standards, e.g. the DIN EN ISO standard 7730 (2006).

There are different improvements which were considered to meet this required comfort threshold:

- Internal shading device
- Fair-faced concrete ceilings versus suspended ceilings
- Daylight dimming sensors
- Window size
- Glazing type (g-value)
- Passive cooling by night ventilation

Dynamic thermal simulations using TRNSYS were done for a typical office floor within the tower of the new university main building (Fig. 1). The floor was simulated as a multi-zone floor to analyze the effects of the different compass orientations. Figure 7 shows the single effects of these improvements on the room air temperatures for the southeast orientated zone.

The different ventilation strategies were simulated using different controllers in TRNSYS. Such controllers allow simulating the influence of the user on the natural ventilation based on the room temperature. The higher the room temperature the higher is the percentage of users which open the windows (Herkel et al., 2008). Furthermore, 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. To implement such an user behaviour in TRNSYS a second controller was used which checked the room temperature only one time at the end of working day and simulated a required natural air change rate during the course of the night.

The night ventilation obviously has the greatest influence on the room temperature (Fig. 7). Furthermore the importance of the optimal 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 with a high thermal inertia.

5.3 Simulation of the air change rate by night ventilation

Because the night ventilation has the greatest influence on the building´s thermal comfort (Fig 7), the assumed air change rate (Chapter 3.3) should be verified using two different software tools. On the one hand the multi-zone air flow model TRNFLOW, which is based on COMIS and coupled with the dynamic thermal model TRNSYS. On the other hand the software LESOCOOL was used in order to compare these results. This is a simplified thermal model which allows calculating the thermal effect of natural ventilation over duration of a maximum of 24 hours.

Two different kinds of days were simulated. A standard summer day and the hottest day of an average year based on the climate in Luxembourg, according to values obtained from the library of Meteonorm weather data, were analyzed.

On the hottest day the outside temperature increased in the afternoon to over 30 °C. At night there was a significant decrease in temperature to about 15 °C, whereas on the following day the temperatures reached again 30 °C. The solar radiations (Fig. 9) also reached high values which led to high solar gains in the room throughout the day.

Secondly, a “standard summer day” with somewhat lower temperatures during the course of the day was analyzed. The daily maximum is approximately 25 °C, which is typical for a summer day in Luxembourg. The solar radiations on this second day are noticeably lower especially in the early morning and the afternoon hours, which required temporary artificial light (Fig. 8).

The solar gains and the outside temperatures were established equivalently in both programs. The internal loads from people and office equipment were calculated according to the methodology described in Chapter 3.2. Standby loads during non-working hours were considered to equal 2 W/m^2. The loads by artificial light including a daylight dimming system were estimated to be 10 W/m^2. The full load hours were calculated to a quantity of 1200 with a window ratio of 44 %.

In LESOCOOL the input value for heat loads is the sum of solar and internal gains. Additionally it is necessary to assume a fixed radiative part for all gains of the simulated 24 hours. This value was estimated to be 50 %. Hence differences of the room temperatures between both software tools were expected, because the part of the solar gains is variably related to the total heat loads and TRNSYS simulates the radiative and convective part each hour dynamically.

5.3.1 Trnflow

With the help of TRNFLOW the in- respectively out-streaming mass flow rate could be calculated. To compare the results with those of LESOCOOL it was necessary to convert the mass flow rate to volumetric air flow rate. For this purpose the mass flow rate was divided by the air density. To simplify matters an average value of air density ρ = 1.204 kg/m^3 was assumed, which is equal to an air density at a temperature of 20 °C.

$$\dot{m}_{12} = C_d \int_0^H \sqrt{2\rho(z)\Delta p_z(z)}\, w(z) dz \qquad (2)$$

With:

w(z) = Width of the opening at the height z [m]

△p(z) = Pressure difference at the height z [Pa]

The discharge coefficient (C_d) was assumed to 0.6 for the TRNFLOW simulation. This is a typical „Default"-value and can be found often in literature for usual window openings (TRNFLOW, 2006). Also TRNFLOW is able to calculate dynamically this value, which considers the influence of the wind fluctuation for openings to the outside (Dascalaki et al. 1995):

$C_d = C_w$,if $0.6 \le C_w \le 1.5$

$C_d = 0.6$,if $C_w < 0.6$

$C_d = 1.5$,if $1.5 < C_w$

$$C_w = 0.08 \times \left(\frac{Gr}{Re^2}\right)^{-0.38} \qquad (3)$$

As the influence of the wind was not considered in the analyzed case, the wind velocity was assumed with 0 m/s, what results in a Reynold-number (Re) of zero. Therefore a discharge coefficient of $C_d = 0.6$ could be verified.

5.3.2 Lesocool

The software Lesocool uses ventilation models which rely on the Bernoulli algorithm to describe air flow rate through large openings (Flourentzou et al., 1998), which means the same equations as those used by TRNFLOW. For a single opening without the influence of the wind, the integration of equation (2) divided by the air density gives an air flow rate Q:

$$Q = C_d * \frac{A}{3}\sqrt{\frac{\Delta T g H}{T}} \tag{4}$$

With:

A = Cross section area of the opening [m^2]

g = Gravitational acceleration = 9,81 m/s^2

H = Height of the opening [m]

ΔT =Temperature difference between inside and outside [K]

T = Maximum temperature [K] (inside or outside temperature)

The discharge coefficient C_d was defined at 0.6 for the simulations with LESOCOOL and TRNFLOW. Flourentzou et al. (1998) confirmed this dimension for usual window openings based on measurements in real office buildings.

5.3.3 Results

All the following analyses refer to the most problematic southeast-orientated corner office. It was ascertained that the results of TRNFLOW and LESOCOOL are approximately equivalent. The small differences between the simulated temperatures of the two software models are on the one hand the result of the different considerations of the radiative and convective part of the gains. On the other hand, they relate to the influence of the storage effect of the walls and ceilings. LESOCOOL starts the simulation with the analyzed day and the surplus heat can be stored in the walls and ceiling whereas TRNFLOW simulates a whole year. Therefore heat can be already stored in the thermal mass at the beginning of the analyzed summer day in August and can influence the room temperature.

“Standard summer day”

The further analyses are based on the TRNFLOW results. The simulated room temperature of a „standard summer day“ reaches 25 °C at 5:00 p.m. (Fig. 9). The air flow rate during the night ventilation period and the resulting heat removals are high enough to ensure acceptable room temperatures less than 26 °C. In the evening at the beginning of the night ventilation, the calculated air change rate is approximately 4.5 h^{-1} and increases by the morning at 7:00 a.m. to 11 h^{-1}. This value exceeds significantly the assumption of 4.0 h^{-1} in chapter 3.3.

Figure 9, right hand side, shows a significant difference of air flow rates in the time period 19:00 – 21:00. This is a consequence of the deviation of room air temperatures between both simulation programs. During the night hours the room temperatures and air flow rates of both simulations slowly approach.

The following diagram (Fig. 10) shows the total heat removal by night ventilation on a standard summer day in the southeast orientated corner office. The sum is approximately 360 Wh/(m^2d) and exceeds considerably the reference value of 150 Wh/(m^2d) for passive heat removal by night ventilation (Zimmermann, 1999). This leads to a theoretical 7 – 8 K temperature decrease during the night.

On the other hand the internal (lighting, persons, office equipment) and solar loads (Fig. 10) are considered as heat sources during this day. The total heat loads are 310 Wh/(m^2d) and are slightly lower than the heat removal by night ventilation. The total decrease of the room temperature after 24 hours was calculated to be approximately 1 K.

But it is to note that the heat removal is only based on the night ventilation and the heat sources only consider the solar and internal gains. Additional heat losses due to transmission and ventilation during the working hours as well as the energy stored in the building mass is not included in Figure 10 and 12. So these figures do not illustrate a complete heat balance.

“Hottest summer day”

The analysis of the hottest day of an average year shows that night ventilation has a negative impact on the room temperature in the evening (Fig. 11) because the outside temperature is then higher than the inside temperature. This warm air flow decreases continuously until around midnight. At this moment the room and outside temperatures are approximately identical. In the following hours the room cools down further due to the lower outside temperature. The maximum calculated air change rate in the southeast office is $10.5h^{-1}$ during the morning hours.

This case shows the limits of manual window control. Such a negative effect can be prevented with windows which can be opened mechanical only if the room temperature is higher than the outside temperature.

Despite the reduced potential of night ventilation the room temperatures still drop to acceptable level of 20 °C by the next morning. Any additional positive effect of natural window ventilation in the cold morning hours is not taken into account. Through such early morning ventilation, the effect of passive cooling can be reinforced.

The simulated heat removal through night ventilation is only 210 $Wh/(m^2d)$ as the estimated positive effect is limited to 8 hours on such warm days (Fig. 12). During the first hours of night ventilation a negative influence on the heat balance and additional loads of 120 $Wh/(m^2d)$ are to be considered. Therefore the effective heat removal of this analyzed day is limited to 90 $Wh/(m^2d)$.

This heat removal is compared with the internal and solar loads in the room (Fig. 12). The additional heat sources from ventilation and transmission are not considered in this graph as well as the described additional heat sinks during the cold morning hours.

The sum of the solar and internal loads is 390 Wh/(m^2d) and significant higher as the heat removal. Nevertheless after one hot day the room temperature can still be kept at 20 °C. This is mainly due to the high air change rates in the morning but also the heat storage effect of the massive elements. This buffering capacity is not obvious and not reflected in the energy balance in both graphs in Figure 12. This is the explanation why the room temperatures increase only by 0.5 K during the analyzed 24 hours. In fact an analysis over a larger period with repeated hot days would lead to much higher unacceptable room temperatures as the maximum buffering capacity would be reached. Without the thermal mass and the possibility to absorb heat during the day, the room temperatures would increase significantly.

6. CONCLUSION

A main focus during the planning of the new university buildings was energy efficiency and thermal comfort. A difficulty was posed by special facade elements which were set-up as a grid over the complete outer surface. Measurements and dynamic simulations were performed to improve the building step by step starting at the initial planning stage. In the end, the installation of an active cooling system could be avoided by optimizing the window sizes and the internal loads. Thus, the simulation results confirmed theoretical low energy consumption and a high thermal comfort in the office rooms.

The night ventilation has obviously the greatest influence on the thermal comfort of the office rooms. A decrease of internal and solar loads is required to ensure an efficient use of passive cooling. Measurements of a state-of-the-art lighting system were performed to verify the daylight simulations and analyze the benefit of daylight controllers. Also air flow simulations using TRNFLOW and LESOCOOL were performed to validate the estimated air change rate when using night ventilation.

The results of the lighting measurements show a saving effect of 45 % for the full load hours of artificial light due to the use of daylight dimming sensors. Daylight simulations using RELUX for the new university building calculate approximately equivalent saving effects. These lower internal loads allowed the development of a natural ventilation concept for the new buildings.

An air change rate of 4.0 h^{-1} during the night ventilation period was assumed to ensure a high thermal comfort with acceptable room temperatures. Two different software tools were used to calculate the theoretical air change rates. Both programs gave approximately equivalent results. Air change rates between 2.5 h^{-1} and 6.5 h^{-1} can be reached during nights of the warmest period of the year. During the cold morning hours air change rates with a maximum of 11 h^{-1} are realistic in the southeast-orientated office as a result of the larger cross section of the openings relative to the room surface area.

As the opening of the windows shall be manually controlled a heightened awareness on the part of the user is required. During heat waves, the cooling effect of natural window ventilation during the morning hours should be used. Typically the outside temperatures do not exceed the room temperatures before 10:00 a.m.. Such an additional positive effect of window ventilation was not considered in the previous simulations. In the evening on hot summer days night ventilation will have a negative influence on the room temperature due to the high outside temperatures. Additional heat loads increase the inside temperature and the positive effect of night ventilation is reduced significantly. A mechanical "intelligent" window ventilation can avoid such an effect and the windows will not be opened before the outside temperature is lower than the room temperature.

Furthermore, a test room at the University of Luxembourg was simulated and measured during a heat wave in the summer of 2009. The measurements should help to analyze the user and building behavior in a new naturally ventilated office building without mechanical ventilation system. The results show that the user opens the windows to ensure the required fresh supply air regardless of the high outside temperatures. Comparison of the measurement and simulations based on a parameter study for the air change rates shows an average value of 1.3 h^{-1} for tilted windows during the course of the working day.

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FIGURE CAPTIONS

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

Figure 2: Fair faced concrete ceiling and raised floor system

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

Figure 4: Test installation at University of Luxembourg – old and new lighting system

Figure 5: Comfort measurements versus thermal simulation in a single office at University of Luxembourg

Figure 6: Correlation between window ratio of the facade, electricity consumption by lighting and overheating hours in an office room

Figure 7: Effect of each parameter on the thermal comfort for an office room with southeast orientation

Figure 8: Total radiation of a "Standard summer day" and the "Hottest day of an average year"

Figure 9: Room temperatures and air flow during the night ventilation in a southeast-orientated office room on a "Standard summer day"

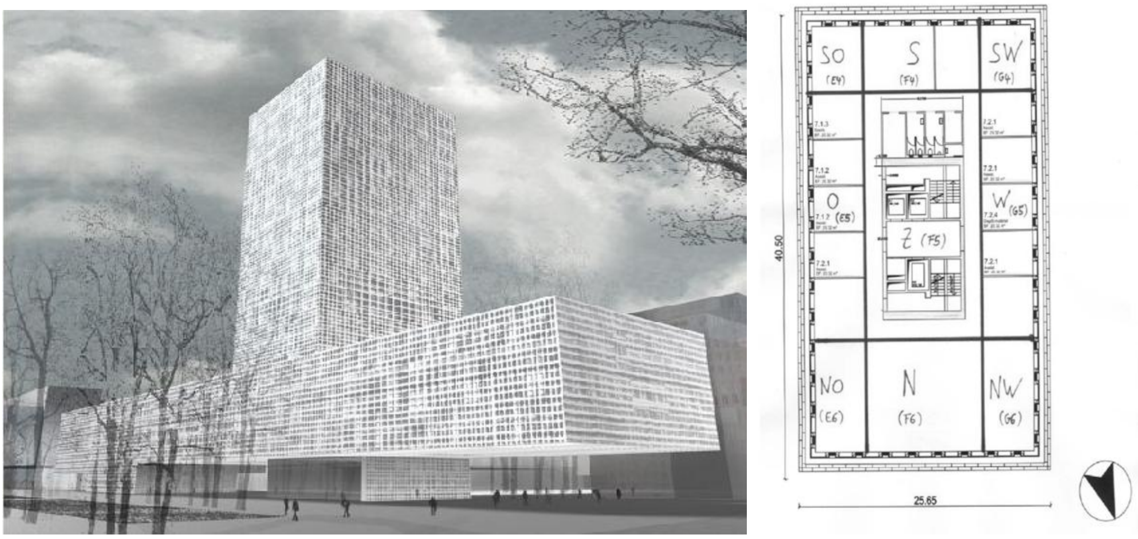
Figure 10: Heat removal by night ventilation and heat gains in a southeast-orientated office room on a "Standard summer day"

Figure 11: Room temperatures and air flow during the night ventilation in a southeast-orientated office room on the "Hottest day of an average year"

Figure 12: Passive heat removal by night ventilation and heat gains in a southeast-orientated office room on the "Hottest day of an average year"

FIGURES

FIGURE 13:



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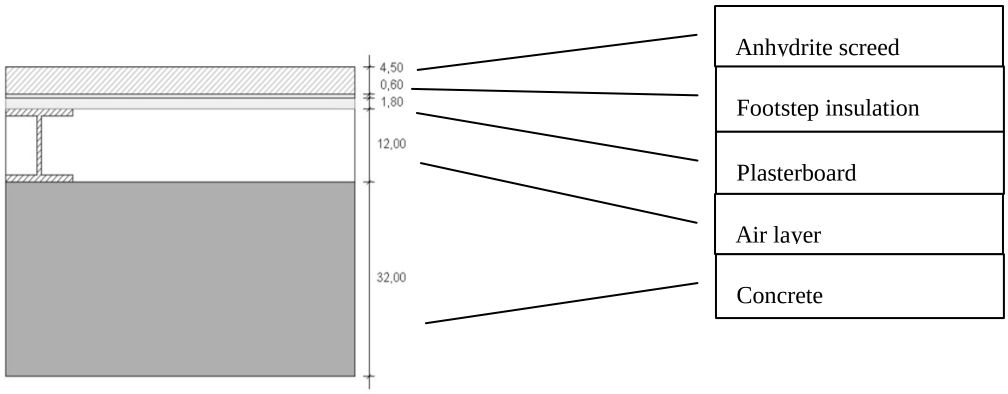

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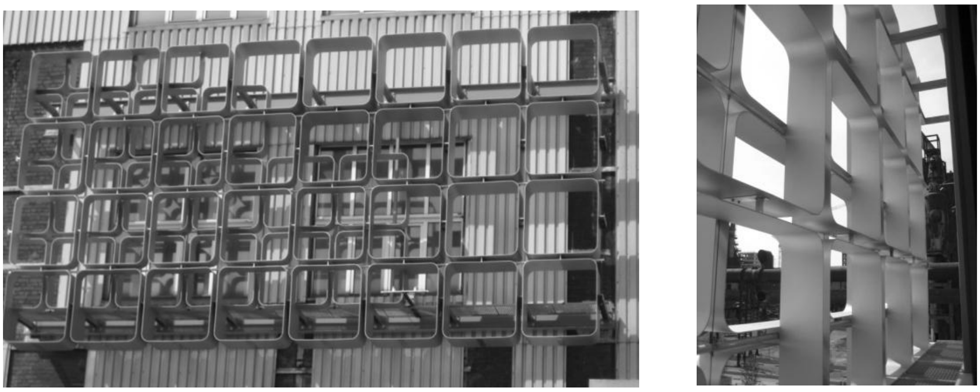

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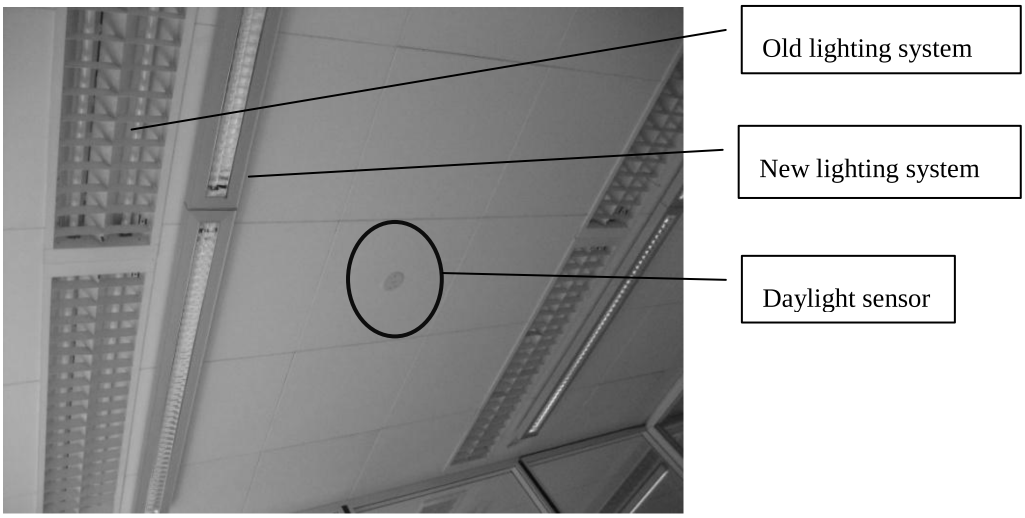

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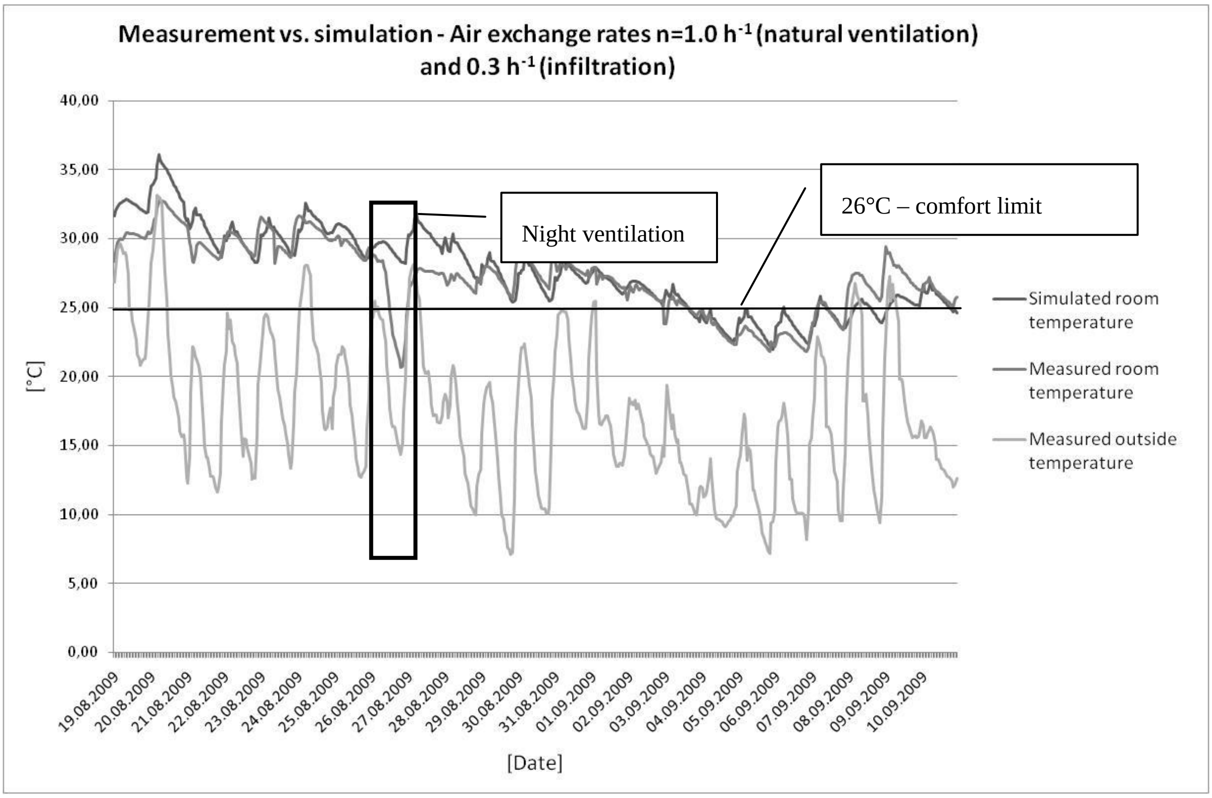

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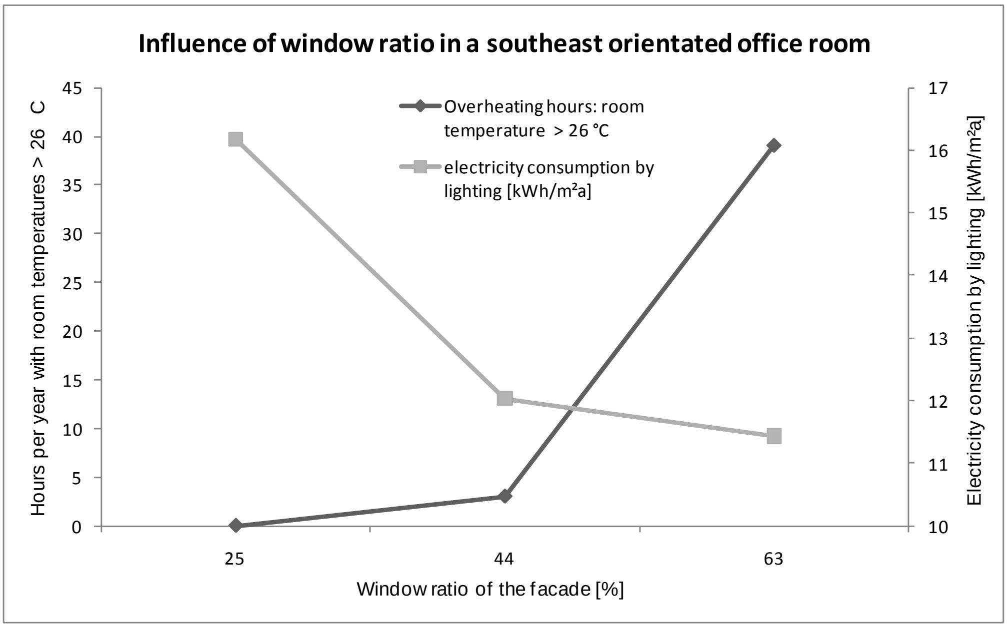

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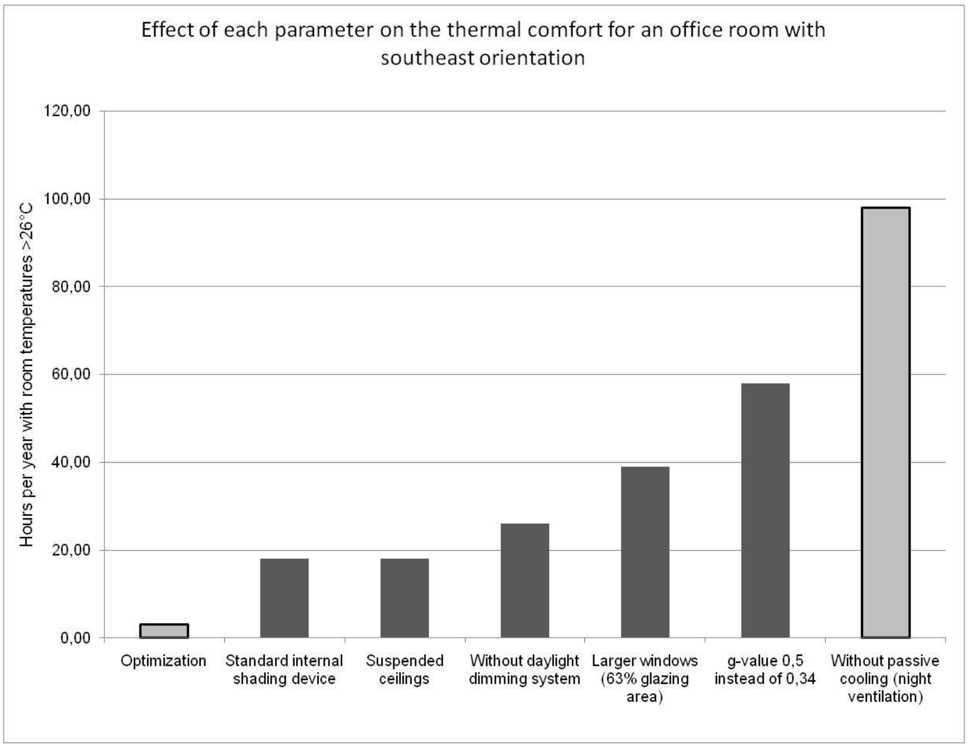

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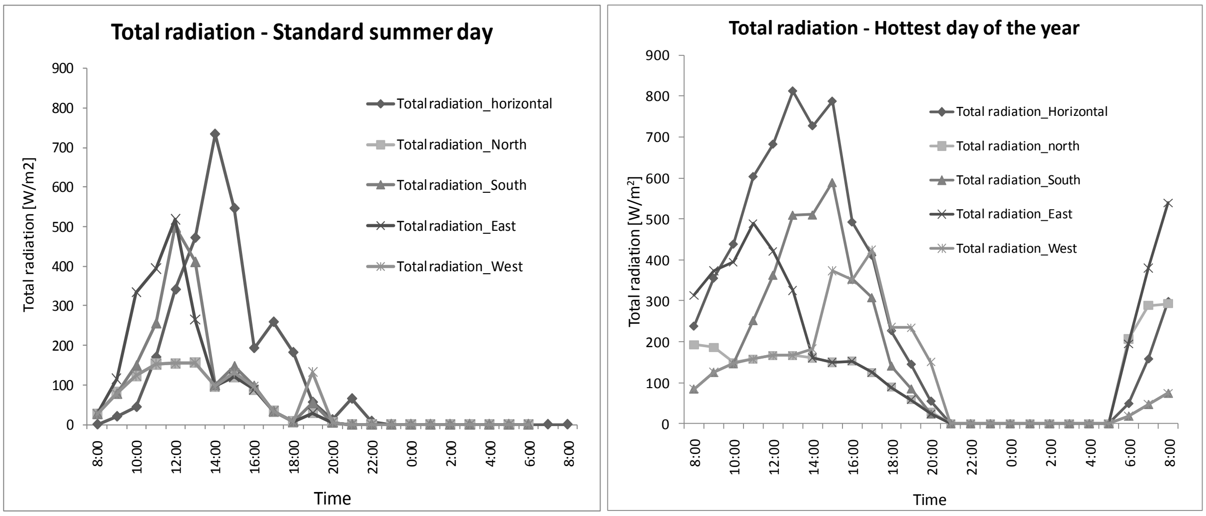

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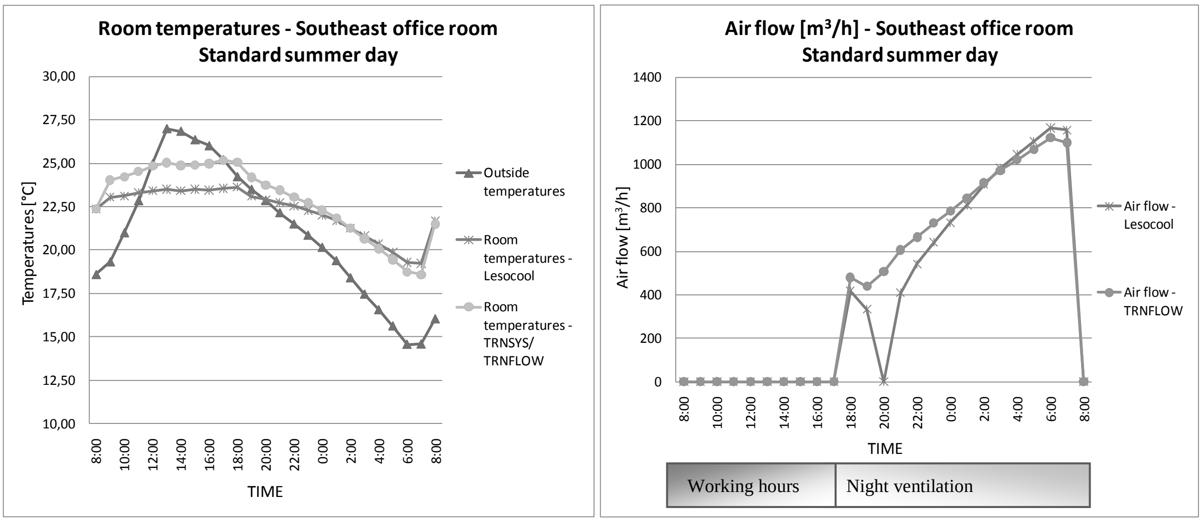

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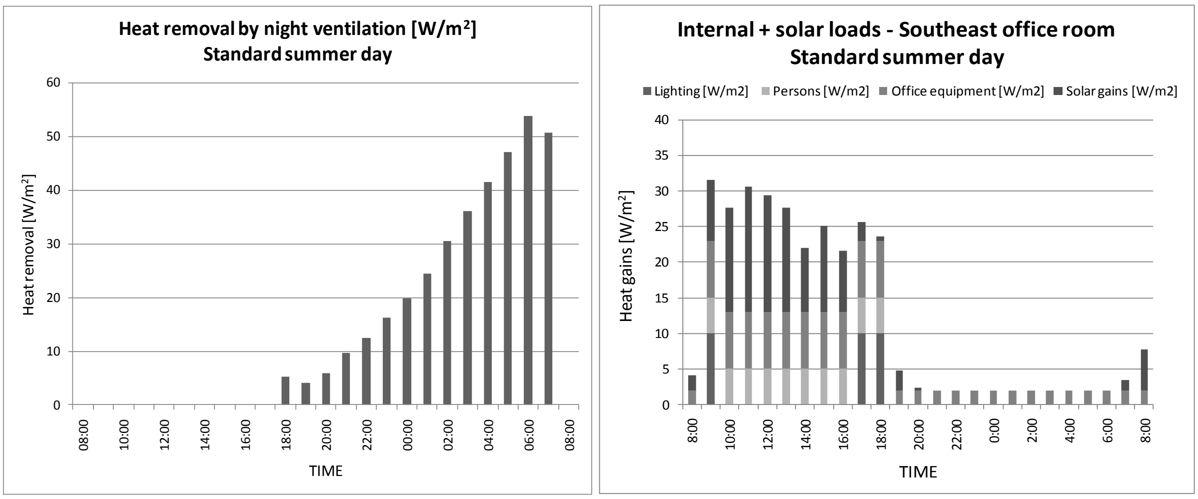

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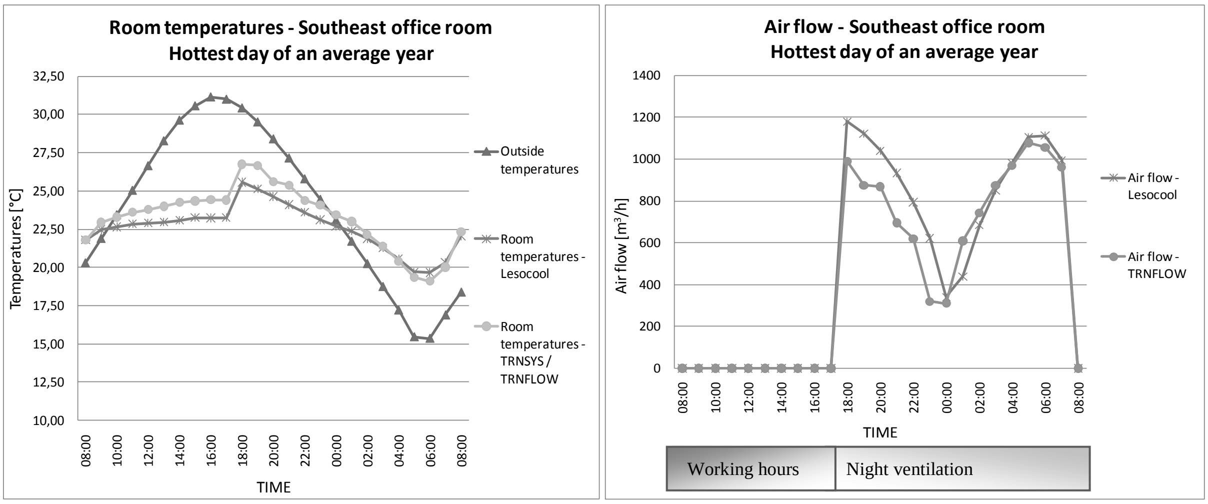

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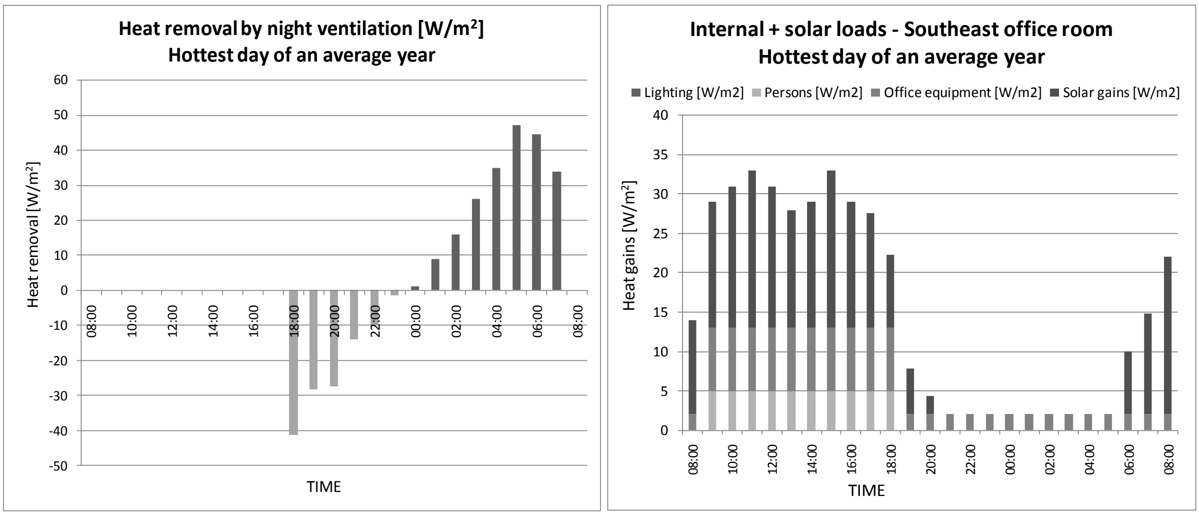

*Title Page

Dynamic simulations to develop a natural ventilation concept for an office building

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