Passive solutions for the optimization of the indoor environmental quality: a case study

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Abstract

An integrated energy concept of a building should include not only its energy consumption but also the quality of the indoor environment in terms of thermal, visual comfort and indoor air quality.
Shadings, window construction materials and ventilation strategies have a significant impact on the "health" of the building and of its occupants; they should be studied carefully during the pre-design phase of the building.
Evaluating thermal, visual comfort or IAQ individually is quite easy thanks to reference standards and simulation tools but it can imply non-optimised solutions or even design errors.
Conversely, an integrated approach should include a simultaneous analysis of all these aspects of the indoor environmental comfort in order to propose optimised technical solutions or design strategies.
Previous studies have proposed statistical indicators to manage thermal and visual comfort simultaneously. In the present study further indicators of IAQ (here CO_2 was considered) were included in order to achieve a global environmental quality. This integrated approach was used for the optimisation of a new large office building in Switzerland. A parametric multi-objective analysis was carried out by means of EnergyPlus. This approach allowed for the optimization of design strategies (shadings, window materials, ventilation) for both energy savings and indoor environmental quality of the building.

1. Introduction

During the concept and the design of a new building, one of the hardest tasks for a building physics engineer is probably to fulfil the occupant wellness. A "healthy building" means a building where the majority of the occupants feel comfortable from a thermal, visual and IAQ point of view. Following a bioclimatic approach without the use of HVAC systems, the number of the main physical parameters that govern this "feeling of comfort" may be reduced to a few: the operative temperature, the illuminance and the concentration of pollutants. The ranges of their optimal values are defined in the literature and in technical standards (EN 15251, 2007; Nabil et al., 2005).
Actually, in order to understand if the indoor comfort of a building will be achieved or not, one should be able to quantify the intensity of discomfort inside the building and its duration during occupancy.
This kind of analysis can be carried out by using statistical indicators as already described in the literature (Sicurella et al., 2011).
On the basis of such analysis, a building physics engineer should be able to propose optimised technical solutions in order to fulfil thermal, visual and IAQ comfort simultaneously.
In the present work a case study of a real building design will be presented as well as a method to find out optimised technical solutions. This optimisation analysis concerned the choice of glazing, shadings and ventilation strategies.

2. The methodology

The main goal of this study was to propose technical solutions in order to fulfil thermal, visual and IAQ comfort simultaneously.
It is important to state that the shape and orientation of the building as well as the WWR were already defined by the architect. Other

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constrains were given by the client who did not want to have mechanical ventilation for the building but he wanted a “bioclimatic building” exploiting natural ventilation and daylighting.
As a consequence, our analysis was focused on the optimisation of glazing, shading devices and natural ventilation strategies.
Due to the fact that ventilation does not have an impact on daylighting, the authors decided to optimise first the windows and the shadings devices and then the natural ventilation strategies.
For this reason, the present work is divided in two main phases (Figure 1): the first one, in which the characteristic of glazing and shading devices were optimized for thermal (TC) and visual comfort (VC) purposes; the second one in which the ventilation strategies were analysed for thermal and IAQ comfort purposes.

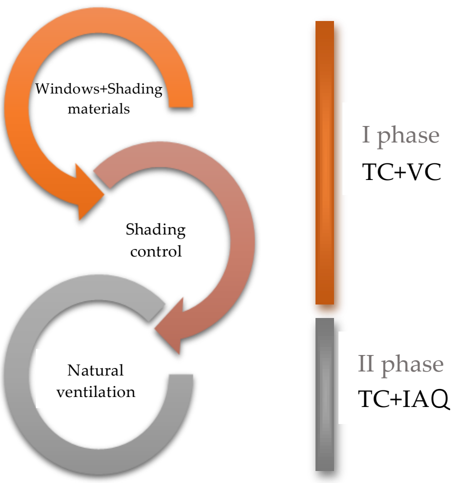

Fig. 1 – Work phases of the optimization process

The analyses were evaluated from June to September during occupation hours (from 8.00am to 7.00 pm). All the performances of the office were simulated on EnergyPlus v.8.1 (EnergyPlus, 2013), able to analyse simultaneously different conditions.
Simulations were run in free running mode; the parametric optimization was made by using the simulation manager jEPlus.

2.1 Thermal Comfort evaluation

Thermal Comfort was evaluated considering the adaptive comfort, according to the standard EN15251, category II: “Normal level of expectation and should be used for new buildings and renovations” (EN 15251, 2007).
The objective function was the minimization of the number of occupation hours in the office room during which the operative temperature were out of the range limits defined by the above-mentioned standards.

2.2 Visual Comfort evaluation

Concerning daylighting, the range of visual comfort should take into account the actual working context, the visual task, the luminance all around, etc. Many studies provide full credit only to values between 100 lux and 2000 lux by suggesting that horizontal illumination values outside of this range are not useful (Nabil A et al., 2005). Due to the fact that the landscape is often snowy the authors decided to prudently reduce the optimal daylight illuminance range from 300 to 1500 lux.
The objective function was the minimization of the number of occupation hours during which the workplane illuminance is out of this range. This value was obtained as an average calculated upon two points inside the office room at a height of 0.8m (Figure 2).

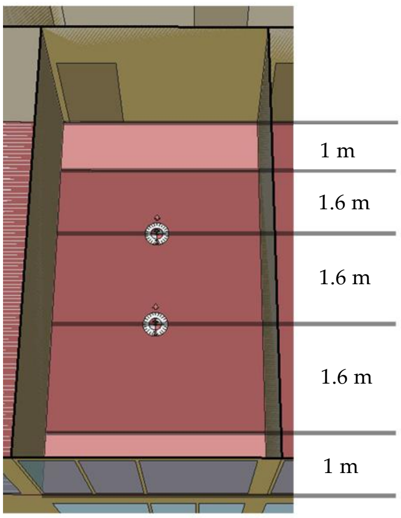

Fig. 2 – Sensors position inside the office room

The two illuminance sensors were considered to be at 2.6m and 4.2m from the façade respectively in order to limit the impact of the boundaries. (Fig. 2)

2.3 Indoor Air Quality evaluation

The calculation model used for simulating the ventilation airflow rate is a function of wind speed and thermal stack affect, combined with the infiltration effect.

The equation used to calculate the ventilation rate driven by wind is:

$$Q_w = C_w A_{opening} F_{schedule} V$$

where:

Q_w=Volumetric air flow rate driven by wind [m^3s^{-1}]
C_w= Opening effectiveness [dimensionless]
$A_{opening}$ = Opening area [m^2]
$F_{schedule}$ = Open are fraction [dimensionless]
V = Local wind speed [ms^{-1}]
The equation used to calculate the ventilation rate due to stack effect is:

$$Q_S = C_d A_{opening} F_{schedule} \sqrt{\underline{\quad (|T \qquad |/ \quad}}$$

where:

Q_s= Volumetric air flow rate driven by wind [m^3s^{-1}]
C_d=Discharge coefficient for opening [dimensionless]
$A_{opening}$ = Opening area [m^2]
$F_{schedule}$ = Open are fraction [dimensionless]
ΔH_{NPL}= Height from midpoint of lower opening to the neutral pressure level [m]
T_{zone}= Zone air dry-bulb temperature [K]
T_{odb}=Local outdoor air dry-bulb temperature [K]
The total ventilation rate is given by:

$$Ventilation_{\ Wind\ and\ Stack} = \sqrt{\underline{Q \qquad\qquad}}$$

Concerning IAQ, in literature and technical standards it is possible to find different values of suitable ventilation rate (AiCARR, 2009; UNI EN 15251, 2007; ASHRAE 62.1, 2007).

A way to evaluate IAQ is to refer to the actual CO_2 concentration inside the building.

Following the ASHRAE Standard 62, 1989, this limit can be set at 1000 ppm even though the standard revision (ASHRAE Standard 62, 1999), suggests 700 ppm above the outdoor concentration as an upper limit. According to studies of Bern University, published by the Swiss Federal Office for the Environment (OFEV,2008) the outdoor CO_2 concentration is 400 ppm.

As a consequence the authors decided to choose the more restrictive of these rate values for CO_2 concentration, which in this case study was set at 1000 ppm.

The objective function was to minimize the number of working hours during which the CO_2 concentration is higher than 1000 ppm.

3. The case study

The analysed building is a multifunctional three-story building of around 14.500 m^3 designed by the Atelier of architecture Manini Pietrini based in Neuchâtel for the Chocolate Manufacture enterprise Camille Bloch. It is located in Northern Switzerland (Courtelary, near Basel) at 800m asl and includes offices, conference rooms, a restaurant and exposition halls.

It is a north/south oriented building with large glazing on the main façades (on average WWR of 43%), (Figure 3).

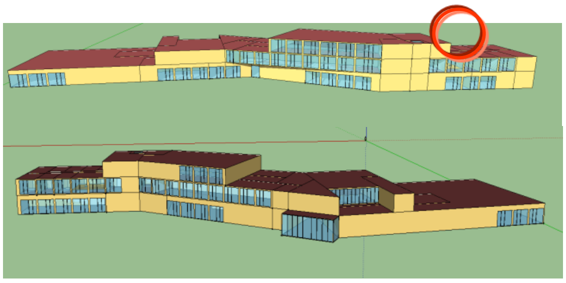

Fig. 3 – Southern and Northern view of the building with in evidence the analysed office (red circle)

For brevity, the results presented in this work will refer to a south-oriented office room only. It is 3.65 m wide, 6.80 m long and 2.8 m high (Figure 2 and 3), and it is occupied by two people from 8.00 am to 7.00 pm. Each office is characterized by 8.8m^2 of window, only 2.2 m^2 is an openable area.

On the eastern side of the building there are two openable bottom hung windows of 2.2 m^2 (Fig. 4) (opening area: 25%).

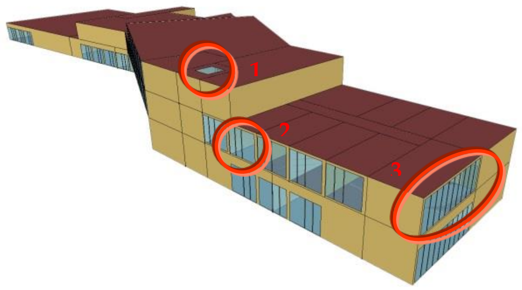

Fig. 4 – Building model: 1: skylight on the stairs; 2: opening window in office room; 3 opening window at the Eastern facade

The doors between the offices and corridor were considered open all the time; the corridor is connected to a stairwell which has a 4m^2 openable skylight (Figure 4).

4. Thermal and Visual Comfort

4.1 TC+VC Windows + Shading materials Parameters

The windows are low emissivity triple glazing (Ug-value of 0.6 $Wm^{-2}K^{-1}$ filled with Ar) with PVC frames (Uf-value of 1.1 $Wm^{-2}K^{-1}$).

Exterior perforated protections placed in front of the windows are automatically lowered when the total solar irradiance on the façade exceeds 200 Wm^{-2}.

Infiltrations were taken into account following the Sherman and Grimsrud model (Sherman et al., 1980), and by using the coefficient recommended in ASHRAE HoF 2009, while, only during this first phase (windows and shadings optimisation), the hygienic ventilation was set equal to 0.5 ACH.

The reflectivity of interior walls, ceiling and floor was set at 0.5, 0.7 and 0.3 respectively.

The Solar Transmittance (G_v) and the Visible Transmittance (T_v) for both glazing and shadings were varied so obtaining 3^4 combinations (Table 1). Similar combinations can be achieved by real glasses.

Table 1 – Properties of glazing and shadings considered for the parametric analysis

Window glazing	W_ Gv	{0.35,0.45,0.55}
	W_ Tv	{0.55,0.65,0.75}
Shadings	S_ Gv	{0.10,0.15,0.20}
	S_ Tv	{0.15,0.20,0.25}

4.2 TC+VC Windows + Shadings materials Optimization Results

The results of this first parametric analysis are shown in Figure 5 and 6.

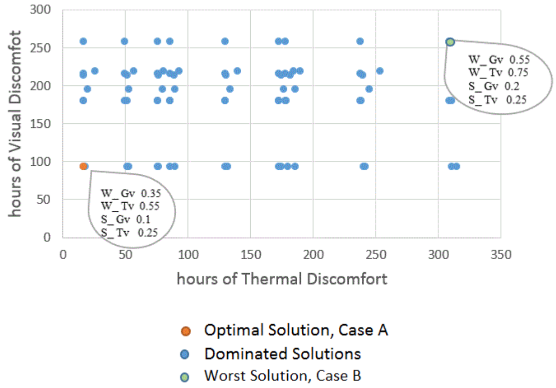

Fig. 5 – Results of windows and shading materials optimization

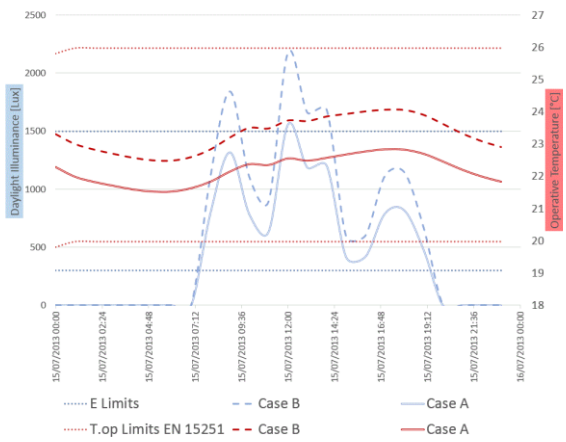

Fig. 6 – Comparison between the best and worst case in a typical day

As can be observed in Figure 5, the best results are obtained by the combination W_ G_v: 0.35; W_ T_v: 0.55 for the windows glazing, and S_ G_v: 0.1 S_ T_v: 0.25 for the shadings materials.

As can be seen in Figure 6, during a typical summer day, with a high value of visible transmittance (Case B: W_ T_v: 0.75; S_ T_v: 0.25) visual discomfort can occur while the lowest solar transmittance value (Case A) is always preferable for thermal comfort.

4.3 TC+VC Shading control Parameters

Once the window and shading characteristics were set, a further optimization was focused on the set point of solar irradiance for shadings control.

The simulations were run with three different set point values for the incident total solar radiation upon the façade (100, 150 and 200Wm^{-2}), and with a so called "shading control based on the daylight glare". This method consists in activating shadings when the daylight glare index at the first reference point, calculated with the eq. of Hopkinson, (Hopkinson, 1970,1972) exceed the value of 22.

4.4 TC+VC Shading control Optimization Results

The results are shown in Table 2 from 01/06 to 30/09 and in Figure 7 for a typical sunny day.

As can be seen in Table 2 and in Figure 7, the daylight glare control is not optimized for thermal purposes. On the other hand, the 800-1600 lux range seems to be the optimal range for visual comfort following this control strategy.

Table 2 – Results of shading control evaluation

Type of shading control	Hours of thermal discomfort	Hours of visual discomfort
"Daylight glare"	73	194
Total solar irradiance ≥ 100Wm^{-2}	12	254
Total solar irradiance ≥ 150 Wm^{-2}	12	75
Total solar irradiancev≥ 200 Wm^{-2}	17	93

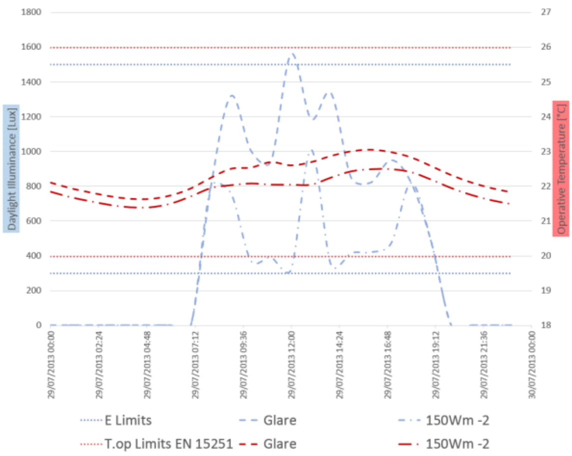

Fig. 7 – Comparison between "daylight glare" and 150 Wm^{-2} irradiance control for shadings in a typical day

In the authors' opinion this type of shading control might empathise daylighting for a long part of the occupation hours while penalising thermal comfort.

Due to the fact that the site is often snowy and in a seasonal optimisation perspective the authors decided a shading control based on solar irradiance upon the façade set at 150 Wm^{-2}.

In fact this value reduces both thermal and visual discomfort (Table 2).

5. Thermal Comfort and Indoor Air Quality

5.1 TC+IAQ Parameters

For the following part of the study the hygienic mechanical ventilation was removed, while the shading control previously optimised was maintained.

This analysis considered a carbon dioxide generation rate in the office room of 3.82*10^{-8} m^{3}s^{-1}W^{-1}, obtained from ASHRAE Standard 62.1 by assuming a constant activity level of 1 met.

A constant outdoor CO_2 concentration of 400 ppm was considered according to studies of Bern University, published by the Swiss Federal Office for the Environment (OFEV, 2008).

As already introduced in paragraph 3, only 25% of the glazing is an openable window. This part of the window can be opened in two different modes: automatically (by assuming an ideal occupant's behaviour) in bottom hung mode and manually in side hung mode.

Concerning the automatic mode, it is based on outdoor/indoor temperature gradient and on the internal temperature. The window is open when the gradient temperature is higher than 1°C and when the indoor air temperature is over 22 °C; the occupants may open the window partially (in bottom hung mode) or totally (side hung mode).

The simulations were run considering different opening type mode combined with different time ranges of possible opening, and with the opportunity or not to exploit the cross ventilation by the skylight over the stairs and by the opening windows at the Eastern facade (Figure 4).

5.2 TC+IAQ Optimization Results

The results are shown in Figure 8 and 10 from 01/06 to 30/09 and in Figure 9 for a typical sunny day.

In Figure 8, the number of occupation hours from 8.00am to 7.00pm during which the operative temperature and CO_2 concentration surpass the comfort range are plotted simultaneously.

Figure 9 shows the operative temperature and CO_2 concentration profiles for four different cases in a typical day.

A number of simulations for different ventilation strategies were run; here, for brevity, only the following cases are reported:

- Case 0: without natural ventilation, only infiltration;
- Case A: natural ventilation through the skylight (100%) all day long;
- Case B: natural ventilation through the skylight (100%) and through the eastern windows (in bottom hung mode) all day long;
- Case C: Case B + office windows in bottom hung mode (during occupation hours);
- Case D: office windows in side hung mode from 6.00am to 7.00pm only;
- Case E: office windows in side hung mode from 8.00am to 7.00pm only;
- Case F: natural ventilation through office windows in bottom hung mode from 7.00pm to 8.00 am only (night ventilation).

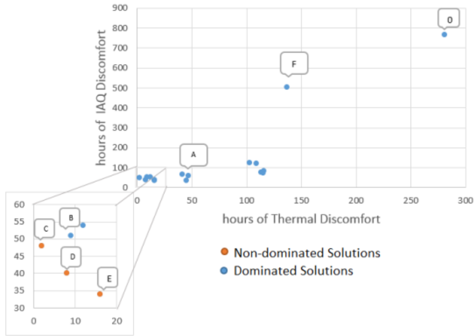

Fig. 8 – Thermal and IAQ discomfort for different ventilation strategies

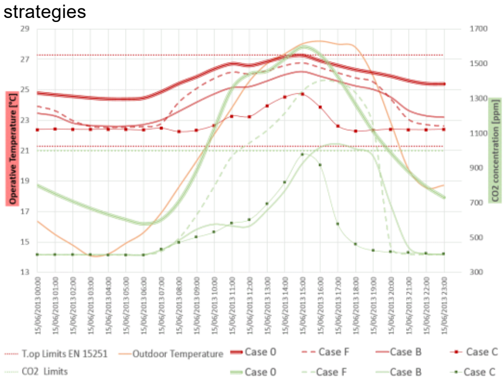

Fig. 9 – Comparison between operative temperature and CO2 concentration for four different cases in a typical day

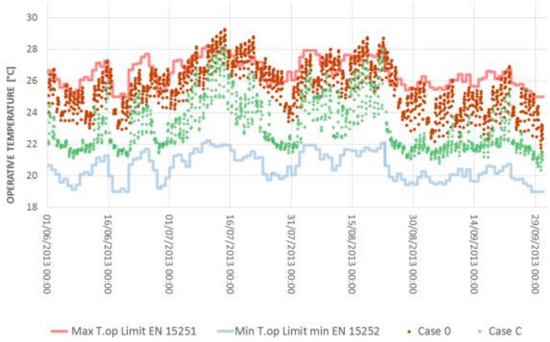

Fig. 10 – Adaptive thermal comfort: comparison between Case 0 and Case C

As can be expected, the worst case for IAQ occurs without natural ventilation (Case 0).

Night ventilation reduces thermal discomfort but the IAQ is not good enough (Case F); this strategy may result in discomfort for excessive CO_2 since people might hesitate to open windows in the early morning (Figure 9).

Only by exploiting natural cross ventilation (Case A and B) does the IAQ increase significantly even without opening the window in the office room. These strategies can be considered very effective for those sites where the window is open infrequently (for example in noisy sites).

The solutions C, D and E represent the non-dominated solutions and they are very similar and excellent solutions for IAQ.
In Figure 10, the operative temperature for Case 0 and Case C is shown from June to September; as can be seen a good IAQ strategy has a positive effect on thermal comfort too. This last strategy was retained for the project since it is relatively easy to apply and does not significantly depend on occupant behaviour.

6. Conclusion

In the present study the results of a parametric analysys for comfort and IAQ design optimisation were presented.
Simulations run on EnergyPlus for a real case study allowed us to define the characteristics of glazings and shading devices as well as natural ventilation strategies in a "healthy building" design perspective.
The results show the importance of simulation in order to find the best compromise for thermal, and visual comfort and for IAQ by choosing optical characteristics of materials, shading control and ventilation strategies.
Solar and visual transmittance of glazings and shading devices as well as shading control have a significant impact on thermal and visual comfort and have to be chosen carefully to fulfil both perspectives simultaneously.
Cross natural ventilation through skylights when the openings are correctly sized, can be enough and is not very influenced by occupant behaviour.
On the basis of the methodology and the statistical indicators presented in this study, thermal and visual comfort, as well as IAQ can be managed and otimised simultaneausly. By following this approach it is also possible to evaluate the discomfort given by other polluants (TVOC, Formaldehyde, noise, etc) if they occur.
These results will be presented in a future work.

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