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Summer overheating in a new multi-storey building in Berlin: numerical study for improving the indoor microclimate

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Abstract

The topic of indoor overheating in a modern and well-insulated building is investigated. A real case study is proposed, where, even if the summer ambient conditions are not extreme, thermal discomfort has been verified during the first years of operations. The office building, built recently in Berlin, fulfils the German requirements in matter of energy performance of buildings and heat protection in summertime. Active system for the space cooling are not installed. In the frame of the new international approach to the cost-optimality, by adopting the adaptive comfort criteria for naturally-ventilated buildings, strategies for improving the indoor conditions during the cooling season are here investigated, by analysing various typologies and management strategies for solar shadings.

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Keywords: Energy efficient buildings, summer overheating, nonresidential buildings, building performance simulation, cost-optimal

1. Introduction

The next goal of the worldwide construction activity looks to buildings that require zero or very low energy demand for their operation, fulfilling requirements of cost-optimality [1]. During the last years, high efficient new buildings have been erected all around Europe, with care to the reduction of energy demand for the winter heating. The high attention to the efficiency in the space heating has mainly two motivations: a) this has the highest share of energy demand among the various energy uses, b) the European cultures and politics in matter of energy efficiency in buildings have been historically

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developed in "heating dominated climates". Due to the increase of the thermal insulation and the use of solar gains, also in cold climates, overheating phenomena during the warm season can occur. The use of air-conditioning systems and equipment is quite common in Mediterranean Countries. Diversely, it is not common, and not recommended, in other European countries. This paper, with reference to a German case study, proposes some investigations, based on the concept of the cost-optimality, for improving the indoor summer conditions.

2. Overheating in naturally ventilated buildings: Literature State of Art

The thermal comfort during the warm season, in naturally ventilated buildings, is usually investigated by considering an adaptive approach, as proposed by international methods (e.g., EN 15251/2007). The topic is quite complex [2] and some questions are not yet completely investigated [3]. In France, Moujalled *et al*. [4] show high temperatures in offices during the warm season, in a case study located in France. In the same nation, Brun *et al*. [5] propose the adoption of a thermal energy storage based on the phase change technology, while, in Germany, Eicker [6] described the monitored energy performances of an office building rehabilitated according to passive criteria. In order to evaluate the risks of overheating in residential buildings, Jenkins *et al*. [7] proposed a surrogate model that integrates probabilistic climate projections and dynamic building simulations. Yang *et al*. [8] underline the contrasting effects concerning the variations of energy use for heating and cooling. Generally, the decrement of the first implies an increment of the second. Yao *et al*. [9], by co-simulations based on the use of EnergyPlus [10], have investigated the control of solar shadings for the reduction of the solar heat gains through windows in office buildings. Bellia *et al*. [11] and Katunský and Lopušniak [12] studied the capability of various kinds of external shading systems in improving the building performances. High-insulated buildings are aimed at reducing the energy transferred through the envelope, and these are obviously characterized by low energy losses in winter. According to Badescu *et al*. [13], the summer overheating is much more frequent and problematic for high-insulated buildings compared to standard ones.

1. Description of the case study

The office building is located in Berlin and it was completed during 2012. The building is used by the German Federal Office for Building and Regional Planning. It has six-floors, with a rectangular shape mainly developed in the north-south direction. Table 1 provides the main information. The building is not equipped (with the exception of the meeting rooms) with mechanical cooling systems. During the first years of operations, indoor overheating problems have been recorded. The thermal-physical properties of the building envelope respect the requirements of the German regulation into force at the building time, for both the opaque and the transparent envelopes (EnEV 2009 [14], DIN 4108-2:2003[15]). The building was equipped with an extensive green roof. Large fenestrations allow solar gains during the entire year.

The present study will analyse, by taking into account tailored boundary conditions, several possible strategies for improving the indoor microclimate in summer, by reducing the indoor overheating without penalizing the achievable daylight. The European criterion of cost-optimality is considered. The EPBD Recast [1] establishes the approach of the cost-optimality. Once defined a reference building (step 1), a set of energy efficiency measures is selected (step 2). Then, primary energy demand for the building operation (step 3) and global costs (step 4) are evaluated. Furthermore, a sensitivity study is performed (step 5), by varying the boundary conditions. Finally (step 6) is the identification of the cost optimal configuration. For the investigated building, the possible solutions are very limited. Indeed, structural or "heavy" measures (e.g. overhanging systems for better shading, mechanical ventilation system) are not suitable, because the building is new and went in operation recently. A green roof is already installed and the natural ventilation at nighttime is limited, because of reasons of security.

Table 1. Building information and geometrical characteristics

Positions and Dimensions	Englische Straße 5, 10587 Berlin – Charlottenburg, Germany		
Latitude	52°30’54’’ North	Longitude	13°19’54’’ East
Length (South-North)	80 m	Width (East-West)	14 m
Height	24.5 m	Gross Volume	28’749 m^3
Surface to volume ratio	0.26 m^{-1}	Building net floor Area	7’585 m^2
Gross Wall Area	4728 m^2	Window-Wall Ratio [%]	43.5

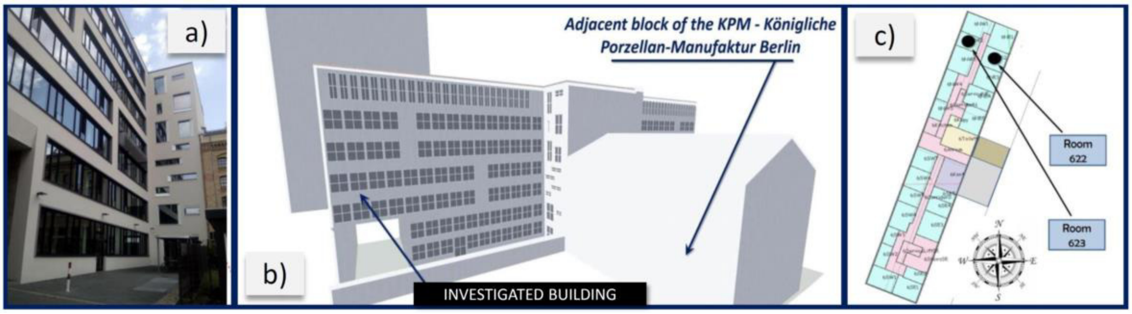

Fig. 1. Pictures and model of the investigated building in Berlin

Finally, only the optimization of solar shading solutions seems to be compatible with the constraints. The critical façades are those exposed at west and east and thus horizontal shadings would not be completely effective. Changes in the solar shading have an effect not only on the solar gains but also on the demand of artificial lighting. This dependence and the resulting effects have to be taken into account in the cost-optimal analysis. In our study, the total costs are considered as sum of investment costs and annual costs for operation, maintenance, replacement. The investigations, by considering common European prices of technologies, take into account investment costs of several typologies of shading systems as well as operational costs of artificial lighting, variable depending on: a) the daylight allowed by the glazed envelope and b) the considered shading system and its control.

For the dynamic simulation of the building performances, the used code is EnergyPlus 7.2.0 [10], with the geometry definition by means of DesignBuilder [16]. Several scientific papers underline the high capability of this energy program. Recently, Chan and Chow [17] and Pisello *et al.* [18, 19] have successfully used it. In equation 1, C_g is the total cost referred to the starting year, C_I is the initial expenditure, R and V are, respectively, the discounting factor and the residual value of the energy efficiency measure at the end of the calculation period.

$$C_g(\tau)=C_I+\sum_j\left[\sum_{i=1}^{\tau}\left(C_{a,i}(j)\times R_d(i)\right)-V_{f,\tau}(j)\right] \tag{1}$$

2. Results and Discussion

The Standard EN 15251 evaluates the comfort conditions as strictly related to the outside temperatures. In particular, the exponentially weighted running mean of the daily external temperatures’ series influence the admitted comfort ranges of the indoor operative temperatures. In our study, in order to combine both accuracy and readability of the values, a period of two-weeks has been considered. Then, the limits of the EN 15251 for operative temperatures according to the Categories I, II and III have been calculated. Only like reference, for evaluating the achievable indoor comfort conditions in the studied building, normally the Category II shall be achieved for the design of new erected German Federal Buildings. Really, the investigated case study is not owned by the German Institutions, and thus this constraint has been not considered during the designing phase.

2.1. Present building

The achievable summer comfort in the present building has been calculated by taking into account both the activation (a threshold of solar radiation equal to 150 W/m^2 has been fixed for the activation of the shadings) and deactivation of the present dark-colored external shading systems. The outcomes are referred to the working hours. The results concern the last floor of the building, and thus one office east-exposed on the north side of the building (room 622) and another one west-exposed, facing on the same corridor (room 623) (see Fig. 1c). In case of a deactivated solar shading system, the indoor comfort is very poor, mainly in the periods characterized by outdoor temperatures not very warm, when the acceptable operative temperatures inside the buildings should be quite moderate. In this period, diversely, the solar radiation is very high at the Berlin latitude, and thus the operative temperatures inside the building are too high for being comfortable. The activation of solar shading systems allows an indisputable and obvious improvement of the indoor comfort (measured by the number of comfortable hours), but does not allow a full comfortable time for the entire season (Fig. 2).

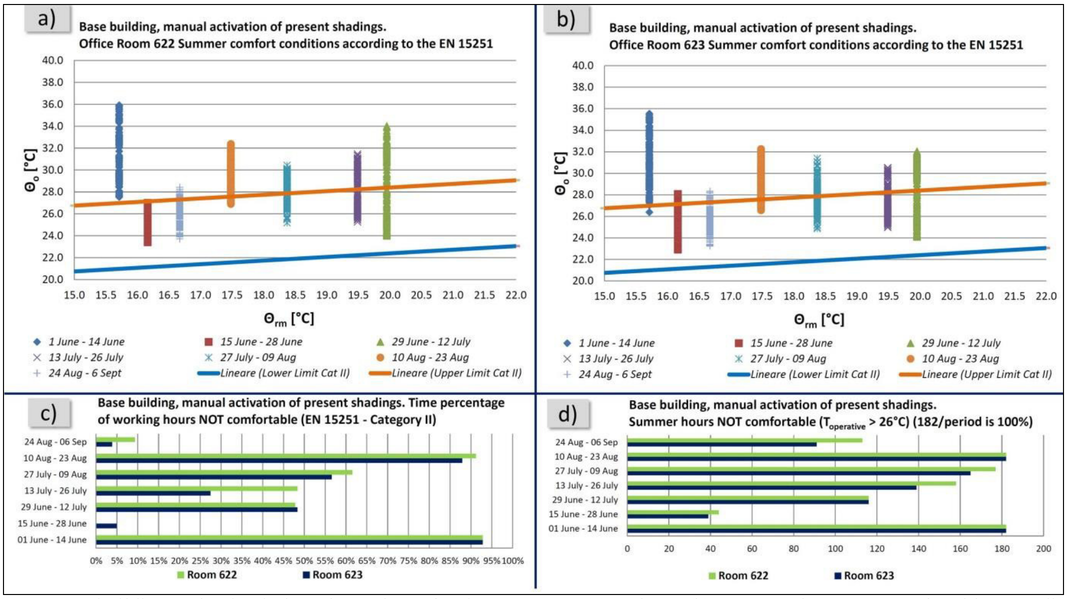

Fig. 2. Present building. Adaptive indoor thermal comfort in rooms 622 (a) and 623 (b). Summer hours not comfortable according to the EN 15251 (c) and absolute number of not comfortable hours according to a simplified criterion (T_{op} > 26°C) (d)

According to our simulations, the use of the solar shading systems induces a decrement of the indoor temperatures of around 4÷6 °C in the building rooms east-exposed, of around 3÷5°C for the office facing on the west façade. These results are valid for almost all considered periods and underline the worse conditions of the east exposure, because of the combined effect of solar gains at the sunrise (and for the entire morning) and of the endogenous gains related to the building use. Diversely, on the west side, even if the solar radiation is significant in the afternoon, however for a long time this enters when the building is no more occupied. In the graphs (c) and (d) of Fig. 2, the not-comfortable time is diagrammed respectively in percentage terms and in absolute value with respect to all summer working hours.

The graph (c) considers the acceptable range of EN 15251 Category II, the graph (d) evaluates the comfortable time by adopting a simplified criterion: the operative temperatures are acceptable if lower or equal to 26°C. This last approach, derived from the theory of Fanger, is still today quite common.

Fig. 3 compares the share of natural daylight achievable in the rooms 622 and 623, without (graph a) and with (graph b) the activation of solar shading system. The results are referred to the period in which the building has the maximum crowding, and thus from 8.00 in the morning to 17.00 in the evening. Without activation of solar screens, the most of the working hours is characterized by indoor illuminance between 500 and 1250 lx. The activation of the solar shading produces hourly illuminance levels in the range between 150 – 750 lx for the large part of the working time.

Regarding to the German standard DIN 12464-1:2011 [20], the required illuminance level at the working place is minimum 500 lx. This value has been considered as reference in our analysis. Thus, for the evaluation of the global costs, the gap between natural illuminance and required illuminance level has to be assured by artificial lighting.

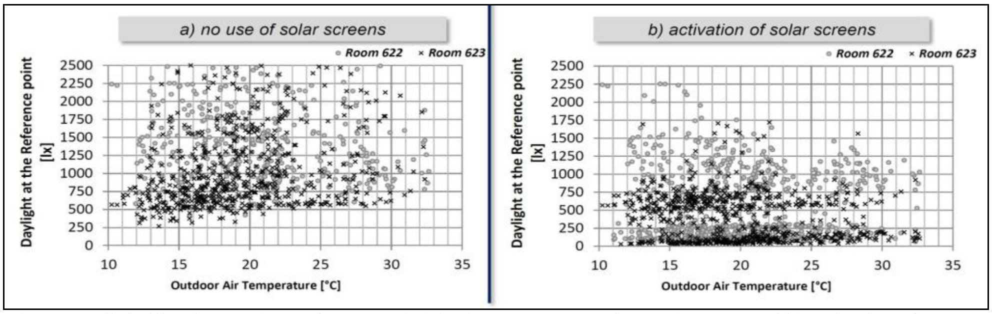

Fig. 3. Daylight illuminance (at a reference point) in the rooms 622 and 623: a) no use and b) activation of screens

2.2. Optimization measures

As seen in Fig. 2, also the use of present dark solar shading does not guarantee summer thermal comfort. As previously discussed, heavy actions should not be considered as well as other passive cooling solutions. Moreover, also the natural ventilation during the night is not admitted by the owners, because of reasons of preservation of the building. Finally, in order to achieve an improvement of the indoor microclimate, without altering significantly the present building, only the reduction of the solar gains can be considered, by evaluating other typologies and controls of the exterior shading systems. The proposed systems for the optimization of the thermal performance in summertime are aimed to avoid both the direct solar radiation as well as the increase of the temperature in the air buffer between the exterior face of windows and the rear side of the external curtains. Indeed, the dark colour of the present systems is not helpful. Diversely, white shadings can reflect the most part of solar radiation, and thus the curtains themselves and the air at their back can be cooler. Beyond the analyses of the present performances, without (Case 0) and with (Case 1) the activation of the present dark-grey curtains, the following alternative solutions have been considered:

- Case 2: new white external curtains (automatic activation when solar irradiance on windows is higher than 150 W/m² (I > 150 W/m^2),
- Case 3: new white external curtains (auto-activation when I > 120 W/m^2 (on window)),
- Case 4: new white external curtains (auto-activation when horizontal I > 100 W/m^2),
- Case 5: new white external curtains (auto-activation when horizontal I > 200 W/m^2),

- Case 6: new white external curtains (auto-activation when horizontal I > 300 W/m^2).

In the following feasibility study, for the lifetime of the building, a usual period of 30 years has been considered. For the lifetime of the shading systems, as well as all parts necessary for their functioning (i.e., control systems, pyranometers), a lifespan of 15 years is assumed. The Cases 2 and 3 require 10 pyranometers and the same number of control units. This relevant number is necessary for dividing the facades in homogenous areas under the point of view of exposure to the sun.

With reference to the summer period, Table 2 proposes the achieved results in terms of achievable comfort hours, for each considered design alternative, from 7.00 in the morning to 19.00 in the afternoon. Moreover, both criteria have been considered, and thus the adaptive approach of the standard EN 15251 and the criterion that, in the cooling season, considers not comfortable operative temperature higher than 26°C. By comparing the simulation results for the proposed solutions and the base cases (Case 0 and Case 1), it can be determined that the solutions are causing a better thermal comfort, in general, but the effect of optimization is not complete. In terms of improved comfort, the best solution is the one that activates the solar white shadings when the horizontal solar irradiance (I) on the roof is higher than 100 W/m^2.

Table 2. Variation of summer comfortable hours (two criteria of evaluation), on varying the shading systems

Case	Kind of building solar shading system	Comfort Hours (EN 15251)	% on total (1274 h)	Comfort Hours (T ≤ 26 °C)	% on total (1274 h)
0	Base Case building - No blinds' use	196.0	15.4%	49.0	3.8%
1	Base Case building - Use of present Blinds	661.5	51.9%	331.0	26.0%
2	White screen: auto-activation if I on windows > 150 W/m²	679.0	53.3%	352.0	27.6%
3	White screen: auto-activation if I on windows > 120 W/m^2	714.0	56.0%	408.5	32.1%
4	White screen: auto-activation if horizontal I > 100 W/m^2	731.0	57.4%	435.5	34.2%
5	White screen: auto-activation if horizontal I > 200 W/m^2	705.5	55.4%	400.5	31.4%
6	White screen: auto-activation if horizontal I > 300 W/m^2	636.0	49.9%	299.0	23.5%

Table 3. Variations of energy demand for lighting and costs, on varying the shading systems and their management

Case	Kind of building solar shading system	Electric Energy for lighting (kWh)	Annual Variation (%)	Lighting Cost (€/year)	Variation of costs (€/year)
0	Base Case building - No blinds' use	116270	-15.4%	33951	-6196
1	Base Case building - Use of present Blinds	137488	----	40146	----
2	White screen: auto-activation if I on windows > 150 W/m²	136439	-0.8%	39840	-306
3	White screen: auto-activation if I on windows > 120 W/m^2	146410	6.5%	42752	2605
4	White screen: auto-activation if horizontal I > 100 W/m^2	214301	55.9%	62576	22429
5	White screen: auto-activation if horizontal I > 200 W/m^2	187204	36.2%	54663	14517
6	White screen: auto-activation if horizontal I > 300 W/m^2	165174	20.1%	48231	8084

Really, the activation for I > 100 W/m^2, as shown in the following lines and Table 3, would imply a massive use of artificial lighting. On the other hand, an improved comfort can be achieved also by means of the solution that activates the solar shading on the basis of the solar irradiance incident on the windows (Cases 2 and 3). These are the only automatic solutions that differentiate the use of solar shadings on the basis of the exposure (i.e., these have also the most complex regulation system). The results of Table 2 have been calculated by averaging the results obtained in the offices west and east exposed. Of course, the use of shadings implies a lower indoor daylight.

In Table 3, the annual requests and costs of artificial lighting are reported. The base case for the comparison is the Case 1. For the evaluation of the costs for the artificial lighting, it has been used the electric price suggested by Eurostat for Germany, equal to 0.292 €/kWh.

The activations of screens for solar irradiance higher than 100 or 200 W/m^2 are the strategies that induce higher costs for the artificial illumination. About it, the increment of energy and economic costs are very relevant, with annual increase respectively around +56% (i.e., 22’450 €) and +36% (i.e., 14’500 €).

The next study compares the indoor comfort and the artificial lighting demand. Indeed, the "utopic" target (black marked point in Fig. 4) is the solution that improves the indoor thermal conditions without penalizing the daylight. The "utopia" solution, of course, cannot be found when an energy efficiency measure has conflicting effects. About it, the use of shading, on one hand, reduces the indoor temperatures (i.e., higher summer comfort) and, on the other side, reduces the natural illuminance.

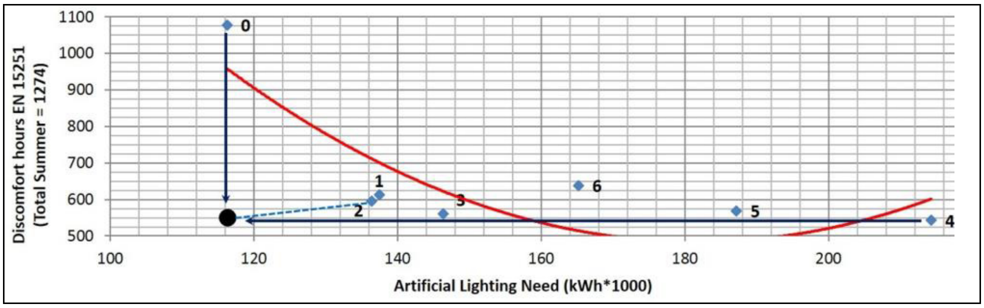

Fig. 4. Thermal Discomfort (Criterion of adaptive comfort EN 15251) vs necessity of artificial lighting

By giving the same "weight" to these necessities, commonly, for optimizing the design choice, the criterion of the lower graphical distance between the performance of one solution and the "utopic one" is considered. For reason of brevity, Fig. 4 shows the outcomes only for the comfort criteria EN 15251. The lowest thermal discomfort in summer is determined by the Cases 3 (i.e., new white screens with diversified activation depending on the exposure) and 4 (i.e., automatic activation if the horizontal irradiance is higher than 100 W/m^2). Diversely, the point closest to the Utopia one is the Case 2 (new white screen with auto-activation for I on windows > 150 W/m^2). Compared to the Case 2, the present building (Case 1) has both higher costs for lighting and lower thermal comfort. The Case 0 (i.e., no use of screens) is immediately excluded. In terms of variation of costs, with reference to the base case (Case 1), the Case 2 implies a saving of around 300 €/year, the Case 3, diversely, increases the present energy demand for artificial lighting and therefore the costs by around 2'600 €/year. Obviously, the building that does not activate the shading systems allows an economic saving for lighting. Fig. 4 shows that also the centralized activation of the solar shading is not suitable, determining too high lighting costs.

2.3. Design choice: the cost-optimal approach

The above presented outcomes reveal that there are – as obvious – conflicting effects caused by the solar shading. As primary effect, there is a reduction of solar gains associated with a decrease of indoor temperatures. But, as secondary effect, there is an increment of artificial lighting, and thus higher energy demand and energy costs. In this section, a global criterion for choosing the most suitable solution, that fulfils the cost-optimal procedure of the Commission Delegated Regulation (EU) No 244/2012, is proposed. For this study, the EU procedure has been adapted to the specific aim, and thus it was searched the solution that allows the "lowest cost of the improved comfort conditions". Therefore, by considering the entire building life, the most suitable solution is the one that reduces, as much as possible, the cost of an additional "comfortable hour/year". The global costs have been calculated according to the method proposed in the Section 1 [1]. For this study, the base case is the present building without use of shadings (Case 0). Indeed, also the present solar shading (Case 1) requires a periodical replacement, and thus this one has been considered like the other solutions. In the application of equation 1, the running costs for the building operations are considered, as well as the periodical replacement of the present system for the solar shadings. For all cases, the actualization of the future investments for replacing the systems does not consider discount factors. Indeed, according to one example proposed by the BPIE [21], "*it was assumed that the price for maintenance and replacement would not increase – i.e. the nominal price increase, which will occur overtime, will be in line with the general inflation rate*".

The calculated C_I costs (investments in equation 1), at the first year, are 85'696 € for the Cases 4, 5 and 6, while the initial expenditure is higher for the solutions 2 and 3 (111'571 €) because of the 10 pyranometers and controllers. The Case 1 has a cost of 82'821 €, to be paid at the end of the 15th year. Being the calculation period equal to 30 years and the interval of the periodical replacements set at 15 years, at the end of the calculation period, the residual value of the energy efficiency measures is zero. The discount factor is equal to 3%/year. All results of the investigations are reported in Fig. 5.

Immediately, it should be noted that the operational costs have an impact, on the global costs, much higher compared to the investments for energy efficiency measures. In Fig. 5a, the highest global costs of the Case 4 are quite evident. This is due to the higher operational costs due to the use of artificial lighting, being the shading systems activated also for low value of horizontal radiation (> 100 W/m^2). It means that, in the first hours of the morning, also the west windows are shaded, because the control system is centralized. This solution is the one that minimizes the solar gains in the building and thus the one that increases the comfortable time. Really, the improvement of thermal comfort, compared to Case 3 (activation of screen diversified for exposure) is not very significant. The high global cost of Case 4 is due to the great additional amount of electric lighting that, of course, produces also an increment of indoor operative temperatures. This last point, here cited only as further "food for thought", would require specific investigations. The Case 3 (i.e., adoption of white screen automatically activated on the basis of the actual irradiance on the windows) increases significantly the comfortable hours, with acceptable investments and reasonable increment of electric energy for the artificial lighting. Of course, by requiring 10 pyranometers and the same number of control systems (analogously to the Case 2), this is a little bit more expensive compared to the other energy efficiency measures, even if, as said, the investments have a limited impact on the global costs. The aforementioned Case 2 shows good results too.

It can be noted that, even if the Cases 4, 5 and 6 have the same "hardware" (activation of shadings on depending on the horizontal irradiance), these provide very different global costs: lower for solution 6 (being this the one that minimizes the indoor shading and thus the lighting cost), higher for solution 4 (due to the high artificial lighting). Moreover, by comparing Fig. 5a and Fig. 5b, it can be noted that the increments of thermal comfort and global costs go in the same directions.

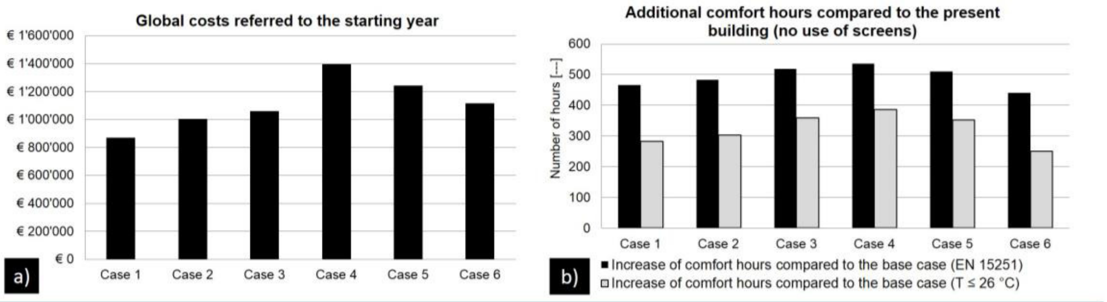

Fig. 5. Global costs due to the application of the energy efficiency measures (a) and improved indoor thermal comfort (b)

All told, a possible criterion of choice is the lowest specific cost of the additional achieved comfortable hour/year in the building. Here, only the criterion of EN 15251 has been considered, for reason of brevity. The best cases are the solutions numbered as 2 and 3, with specific costs of the additional comfort hour of about 40 €. This cost has been calculated on the basis of the global costs for the entire lifespan.

Diversely, the worst result is achieved by the solution 6, which does not allow a satisfactory increment of comfortable hours, so that the specific cost is higher (51 €/additional hour of comfort).

Finally, starting from the base case (solution 1) and with reference to the entire period from 1st May to 30 September, also the avoided "kelvin * hours" (Kh), by applying the best solution, have been calculated. In particular, the hourly indoor operative temperatures, for the last floor of the building and by taking into account the dimension of each room, have been averaged, by achieving the hourly mean temperature (Kh). Then, for each hour, the differences among the Kh of Case 1 (base solution) and 3 (best solution, according to the cost-optimality) have been evaluated and summed for the entire period. The results, by considering 7 days per week, reveal that the sum of hourly differences of the indoor averaged operative temperature between present building and refurbished ones are:

- ✓ 1016 Kh if 24 hours/day are considered,
- ✓ 545 Kh if the mere working period is taken into account.

This is only a suggestion, but reveals an evident achievable improvement of the indoor conditions.

Conclusions

The paper has investigated light energy efficiency measures aimed at improving the indoor comfort during the warm season in a new office building in Berlin (Germany). Indeed, during the first two years of operation, indoor operative temperatures not comfortable have been registered. In order to evaluate only feasible energy efficiency measures (more efficient actions, as, for instance, a lower share of glazed surface, would require massive works), only different systems for the building protection against the solar gains have been considered. More in detail, high-reflective shadings (presently, the building has exterior dark curtains) have been proposed and analyzed by means of transient numerical models. The energy performances, in terms of indoor comfort and variation in the use of artificial lighting (for conserving the illuminance-target of 500 lx at the work places) have been tested and then, as criterion of selection, the cost-optimal procedure has been considered. The cost-optimality, as suggested by the recent European guidelines in matter of design of nearly-zero energy buildings, has been adapted to the study of thermal comfort. According to the achieved outcomes, the optimal solutions are those characterized by white screens, managed by controllers that allow a diversification of the shading use on the basis of the irradiance conditions at specific areas of the vertical envelope. On the other hand, centralized controls, based on the use of a unique pyranometer on the flat roof, do not allow optimal performances. Indeed, these induce, on the basis of the threshold values of the solar irradiance for the shading activation, high energy costs for the artificial lighting (when the threshold for the activation is 100 W/m^2) or not comfortable indoor operative temperatures (when the irradiance value for the use of screens is too high). All investigated light energy efficiency measures induce an improved thermal comfort in summer. However, none of these measures leads to a thermal comfort that is completely satisfactory.

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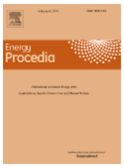

Biography

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