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Cost effectiveness of thermal mitigation based on the long term thermal analysis of a large office building

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Abstract

Multi-storey steel-and-glass office buildings suffer from a strong thermal load during the summertime, particularly in Mediterranean countries, and thermal discomfort is a very likely occurrence, even when a massive air conditioning centralized system is operated. Significant departures from thermal comfort conditions have been proven to result in decreased performance for office workers, which translates into a additional costs for the employer.

In this work we initially use the results of an extensive measurement campaign to characterize the overall summer comfort, using long term descriptors which also integrate a method to select the appropriate thermal quality class for each environment. We then simulate the change in the thermal environment produced by the use of solar control films, a very simple and low cost thermal mitigation action, and calculate the associated thermal-induced increase in performance. Finally, we estimate the costs and benefits so that the cost-effectiveness of such an action is calculated. Results show that the fractional discomfort time (PMV outside the -0.5 to 0.5 range) is 15 – 20% at best and can grow up to 70 – 80% in specific rooms. Performance improvements up to 1.5% can be achieved. Although this figure may look unimpressive, the implied cost to benefit ratio is nonetheless very small (1/8 to 1/3 – that is benefits exceed costs by a factor 3 to 8). Considerations based on economics as well as general well being of employees strongly recommend the adoption of solar control films or similar technical improvements.

Keywords
Long term thermal comfort, cost effectiveness

1. Introduction

Many multi-storey steel-and-glass office buildings were built in Italy during the 60's and the 70's with limited if any consideration of energy savings technologies and thermal comfort issues. Because of the presence of single glazed glass and the absence of any insulating layer, these buildings suffer from a strong thermal load during the summertime, particularly in Mediterranean countries. Although the general sensitivity to thermal comfort issues is much higher today, the limited budget typically allocated for thermal mitigation actions poses strong limitation to the introduction of technological elements for comfort improvements. It is therefore of primary importance to have reliable estimates of costs/benefits ratios for several different options, in order to make a sensible decision. However, while costs are usually straightforward to calculate, benefits can be much harder to quantify.

Purpose of the study

This paper's objective is twofold:

a) to complete a thorough assessment of the current thermal state of a large office building. To this aim, the statistical distribution of PMV is discussed, several long-term discomfort indexes are calculated for the whole summer, and a criterion is established for the selection of the one which is most adequate to predict work productivity.

b) to determine costs and benefits of a very simple thermal mitigation action. To this aim, simulations are carried out to predict the thermal impact of improving existing window glasses with solar control films. Costs and benefits are calculated, the latter taking into account the higher performance of employees.

2. Method

The target of our investigation is a large, five-storey office building located in a flat area near Milan, Italy. The building has a latin cross shape, with its major axis roughly aligned in the N-S direction. Figure 1 provides a sketchy map of the bulding's third floor where most measurements have been performed. Measurement sites are marked with red dots.

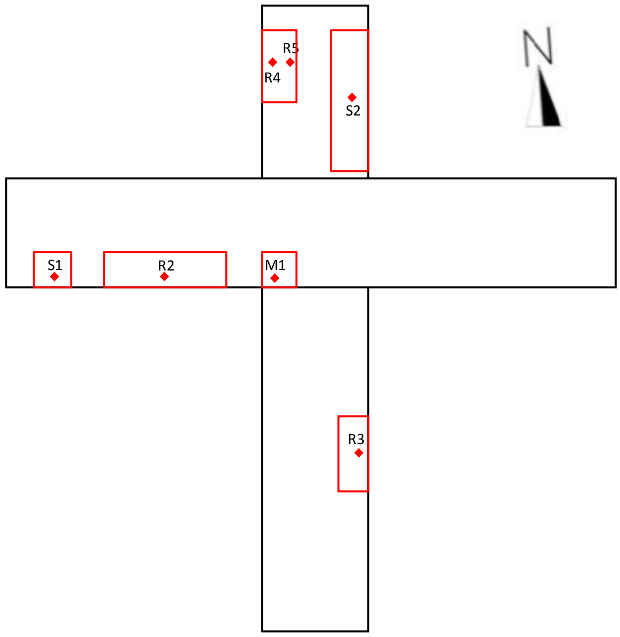

Figure 1 – Map of the building's 3rd floor. Investigated rooms marked with red lines; measurement sites marked with red dots.

Measurements have been carried out in nine different locations inside eight different rooms. Measurement sites have been selected in order to collect a sample which is representative of the thermal variability occurring in the building, with respect to a) orientation, b) floor; c) position within a given room, in descending order. All tested rooms are multiple offices, with areas between 35 and 300 m^2. The maximum (theoretical) number of occupants in each room, taken equal to the number of workstations, ranges between 5 and 73. Table I provides a synthesis of all tested locations, including the relevant room, its size, orientation and the number of employees.

Position ID	Room ID	Orientation	Floor	Floor area (m^2)	Window area (m^2)	Number of employees
M1	01	S-W	3	45.1	22.54	10
R1	02	S	1	121.6	33.81	18
R2	03	S	3	300.9	90.16	45
R3	04	E	3	36.5	11.27	5
R4	05	W	3	121.7	33.81	30
R5	05	W	3	121.7	33.81	30
S1	06	S	3	54.7	11.27	9
S2	07	E	3	360.4	101.43	73
S3	08	E	2	150.3	33.81	20

Table I – Synthesis of measurements

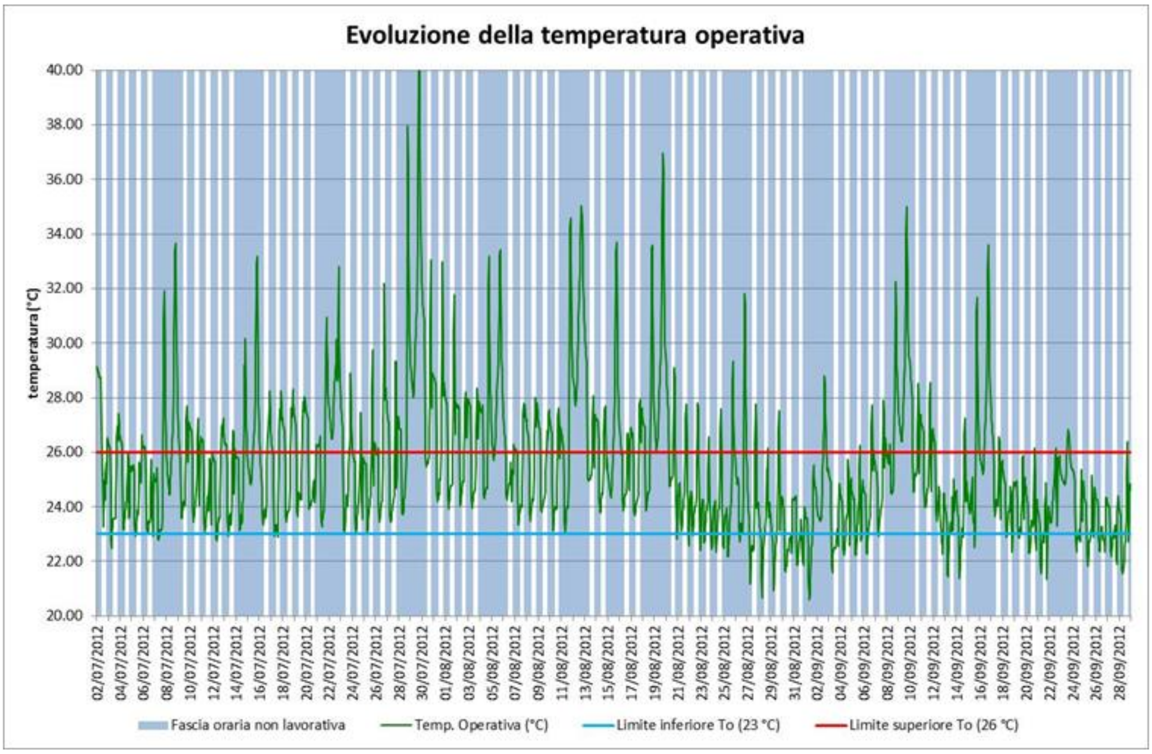

Figure 2 – Operative temperature as a function of time

Simultaneous measurements of the environmental quantities relevant to thermal comfort (air temperature and relative humidity, air velocity, globe temperature) have been carried out using a set of dedicated sensors remotely connected to a data logger. All instrumentation is commercialized by LSI-LASTEM [1].Measurements have been taken non-stop for the 10 weeks from July 2 to September 7, 2012. Some data were eventually discarded after scrutiny for possible instrumental malfunctions. After averaging all data over consecutive 15 minute periods, and discarding data outside office work hours (9 am to 6 pm), a total of 1850 datasets resulted. The full summer time evolution of the operative temperature at the position R4 is shown in Figure 2. Vertical white lines mark working days. Besides four very warm days between the end of July and the beginning of August, which also include the highest operative temperature recorded ($t_{o\text{-}max}$ = 33°C), the systematic occurrence of temperatures around 28°C is a clear indication of strong and consistent discomfort.

3. Results

Long term comfort

In the building targeted by our investigation employees are engaged in office work. Calculations of PMV have accordingly been carried out assuming the same metabolic activity of 1 met and the same clothing thermal insulation of 0.5 clo for all employees in all office rooms at all times. The value of 0.5 clo is very similar to that found in an extensive experimental survey carried out in a few southern Italy office building, both with and without air conditioning [2]. The time history of PMV has been synthesized in a single value, representative of long term summer comfort (LTC = Long Term Comfort), using method C and method D as detailed in Appendix H of the ISO 7730 standard [3]. According to method C we have

$$LTC_C = \sum_j wf_j \times t_j \qquad (1a)$$

where t is time in [h]. As for the weighting factor wf, the following rules apply:

- wf =1 if PPD < PPD_{lim}
- wf = PPD/PPD_{lim} otherwise

In order to improve its "readability", LTC has been scaled in this paper to give a dimensionless value

$$LTC*_C = \frac{\sum_j wf_j \times t_j}{\sum_j t_j} \qquad (1b)$$

According to method D, LTC is the simple arithmetic mean of all PPD values

$$LTC_D = \frac{\sum_j PPD_j \times t_j}{\sum_j t_j} \qquad (2)$$

LTC_C has dimensions [h], whereas both LTC^*_C and LTC_D are dimensionless.

Thermal quality class

Calculation of LTC_C and LTC^*_C requires that PPD_{lim} is known. ISO 7730 provides three different values of PPD_{lim} (6% – 10% – 15%) according to the quality class which is adopted in the comfort assessment, but fails to include any method to identify the correct quality class. In this work the quality class has been found using a method [4] that takes into account:

1. the individual thermal sensitivity (function of age);
2. the accuracy of the task to be performed;
3. the practicality of thermal technical manipulation

ranked according to relevance. Each of the three factors is quantified by a score F_i on a 0 to 10 scale. The overall score F is found using the algorithm

$$F = \prod_i F_i^{p_i} \qquad (3)$$

where $p_1 = 5/3$, $p_2 = 4/3$ and $p_3 = 1$. Two thresholds exist that separate Class A (F> 3000), from Class B (500 < F < 3000) from Class C (F < 500) environments. In the case under consideration, we set $F_1 = 5$ (healthy adult individual) $F_2 = 8$ (mentally demanding task) and $F_3 = 5$ (no structural constraints to air-conditioning devices). Equation (3) then gives an overall score F = 1260 which in turn implies that all the environments which are targeted in this study belong in Class B, with summer comfort limits for acceptability $PMV_{lim} = 0.5$ and $PPD_{lim} = 10\%$.

Position ID	**PMV_{min}**	**PMV_{max}**	**LTC^*_C**	**LTC_D**	$\overline{P}$
M1	-1.36	2.46	1.36	11.81	0.991
R1	-0.15	1.31	1.24	11.20	0.982
R2	-0.06	2.06	1.95	18.93	0.977
R3	-0.88	1.94	1.49	12.25	0.985
R4	-1.60	2.68	1.48	13.07	0.991
R5	-0.73	2.42	1.10	8.26	0.990
S1	-0.74	2.19	2.06	19.58	0.977
S2	-0.43	1.57	1.42	12.06	0.982
S3	-0.26	1.76	1.89	18.20	0.977

Table II – Summary of thermal comfort and productivity

The long term comfort descriptors LTC^{*}_{C} and LTC_{D} have been calculated for each measurement point, and results are shown in Table II, along with the highest and lowest value of PMV found during the office hours.

Thermal comfort and productivity

Thermal discomfort is well known to have a significant impact on both physical and mental performance, including workplace productivity [5]. In order to estimate the productivity change due to thermal factors, we use the relationship found by Jensen et al. [6]

$$RP = -0.0069 \times tsv^2 - 0.0123 \times tsv + 0.9945 \quad (4)$$

This relationship links the relative productivity (RP) for office tasks to the thermal sensation vote “tsv”. This function has a maximum at tsv = -0.9, which agrees with other study indicating that optimal performance is achieved with slightly below comfort temperatures [7].

The focus of this paper is on integrated summer productivity. This quantity is readily calculated from the detailed time evolution of productivity. In order to calculate the latter, it has to be recognized that each value of PMV resulting from our experimental field measurements is the weighted mean of various thermal sensation voted cast by different individuals [3]. This “biological diversity” is well approximated by a normal distribution with a standard deviation of 0.75 *tsv* units. Accordingly, each value of PMV has been used to generate a distribution of thermal sensation votes, and RP at any generic time t_k has been calculated as a weighed mean

$$P(t_k) = \frac{\sum_j P_j\left(tsv_j\right) \times w_j}{\sum_j w_j} \quad (5)$$

where individual weights are given by the fractional abundance of subjects casting the thermal sensation vote tsv_j. Once the productivity has been calculated at any given time t_k, the time-integrated summer productivity is the simple arithmetic mean over the K time slots

$$\overline{P} = \frac{\sum_{k=1}^{K} P(t_k)}{K} \quad (6)$$

Values of $\overline{P}$ are shown in the last column of Table II.

4. Discussion

The current thermal environment 1: Probability distributions of PMV

The probability density function of PMV values is roughly normal in environments where deviations from comfort are of minor relevance (eg, room S2, Figure 3a), whereas it shows a more significant bimodality in environments where deviations from comfort are larger (eg. Room S1, Figure 3b). Using two normal distributions very good fits are usually achieved, with rms departures on each point of order 4×10^{-3} to 6×10^{-3}, three to five times better than using a single normal distribution. In three out of nine points the fraction of measurements resulting in PMV within the appropriate acceptability range [-0.5 +0.5] is below 30%; this fraction is between 50 and 60% in four points and greater than 70% in just two points (Figure 4).

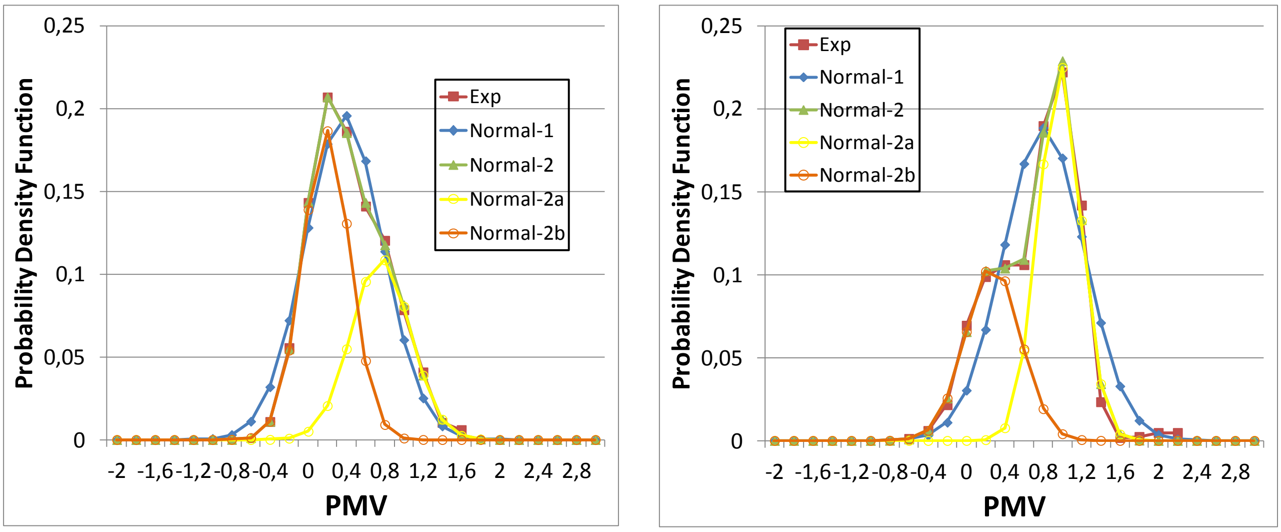

Figure 3 – Probability Density Function of PMV – a) Room S2 – b) Room S1
Blue: One normal distribution – Green: cumulated two normal distributions – Orange and Yellow: individual components of two normal distributions

The PMV value requested to cumulate 95% of measurements (hereafter $PMV_{95\%}$) ranges between 0.6 and 1.5, and is shown in Figure 5. In line with statistical arguments which assign particular significance to the 95% fraction, we think that $PMV_{95\%}$ is a suitable indicator of long-term discomfort. With respect to the identification of a possible limit of acceptability for $PMV_{95\%}$, the only real constraint is that it cannot be lower than 0.5, which is the limit set by ISO 7730 (Class B), and usually applied to thermal comfort assessment on short timescales.

Figure 5 shows that results fall into one of two classes: five measurement sites (R2, R3, S1 S2 and S3) have $PMV_{95\%}$ well above 1; in the remaining four sites (M1, R1 R4 and R5) $PMV_{95\%}$ ranges between 0.65 and 0.83. We use these findings to set the a tentative limit of acceptability around the median of the lower range, that is $PMV_{95\%} = 0.75$. This is 1.5 times the relevant comfort limit set by ISO 7730 for Class B environments. Admittedly, this is presently little more than a guess, since results of this study are not necessarily representative of the whole class of large office buildings. Neither can we prove that some of the thermal environments evaluated in this study can indeed be deemed acceptable. This said, it is our perception that if the limit is set so low that all rooms become thermally unacceptable (below 0.65 in this case), there is very limited chance that any real mitigation action will be implemented. In the opposite extreme, if limit is set too high, comfort would be compromised to an unacceptable degree. Any meaningful limit should be established balancing comfort and practicality.

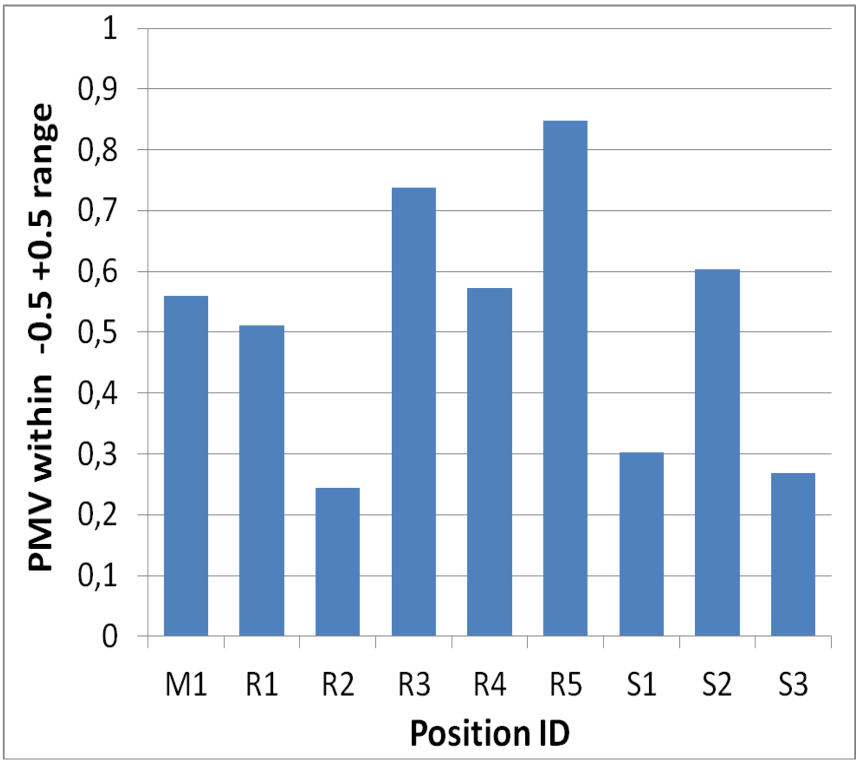

Figure 4 – Fraction of measurements with PMV inside the acceptability range

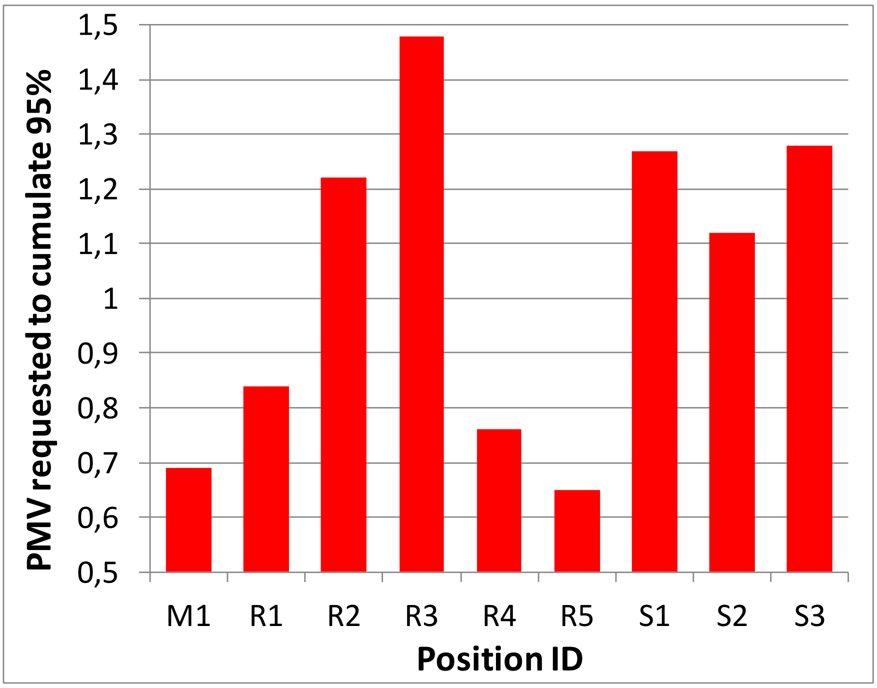

Figure 5 – 95th percentile of the cumulated PMV distribution

The current thermal environment 2: Correlation of LTC indexes with productivity

The correlation of LTC^*_C and LTC_D with $\overline{P}$ is almost identical (r^2 = 0.66 vs. 0.69). Both are adequate estimate of long term comfort in the context that we are exploring in this paper. Figure 6 shows productivity as a function of LTC^*_C. Figure 7 shows the integrated (relative) productivity calculated as detailed in the previous section.

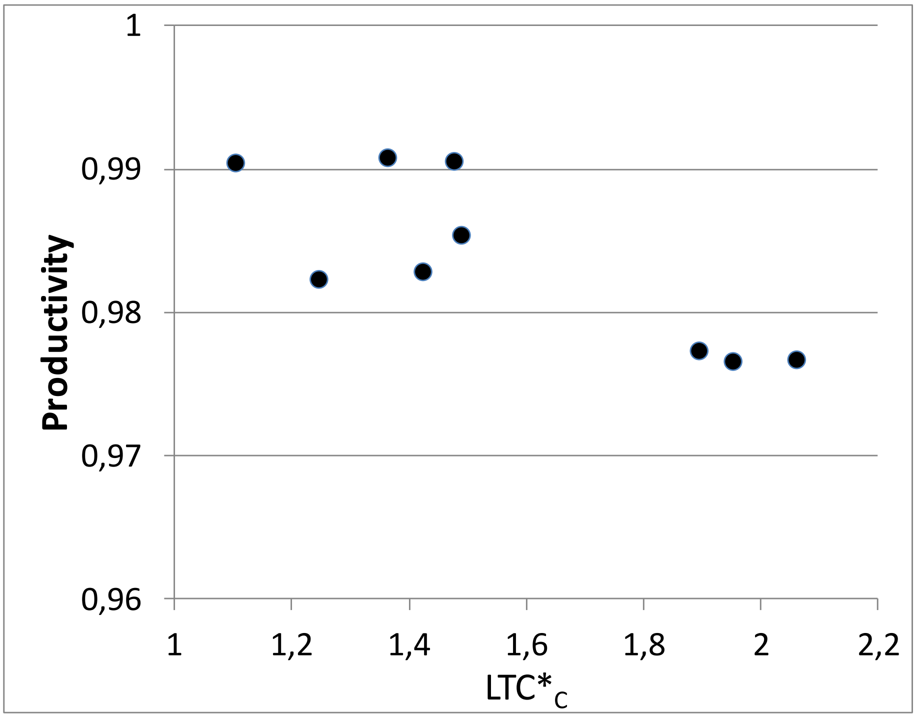

Figure 6 – Integrated productivity vs. LTC^*_C

Figure 7 – Integrated productivity for the different measurement points

Thermal mitigation actions

The building air-conditioning system provides a total airflow of 240000 m^3/h. Summer set point temperatures are 22 – 26°C, with a relative humidity of 50%. The system is periodically inspected and either found compliant to relevant standard of fixed to achieve compliance. However, summer thermal comfort in the building has been found to be generally poor and sometimes very poor (see Figure 4 and Figure 5). Because of a combination of warmer summer conditions, technical obsolescence and a layout which has been repeatedly changed over the years, the air-conditioning system is today clearly inadequate even if correctly operated. Further upgrading the air-conditioning equipment is a costly option. Several cheaper and more eco-friendly alternatives are available.

In this paper we consider a very simple mitigation action, consisting in laying out a solar control film upon the existing window glass. Solar control films, also known as heat rejection films, can be directly applied to the interior of single glass windows to reduce the amount of infrared, visible light, and ultraviolet radiation entering windows. Such films convert incoming solar radiation to infrared radiation, which is then rejected back through the glass to the exterior. More sophisticated and effective solar control systems are available. However they are usually much more expensive (solar control glass) and their implementation often implies significant structural work (external shields / brise soleil). It is extremely unlikely that such devices will be adopted on a the large scale required in building of this size, given the implied time, costs and hassle. On the opposite, the low cost, easy and fast installation, and minimal invasiveness of solar control films make it more likely to be perceived as acceptable even by firms with a low sensitivity to this topic.

Here we assume a polyester film with sputtered treatment, having solar factor (g-value) equal to 0.34, shading coefficient equal to 0.39, visible light transmittance equal to 0.34, visible light reflection equal to 0.24 and total fraction of solar energy rejected of 66%. While films with better solar control properties are commercially available, their visible light transmittance is too poor and unsuitable for offices. From a technical standpoint, this film guarantees a good compromise between low thermal conductivity and good transparency to visual radiation. Overall, when considering also its moderate cost, it represents a good option in those cases where substantial improvement can be expected even with simple devices, and no strict requirements on the thermal and visual environments exist.

Predictions of the thermal improvements induced by this solar control film have been made using the software STEP (Summer Thermal Environment Performance). Simulations have been run for three measurement points, R2 R4 S2, where the window surface faces south, west and east respectively. New (lower) values of the indoor temperature and the radiant temperature have been predicted for the full summer period. Once a new value of t_a is known, a new value of RH has been calculated, by keeping the absolute humidity constant. Every other parameter kept constant, a new value of PMV has been calculated. Finally, application of equations (5) and (6) has led to a new (higher) value of productivity associated to the improved thermal comfort.

Both costs and benefits have both been calculated per capita and per year. Costs have been calculated by dividing the full cost (raw materials + labor cost) of solar control films in each room, by the average number of employees working in the room and by the predicted lifetime of the film.

The film cost has been estimated at 60 € per m^2 of window surface. The average number of employees has been set at 2/3 of the official value shown in Table I. The value of 2/3 has been estimated considering that employees are routinely displaced to work in other locations both in Italy and abroad, for extended periods of time which we estimate at roughly 1/3 of their total work load.

A conservative film lifetime of five years has been assumed. The economic benefit deriving from the improved thermal comfort has been calculated by multiplying the productivity fractional gain $\Delta P/P$ by the per-capita gross income of the work force in the building and by the film fractional effective time, that is the time of the year over which it provides thermal benefits. We adopt for the gross income a figure of 65000 €/year [8], while the fractional effective time is conservatively estimated equal to the fractional time spanned by our investigation, which gives 10 weeks/1 year = 0.19. Table III summarizes the outcome of the simulations: values of the long term comfort index LTC^*_C before (subscript-1) and after (subscript-2) the implementation of the thermal mitigation actions are shown in columns 2 and 3. Integrated productivity gains are shown in column 4, benefits in column 5, and costs in column 6. Finally, the cost to benefit ratio C/B is shown in column 7.

Position ID	**LTC^*_{C-1}**	**LTC^*_{C-2}**	$\Delta \overline{P}$	**Benefits (€)**	**Costs (€)**	**C/B**
R2	1.95	1.17	0.0153	191	24	0.125
R4	1.48	1.61	0.0037	46	16	0.344
S2	1.42	1.04	0.0072	90	18	0.203

Table III – Synthesis of thermal comfort improvements and cost to benefit ratios associated to the use of solar control films

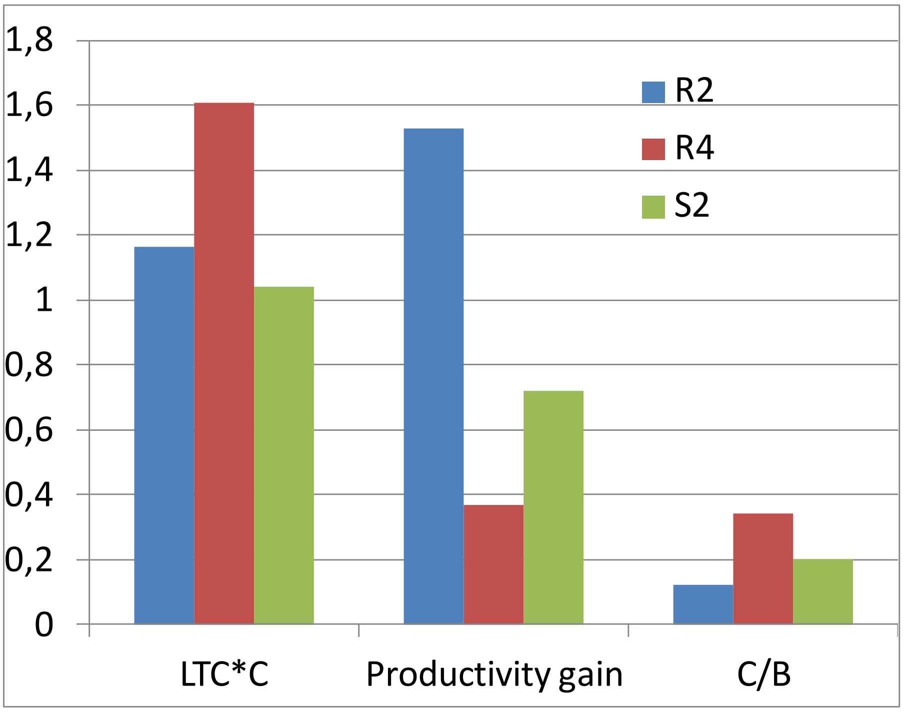

Figure 8 – Long term comfort, productivity gain (×100) and cost to benefit ratio

It is fair to say that estimates of both costs and benefits are quite uncertain: uncertainty on costs derives from the wide variety of solar control films which are commercialized and the poorly known average number of employees in any given room. Uncertainty on benefits is mostly associated to the uncertain estimate of the per-capita gross income of the employees working in this building. This said, the huge mismatch between costs and benefits leaves little room for debate over the meaningfulness of this type of thermal mitigation action. With benefits exceeding costs by factors 3 – 8 (Table III, column 7), the solar films pays for itself in 1/8 to 1/3 of its predicted lifetime, that is, on average, just one summer. Given this very short time, a thorough assessment of the economic impact of the operation should be feasible already at the end of the year immediately following installation, providing direct and relatively quick proof of the achieved benefits. The largest productivity increase is not surprisingly obtained in the south-facing room R2, while the effect is smallest in west-facing room R4 (Figure 8). The fact that a small but positive productivity change is accompanied in R4 by a higher value of LTC*C (higher discomfort) is due to the fact that productivity has a maximum at PMV ≅ -0.9, so that comfort and productivity are not always strictly correlated.

Finally, some extra thermal benefit will undoubtedly be achieved even before (May, June) and after (September) the two months investigated in this work. A tentative estimate has been performed calculating first the total number of “degree-hours”

$$f = \sum_{h=1}^{H} (t_{out} - t_{neutr}) \qquad (7)$$

for each month, and then taking the ratio

$$F = \frac{f_{May} + f_{Sep} + f_{Oct}}{f_{Jul} + f_{Aug}} \qquad (8)$$

In equation (7), t_{out} is the outdoor temperature, t_{neutr} the neutral temperature below which no benefit is expected. The sum is carried out over the total number of office hours in a month H, and includes only non negative terms. Values of F range between 0.40 and 0.32 for neutral temperatures t_{neutr} between 24°C and 26°C. Taking into account this extra benefit would therefore imply a further 25% decrease in the cost/benefit ratio.

5. Conclusions

Widespread summer thermal discomfort is the rule, not the exception in large office buildings, at least in Italy. Built in the 60’s or in the early 70’s with little or no awareness of energy savings concepts, they have been taken into the 21st century virtually untouched. The growing sensitivity to thermal comfort issues has been handled just by overloading air conditioning systems, with large costs and dubious benefits. This is clearly demonstrated by the extensive whole-summer experimental campaign presented in this paper. Long term comfort indexes show that at most 1/3 of offices have thermal conditions at the edge of thermal acceptability. In most rooms limits are exceeded more than 50% of the time, with PMV values extending up to, and sometimes exceeding 1.5 – *this is with the air conditioning system in operation*. In this paper we show that a small but significant productivity increase can be achieved with the adoption of even the most simple-minded and low cost thermal mitigation action (solar control films). Although the mere consideration of arguments related to the workers' comfort should already be sufficient to trigger thermal control actions, the additional force of economic arguments presented here might provide that extra push need to overcome the reluctance to invest time and money into any energy saving technology.

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