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A CLIMATE PERFORMANCE INDICATOR FOR ANALYSIS OF LOW ENERGY BUILDINGS

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ABSTRACT

The climate indicators that are currently used in the building energy area, summations of degree-days, are not suitable for net-zero and low energy analysis, because they fail to characterize the building-climate interaction.

This paper presents a new set of climate indicators that focuses on overall climate and building performance, as well as specific climate statistics that have a relevant impact in NZEB and passive buildings. The proposed framework is based on three interrelated energy performance indicators. The total building climate performance indicator (*BCP*) is the product of the climate potential (*CI*) and building indicator (*BI*). *BI* is building dependent and characterizes the capability of a given building to maximize the existing climate potential (*CI*). The best climates and buildings are expected to have *CI*s and *BI*s that are close to one.

INTRODUCTION

The climate indicators that are currently used in building energy analysis were developed in the 70s and 80s and have a narrow focus that makes them unsuitable for net-zero energy buildings (NZEB) and passive building design analysis [Cory et al., 2011]. In addition, current European building energy ratings are based on total energy consumption [Directive 2010/31/EU], as opposed to the capability of a building to maximize the available climate potential, which is an essential feature of any NZEB. In this context, there is a need for simple indicators that can clearly identify the best climates and the buildings that achieve optimal interaction with a given climate.

The first part of the paper presents a set of primary indicators that focus on a given building's energy performance and its relation with local climate and allow for a clear and quantitative assessment of the challenge presented by a given climate as well as the building performance for that climate.

In addition to these primary indicators, the first part of the paper also presents secondary indicators that allow for further insight into the building/climate interaction, analyzing both climate availability and building requirements for a given energy saving solution (daylighting, natural ventilation, etc.). The proposed analysis framework is applicable to different types of buildings and geographic locations.

This paper presents its application to a single story office building tested in different cities of the Mediterranean region. The development of this framework was based on detailed hourly simulation of a United States Department of Energy (DOE) standard small office building model in five different cities of the Mediterranean region: Lisbon, Montpellier, Rome, Istanbul and Cairo. Special emphasis was given to this region as it has been identified as one of the most vulnerable to climate change [Giorgi, 2002, Solomon et al., 2007].

These cities were also chosen due to their cooling degree-day classification. The first four have comparable cooling degree-days, while the fifth city, Cairo, was chosen due to the large discrepancy with the others, as shown by Table 1 [ASHRAE, 2009].

Table 1
Cooling degree-days [°C h*] of analyzed cities*

Lisbon	Montpellier	Rome	Istanbul	Cairo
599	514	555	616	1767

The second part of this paper presents the simulation results of the standard DOE model and several performance improvement scenarios, which are evaluated using the proposed primary and secondary indicators.

PRIMARY INDICATORS

Climate Indicator

We propose the following three interrelated primary indicators:

$$BCP = CI \times BI \quad (1)$$

The climate indicator (*CI*) assesses a given climate's intrinsic aptitude to match a building's thermal and interior lighting requirements. For a given climate, *CI* is evaluated considering a virtual building with a perfect dynamic envelope with the ability to react to the local climate conditions, maximizing its usability:

- Filtering outside light to obtain the ideal internal lighting conditions

- Containing internal gains to maintain comfort temperature (if needed)
- Using the outside temperature directly whenever it is acceptable.

Overall, this indicator measures the availability of inherent comfort conditions in the outside climate.

CI is quantified using equations 2 and 3, which render, respectively, the fraction of yearly building operation period during which outside air temperature does not exceed 26 °C [EN ISO 7730] and horizontal illuminance does not fall below 500 lx [EN 15251].

$$CI_T = \sum_{\substack{i=1, \\ \text{if } T_{out,i} \leq 26\,°\text{C}}}^{N} \frac{1}{\text{N}} \quad (2)$$

$$CI_L = \sum_{\substack{i=1, \\ \text{if } L_{out,hor,i} \leq 26\,°\text{C}}}^{N} \frac{1}{\text{N}} \quad (3)$$

Figure 1 shown (in gray) the value of CI_T over a three-day span. The value of the indicator increases as long as, during the occupied period the outside temperature is below 26 °C.

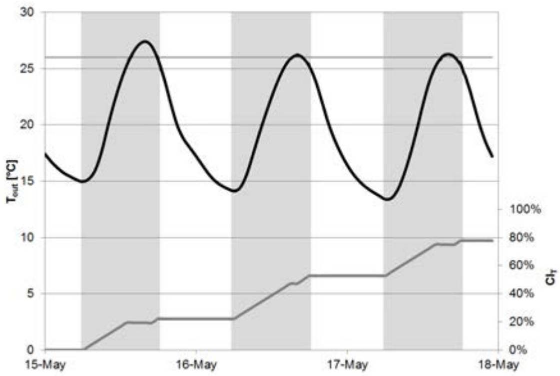

Figure 1
Outside temperature and CI_T

The climate indicator varies between 0 and 1, with the minimum value corresponding to a climate that never satisfies the required thermal or lighting needs. On the other hand, a *CI* equal to 1 represents a climate with the potential to provide comfort during the entire building operation period.

Table 2
CI_T and CI_L of analyzed cities

[%]	Lisbon	Montpellier	Rome	Istanbul	Cairo
CI_T	86	78	77	76	59
CI_L	92	91	89	85	85

The cities analyzed have similar cooling degree-day classifications, and, therefore also have similar CI_Ts (except for Cairo). Considering the CI_L classifications, the difference between the five cities is also very low. The ten-year average, using data from a synthetic database [Giorgi et. al., 2009] for this primary indicator is shown in Table 2.

Building Climate Performance

The building climate performance indicator (*BCP*) assesses a building energy performance, for a given climate, and is calculated using Equations 4 and 5:

$$BCP_T = 1 - \frac{E_T}{E_{T,ref}} \quad (4)$$

$$BCP_L = 1 - \frac{E_L}{E_{L,ref}} \quad (5)$$

This indicator is related to the building's heating, ventilation and air conditioning (HVAC) final energy consumption, evaluated through hourly thermal simulation (in the present case using EnergyPlus [Crawley et al., 2001]). This approach is required in order to model the dynamic heat exchange between internal air and building internal mass (heavy walls and floors).

The calculation of this indicator requires a reference HVAC consumption, which in contrast to *CI*, is based on a virtual building that, apart from ventilation requirements, has no contact with outside conditions. In this way, *BCP* characterizes the building capacity of reducing its HVAC energy needs through an effective interaction with the climate.

This indicator has no lower limit, as HVAC consumption also has no upper limit and has 1 as its maximum value, representing a perfect building with zero HVAC energy requirements.

Building Indicator

Finally, the building indicator (*BI*) quantifies the effectiveness of the relation between the building and the climate, according to Equation 1: *BI* characterizes a building's capability of using local climate to obtain adequate indoor conditions.

Despite the separate calculation of these three indicators for thermal comfort and illumination, it is desirable to combine them into a single indicator. This aggregate indicator is obtained using a weighted average of the two separated indicators, with the weighting factors equaling the previously mentioned reference HVAC and interior lighting energy consumption:

$$I = \frac{E_{T,ref} \times I_T + E_{L,ref} \times I_L}{E_{T,ref} + E_{L,ref}} \quad (6)$$

The increased insight of this approach is clear: a good *BCP* can be the result of an average building (low *BI*) in a good climate (high *CI*) or the opposite. The best passive buildings should achieve a positive resonance with the climate that results in a *BI* that is close to one.

SECONDARY INDICATORS

Secondary climate indicators allow for a more detailed analysis of climate particularities that have a significant effect on the performance of the passive solutions. Optimal NZEBs use passive strategies, with the goal of meeting indoor comfort requirements with very low energy consumption. However, a given passive strategy can have variable performance in climates with similar *CI*s, leading to different *BCP* classifications. This paper focused on daylighting and natural ventilation passive systems. The secondary indicators developed focus on these two strategies.

Daylighting

In order to characterize a climate's daylighting potential, two aspects must be considered. During the cooling period, excessive natural lighting might lead to an unwanted increase in the cooling demand. On the other hand, during the heating season, low availability of solar light might lead to an excessive increase in the heating load, compromising the building performance. The secondary daylighting indicator can be calculated for each of these situations, according to Equations 7 and 8, respectively:

$$SI_{DL,cool} = \sum_{\substack{i=1, \\ \text{if } T_{out,i} \geq 14\ ^{\circ}\mathrm{C}}}^{N} L_{hor,out,i} \tag{7}$$

$$SI_{DL,heat} = \sum_{\substack{i=1, \\ \text{if } T_{out,i} < 14\ ^{\circ}\mathrm{C}}}^{N} L_{hor,out,i} \tag{8}$$

For the first indicator, climates with lower results are expected to have a more significant reduction in energy requirements as a result of increased daylighting. For the second indicator, a higher result will likely lead to a better performance. A single indicator for daylighting, combining both of the previous indicators, can be calculated:

$$SI_{DL} = \frac{SI_{DL,cool}}{SI_{DL,heat}} \tag{9}$$

Natural Ventilation

Natural ventilation can be used with two different purposes: meeting fresh air requirements or reducing cooling thermal load. This paper focused on wind-driven natural ventilation in order to reduce thermal load [Carrilho da Graça et. al., 2012].

For wind-driven cooling there are two strategies:

- Direct daytime cooling, by allowing outside air at a lower temperature to enter the building during the occupied period;
- Nighttime cooling of thermal mass in a similar way during the unoccupied period.

The developed secondary indicator for daytime cooling calculates the cooling potential according to equation 10 [ASHRAE, 2009]:

$$SI_{NV^*} = \sum_{\substack{i=1, \\ \text{if } 0\ ^{\circ}\mathrm{C} \leq \\ T_{in,i}-T_{out,i} \\ \leq 8\ ^{\circ}\mathrm{C}}}^{N} \rho_{air} \times c_{air} \times C_D \times A_{open} \times u_i \times \sqrt{C_{p,inc,i} - C_{p,opo,i}} \times \left(T_{in,i} - T_{out,i}\right) \tag{10}$$

This indicator presents the sensible cooling potential, combining the difference in temperature, and climate availability, through wind velocity and direction (represented by the pressure coefficients on the ventilation openings).

The secondary indicator for nighttime cooling accounts for both the cooling potential during that period and the heat capacity of the first 10 cm of all high thermal mass surfaces [Serway et al., 2000] in contact with internal air (Equation 11):

$$SI_{NV+TM} = \sum_{\substack{\tilde{i}=1, \\ \text{if } 0\ ^{\circ}\mathrm{C} \leq \\ T_{in,\tilde{i}}-T_{out,\tilde{i}} \\ \leq 8\ ^{\circ}\mathrm{C}}}^{\tilde{N}} \rho_{air} \times c_{air} \times C_D \times A_{open} \times u_{\tilde{i}} \times \sqrt{C_{p,inc,\tilde{i}} - C_{p,opo,\tilde{i}}} \times \left(T_{in,\tilde{i}} - T_{out,\tilde{i}}\right) \times \sum_{j} \left(\rho_j \times c_j \times d_j \times A_j\right) \tag{11}$$

SIMULATION OF A STANDARD BUILDING

Base Scenario

The proposed primary and secondary indicators were tested using a standard United States Department of Energy one-story Small Office building model [DOE, 2012]. This standard model was used to evaluate the base performance and impact of passive strategies in the five climates considered.

The first scenario, identified as *Base*, refers to the building model in its original form, without performance-enhancing strategies (Figure 2).

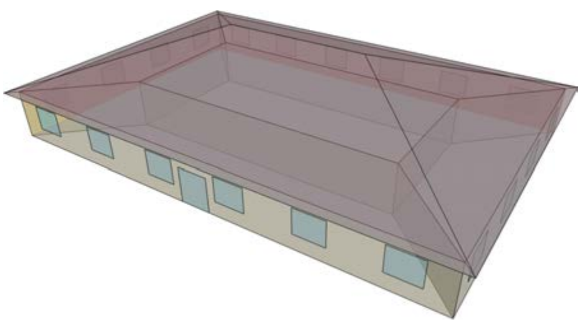

Figure 2
Standard DOE Small Office model

DL Scenario

The second scenario, *DL*, has its focus on daylighting (Figure 3). Indoor illuminance meters are used to adjust artificial light operation, by prioritizing natural light use. This scenario includes the following improvements:

- Artificial light power is decreased through efficiency increase, reducing installed power from 11 to 6 W m^{-2} [DCCEE, 2012].
- Improved glazing with a higher visible light transmittance-solar factor ratio is introduced, allowing for a higher availability of natural light, without a significant increase in solar gain.
- Indoor windows are considered. Although this is expected to not have a significant impact on daylighting, these windows will be used as inside pathways for the wind-driven airflow further ahead regarding the natural ventilation scenarios.
- Shading devices are used on the external windows, in order to decrease excessive solar gain. These devices are controlled by incident solar radiation (activate when a predetermined threshold is exceeded).
- Finally, tubular daylighting devices are used to increase available indoor natural light, especially in the building core [DOE, 2011]. However, it must be noticed that the use of these devices is limited to the uppermost, or at the most, the second highest floor of a building.

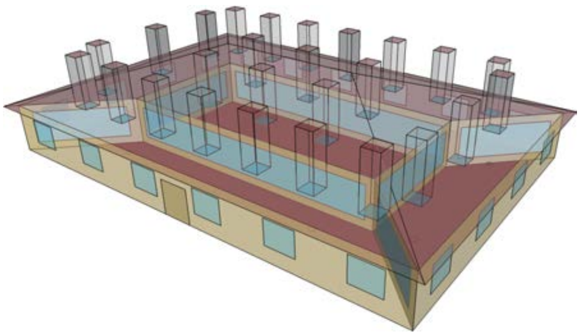

Figure 3
Modified building model

DL+NV Scenario*

The third scenario, *DL+NV**, focuses on wind-driven natural ventilation. This passive method is used during the operation period of the building and consists of the opening of windows whenever the outside temperature is lower than inside. These openings allow wind to enter the building and reduce internal air temperature, therefore, decreasing the cooling thermal need. Window openings were only considered in the northern and southern façades, in order to represent the limitations of the use of this method in a real case scenario. In addition to the reduction in thermal load, whenever the wind-driven airflow was sufficient, mechanical ventilation was turned off.

DL+NV+TM Scenario

The fourth, and final scenario, *DL+NV+TM*, considers the use of natural ventilation for cooling associated with an increase in thermal mass.

- Natural ventilation is used in the occupied and the unoccupied periods.
- The raised floor and suspended ceilings are removed (increasing exposed thermal mass).
- The concrete and insulation layers of the external walls are switched, resulting in the insulation layer being closer to the outside.
- An additional layer of concrete is added to the ceiling.

Table 3
Summary of simulation scenarios

Scenario	Changes
Base	None (original building model)
DL	Use of daylight for lighting requirements, increase in available natural light, window shading
*DL+NV**	Natural ventilation during occupied period
DL+NV+TM	Natural ventilation during occupied and unoccupied periods, increase in thermal mass

These four building model scenarios were simulated for the five previously mentioned cities and for ten years of weather data (Giorgi et. al., 2009). Simulation with multiple years allows for more statistically significant results, when compared to the use of a single "typical" year [Adelard et al., 2000].

DISCUSSION AND RESULT ANALYSIS

Primary Indicators

Despite the similar climate indicators, the model scenarios resulted in different energy requirements. The evolution of thermal load shown in Figure 4 is reflected in the thermal Building Climate Performance indicators shown in Figure 5 (*BCP_T*) and Figure 6 (*BI_T*).

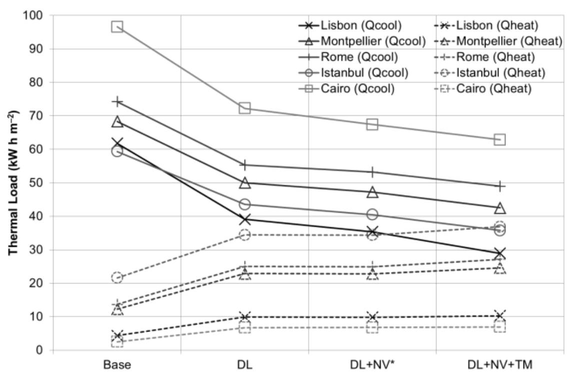

Figure 4

Average thermal loads

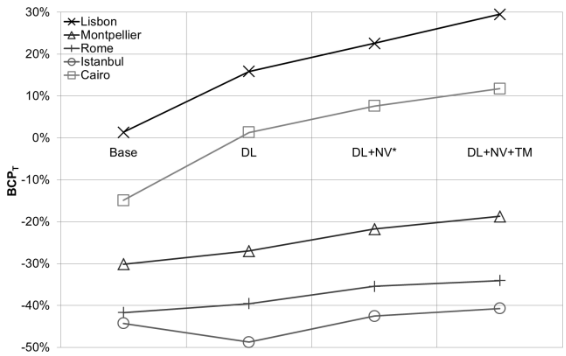

Figure 5
Average BCP_T

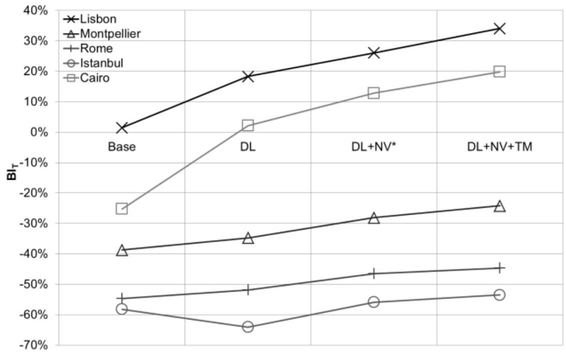

Figure 6
Average BI_T

When lighting energy requirements are included, the difference between the five cities is diluted, as the improved scenarios present high increases in BCP_L and BI_L, which has a significant impact on the aggregate *BCP* and *BI* (shown in Figure 7 and 8).

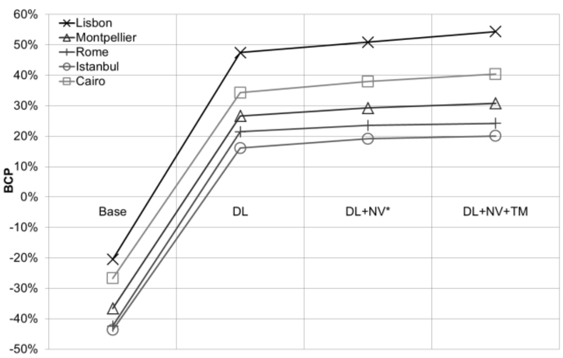

Figure 7
Average BCP

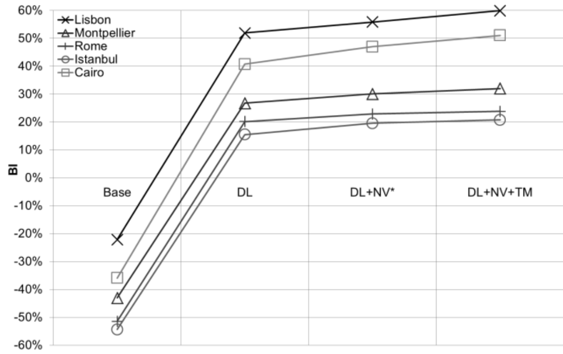

Figure 8
Average BI

As expected, similar measures have different impacts on energy requirements and, thus, lead to different performance indicators, as can be seen in the slightly different slopes for the different cities considered. These differences can be clustered, allowing a simplified analysis further ahead regarding secondary indicators, shown in Table 4.

Table 4
Performance improvement climate clusters

Scenario	Cluster 1	Cluster 2	Cluster 3
DL	Lisbon Cairo	Montpellier Rome	Istanbul
*DL+NV**	Lisbon Cairo	Montpellier Istanbul	Rome
DL+NV+TM	Lisbon	Montpellier Istanbul Cairo	Rome

By plotting the variation in thermal load and the previously mentioned secondary indicators for each simulated year and location, it was possible to explore the correlation between the secondary indicators proposed and the impact of the passive methods for any given climate.

<u>*Daylighting*</u>

The first secondary indicator focuses on available natural light during the cooling and heating season. One can observe that during the former, the use of natural light decreases the heating load, while in the latter, cooling load increases. As expected, Figure 9 shows that climates with less available light during the cooling period lead to higher decreases in the cooling load.

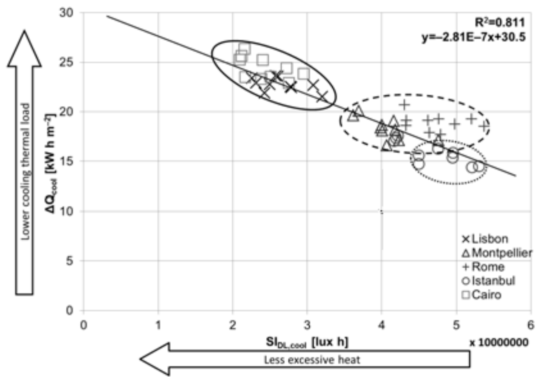

Figure 9
$SI_{DL,cool}$ and decrease in cooling load

On the other hand, locations with more daylight during heating hours lead to a lower increase in heating demand, as can also be seen in Figure 10.

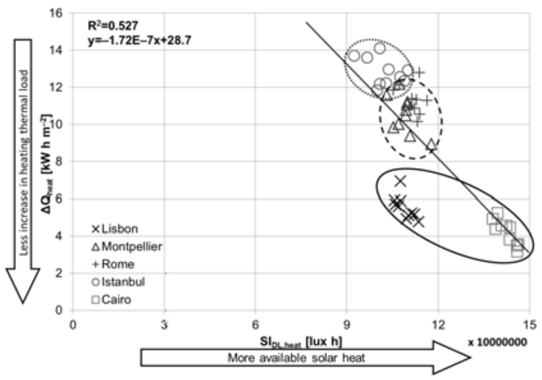

Figure 10
$SI_{DL,heat}$ and increase in heating load

In both cases, the regression line does not cross the chart's origin. This is due to additional, non-modelled effects, on the thermal loads, such as shading and more efficient lights and glazing.

The aggregated daylighting secondary indicator, as well as the separate cooling and heating counterparts, confirm (Figure 11) the climate clusters mentioned in Table 4.

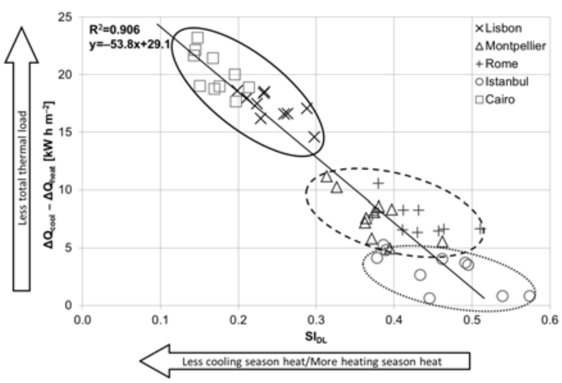

Figure 11
SI_{DL} and total thermal load variation

Again, in this case, the regression line does not cross the origin, meaning that a high SI_{DL} leads to a higher increase in the heating load than in the cooling load, which would decrease the building's *BCP*.

Natural Ventilation

This secondary indicator assesses the potential for wind-driven cooling, reflecting the directionality of the ventilation openings, which face north and south in the simulated models. For this assessment, two cases were considered: *NV** is the previously mentioned *DL+NV**, while for *NV*2* opening area is doubled.

Higher secondary indicator results are expected to lead to lower cooling needs. Equation 12 presents an energy-conservation equilibrium that reflects this decrease. However, this equation also shows that as the thermal load decreases, the effect of the secondary indicator also decreases, which is also demonstrated by the solution of the following differential, conservation, equation:

$$k_1 \times \frac{dQ}{dSI} + Q = k_2 \qquad (12)$$

$$\Delta Q_{cool} = k_3 \times \left(1 - \exp\left(-\frac{SI_{NV^*}}{k_{1,NV^*}}\right)\right) \qquad (13)$$

Figure 12 confirms this, with *NV*2* having higher values of this secondary indicator and also higher decreases in cooling load, with a lower increase in the latter than the increase in the former.

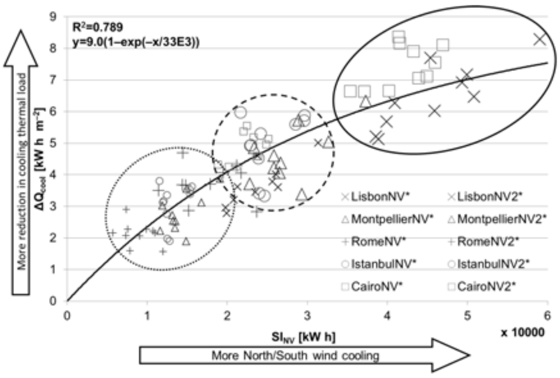

Figure 12
SI_{NV^*} and decrease in cooling load

Natural Ventilation + Thermal Mass

Finally, the third secondary indicator quantifies the effect of wind driven cooling during the unoccupied period resulting from additional exposed thermal mass.

Again, a higher secondary indicator leads to a higher decrease in cooling load (Equation 14).

$$\Delta Q_{cool} = k_4 \times \left(1 - \exp\left(-\frac{SI_{NV+TM}}{k_{1,NV+TM}}\right)\right) \qquad (14)$$

Four cases were considered for this assessment, with 1.0 *TM* representing the building before the increase in thermal mass, 6.3 *TM* equivalent to the results presented previously as *DL+NV+TM* and 2.6 and 4.8 *TM* intermediate situations.

The low-mass cases, shown near the origin of the chart in Figure 13, show that without the increase in thermal mass, use of natural ventilation during the night period has a very low effect. However, the increase in thermal mass leads to a more significant decrease in the cooling load.

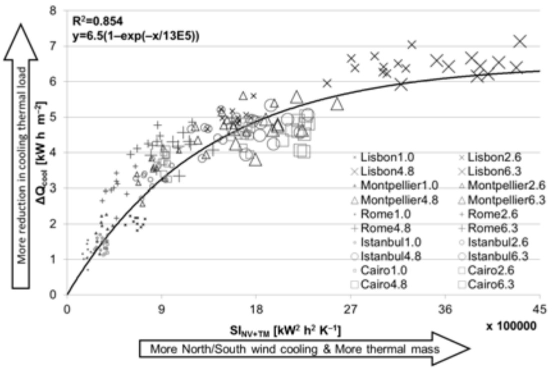

Figure 13
SI_{NV+TM} and decrease in cooling load

In order to simplify these results, Figure 14 presents average the secondary indicator classification and respective average decrease in thermal load for each scenario, allowing the considered climate clusters to be easily seen.

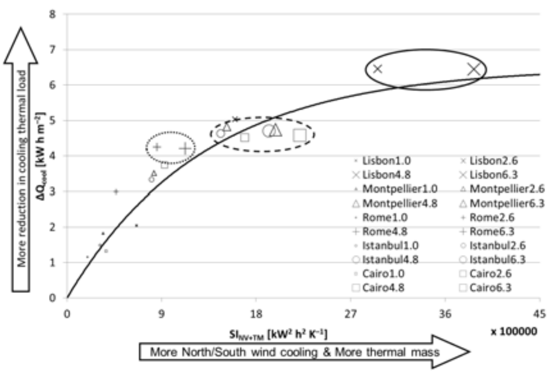

Figure 14
Average SI_{NV+TM} and average decrease in cooling load

This passive cooling method leads to a slight increase in heating, as the inside temperature is lower at the beginning of each operating day and, due to the higher inertia, the building takes longer to heat.

CONCLUSION

This paper presents a framework to evaluate and classify climates and buildings according to their capability of providing comfortable indoor lighting and thermal conditions with low energy demand. The proposed methodology is based on primary and secondary indicators.

The primary indicators (*CI, BI* and *BCP*) evaluate climates and buildings in a simple and precise way. *CI* assesses the climate according to their potential to provide lighting and thermal comfort. *BI*, on the other hand, classifies the building capability of maximizing the existing *CI*. Finally, *BCP* characterizes the overall result of the two potentials.

Secondary indicators provide a more detailed analysis, evaluating climate availability and building necessity for particular passive solutions. By comparing these indicators and their impact on the simulation results, empirical relations were determined, allowing an estimation of the impact of a given solution without the need for detailed thermal simulation.

Although these indicators allow for mapping of climate potential, climate zoning was not a goal: each location is assessed through its climate alone, regardless of neighboring locations. Nonetheless, the proposed indicators are inherently related to a given comfort model and building operation schedule. Therefore, considering of different models, based on other parameters with different comfort ranges, and other operation schedules will lead to different indicator results. For any specific building, a new mapping can be performed, determining the locations where building performance can be optimized.

The proposed secondary indicators require further development, which should allow for improved correlation results and expansion to other locations and passive methods.

NOMENCLATURE

A: Area
BCP: Building Climate Performance
BI: Building Indicator
C: Coefficient
CI: Climate Indicator
E: Electric load
I: Primary indicator
L: Illuminance
N: Number of occupied hours
Ñ: Number of unoccupied hours
Q: Thermal load
R^2: Regression coefficient
SI: Secondary Indicator
T: Temperature
c: Specific heat
d: Width
u: Wind velocity
Greek

ρ: Density
<u>*Subscript*</u>
D: Discharge
DL: Daylighting
L: Lighting
*NV**: Natural ventilation (occupied period only)
NV+TM: Natural ventilation with thermal mass
T: Thermal load
air: Air property
cool: Related to cooling load
heat: Related to heating load
hor: Horizontal
i: Occupied hour number *i*
$\tilde{\imath}$: Unoccupied hour number $\tilde{\imath}$
in: Inside
inc: Incident surface
j: Surface layer *j*
k: Equation parameter
open: Opening
opo: Opposite surface
out: Outside
p: Pressure
ref: Reference condition

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