Contribution of building energy simulations for the assessment of overheating health risks in urban dwellings

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Abstract
This paper introduces a methodology aiming to characterize individual indoor exposure for health risk assessment related to overheating using building energy simulation (BES). Heat stress in BES is currently assessed by stationary indicators, whereas nonstationary thermoregulation models are more appropriate for prolonged exposure. On this basis, this contribution suggests a new set of indicators suited for heat stress analysis on two timescales. To test the methodology, current BES is carried out for different types of urban dwellings and cooling strategies. Results highlight effects of dwelling type and urban climate on the strategy’s efficiency regarding health indicators and limits of current models.

Key Innovations
• Introduction of heat stress analysis method based on BES and heatstroke and recovery indicators deduced from nonstationary thermoregulation models (Deng et al. 2018; Zhao et al. 2020). Day and night indicators and related thresholds are suggested.
• Discussion of the limits of current BES and thermoregulation models on the assessment of overheating health risk.

Practical Implications
This work suggests a method to assess night and day heat stress in urban dwelling using BES for different cooling strategies. New indicators are suggested for a seasonal and daily analysis of the heat stress and the risk of heatstroke: statics indicators derived from current comfort approaches and dynamic indicators derived from thermoregulation models. These indicators highlight on the best materials, configuration, and practices to avoid heatstroke. Results are conditioned on:
• thresholds and acclimatization duration hypothesis;
• the thermal indoor initial conditions;
• the BES boundary conditions.

Introduction
The intensification in peak and frequency of heat waves raises a public health issue, which challenges the way in which building are designed, especially in urban areas due to the urban heat island phenomenon. Prolonged heat exposure overwhelms the body’s thermoregulatory capacity thus potentially inducing life-threatening health risks and diseases (Cheshire 2016). The hyperthermic state, classically defined having a core temperature (temperature of the vital internal organs, T_core [°C]) over 40.5°C, affects human health through several disorders (McGeehin and Mirabelli 2001; Clark and Lipton 1984).

Current health risk indexes used to assess the health risks associated with heat waves are mostly based on large scale statistical data or on outdoor standard weather data (WHO and WMO 2015). Yet, in Europe and North America people spend more than 80% of their time indoors (at work, at home, at school, when travelling...), (ADEME 2015). Health indicators at the dwelling scale appear thus necessary to better assess a healthy design of buildings with respect to heat stress. Adapted methods and tools are therefore required (Amengual et al. 2014).

Classical building design standards address heat stress with respect to comfort stationary index deduced from numerical regression models as WBGT, and Heat Index used for instance in the RELi certification (RELi 2018). Other standards use stationary indexes deduced from human body heat balance models such as the PMV, PDD in the ASHRAE55 (Fanger 1973) or the PET (Höppe 1993; WHO and WMO 2015; van Hooff et al. 2015) based on a BES output for comfort analysis. However, nonstationary thermoregulation models seem to be more appropriate to assess the health impact of heat exposure, as they aim to predict the dynamic response of thermoregulatory system. Among health indicators, the T_core has a clinical importance to predict heatstroke (Cheshire 2016), however it is not the only indicator, more important is the clinical condition of people (Anderson 1983). Individual behaviour also influences the T_core evolution in response to thermal sensory input (Cheshire 2016). Inhabitant behaviour can be building-oriented, by deploying building specific cooling strategies, or body-oriented by acting directly on body to reduce the T_core. The effects of building-oriented behaviour can be studied by BES.

Beyond the T_core, several health indicators can be assessed from thermoregulation models. In this work a “survival time” indicator (τ, [h]) is used (Deng et al. 2018). τ represents the estimated time of heatstroke occurrence within the exposure interval, corresponding to the time needed for the T_core to reach 40.6°C. By an extension of Deng’s model, Zhao et al (2020) endeavour to model the process of recovery from heatstroke. The model predicts the possibility to recover, and the time needed to recover, depending on environmental conditions: air temperature
Methods

(i) Health indicators and thresholds

Two sets of indicators are introduced. The first set of indicators (ENV) derives directly from environmental parameters (physical exposure parameters such as temperature, humidity, wind speed,...) and their statistical thresholds are based on averaged values or regression models. For ENV indicators, the indoor operative temperature ($T_o$ [°C]) is used as the variable of interest. To assess the acclimatization process taking place generally after 5 days to 6 weeks of exposure (WHO and WMO 2015), indoor adaptive models relating to outdoor temperature ($T_{os}$ [°C]) and room function (ex. bedroom, living room) are used to fix indoor neutral temperature ($T_o$ [°C]) thresholds (de Dear and Schiller Brager 2001; van Hooff et al. 2015; Peeters et al. 2009). ENV indicators are:

- The number of days of heat stress (NdHS [day]) reports the long-term heat stress load. It is defined as the number of episodes during the summer period where the average of the daily maximal $T_o$ over 3 sliding days exceeds 32°C and the average of the daily minimal $T_o$ over 3 sliding days exceeds 18°C. These thresholds are inspired from Meteo France Rhône’s thresholds, to which the averaged maximum and minimum outdoor temperatures are fixed to 34°C and 20°C respectively (Meteo France Rhône 2020). More precisely, the 32°C indoor threshold is fixed by using the ASHRAE adaptive comfort standards correlating acceptability limits of $T_o$ to averaged outdoor temperatures. Equation (1) is used to calculate the maximal $T_o$ satisfying 80% of the population (de Dear and Schiller Brager 2001):

$$T_{o,max} = 21.3 + 0.31 \times T_{e,max}$$

(1)

Where $T_{o,max}$ is the maximal neutral temperature threshold, corresponding to the $T_o$ threshold when the maximal external temperature threshold is applied $T_{e,max}=34°C$ (Meteo France Rhone 2020). $T_{o,max}$ is here approximated to 32°C.

The 18°C indoor threshold refers to the national health recommendations on bedroom temperature for optimal sleep (Institut National du Sommeil et de la Vigilence 2020).

- The day degree hour (DDH [°C.h]) reports on the day overheat intensity. It is calculated between 7 a.m. and 9 p.m w..hen $T_o > 32°C$ as follows:

$$DDH = \sum hr_{day} \times (T_o - 32)$$

(2)

- The night degree hour (NDH [°C.h]) reports on the night overheat intensity. Two night overheat thresholds ($T_{night}$[°C]) are fixed for the night threshold analysis: the first, 18°C, refers to the national health recommendations on bedroom temperature for optimal sleep (Institut National du Sommeil et de la Vigilence 2020); the second, 26°C, refers to the CISBE guide and the adaptive temperature limits (ATL) method. $NDH$ is calculated between 10 p.m. and 6 a.m when $T_o > T_{night}$ as follows:

$$NDH = \sum hr_{night} \times (T_o - T_{night})$$

(3)

The second set of indicators (PHYSIO) derives from thermoregulation models (Deng et al. 2018; Zhao et al. 2020) and uses $\tau_i$ as variable of interest. PHYSIO indicators are:

- The number of hours of heat stress (NhHS [h]) is a complementary approach to the NdHS to assess the health risk of overheating exposure. NhHS is based on the $\tau_i$ indicator (Deng et al. 2018). $\tau_i$ is calculated on an hourly interval basis using BES and equations (4) and (5) valid for indoors ($v_a = 0$, 1m/s and human metabolism = 1 met).

$$\tau_i = e^{50-ISI}$$

(4)

$$ISI = 44.2 + 0.02 \times T_o + 0.209 \times RH - 6.55 \times \frac{RH}{T_o}$$

(5)

where ISI is the indoor stress index. NhHS is here defined as the number of hours where $\tau_i \leq 5$ days. The valuation of NhHS is therefore done on an instantaneous basis to characterize a risk of heat stroke occurrence within the next 5 days. The 5 days threshold is suggested assuming that the first 5 days of heat stress exposure are the most critical as the physiological acclimatization may have not yet been activated (WHO and WMO 2015). Longer survival time ranges could be set, but the relevancy of the analysis could be compromised by adaptive mechanisms that take place at the physiological and behavioural levels (outside intervention, cooling body strategies).

- The heatstroke risk (hstk [Boolean]) is a short-term analysis indicator. It evaluates the risk of heatstroke within 5 sliding days exposure period by calculating the $\tau_i$ sliding average over 120 hours ($\tau_{5days}$ [h]) as follows:

  - If $\tau_{5days} \leq 120$ then hstk = true (heatstroke can occur within the following 5 exposure days)
  - otherwise hstk = false.

- The possibility of recovery (recov [Boolean]) evaluates if recovery is possible after a heatstroke occurrence based only on environmental exposure parameters. According to Zhao et al.’s (2020) recovery model and experimental observations, the recovery process depends on the severity of the heatstroke and the recovery environmental conditions and more particularly on $T_o$ and $v_a$ during the recovery
period. Assuming a constant $HR=60\%$ the recovery thresholds shown in Table 1 are obtained from Zhao et al.’s model (2020). The first column thresholds ($v_\text{e}=0.1\ m/s$) are chosen for our analysis assuming that the maximum indoor wind speed is less than 0.2 m/s. The second column thresholds can be used when natural cross ventilation or a fan are used.

\textbf{Table 1: Recovery threshold approach after heatstroke based on J. Zhao (2020) et al thermoregulation model}

<table>
<thead>
<tr>
<th>$T_a$ [°C]</th>
<th>Recovery time [h] $v_\text{e}=0.1\ m/s$</th>
<th>Recovery time [h] $v_\text{e}=3\ m/s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_a \geq 28\ ^\circ\text{C}$</td>
<td>No recovery</td>
<td>No recovery</td>
</tr>
<tr>
<td>28°C$&gt;T_a \geq 24\ ^\circ\text{C}$</td>
<td>18 $&gt;h_r \geq 13$</td>
<td>10 $&gt;h_r \geq 7.9$</td>
</tr>
<tr>
<td>24°C$&gt;T_a \geq 22\ ^\circ\text{C}$</td>
<td>13 $&gt;h_r \geq 11$</td>
<td>8 $&gt;h_r \geq 7$</td>
</tr>
<tr>
<td>22°C$&gt;T_a \geq 20\ ^\circ\text{C}$</td>
<td>11 $&gt;h_r \geq 10$</td>
<td>$h_r \approx 7$</td>
</tr>
</tbody>
</table>

(ii) Set up and carrying out of BES case study

BES is performed using EnergyPlus through the DesigBuilder software.

\textbf{BUILDING TYPOLOGIES}

Four non crossing, south exposed typologies of dwellings are considered for this study. Thermal envelope properties are based on the TABULA database (Rochard et al. 2015):

1. '1915': highest apartment of a 6 storey building built before 1915, without insulation;
2. '60': highest apartment of a 9 storey building built between 1949 and 1947, without insulation;
3. RnvEx: highest apartment of a 9 storey building renovated with exterior insulation;
4. RnvIn: highest apartment of a 9 storey building renovated with internal exterior insulation.

All the dwellings, except the 1915, have an activated mechanical ventilation system and have the same architecture (Figure 1). It is worth mentioning that mechanical ventilation has been mandatory in France since the 1969.

\textbf{COOLING STRATEGIES}

Two kinds of cooling strategies are modelled. The first are passive strategies easily accessible to the occupants consistent with the most common practices of Métropole de Lyon inhabitants in their dwelling during a period of heat wave (Métropole de Lyon survey, 2020):

- Natural ventilation (NV): activated using the EnergyPlus airflow network based on occupant scenario and when $T_{\text{ext}} < T_a > 18^\circ\text{C}$. In order to evaluate the impact of wind pressure coefficients ($C_p$) when NV is activated, two BES simulations have been carried out for the four dwellings : the first with the default Design Builder $C_p$ referring to a 3 storey building with no obstructions, the second with $C_p$ referring to a 3 storey building surrounded by obstructions (Liddament 1986).
- Window shading (OCLT): activated with external Venetian blinds when solar radiation on windows is $> 200\text{W/m}^2$. Outdoor shade effects due to surrounding buildings are integrated in the solar radiation balance calculated in EnergyPlus.

- Indoor heat sources reduction (HS): passing from 24 hours per day 13W/m$^2$ to 3W/m$^2$ as recommended in the French RT2012 regulation.

\textbf{BES SCENARIOS}

For the four typologies of building, 8 scenarios are simulated. The starting point is the base scenario (BASE) where none of the cooling strategies are applied (Table 2). To compare the efficiency of each cooling strategy on building typologies, five scenarios corresponding to the application of only one of the cooling strategies described above are then simulated for each building typology. Two additional scenarios are also simulated : the first (3CM), combining the 3 passive strategies; the second (5CM) combining all five cooling strategies.

\textbf{Figure 1: Dwelling plans.}

Strategies requiring a more complex implementation or final energy consumption:

- Envelope and roof albedo improvement (AWR): modification of solar absorbance from 0.9 to 0.15.
- Evaporative cooling activation (EVAP) with the Direct CelDekPad module of EnergyPlus.

\textbf{Table 2: BASE scenario per building typology}

<table>
<thead>
<tr>
<th></th>
<th>1915</th>
<th>'60</th>
<th>RnvEx, RnvIn</th>
</tr>
</thead>
<tbody>
<tr>
<td>U envelope (W/m$^2$)</td>
<td>1.67</td>
<td>2.64</td>
<td>0.19</td>
</tr>
<tr>
<td>U ground floor (W/m$^2$)</td>
<td>2.6</td>
<td>2.4</td>
<td>0.2</td>
</tr>
<tr>
<td>U windows (W/m$^2$)</td>
<td>1.96</td>
<td>1.96</td>
<td>1.4</td>
</tr>
<tr>
<td>Infiltration (Kg/s.m$^2$@1Pa)</td>
<td>2E-4</td>
<td>1E-4</td>
<td>4E-5</td>
</tr>
<tr>
<td>Sources (W/m$^2$)</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Mech. Vent.</td>
<td>5 l/s/person</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
WEATHER FILE

Two weather files are used for comparison: the Meteonorm weather file for Lyon (Satolas airport) and an urban adaptation using the urban weather generator (UWG) model (Bueno et al. 2012).

OCCUPANCY

An occupant is assumed to be in the bedroom from 10 p.m to 6 a.m and in the living room from 7 a.m to 9 p.m. DDH and NDH are therefore respectively calculated in the living room and in the bedroom.

SIMULATION SET UP

Simulation is run from the first of April to 30th of September including a one month initialization period. The simulation interval is on an hourly basis. The convective model uses the TARP algorithm for indoor and the DOE-2 model for outdoor.

Results

Four kinds of analysis are driven: (i) the impact boundary conditions on exposure levels; (ii) the impact of the dwelling type on the effectiveness of cooling strategies; (iii) the comparison of combined cooling strategies by dwelling types and (iv) the comparison of ENV indicators and PHYSIO indicators derived from nonstationary thermoregulation models. \( T_{\text{o}} \), \( T_{\text{n}} \) and \( HR \) resulting from the BES are used as inputs to calculate the indicators described previously.

(i) Impact of the boundary conditions on indoor exposure levels

Figure 2 highlights the influence of the UWG weather file on the urban heat island (UHI) phenomenon which nearly doubles the \( \text{DDH} \) and increases the \( \text{NDH} \) of 18%. Simulations resulting from \( C_p \) values of the AIVC tables (Liddament 1986) with and without obstructions show a deviation of less than 1% of the airflow and \( T_{\text{o}} \). As the dwelling windows all have the same orientation, these results suggest that the thermal buoyancy is predominant.

(ii) Impact of the dwelling type on the effectiveness of cooling strategies

Results presented in Figures 3 to 7 refer to simulations using the UWG weather file. Figure 3 and Figure 4 present the impact of each individual cooling strategy on \( \text{DDH} \) and \( \text{NDH} \) (for \( T_{\text{night}} = 18^\circ \text{C} \)) respectively, for the month of July, for each dwelling typology compared to the BASE case.

Results show that:

- The NV strategy is the most efficient strategy for all dwelling typologies. It cancels almost all the \( \text{DDH} \) and reduces between 40% and 60% the \( \text{NDH} \).

(iii) Comparison of combined cooling strategies by dwelling types

Figures 5 to 7 compares for each dwelling the effect of 3M and 5M cooling strategies on DDH and on NDH with \( T_{\text{night}} \) respectively fixed to 18°C and to 26°C. Results show that:

- The HS measure is more effective on insulated dwellings (\( R_{\text{nvEx}} \) and \( R_{\text{nvIn}} \)) as they retain more heat, especially at night.
- The AWR measure is more effective on non-insulated dwellings (‘60 and 1915), as solar radiation flux is already reduced by the insulation layer in the insulated dwellings.
- The OCLT strategy is less effective than the HS strategy. However, this result is certainly very case specific given the quite high basic internal loads (13W/m²).
- The benefits of the OCLT strategy has repercussions not only in terms of \( \text{DDH} \) but also in terms of \( \text{NDH} \).
- The EVAP measure is more effective for insulated buildings and globally more effective during the day.
3CM measures are sufficient to drastically reduce the DDH (over 99%) for all the dwelling typologies (Figure 5).

Whatever the combined cooling measure chosen (3CM or 5CM), the 1915 dwelling has the lowest NDH (Figure 5 (a) and (b)). This is mainly explained by the solar exposition of the 1915 within a street canyon, which receives less solar radiation in the bedroom.

The BASE scenario shows a higher NDH for the RnvEx than for the RnvIn dwelling (Figure 5 (c)). This is explained both by the lower inertia of the RnvIn dwelling and a \( T_{\text{night}} \) threshold set to 26°C. Low RnvIn inertia induces higher \( T_o \) variation amplitudes compared to the RnvEx dwelling. Minimal temperatures are therefore lower for RnvIn than for RnvEx (which explains lower NDH) and maximal temperatures are higher for RnvIn than for RnvEx (which explains higher DDH).

When \( T_{\text{night}} = 18°C \), the NDH reduction is limited to 75% and 61% for insulated and non-insulated dwellings, respectively. While when \( T_{\text{night}} = 26°C \) the NDH reduces to almost 99% (3M scenario). This highlights the substantial impact of the chosen threshold on results analysis. The 5M scenario is from 1% to 8% more effective than the 3M scenario in terms of NDH. 5M is more effective for non-insulated dwellings, as the gain induced by this strategy is basically related to the albedo optimization.

(iv) Comparison of environmental overheating indicators and indicators derived from nonstationary thermoregulation models

Both NdHS and NhHS indicators give information on the duration of heat stress and its time of occurrence (Figure 6). While the first is based on the night and day threshold set for \( T_o \) calculated a day basis, the second is derived from a thermoregulation indicator \( (\tau) \) and is calculated on an hourly basis. Figure 6 compares NdHS and NhHS for the four dwelling typologies when BASE, 3M and 5M scenarios are simulated. Results show that:

- A short-term analysis of hstk is driven for the '60 dwelling BASE case as it presents the largest range of heat stress. Figure 7 shows the periods where \( T_{\text{5days}} \leq 120 \) hours, which is the condition for which the heatstroke can take place in a time less than or equal to 5 days \( (hstk = \text{true}) \). \( T_o \) is also shown in regards of the 28°C recovery threshold. Table 3 shows more in details the \( T_{\text{5days}} \) (showing the average time of heatstroke occurrence), and the hstk value and the recov value for some of the periods are illustrated in Figure 7. In our study case, results shows that no recovery is possible as \( T_o \) following the heatstroke does not last long enough below 28°C after a heatstroke. Also, it is interesting to notice that although overheating is present from May onwards (Figure 6), the heatstroke risk is only present over specific periods from June onwards (Figure 7).
Figure 6: NdHS and NhHS for dwelling typologies and for the BASE, 3M and 5M cooling strategies.

Figure 7: Exposure periods where $\tau_s^{5\text{days}} \leq 120$ hours, $Ta$ exposure and recovery temperature threshold.
Table 3: Heatstroke analysis examples for BASE case on ’60 dwelling

<table>
<thead>
<tr>
<th>Exposure starting period</th>
<th>(T_{5\text{days}})</th>
<th>(hstk)</th>
<th>recov</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 Jun, 7 am</td>
<td>62 h</td>
<td>True</td>
<td>False</td>
</tr>
<tr>
<td>7 Jul, 7 am</td>
<td>117 h</td>
<td>True</td>
<td>False</td>
</tr>
<tr>
<td>15 Jul, 11 pm</td>
<td>119 h</td>
<td>True</td>
<td>False</td>
</tr>
<tr>
<td>13 Aug, 6 am</td>
<td>87 h</td>
<td>True</td>
<td>False</td>
</tr>
<tr>
<td>24 Aug, 11 a.m.</td>
<td>108 h</td>
<td>True</td>
<td>False</td>
</tr>
</tbody>
</table>

Discussions

Different conclusions can be drawn from the present case study. However, it is worth mentioning that these conclusions are case specific. The effectiveness of the different cooling strategies depends on several factors among which are the external climatic conditions (Lassandro and Di Turi 2019), the surrounding environment, building architecture, thermal properties, and inhabitant behaviour. Nonetheless, results show the benefits of NV. 3M cooling strategy cancels almost all the DDH and reduces the NDH to more than 60%. It also prevents hstk. The average benefit for the 4 dwelling typologies of the 5M cooling strategy compared to the 3M is less than 8% in terms of NDH.

Results also show the complementarity of the suggested set of indicators to assess indoor heat stress and health risk. While ENV indicators report on the indoor heat stress intensity over a long period in a daily basis, PHYSIO indicators report on the heat stress within a long-term period on an hourly basis (NhHS). Moreover, PHYSIO indicators give information on the impact of a cumulative overheating exposure over a short-term period (5 days) on the risk of heatstroke occurrence (hstk) and on the ability to recover from it (recov). This additional analysis can affect design decisions by considering adaptive measures over a specific exposure period.

However, it is important to notice that the suggested threshold values can be discussed and adapted on a case-by-case basis to consider the purpose of the analysis. In addition, this study shows the interest to pursue the assessment of heat stress and health impacts induced by long-term exposure (over the summer period). For this purpose, thermoregulation models and BES tools need to be improved. In particular:

- further developments are needed to model specific individual behaviours or cooling strategies, such as local evaporative cooling strategies, in BES which should also be coupled with thermoregulation models;
- the environment surrounding the dwelling should be considered to relevantly assess the boundary conditions for the BES and thus the building’s effective thermal load.

Conclusions

This paper aims to introduce a heat stress analysis method based on exposure dynamics to indoor overheating.

- Two sets of health indicators ENV and PHYSIO are introduced based on indoor \(T_o\) and on thermoregulation models, respectively. Compared to traditional stationary indicators, PHYSIO indicators are more appropriate to assess the heat stroke risk as they are based on dynamic indicators which integrate the individual’s exposure history over a short-term period. PHYSIO indicators can therefore be used by building designers to figure out the best adaptive passive measures to implement during critical overheating exposure periods.

- Threshold values are suggested to assess the indoor night and day overheating intensity and the heatstroke risk over a short time range.

- A case study is presented to assess the effectiveness of cooling measures regarding the suggested health indicators. The separate daily and night-time analysis, highlight the influence of materials and their configuration on overheating.

- The case study also shows the importance of integrating the behaviour of the inhabitants into the design practices of the buildings. In this sense, building designers should consider in their common practices to make recommendations on user behaviour.

- The introduced method highlights the limit of the approach in terms of BES models, which do not currently integrate thermoregulation models.

Hence, this contribution gives a first method to assess overheat health risks and opens new research perspectives on the definition of health indicators based on coupled BES and thermoregulation models.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Designation</th>
<th>Unit</th>
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<tbody>
<tr>
<td>(T_{\text{ext}})</td>
<td>Outdoor temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{\text{n}})</td>
<td>Neutral temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{\text{ext,\text{max}}})</td>
<td>Maximal external temperature threshold</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{\text{max}})</td>
<td>Maximal neutral temperature threshold</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{\text{o}})</td>
<td>Operative temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{\text{a}})</td>
<td>Indoor temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{\text{core}})</td>
<td>Core temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{\text{night}})</td>
<td>Night indoor temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(HR)</td>
<td>Relative humidity</td>
<td>%</td>
</tr>
<tr>
<td>(v_{\text{a}})</td>
<td>Indoor air velocity</td>
<td>ms⁻¹</td>
</tr>
<tr>
<td>(C_{\rho})</td>
<td>Pressure coefficient</td>
<td>-</td>
</tr>
</tbody>
</table>

Dwelling typologies

- ’915 building built before 1915, without insulation
- ’60 building built between 1949 and 1947, without insulation
- RnvEx building renovated with exterior insulation
- RnvIn building renovated with internal exterior insulation
Cooling strategies

BASE  No cooling strategies  -  
NV  Natural ventilation  -  
OCLT  Window shading  -  
HS  Indoor heat sources reduction  -  
AWR  Solar absorbance reduction  -  
EVAP  Evaporative cooling  -  
3CM  NV+OCLT+HS strategies  -  
5CM  NV+OCLT+HS+AWR+EVAP strategies  -  

Indicators

ENV  Indicators based on environmental parameters and their statistical thresholds  -  
NdHS  Days of heat stress per day  
DDH  Day degree hour °C.h  
NDH  Night degree hour °C.h  

PHYSIO  Indicators based on physiological parameters and their statistical thresholds  -  
NhHS  Hours of heat stress per hour  
htsk  Heatstroke risk Boolean  
reco  Possibility of recovery from a heatstroke  Boolean  
τr  Estimated time of heatstroke occurrence hour  
\[ \tau_r \]  Sliding average over 5 days hour  

References