Summer Passive Strategies Assessment Based on Calibrated Building Model Using on Site Measurement Data

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Abstract
Existing state of the art often view passive strategies as a mean for energy efficiency, while their effect on summer thermal comfort in temperate climatic conditions has been given lesser attention. Assessing these strategies require practitioners to provide the right combination of tools; proper measurement indices; and perform simulations as close as possible to real-life circumstances. This paper studies the issue with reference to an existing apartment building in real settings. Results here are in line with previous findings that recommend a synergy of passive summer strategies to reduce the impacts of over temperature in buildings.

Key Innovations
- Contam-Trnsys coupled building model was calibrated with on situ data
- Typical Weather file was modified with data collected from the site
- Hourly thermal comfort of a real building over two months of summer was gauged with adaptive and static thermal comfort indices
- Impact of window openness ratio and window blindsers were assessed to see if they can reduce thermal discomfort in overheated periods.

Practical Implications
Practitioners can use the methodology proposed here to measure and optimize the effect of passive strategies in reduction of thermal discomfort due to over temperature. Using multiple indices to measure thermal comfort allows practitioners to take into account cultural norms as well as occupants’ thermal expectations and preferences in their decisions.

Introduction
With the changes in worldwide climate conditions, extreme weather events will become more frequent and severe that would lead to substantial impacts. Heatwaves in particular can cause severe overheating in buildings causing several problems ranging from thermal discomfort and productivity reduction to illnesses and even death of occupants (Gamero-Salinas et al. (2020); Ozarisoy and Elsharkawy (2019)). Occupants in such circumstances contribute decidedly in energy consumption and indoor thermal comfort. For instance, changing set point temperature in mechanically ventilated buildings; or by manually adjusting windows, shutters and etc in mixed mode and naturally ventilated buildings. Their contribution is also recognized as a significant factor in uncertainty of building performance modelling.

Modern validated whole building energy modelling tools such as Trnsys, DOE-2, EnergyPlus and Pleiade Comfie provide valuable insights into energy use and thermal comfort of occupants in the buildings. They are capable of addressing a broad spectrum of energy and temperature related issues in various combinations. However, none of them alone offer sufficient capabilities to model whole building subsystems and interaction of occupants in those subsystems in isolation without making oversimplified assumptions. One approach to overcome this limitation is to use collaborative-simulation (co-simulation) as an integrated method to simulation. It is based on the idea that distinct interacting building subsystems are best simulated in specialized mature tools, dedicated to the given subsystem (Taveres-Cachat and Goia (2020); Dols et al. (2016)).

To cover given issues, this study first modifies typical weather data file with measured data; calibrates co-simulation model of coupled Contam and Trnsys with observed temperature data using Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and Coefficient of Variation of the Root Mean Square Error (CV RMSE) statistical performance indicators employed by Taveres-Cachat and Goia (2020); then it proceeds with selection of thermal comfort measurement indices; and at the end assesses how openness ratio of windows and window shutters affect indoor thermal comfort of occupants during an overheated period.

Site Introduction
Observational study was carried out on a five storey apartment building located in northeast of Nantes (47.2184 °N, 1.5536 °W). Continuous measurement of data from window status, outside air temperature
and inside air temperature from three apartments and stairwell in the fifth storey of the building were recorded at an interval of 10 minutes. Readers can have more details about the building data collected in Rodler et al. (2018) paper. Specification of data collection equipment for the given items are described in Table 1. In this apartment building, there were two types of windows with manual roller blinds/shutters. Window type 1 was 2.65 $m^2$ and type 2 was 3.01 $m^2$. Frame, glazing and other properties of the both window types were identical. Both window type 1 and type 2 had 1600 $mm^2$ trickling vent. Both window types were single side hung casement windows with two fully operable windows which opened inside. Windows were equipped with roller blinding to control solar gains. Discharge coefficient of windows was estimated 0.5. Window sensors recorded the state of window with boolean signal (0,1), where 1 indicates window is open and 0 when it is closed. The sensor did not read any information about the openness ratio and the state of shutters. Figure 1 shows detailed plan of indoor air temperature reading points (1, 2, 5, 6) and windows’ sensors (45b, 45a, 47a, 47b, 44a, 44b, 49a, 49b, 50a, 50b, 52a, 48b, 48a, 51b). Indoor temperature sensors were installed in the living room of apartments away from direct exposure to sunlight.

Local authority of housing provided information about the U value of composite exterior wall and double glazing windows, which were 0.380 [W/$m^2$K] and 2.89 [W/$m^2$K], respectively. Information concerning U value of roof was not available in the local authority for this building. All apartments had mechanical exhaust-only ventilation in the kitchen and bathroom. Quantity of air exhausting via each mechanical fan was given in the range of 40 to 100 $m^3/hour$. There were two types of doors in each apartment: bedroom doors were 2 by 0.8 $m$ and discharge coefficient was estimated to approximately 0.75; bathroom doors were 2 by 0.75 $m$ with a similar discharge coefficient. Bedroom doors were assumed to be open during the day from 8h to 22h and closed at night. Under-door crack in bedroom doors’ were measured to be 4 $mm$ by 0.8$m$. Bathroom doors were considered to be closed during day and night, but in contrast to bedroom doors, they had a larger under-door orifice of 10 $mm$ by 0.75$m$ and an over-door crack of 4 $mm$ by 0.75$m$ allowing living room air to be extracted through the extraction vent in the bathroom.

**Co-simulation tools**

Trnsys package is a combined dynamic modeling software that allows the evaluation and assessment of thermal and electrical energy systems. The package consists of graphical front-end interfaces to intuitively create simulations; for multi-zone buildings it is type56. Trnsys type56 is a non-geometrical balance model with one air node in a zone illustrating thermal capacity of air volume in the zone. This thermal capacity is separate from the volume of zone, which is an additional input. Trnsys type56 automatically generates inputs of multi-zone building such as view factors, sunlit factors and distribution factors from geometric information. Transient heat conduction through envelope elements in type56 are calculated using conductive heat transfer function method developed by Mitalas and Stephenson. Windows thermally in Trnsys are viewed as an external wall with no thermal mass; partially transparent to solar radiation but opaque to long wave heat gains. Long-wave heat gains are regarded to only occur at the surfaces. Incident shortwave radiation is calculated by surface modulus using solar absorbance coefficient of material (Type56-Manual (2017); Khalifa et al. (2015)). Convective heat fluxes to the air node is calculated as a summation of infiltration gains; ventilation gains;internal convective gains (by equipment, people, lighting, etc); and gains due to convective air flow between air zones’ boundary conditions. The user can define manually air mass flow into a zone in type56; but type56 alone does not automatically calculate air mass flow to adjacent zones. Calculation and definition of air mass flow rate exchanges between adjacent zones in type56 can be a tedious task for user if done manually. Contam on the other hand can automatically calculate air mass flow rate between zones, knowing the geometry and status of airflow paths between zones.

Contam like Trnsys has been in practical use for many years. It is used in a variety of applications, most notably in assessment of ventilation systems, analyses of smoke management systems, contaminant transport, etc. It allows the user to define various air paths such as, stairwells, ducts, orifices, cracks, doors, windows etc. Airflow calculations in Contam are based on non-linear airflow-vs-pressure relationships.

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**Figure 1: location plan of data collection sensors: circled numbers show indoor air temperature sensors in the living rooms and stairwell**
Table 1: Specification of data collection sensors

<table>
<thead>
<tr>
<th>Measurement type</th>
<th>Quantity</th>
<th>Sensor reference</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside air temperature</td>
<td>2</td>
<td>AMR WM-us ambient sensor</td>
<td>±0.1°C to ±0.5°C</td>
</tr>
<tr>
<td>Inside air temperature</td>
<td>5</td>
<td>AMR WM-us ambient sensor</td>
<td>±0.1°C to ±0.5°C</td>
</tr>
<tr>
<td>Window opening sensor</td>
<td>13</td>
<td>AMR wM-Bus 0-10V, mA on/off, ARF8041AA</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 2: Modelled indoor air temperature of whole building during the overheating period on 05 August at 16h00

tam assumes all airflow through the building envelope openings and between zones (large, small, intentional or accidental airflow paths) are governed by Bernoulli hydro-static equation.

\[
\Delta P = \frac{P_1 + \frac{\rho V_1^2}{2}}{} - \frac{P_2 + \frac{\rho V_2^2}{2}}{} + \rho g (z_1 - z_2) \tag{1}
\]

Where:
- \( \Delta P \) = total pressure drop between points 1 and 2
- \( P_1, P_2 \) = entry and exit static pressures
- \( V_1, V_2 \) = entry and exit velocities
- \( \rho \) = air density
- \( g \) = acceleration of gravity (9.81 m/s\(^2\))
- \( z_1, z_2 \) = entry and exit elevations.

Coupling between the heat transfer (type 56) of Trnsys and airflow calculations (type 98) is accomplished via the quasi-dynamic method. In other words, it refers to the coupling between simultaneously running processes where data is exchanged only once within each time-step like in ping-pong. This coupling allows type 56 multi-zone building heat transfer model in Trnsys to share input and output with Contam representation of multi-zone building (Khalifa et al. (2015); Dols et al. (2016)). The exchange of input and outputs for airflow and temperature data is shown in figure 3.

![Figure 3: Schematic representation of data exchange between Type 98 (Contam) and Type 56](image)

Method

As can be seen in the figure 2 the building consists of five storeys connected through a central stairwell. All five storeys have similar floor plans; window sizes; and wall thermo-physical properties. Each piece in the apartment i.e. bedroom, living room, and bathroom was treated as a separate zone in the simulation tool connected to other pieces via doors and airflow paths (cracks) under and over the doors. The time step of the simulation was set to 15 min but the output of simulation was collected at hourly intervals. Temperature and humidity ratio of typical weather data file for the given location was modified with measured ones for July and August and used in simulations. Heat gains from occupancy were calculated by dividing the average load per person to average area per person. Load gains from lighting and equipment were calculated from ASHRAE tables for the number of appliances and light bulbs in the apartments (figure 4). Data collection was carried out in a non-intrusive manner in the occupied apartments of the building. As a result, a limited set of on board measured data was collected. Considering case specific limitations and possibilities, RMSE, and MAE statistical indica-
tors were selected to evaluate the goodness of fitting parameter to actual physical parameter of building in calibration stage. Multiple simulations were iterated manually for each uncertain building parameter and the value with the lowest RMSE was used to determine the missing physical parameter. The following series of steps where taken to tune the missing physical parameters of building:

First, roof U value was tuned by comparing the co-simulation temperature with measured one in the stairwell. Mainly because the stairwell is less affected by direct solar radiation and airflow through the windows. After running multiple simulations, the U value of roof equals to $1.563 \, [W/m^2 \cdot K]$ was found to fit best with observed temperature (figure 5).

Second, quantity of air exhausting via each mechanical air extraction fan was tuned by fitting modelled indoor temperature with observed one in apartment 2 during vacation time when windows and doors were closed. Air extraction rate at $60 \, m^3/h$ from kitchen air vent and $40 \, m^3/h$ from bathroom was found to fit best the observed temperature.

Finally, calibration of window openness ratio and shading factor is more complicated as it can vary depending on the behavior of occupants, different sizes of windows, orientation, time of the day and etc. In addition, data collection sensors in windows had returned a boolean value that only showed the status of window as opened or closed. In order to calibrate the two parameters, window openness ratio and shading factor were equally changed in all windows and the correlation between goodness of fit to observed data and modelled data was different in each apartment and stairwell as shown in figure 6. The values with smallest RMSE in apartments and stairwell were selected as calibrated values.

Moving forwards with the assessment of passive summer strategies on the calibrated co-simulation model. Three widely used comfort indices were employed to measure and compare summer comfort: predicted mean vote (PMV); upper limit values of EN 16798 adaptive thermal comfort; and upper limit values of ASHRAE 55 adaptive thermal comfort. PMV index rate were calculated using python package developed by Tartarini and Schiavon (2020). This package calculates clothing level as function of outdoor temperature at 6AM in accordance to ASHRAE 55 2017. Indoor average air speed was assumed 0.1 m/s and metabolic rate 1.2 representing a light

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Figure 4: Average calculated internal heat gain profiles for apartments

Figure 5: Roof U value calibration

Figure 6: Calibration of window openness ratio for air inflow and external shading factor
physical activity and nearly stationary air velocity. In EN 16798 and ASHRAE 55 adaptive thermal comfort measurement approaches, the sum of degree hours (DH) exceeding maximum allowable operative temperature was analyzed. In both EN 16798 and ASHRAE 55 maximum allowable operative temperature ($T_{MAX}$) is related to exponentially decaying weighted mean outdoor temperature ($T_{RM}$) (ASHRAE (2017); Chirico and Magnavita (2019)).

$$T_{RM} = (1 - \alpha)[T_{N-1} + \alpha T_{N-2} + \alpha^2 T_{N-3} + \alpha^3 T_{N-4} + \alpha^4 T_{N-5} + ...](\circ C)$$ (2)

Where:
- $T_N$ = Mean Daily temperature of previous day
- $\alpha$ = Constant between 0 and 1.

$\alpha$ controls the speed at which running mean outdoor temperature changes. Recommended value for it is between 0.6 and 0.9 corresponding to slow and fast response, respectively. Adaptive comfort theory suggests 0.9 for climates where synoptic-scale (day to day) temperature variations are minor but SCAT (Smart Controls and Thermal Comfort) project which was undertaken in European Union has recommended 0.8 for the region where this study has been carried out. According to ASHRAE 55 in weighted average calculation, prevailing outdoor mean temperature shall be based no fewer than 7 sequential days prior to the target day. In this study mean temperature of 30 previous sequential days were used to calculate mean weighted running temperature. EN 16798-1:2019 which replaces EN 15251 illustrates indoor thermal comfort at category I, II, III level and sometimes level IV. Compliance to level I upper and lower boundary limit is best, and III and IV is considered worst. In ASHRAE 55, two sets of operative temperature acceptability limits are proposed; 90% acceptability is considered for cases when higher standard of thermal comfort is desired; 80% acceptability limit is for typical situations. In this study we concentrate on upper boundary limits because the focus is on summer comfort.

Following equations determine the maximum allowable operative temperatures ($T_{MAX}$) for EN 16798 and ASHRAE 55: (Gamero-Salinas et al. (2020); Chirico and Magnavita (2019); ASHRAE (2017))

$$T_{MAX}(\text{Category I})(\circ C) = 0.31T_{RM} + 20.8$$ (3)

$$T_{MAX}(\text{Category II})(\circ C) = 0.31T_{RM} + 21.8$$ (4)

$$T_{MAX}(\text{Category III})(\circ C) = 0.31T_{RM} + 22.8$$ (5)

$$T_{COMFORT}(\circ C) = 0.31T_{RM} + 18.8$$ (6)

$$T_{MAX}(\text{ASHRAE 80%})(\circ C) = 0.31T_{RM} + 21.3$$ (7)

Discussions and result analysis

As can be seen in figure 6, openness ratio of windows in the apartments, when shading factor is in the range of 0 to 20%, does not significantly affect the indoor temperature in the stairwell because the doors that connect apartments to stairwell are most of the time closed. Nonetheless, within this shading range, best fit between observed and modelled temperatures in apartment 1 was achieved when openness ratio was between 10 to 15% and for apartment 2 between 15 to 20%. As for apartment 5, modelled temperature best fits the observed temperatures when the window was fully closed. This could mean that the occupant may have opened the window but closed the shading at the same time reducing the air inflow through the window. It is also important to note that not all occupants behave in a similar pattern. The openness ratio and shading factor can be different for each window in each apartment at different times of the day.

As shown in table 2, MAE and RMSE both in apartment 1, apartment 2, apartment 5 and stairwell are below 1 or just above it indicating a relatively good fit to observed measurements. This goodness of fit is further confirmed in figure 7 where normal frequency distribution of differences between modelled and observed indoor air temperatures are centered around zero, and in figure 8 where time series data of modelled and observed indoor air temperatures in apartment 1 is presented.
Returning to the subject of summer passive strategies assessment, the impact of window openness ratio and window shutters were studied. Three theoretical scenarios in addition to base case scenario, which is the calibrated model, were co-simulated and gauged against the described thermal comfort indices.

In scenario I, window shutters were set to cover 90% of total area of window during the day from 09:00 to 21:00 with base case window openness ratio. In scenario II, openness ratio of window was increased to 100% but window shutters were assumed to be fully open during day and night. In scenario III, window openness ratio was set to 100% and window shutters covered 90% during the day.

For demonstration, modelled indoor air temperature in base case scenario of apartment 1 is depicted in Figure 9 with upper boundary limits of EN 16798 adaptive thermal comfort indices, which are presented in grey, ASHRAE 55 in red, optimal comfort temperature with dashed line, and one lower boundary limit for category II of EN 16798.

Results of analyses in calibrated scenario showed that indoor air temperature did not exceed the maximum allowable operative temperature limit of category III of EN 16798 in any apartment. However, number of hours that indoor temperature exceeded category II of EN 16798 was 3 and 2% of total hours in apartment 1 and 5 respectively. These numbers reached to 9%, 6%, 13% and 11% of total hours in category I of EN 16798 in apartment 1, apartment 2, apartment 5, and stairwell respectively. Similarly, number of hours that indoor operative temperatures exceeded upper limit of 80% acceptability in ASHRAE 55 were 9%, 6%, 12% and 10% of total hours in apartment 1, apartment 2, apartment 5, and stairwell. With 90% acceptability in ASHRAE 55 this number jumped to 22%, 20%, 30% and 44% of total number of hours in the above-mentioned apartments respectively. Number of hours here indicate the frequency of times when operative indoor temperature exceeded the upper limit but does not indicate the intensity of it. To consider both, the exceeding temperature differences between modelled indoor operative temperature and upper limit of thermal comfort index, in every hour was summed up (figure 10a).

Further, analysis of calibrated scenario with PMV comfort index demonstrated that occupants felt comfortable less than 50% of the time in apartment 1, apartment 2, and apartment 5; except in stairwell where this percentage was approximately 60%. Largest percentage of discomfort here was due to temperature drop at night. Only 2.3%, 3.5%, 2.8%, and 2.1% of discomfort in apartment 1, apartment 2, apartment 5, and stairwell respectively, were due to over temperature in the day. As can be seen in figure 10a all three apartments and stairwell display most im-

**Table 2: Goodness of fit between modelled and observed temperatures after calibrations**

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<tbody>
<tr>
<td>Apartment 1</td>
<td>0.72</td>
<td>0.91</td>
<td>26.12</td>
<td>3.5%</td>
<td>CV RMSE ≤ 30 %</td>
</tr>
<tr>
<td>Apartment 2</td>
<td>0.66</td>
<td>0.78</td>
<td>25.99</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>Apartment 5</td>
<td>1.06</td>
<td>1.29</td>
<td>27.2</td>
<td>4.75%</td>
<td></td>
</tr>
<tr>
<td>Stairwell</td>
<td>0.62</td>
<td>0.78</td>
<td>26.91</td>
<td>2.9%</td>
<td></td>
</tr>
</tbody>
</table>

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Figure 9: Calibrated model time series data with adaptive indoor thermal comfort indices in apartment 1

Figure 10: a, sum of degree hours when operative temperature exceeded the upper limit boundary of adaptive comfort indices in EN 16798 and ASHRAE 55; b, percentage of hours PMV index rate fell in each range
provement in scenario i and iii if measured by adaptive comfort indices; but if measured with PMV index, scenario i and ii provide better overall comfort to occupants (figure 10b). However, percentage of discomfort due to over temperature in the day increases by approximately 1% in all apartments and stairwell in scenario ii when measured by PMV index compared to base case scenario. This puts scenario ii at a worse position than base case scenario in terms of summer diurnal over temperature performance.

Conclusions

Passive strategies in the context of buildings are well known in engineering as effective adaptive techniques to achieve an objective with little to no additional input. In the present study, the effect of window shutters/blinds that reduce solar gains and window openness ratios that control natural airflow to the apartments were investigated by dynamic co-simulations of various scenarios. Results of dynamic co-simulation and comparison of scenarios with base case scenario show that excessive passive ventilation achieved by means of increase in window openness ratio brings down the peak indoor air temperature during the day but it can also cause discomfort at night. Similarly, limiting solar gains by window shutters can significantly reduce peak indoor air temperature during the day and in the meantime does not cause notable temperature drop at night; however, it can drastically limit natural visual comfort. Study on this apartment building, which showed evidence of overheating in calibrated scenario, demonstrates that risks associated with indoor over temperature in it could have been considerably reduced with passive strategies without mechanical cooling. As an important outcome of this study for existing buildings, a good synergy between passive natural ventilation and passive measures that limit solar gains should be found with dynamic co-simulations to optimize thermal comfort. It is also necessary to mention that even with best synergies there are limits to what can be achieved by passive methods; for instance, in high demanding comfort level such as ASHRAE 55 with 90% acceptability.

Further work on this should delve into the role of different residential building typologies on summer thermal comfort; future weather scenarios with and without heatwaves; and geographical location of building in the city to take into account urban heat island effect as well.

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