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Published in:
Energy and Buildings

Link to article, DOI:
10.1016/j.enbuild.2021.111465

Publication date:
2021

Document Version
Version created as part of publication process; publisher's layout; not normally made publicly available

Citation (APA):
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PII: S0378-7788(21)00749-0
DOI: https://doi.org/10.1016/j.enbuild.2021.111465
Reference: ENB 111465

To appear in: Energy & Buildings

Received Date: 27 June 2021
Revised Date: 30 August 2021
Accepted Date: 12 September 2021

Please cite this article as: J. Joaquin Aguilera, D-I. Bogatu, O. Berk Kazanci, C. Angelopoulos, D. Coakley, B.W. Olesen, Comfort-based control for mixed-mode buildings, Energy & Buildings (2021), doi: https://doi.org/10.1016/j.enbuild.2021.111465

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Comfort-based control for mixed-mode buildings

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Abstract. International thermal comfort standards are applicable for the design and operation of either mechanically cooled or naturally cooled buildings and limited guidance is given for mixed-mode buildings. In this study, a control framework for mixed-mode buildings was defined based on the adaptive comfort model and PMV-PPD method. The proposed framework was tested using a simulation-based analysis of a central module of an office building. The results were compared with a mechanically cooled building. The objective was to characterize how to control mixed-mode buildings optimally, regarding both energy use and thermal comfort. Five locations were considered: Copenhagen - DK, Edinburgh - UK, Palermo - IT, Tokyo - JPN, and Zurich - CH. The mixed-mode control strategy had a primary energy use between 12 and 51 % lower than the mechanically cooled case. In this context, using the upper limit of the adaptive comfort zone as cooling set point rather than the upper limit of the PMV-based comfort zone showed nearly 20 % more energy savings and fewer switchovers between operation modes. Night cooling led to lower operative temperatures and fewer switchovers between operation modes as well as additional energy savings of 10 % only in Palermo. The results show that a mixed-mode building operated based on the adaptive comfort criteria can have a large reduction of energy use without compromising thermal comfort or indoor air quality, compared to a mechanically cooled building.

Keywords: Mixed-mode, adaptive comfort model, HVAC control, thermal comfort, mechanical cooling, night cooling
1. Introduction

Mixed-mode buildings allow using natural ventilation (NV) in addition to the energy-intensive mechanical cooling (MC), as opposed to traditional buildings that rely only on the latter. A mixed-mode operation can lead to decreased energy use without sacrificing occupants’ thermal comfort [1] [2]. However, mixed-mode buildings usually operate under tight temperature limits based on “field knowledge” which does not fully unleash their energy savings potential [3]. Recent studies advocate the applicability of adaptive comfort models for the operation of mixed-mode buildings [1] [4] [5] [6] [7] [8] [9] [10]. In the NV mode, ventilation and space cooling are supplied through a combination of manually and automatically controlled openings based on the adaptive thermal comfort model. MC should be employed only as a complement to NV for maintaining the thermal environment within acceptable limits.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>Adaptive comfort control</td>
</tr>
<tr>
<td>ACH</td>
<td>Air changes per hour in h^{-1}</td>
</tr>
<tr>
<td>AHU</td>
<td>Air handling unit</td>
</tr>
<tr>
<td>CA</td>
<td>Conserving control approach</td>
</tr>
<tr>
<td>CAV</td>
<td>Constant air volume</td>
</tr>
<tr>
<td>CCS</td>
<td>Central control system</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, ventilation and air-conditioning</td>
</tr>
<tr>
<td>MC</td>
<td>Mechanical cooling</td>
</tr>
<tr>
<td>MV</td>
<td>Mechanical ventilation without conditioning the supply air</td>
</tr>
<tr>
<td>NC</td>
<td>Night cooling</td>
</tr>
<tr>
<td>NV</td>
<td>Naturally ventilated</td>
</tr>
<tr>
<td>PCC</td>
<td>Prescriptive comfort control</td>
</tr>
<tr>
<td>PMV-PPD</td>
<td>Predicted mean vote - Predicted percentage of dissatisfied</td>
</tr>
<tr>
<td>RA</td>
<td>Ramped control approach</td>
</tr>
<tr>
<td>T_{ACM,LL}</td>
<td>Lower limit of the adaptive comfort model in °C</td>
</tr>
<tr>
<td>T_{ACM,UL}</td>
<td>Upper limit of the adaptive comfort model in °C</td>
</tr>
<tr>
<td>T_{month}</td>
<td>Monthly mean outdoor air temperature in °C</td>
</tr>
<tr>
<td>T_{rm}</td>
<td>Running mean outdoor air temperature in °C</td>
</tr>
<tr>
<td>T_r</td>
<td>Return air temperature in the air handling unit</td>
</tr>
<tr>
<td>T_s</td>
<td>Supply air temperature in °C</td>
</tr>
<tr>
<td>T_{s,sp}</td>
<td>Set point for the supply air temperature in °C</td>
</tr>
<tr>
<td>T_{op}</td>
<td>Operative temperature in °C</td>
</tr>
<tr>
<td>VAV</td>
<td>Variable air volume</td>
</tr>
<tr>
<td>ZCS</td>
<td>Zone control system</td>
</tr>
</tbody>
</table>
No consensus over control strategies is present in literature for mixed-mode buildings, partly due to the lack of a unique thermal comfort model covering both NV and MC operation modes. Indoor environmental quality standards such as EN 16798-1:2019 [11] and ASHRAE 55:2017 [12] do not provide specific guidelines to design and operate mixed-mode buildings. Unlike those standards, ISSO 74:2014 defines guidelines for mixed-mode buildings, providing upper and lower comfort limits for winter, summer and transition periods [13]. Some studies suggest that the limits of the adaptive comfort model are directly applicable in mixed-mode buildings, especially during the NV operation [4] [9] [10] [14], while others propose different comfort equations and limits for mixed-mode control, depending on the operation mode [6] [15].

Only a limited number of studies were found in literature that were able to test comfort-based control strategies in mixed-mode buildings. They employed the adaptive comfort model alone or a combination of the limits from adaptive comfort zone and from the predicted mean vote (PMV) comfort zone. Fiorentini et al. [5] tested a comfort-oriented controller that calculated the optimal window opening percentage using the adaptive comfort model and dynamically optimized the set points for the MC operation based on the PMV. Aparicio-Ruiz et al. [1] implemented a controller connected to a building management system that operated based on the optimal comfort temperature of the adaptive model. When using the limits of the adaptive model as set points, the heating, ventilation and air-conditioning (HVAC) control system required a daily adjustment of the set points depending on an outdoor reference temperature. Some control approaches defined the outdoor reference temperature as the monthly average temperature [8], while others employed the running mean outdoor temperature [1] [5] [7]. Other studies [2] [16], used simpler control strategies that relied on fixed set points based on heuristic approaches, which were not guaranteed to be optimal in terms of indoor climate or energy use. Brager et al. [3] analysed the experience from different mixed-mode building case studies and showed that zone classification might be needed as different zones in a building could require different operation modes simultaneously. They suggested to monitor indicators such as indoor temperature, CO$_2$ concentration, relative humidity and radiant cooling surface temperatures in mixed-mode buildings, together with outdoor environmental factors such as air temperature, wind speed, wind direction and rain [3].

Night cooling (NC) techniques offer the possibility of decreasing the requirement for MC by moving outdoor air into the building during night-time and thereby cooling down the thermal mass of the building [16]. The control method proposed by Psomas et al. [17] applied an automatic window opening approach as a function of operative and outdoor temperatures that was able to reduce the periods with overheating. Roach et al. [18] presented an NC control where the ventilation system during night-time was activated based on the difference between outdoor and indoor temperatures. Solgi et al. [19] suggested that the use of NC in mixed-mode buildings allows reducing the energy requirement for mechanical cooling. According to Solgi et al., defining an optimal NC control represents a challenge, since it is affected by the performance of the MC during daytime, and the start-up time, duration, and ventilation rate of the NC operation. Climates with high diurnal temperature fluctuations are optimal for NC, except when outdoor air temperatures are significantly high. The use of NC in buildings with heavy thermal mass constructions can reach higher reductions of energy use compared to light constructions [18] [19]. However, the use of NC may also bring issues related to overheating, insect intrusion, security, rain, dust or noise.

Although some studies have already suggested control strategies for mixed-mode buildings using the adaptive comfort model [1] [5] [7] [8], none of them presented an analysis of indoor climate and energy use for different climatic zones or tested different outdoor reference temperatures to calculate the comfort limits of the adaptive model. Additionally, none of the studies found in the literature proposed control approaches for mixed-mode buildings that applied the adaptive comfort model and were complemented with night cooling strategies. The main objective of the present study was to analyse how mixed-mode buildings could operate optimally, maximizing thermal comfort and minimizing energy use. A control approach for mixed-mode buildings was proposed and tested using a simulation model of a central module of an office building. This framework integrates the operation guidelines for NV and MC buildings, based on the indoor environmental quality (IEQ) Category II from EN16798-1:2019. The intent was to find the optimal operation of the NV mode, the MC mode, and night cooling under different climatic conditions. The results were compared with a reference case where a MC building was operated using the PMV-PPD method.
2. Methodology

The analysis of the different operation strategies was performed through the simulation tool IDA Indoor Climate and Energy [20]. This software allows performing simultaneous analysis of energy use, thermal comfort, and indoor air quality under different boundary conditions. IDA ICE has been validated based on CEN Standards EN 15255-2007 and EN 15265-2007 [21]. This validation, considered the analysis of the dynamic thermal behaviour of reference models prescribed in those CEN Standards. The simulation created in this study made use exclusively of the components included in the IDA ICE software without modifying the default numerical models. Therefore, it was considered that the results obtained from the building model in this study provide a suitable estimation of the physical behaviour of a real building with equivalent characteristics. An accurate estimation of the behaviour of a particular building can only be achieved by performing a validation of the specific building model, which was out of the scope of this simulation-based study.

Figure 1 shows the procedure applied throughout the present study. First, specific locations were selected. Then, a reference building model and HVAC system were chosen for the analysis. Control frameworks were later defined and implemented, considering day- and night-time operation. Finally, the proposed frameworks were simulated and analysed.

Figure 1: Procedure applied to develop and analyse frameworks to operate mixed-mode and MC buildings.

2.1. Locations, weather conditions and criteria for NV buildings

Five locations were selected to account for different geographical regions and climates, defined according to the Köppen-Geiger classification [22]. The selected locations were Copenhagen-Denmark (CPH) with a Marine West Coast climate, Edinburgh-United Kingdom (ED) with a Marine West Coast climate, Palermo-Italy (PA) with a Hot-summer Mediterranean climate, Tokyo-Japan (TYO) with a Humid Subtropical climate and Zurich-Switzerland (ZH) with a Marine West Coast climate. The weather data was obtained from the International Weather for Energy Calculations (IWEC) from ASHRAE [23].

The guidelines for design and operation of NV buildings, based on the adaptive comfort model, define the limits for acceptable operative temperatures depending on the outdoor reference temperature. Some of the first adaptive comfort models [24] used the monthly average outdoor temperature ($T_{\text{month}}$) as the outdoor reference temperature. However, current adaptive comfort models such as Nicol and Humphreys [25] and de Dear and Brager [26] apply the running mean outdoor temperature as the outdoor reference temperature. EN 16798-1 describes two methods to calculate the running mean outdoor temperature: a standard and a simplified formula [27] [28]. The standard formula represented by Eq. (1) is an exponentially weighted average, where $\alpha$ is a constant between 0 and 1, and $T_{ed, \text{i}}$ corresponds to the daily mean outdoor temperature from the $i$th previous day to the present day of the calculation.

$$T_{\text{rm}} = (1 - \alpha) \cdot (T_{ed, \text{i-1}} + \alpha \cdot T_{ed, \text{i-2}} + \alpha^2 \cdot T_{ed, \text{i-3}} + \ldots)$$  (1)

If the values of the running mean outdoor temperature from previous days are not available, EN 16798-1 defines a simplified method to calculate the running mean outdoor temperature, shown in Eq. (2). This allows calculating the running mean outdoor temperature only with the daily mean outdoor temperatures from the previous seven days.
\[ T_{rm} = \left( T_{ed-1} + 0.8 \cdot T_{ed-2} + 0.6 \cdot T_{ed-3} + 0.5 \cdot T_{ed-4} + 0.4 \cdot T_{ed-5} + 0.3 \cdot T_{ed-6} + 0.2 \cdot T_{ed-7} \right) / 3.8 \]  

(2)

The upper and lower limits for acceptable operative temperatures were calculated with Eq. (3) and (4), corresponding to an indoor environment Category II, according to EN 16798-1. The optimal operative temperature from the adaptive comfort model corresponds to Eq. (5). The adaptive comfort limits were applied when \( 10 \, ^\circ C \leq T_{rm} \leq 25 \, ^\circ C \), considering that EN 15251 suggests that above 25 \( ^\circ C \) those limits are based on a limited database [29].

\[ T_{ACM,UL} = 0.33 \cdot T_{rm} + 21.8 \]  

(3)

\[ T_{ACM,LL} = 0.33 \cdot T_{rm} + 14.8 \]  

(4)

\[ T_{ACM,C} = 0.33 \cdot T_{rm} + 18.8 \]  

(5)

Figure 2 shows the annual distribution of \( T_{rm} \) for each location calculated with Eq. (2). The figure also presents the upper limit of the PMV-PPD method as well as the upper limit of the adaptive comfort model calculated with Eq. (3) during the cooling season. The lower limit of the PMV-PPD method for the heating season is also shown in the same figure, which is equal to the lower limit of the adaptive comfort model. The heating and cooling seasons as well as the transition period between seasons were defined based on the \( T_{rm} \) according to EN 16798-1. Figure 2 shows that the adaptive comfort model can be applied for a longer period of the year in locations such as Palermo and Tokyo, which present higher outdoor temperatures than the other locations.
Figure 2: Annual distribution of the running mean outdoor temperature ($T_{rm}$), upper and lower limits of the adaptive comfort model ($T_{ACM,UL}$ and $T_{ACM,LL}$, respectively) as well as the upper and lower limits of the PMV-PPD method ($T_{PMV,UL}$ and $T_{PMV,LL}$, respectively) for (a) Copenhagen, (b) Edinburgh, (c) Palermo, (d) Tokyo and (e) Zurich.
2.2. Building model

The model used for all the simulations was a central module of an office building used by Olesen and Dossi [30] and Kolarik et al. [31]. The module layout (Figure 3) consisted of two identical office rooms facing opposite directions, north and south, with a corridor between the offices. The total floor area of the module was 48.2 m², corresponding to 19.8 m² for each office and 8.6 m² for the corridor. The building construction had a thermal mass of 14 kJ/m², where suspended ceilings, floor coverings and internal walls were in direct contact with the air mass inside each zone. A detailed list of the building components is described in Kolarik et al.

![Figure 3: Office layout used for the simulations. Source: Olesen and Dossi [30].](image)

The windows in the offices had an automatic solar shading system. When the incident solar radiation on the inside glass exceeded 100 W/m², the upper part of the window was shaded with external blinds (3 m x 0.9 m). This shading strategy decreased the visual transmittance of the window by 9 % and the solar gain factor by 14 %. The external blinds did not affect the U-value of the windows.

The total internal heat load in each office was 36 W/m², corresponding to occupants, equipment, and lighting. In each office there were two occupants with an activity level of 1.1 met, accounting for 12 W/m² (234 W), two computers and one printer with a long-wave radiation fraction of 50 %, adding 12 W/m² (238 W) and lighting with a convective fraction of 0.5, corresponding to 12 W/m² (236 W). In the corridor, there was only internal heat gains from lighting of 7 W/m² (141 W), also with the same convective fraction as for the offices. The heat gains from occupants and appliances were extracted from the suggested values for a single office in EN 16798-1, whereas the values for lighting were taken from ASHRAE 90.1 [32]. Occupants were assumed to be present in the building from 9:00 to 12:00 and from 13:00 to 16:00 only during weekdays. This corresponded to the schedule for appliances and lighting for a single office defined in EN 16798-1. The infiltration rate was assumed to be a constant value of 0.2 ACH for the entire building module [32].

2.2.1. HVAC systems

Space heating and cooling were supplied by an all-air system, where a single air-handling unit (AHU) was connected to all zones (Figure 4). The AHU consisted of water-based heating and cooling coils, supply and exhaust fans and a heat recovery unit. Each office room had a variable air volume (VAV) ventilation system in which the supply airflow was controlled by adjusting the position of the dampers in the room. The minimum and maximum supply air flow rates were 1.8 ACH (1.4 L/m²s) and 8 ACH (6.2 L/m²s), respectively, calculated for a low polluting building with IEQ Category II according to EN 16798-1. The corridor had a constant air volume (CAV) system with a supply air flow of 0.9 ACH (0.7 L/m²s). The operation schedule for the ventilation system in all zones was from 8:00 to 16:00 during weekdays, using the minimum supply air flow prior to occupancy to keep an acceptable air quality.
Figure 4: Scheme of the air handling unit used in the simulation. $T_{\text{out}}$: outdoor air temperature; $T_s$: supply air temperature; $T_r$: return air temperature; CCS: Central control system.

Table 1 shows the efficiencies and primary energy factors considered to calculate the primary energy use in accordance with EN ISO 52000-1 [33]. It was assumed that a gas boiler and a compression cooling unit provided hot and cold water to the coils in the air handling unit. The HVAC auxiliary energy considers two fans (supply and exhaust) in the air handling unit (SFP =1 kW/m³/s (supply) and 0.7 kW/m³/s (exhaust); nominal pressure drop =600 Pa (supply) and 400 Pa (exhaust)) and two pumps for the cooling and heating coils (pump efficiency=0.5; nominal pressure drop =30 kPa).

Table 1. Thermal efficiency and primary energy factors used to calculate the primary energy use. Reference values and guidelines from EN ISO 52000-1.

<table>
<thead>
<tr>
<th>Energy use</th>
<th>Energy transformation</th>
<th>Source</th>
<th>Efficiency [-]</th>
<th>Primary energy factor [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling</td>
<td>Compression cooling unit</td>
<td>Electricity</td>
<td>3.00</td>
<td>2.5</td>
</tr>
<tr>
<td>Heating</td>
<td>Gas boiler</td>
<td>Gas</td>
<td>0.95</td>
<td>1.1</td>
</tr>
<tr>
<td>HVAC aux.</td>
<td>Fans and pumps</td>
<td>Electricity</td>
<td>1.00</td>
<td>2.5</td>
</tr>
</tbody>
</table>

2.3. Control methods

The heating and cooling coils as well as the bypass of the heat recovery unit were controlled based on the supply air temperature ($T_s$), as seen in Figure 4. The supply air temperature was regulated in the central control of the AHU based on measurements of the outdoor air temperature ($T_{\text{out}}$). The set point for the supply air temperature ($T_{\text{sp}}$) was defined proportionally between 16 °C and 34 °C for $T_{\text{out}}$ between 22 °C and -12 °C, respectively. The cooling and heating coils were activated when $T_s$ was above or below the value defined in the control system, $T_{\text{sp}}$. The heat recovery unit had two operation modes a) it recovered heat from the exhaust air flow when $T_{\text{out}}$ was lower than the return air temperature ($T_r$) and $T_{\text{sp}}$ was higher than $T_{\text{out}}$ or b) it precooled the supply air by releasing heat to the exhaust air flow when $T_r$ was lower than $T_{\text{out}}$ and $T_{\text{sp}}$ was below $T_{\text{out}}$. The control strategy of the heat recovery unit avoided to preheat or precool the air when not needed, since it was based on $T_{\text{sp}}$ defined in the central control of the AHU.

The two main strategies tested, the prescriptive comfort control (PCC) and the adaptive comfort control (ACC), were based on indoor and outdoor temperatures. In both strategies, the cooling and heating coils were controlled by the CCS while the supply air flow was controlled by the CCS and zone controllers (ZCS) in each office. The fan speed in the AHU was adjusted by the CCS to provide a centralized control of the supply and return air flow in the zones. At the same time, the position of the air dampers in each room was adjusted by the ZCS to regulate the supply air flow locally at a zone-level. The adaptive comfort control was complemented with an automatic window opening system with additional control variables, which were regulated by the CCS and the ZCS.

2.3.1. Prescriptive comfort control, PCC

The cooling and heating set points for the PCC were the upper and lower limits of the PMV-based comfort zone for an IEQ Category II according to EN16798-1. The cooling and heating seasons were defined considering the $T_{\text{ren}}$ calculated from Eq. (2). The CCS calculated the $T_{\text{ren}}$ each day based on measurements of
When \( T_{\text{out}} \) from the previous 7 days. When \( T_{\text{ext}} \geq 15^\circ\text{C} \) (cooling season), an upper set point of 26 \(^\circ\text{C}\) and a lower set point of 23 \(^\circ\text{C}\) were set, while for \( T_{\text{ext}} \leq 10^\circ\text{C} \) (heating season), the lower and upper limits were 20 \(^\circ\text{C}\) and 24 \(^\circ\text{C}\), respectively. For the transition period (10 \(^\circ\text{C}\) \( \leq T_{\text{ext}} \leq 15^\circ\text{C}\)), the heating and cooling set points were defined as the average value between the heating and cooling seasons, as proposed by Olesen et al. [34]. The heating and cooling set points for the transition period were 21.5 \(^\circ\text{C}\) and 25 \(^\circ\text{C}\), respectively.

Whenever \( T_{\text{op}} \) lied outside the PMV-based limits during occupied hours, the supply airflow was increased by the CCS and ZCS, adjusting the speed of the fans and the damper position in each zone. If \( T_{\text{op}} \) was inside the PMV-based limits, the supply airflow was set to its minimum value.

2.3.2. Adaptive comfort control, ACC

The ACC is an approach to operate mixed-mode buildings, where mechanical cooling is applied when \( T_{\text{op}} \) lies above the upper limit of the adaptive comfort zone. The guidelines to operate and design buildings based on the adaptive comfort model do not clearly specify how to maintain occupants’ thermal comfort level when the limits of the adaptive comfort model are exceeded. Parkinson et al. [4] proposed to divide the ACC into two control methods: the adaptive ramped approach (RA) and the adaptive conserving approach (CA). Both strategies use only natural ventilation when \( T_{\text{op}} \) is within the adaptive comfort limits. The main difference between the operation of the RA and the CA were the set points applied. The cooling set point for CA was defined as the upper limit of the adaptive comfort model and for RA was defined as the top of the PMV-PPD comfort zone. Figure 5 shows the operative temperature set points used for the CA and RA. The operation of both approaches is represented by the flow diagram in Figure A1 (Appendix 1). The two input variables considered were the \( T_{\text{op}} \) from each zone and the \( T_{\text{out}} \). The blue area in Figure 5 represents the region where mechanical cooling was applied, whereas heating was applied whenever \( T_{\text{op}} \) was below 20 \(^\circ\text{C}\) (red area). NV through window opening was possible when \( T_{\text{op}} \) and \( T_{\text{out}} \) were inside the yellow area in Figure 5. If \( T_{\text{op}} \) was between the heating and cooling set points, but windows were not open, the heating and cooling supply were turned off and the ventilation system was kept active.

The optimal \( T_{\text{op}} \) from the adaptive comfort model (Eq. 5) was used as the set point for window opening, considering \( T_{\text{op}} \) in each zone as the control variable. The maximum opening area of the windows was assumed to be 55 % of their area with a discharge coefficient \( C_d \) equal to 0.65, considering completely open side-hung windows [35]. Six conditions needed to be fulfilled to enable window opening during occupied hours:

![Figure 5. Diagram with the operative temperature set points used for the adaptive comfort control (CA and RA).](https://example.com/figure5.png)

\( T_{\text{op}} \) : upper and lower limits of the adaptive comfort model. \( T_{\text{PMV}, \text{UL}} \) and \( T_{\text{PMV}, \text{LL}} \) : upper and lower limits of the PMV-PPD method. WO: region where window opening was allowed. Heating: region where mechanical heating was active. Cooling: region where mechanical cooling was activate.
1. $T_{\text{opt}}$ is above 20 °C.
2. $T_{\text{rms}}$ is between 10 °C and 25 °C.
3. $T_{\text{opt}}$ is inside the limits of the adaptive comfort model for an IEQ Category II from EN16798-1.
4. $T_{\text{out}}$ is below $T_{\text{opt}}$.
5. $T_{\text{opt}}$ is greater than or equal to 10 °C.
6. $T_{\text{opt}}$ of the other office is inside the limits of the adaptive comfort model.

The first condition was to avoid opening windows when heating is required. The second and third conditions were used to verify the applicability of the adaptive comfort model (described in Section 2.1.). The fourth requirement was to open windows only when the outdoor air could be used for zone cooling, considering a dead band between $T_{\text{opt}}$ and $T_{\text{out}}$ of 0.5 °C. The fifth condition aimed to avoid the risk of draft discomfort caused by an elevated airflow through the windows. Haldi and Robinson [36] showed that the probability of occupants opening windows with an outdoor temperature below 10 °C was almost zero, which could be partially explained by draft discomfort. The sixth condition was to avoid the use of mechanical cooling when windows were opened, since the air was mechanically cooled in the AHU and then distributed to the different zones.

The CCS from the adaptive comfort control operated the heating and cooling coils and the fans in the AHU. $T_{\text{rms}}$ and the limits of the adaptive comfort model were also calculated in the CCS. The supply air flow was centrally controlled by the CCS and adjusted locally in each zone by dampers, controlled by ZCS. If heating or cooling was required, the supply air flow was increased based on the signal from the proportional controllers. The heat recovery unit was not directly controlled by the adaptive comfort control, because its operation depended on the differences between $T_r$, $T_{\text{out}}$, and $T_{\text{sp},s}$, as explained in Section 2.3. The activation of the night-time operation mode was also performed by the CCS.

### 2.3.3. Night-time operation

Night cooling (NC) was combined with the CA to evaluate the possibility of decreasing the energy use for mechanical cooling in a mixed-mode building on the cooling season. NC was used to release at night the heat that was stored in the thermal mass of the building during daytime. Two different night cooling methods were tested: mechanical ventilation (NC-MV) and natural ventilation (NC-NV). NC-MV used the mechanical ventilation system at night to supply outdoor air to the zones without conditioning it. Therefore, the only energy use for this strategy was the electricity used by the supply and exhaust fans. NC-NV relied on natural ventilation by opening windows at night. Both night cooling strategies were active during unoccupied hours in weekdays, only when the following three conditions were met:

1. $T_{\text{opt}}$ is above 15 °C.
2. $T_{\text{opt}}$ is above the set point for night cooling ($T_{\text{sp,nc}}$).
3. $T_{\text{opt}}$ is above $T_{\text{out}}$.

The first requirement was implemented to ensure that night cooling was only available during the cooling season. A set point for night cooling ($T_{\text{sp,nc}}$) was defined in the second requirement that represented the minimum $T_{\text{opt}}$ to activate night cooling. Three different values of $T_{\text{sp,nc}}$ were tested: 15, 17 and 19 °C, which were similar to the values used by Roach et al. [18]. The third condition was to verify that the outdoor air can be used for cooling, where a dead band between $T_{\text{opt}}$ and $T_{\text{out}}$ equal to 0.5 °C was used. A constant air volume was provided for NC-MV, where two supply airflows of 1.8 ACH and 5 ACH were tested.

Figure A2 in Appendix 2 shows that the night cooling operation was only available on weekdays, assuming that occupants were present all the weekdays of the year. The flow diagram shows that for NC-NV windows were open and for NC-MV the mechanical ventilation was active only when the three previously mentioned conditions were fulfilled.

### 2.4. Cases analysed

Each case presented in Table 2 was simulated for the five locations considered. The comparison between the different cases aimed to define optimal operation strategies for mixed-mode buildings in terms of energy use and indoor climate.
The first scenario corresponded to the prescriptive comfort control (PCC) used as the reference case to represent the operation of MC buildings. The adaptive comfort control based on the ramped approach (RA) was the only case where the limits of the PMV-PPD method were used when the temperature was outside the adaptive comfort limits. The adaptive conserving approach (CA) was applied in all the remaining cases based on the adaptive comfort model. Four different night cooling strategies with mechanical ventilation were studied. In two of them the supply air flow was set to 1.8 ACH and 5 ACH (NC-MV-LF and NC-MV-MF, respectively), whereas $T_{sp,nv}$ was 15 °C. In the other two NC-MV cases, two additional $T_{sp,nv}$ were tested: 17 °C and 19 °C. For night cooling based on natural ventilation (NC-NV), three cases were studied, where $T_{sp,nv}$ was defined as 15 °C, 17 °C and 19 °C. The last three cases (TRM-3D, TRM-7D and TRM-1M) applied different outdoor reference temperatures to calculate the limits of the adaptive comfort model.

Table 2: List of studied cases. *For PCC, only mechanical cooling was applied without NV. **For RA, the upper bound of the NV mode was the upper limit of the adaptive comfort zone using the simplified $T_{rm}$ calculation for 7 days. ***For CA, the upper bound of the NV mode was equal to the set point for MC.

<table>
<thead>
<tr>
<th>Case</th>
<th>Mechanical cooling set point when $10 \degree C \leq T_{rm} \leq 25 \degree C$</th>
<th>Night cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC*</td>
<td>Upper limit of the PMV-based comfort zone.</td>
<td>Not applied</td>
</tr>
<tr>
<td>RA**</td>
<td>Upper limit of the PMV-based comfort zone.</td>
<td>Not applied</td>
</tr>
<tr>
<td>CA***</td>
<td>Upper limit of the adaptive comfort zone using the simplified $T_{rm}$ calculation for 7 days (Eq. 2).</td>
<td>Not applied</td>
</tr>
<tr>
<td>NC-MV-LF</td>
<td>Same as for CA</td>
<td>CAV with a supply airflow of 1.8 ACH and a night cooling set point for $T_{op}$ equal to 15 °C</td>
</tr>
<tr>
<td>NC-MV-MF</td>
<td>Same as for CA</td>
<td>CAV with a supply airflow of 5 ACH and a night cooling set point for $T_{op}$ equal to 15 °C</td>
</tr>
<tr>
<td>NC-MV-17</td>
<td>Same as for CA</td>
<td>CAV with a supply airflow of 1.8 ACH and a night cooling set point for $T_{op}$ equal to 17 °C</td>
</tr>
<tr>
<td>NC-MV-19</td>
<td>Same as for CA</td>
<td>CAV with a supply airflow of 1.8 ACH and a night cooling set point for $T_{op}$ equal to 19 °C</td>
</tr>
<tr>
<td>NC-NV-15</td>
<td>Same as for CA</td>
<td>Natural ventilation with a night cooling set point for $T_{op}$ equal to 15 °C</td>
</tr>
<tr>
<td>NC-NV-17</td>
<td>Same as for CA</td>
<td>Natural ventilation with a night cooling set point for $T_{op}$ equal to 17 °C</td>
</tr>
<tr>
<td>NC-NV-19</td>
<td>Same as for CA</td>
<td>Natural ventilation with a night cooling set point for $T_{op}$ equal to 19 °C</td>
</tr>
<tr>
<td>TRM-3D</td>
<td>Upper limit of the adaptive comfort zone using the $T_{rm}$ calculation for 3 days, (Eq. 1 with $\alpha=0.8$).</td>
<td>Not applied</td>
</tr>
<tr>
<td>TRM-7D</td>
<td>Upper limit of the adaptive comfort zone using the $T_{rm}$ calculation for 7 days, (Eq. 1 with $\alpha=0.8$).</td>
<td>Not applied</td>
</tr>
<tr>
<td>TRM-1M</td>
<td>Upper limit of the adaptive comfort zone using the monthly mean temperature.</td>
<td>Not applied</td>
</tr>
</tbody>
</table>
3. Results

3.1. Operative temperature

The operative temperature obtained from the simulations were analysed to assess thermal comfort. Figure 6 shows a difference between the operative temperature from the MC building (PCC) and the other cases that used mixed-mode operation. In Palermo and Tokyo, the operative temperature from the PCC was confined to a smaller range than for the other cases. This result was expected since in the PCC mechanical cooling was applied when the operative temperature was above the PMV-based comfort limit, which was always lower compared to the adaptive comfort limits used in the other cases. The median operative temperatures for the mixed-mode control strategies were at least 1 °C lower than for the PCC in Palermo, Tokyo, and Zurich. This was not the case for Copenhagen and Edinburgh, where the PCC registered higher operative temperatures compared to the other cases. The results also showed that the RA recorded lower operative temperatures than the CA in Palermo and Tokyo. This was because in the RA, the operative temperature was decreased to the upper limit of the PMV-PPD method once cooling was required, whereas for the CA the operative temperature was kept below the upper limit of the adaptive comfort model, which can reach higher values (Figure 2). Among the different night cooling strategies tested, in Palermo and Tokyo the cases that used NV reached the lowest minimum and median operative temperatures. Specifically, for the case with NV and a night cooling set point of 15 °C (NC-NV-15), the minimum and median operative temperatures were nearly 2 °C lower than for the case without night cooling (CA). The application of night cooling based on MV in those locations only showed a decrease of the minimum operative temperature compared to CA, which was the case with a supply airflow of 5 ACH during night-time (NC-MV-MF). However, the maximum operative temperature in Palermo and Tokyo was approximately the same for all the cases except for the PCC. In Copenhagen, Edinburgh and Zurich, the use of night cooling allowed decreasing the maximum operative temperatures by nearly 1 °C to 2 °C, but the minimum value was the same for all the cases studied. Figure 6 also shows that the cases that defined the outdoor reference temperature differently (TRM-1M, TRM-3D and TRM-7D) did not have noticeable differences regarding operative temperatures compared to CA.

3.2. Energy use

The primary energy used to condition the indoor environment was calculated and compared between the different cases and locations. Three different energy end-use applications were considered in the analysis: space heating and cooling (defined as the thermal energy supplied to the heating and cooling coils in the air handling unit for air-conditioning) and electricity used by the fans and pumps in the air handling unit, named HVAC auxiliary energy (HVAC aux.). Figure 6 summarizes the annual primary energy use for the building model, considering the different cases studied, locations and end-use applications.

PCC showed the largest primary energy use in all locations studied when considering only the cases without night cooling. The energy use was between 12 % and 51 % lower than PCC when the mixed-mode cases were applied without night cooling. The CA reduced the energy use by 51 % compared to the PCC in both Palermo and Tokyo. The RA in those locations had an energy use between 28 % and 32 % lower than that of the PCC. For the other three locations with a low cooling requirement, the CA and RA had a similar energy use, which was between 12 % and 32 % lower than that of the PCC.
Figure 6. Distribution of operative temperatures during occupied hours (left) and annual primary energy use for heating, cooling, and HVAC auxiliary (right). CPH: Copenhagen; ED: Edinburgh; PA: Palermo; TYO: Tokyo; and ZH: Zurich.
The night cooling strategies based on natural ventilation showed a reduction of the energy use compared to the cases without night-time operation only in Palermo. This reduction was between 57 % and 61 % lower than the reduction using the PCC, depending on the set points applied. For the other locations, the use of night cooling based on natural ventilation was related to an increase of heating energy use and auxiliary energy for the all-air system. The implementation of night cooling based on mechanical ventilation achieved a reduction of energy use for cooling in Palermo and Tokyo. However, the operation of the ventilation system during night-time increased the auxiliary energy use, which led to a higher primary energy use. When a supply airflow of 5 ACH was used for night cooling (NC-MV-MF), the primary energy use was larger than for the other cases for all climates, while the cooling energy needed was moderately reduced. When different outdoor reference temperatures were used to calculate the limits of the adaptive comfort model (CA, TRM-1M, TRM-3D and TRM-7D), the difference of primary energy use between them was negligible. Only in Tokyo and Zurich, the energy use was 6 % and 8 % higher, respectively, when using the monthly average temperature instead of the running mean outdoor temperature calculated for seven days with the simplified formula.

3.3. Mixed-mode operation

Figure 7 shows the number of days when windows were opened for at least 15 minutes during the simulated year. The number of days with window opening was divided into days where windows were open without a requirement for mechanical cooling and when there was a switch over between the NV and MC modes. This information aims to show how many times per day and how many days is expected that occupants will be exposed to switch overs between cooling strategies.

The results show that in all cases and locations there were more days with open windows without a requirement for mechanical cooling, than those with switch overs between operation modes. Most of the days when mechanical cooling was needed after opening windows where mainly days with a single switchover between both operation modes. The cases without night cooling in Palermo had the longest period with open windows, which was between 164 and 182 days (corresponding to 63 % to 70 % of the occupied period in a year). In Palermo and Tokyo, the maximum number of switchovers per day was three, which occurred when the RA was applied. There were also more days with switch overs when RA was applied in Palermo and Tokyo, which corresponded to 12 days (5 % of the occupied period within a year). For the other cases, there was mainly one switchover per day, which occurred for less than 10 days (less than 4 % of the occupied period). However, the number of days with switch overs in Zurich was less than 5, while in Copenhagen and Edinburgh the number of switchovers was negligible.

The different running mean outdoor temperatures used to calculate the adaptive comfort limits (last three cases in Figure 7) did not show a difference between the number of days with window opening, except in Palermo. This number decreased - three days (TRM-3D) or increased - seven days (TRM-7D) compared to the case with simplified formula from Eq. (2) (CA). The use of the monthly average temperature for the adaptive comfort model (TRM-1M) reduced the period with window opening in all locations, except in Palermo, where it increased compared to the case using the simplified formula.

Among the different cases with night cooling, the strategy based on natural ventilation and a set point of 15 °C reached the lowest number of days with window opening which was within 14 % to 56 % lower than for the case without night cooling (CA). In Palermo and Tokyo, the number of days with switchovers between NV and MC was close to zero when using natural ventilation during night-time, compared to the other cases. The use of mechanical ventilation during night-time also decreased the number of days with window opening and the number of days with switch overs, but to a lesser extent compared to night cooling based on natural ventilation.
3.4. Indoor air quality

Figure 8 shows the cumulative distribution of CO₂ concentration above the outdoor CO₂ concentration of 400 ppm (ΔCO₂). The ΔCO₂ concentration was below 550 ppm for all cases and locations considered, which corresponds to Category I from EN16798-1. The maximum concentration of CO₂ was similar for all cases and locations (within 320-360 ppm). The results also showed that in Palermo the distribution of the CO₂ was lower than in the other locations, which was also the location where windows were opened for the longest period (Figure 7). This indicates that in the cases based on the adaptive comfort control, window opening provided enough ventilation to have an adequate indoor air quality in the office.
Figure 8. Distribution of the CO₂ concentration above the outdoor level during occupied hours. CPH: Copenhagen; ED: Edinburgh; PA: Palermo; TYO: Tokyo; and ZH: Zurich

4. Discussion

The control strategy for mixed-mode buildings presented in this study applied guidelines from standards to operate and design MC and NV buildings, defined by the PMV and the adaptive comfort model. However, it is not clear in the literature which approach should be applied for thermal comfort evaluation in mixed-mode buildings. De Dear and Brager [26] suggested that the thermal neutrality predicted by the PMV is similar to thermal preference, whereas the optimal temperature predicted by the adaptive comfort model is closer to thermal acceptability. Moreover, studies have shown that thermal preferences can have seasonal variations [37] and thereby discrepancies will occur when evaluating thermal comfort in mixed-mode buildings on a yearly basis. To provide a suitable thermal comfort evaluation of mixed-mode buildings, it is required to characterize occupants’ thermal responses from field studies [2] [6] [10] [15]. Nevertheless, in a simulation-based evaluation such as in the present study, it is only possible to perform a simple thermal comfort
evaluation of mixed-mode buildings by analysing single indoor environmental parameters such as the operative temperature.

As expected, the maximum operative temperature was higher in the cases where mixed-mode cooling was applied, compared to the case with a MC building, except for Edinburgh (Figure 6). This applied specifically to locations with higher outdoor temperatures like Palermo and Tokyo, where the adaptive comfort model was applicable for over half of the year (Figure 2c and d). This indicates that the extent of applicability of mixed-mode buildings is highly dependent on climate. If the proposed control strategy is implemented in a real mixed-mode building located in warm climates, the results from Figure 6 suggest that occupants will probably be exposed to a larger variation of indoor temperatures compared to a MC building. However, the median temperatures will be lower for a mixed-mode building than for the MC case. The adaptive comfort model allows for a larger variation of the operative temperature as long as occupants have easy access to operable windows and other means of adaptation [11]. Therefore, the adaptive comfort control has the potential to decrease the median value of the operative temperature if the assumption that occupants are able to override the system by opening windows, is applicable in an operational building.

It was observed in field studies that occupants’ thermal expectations change when a mixed-mode building switches from the NV to the MC mode and vice-versa [6] [10] [15]. The results from Figure 7 provide a simulation-based estimation of how many times occupants would be exposed to switchovers between the NV and MC modes. A high number of switchovers per day would indicate that occupants will be exposed to both operation modes in a relatively short period of time. Drake et al. [2] observed that occupants tended to feel a slight discomfort during the transition between NV and MC. In that study, occupants’ responses were influenced by the duration of the MC mode once the NV could not maintain the indoor temperature within comfortable limits. However, no other studies were found in the literature that evaluated occupants’ thermal responses resulting from fast or slow changes between the NV and MC modes in mixed-mode buildings. The results from Figure 7 showed that there was a maximum of three switchovers per day, which occurred when the adaptive ramped approach was applied in Palermo and Tokyo. Moreover, sudden changes between NV and MC in the adaptive ramped approach could generate highly drifting operative temperatures caused by the difference between the set points from both operation modes. This could have a negative effect on thermal comfort due to high drifting rates of indoor temperatures, as described by Kolarik et al. [38]. The adaptive conserving approach is not associated with an induced drift of indoor temperatures since it applies the upper limit of the adaptive comfort zone as cooling set point for the MC mode and also as the maximum temperature where the NV mode operates. As observed in Figure 7, the cases based on the adaptive conserving approach led to a lower number of switchovers per day and lower number of days with switch over. This number was nearly zero when the adaptive conserving approach was combined with night cooling strategies based on natural ventilation. The results suggest that the application of the adaptive conserving approach complemented with night cooling will minimize the possibility that occupants are exposed to different operation modes in a day. However, further research is needed to analyse occupants’ thermal responses when a mixed-mode building switches between operation modes.

The adaptive conserving approach achieved a larger reduction of energy use than the adaptive ramped approach compared to the MC building in Palermo and Tokyo. The maximum reduction was respectively 51 % and 32 % for the conserving and ramped approaches in those two locations. In Copenhagen, Edinburgh and Zurich, the energy use was respectively 16 %, 12 %, and 32 % lower than for the MC building, with similar values for the conserving and ramped approaches. As suggested by Parkinson et al. [4], the conserving approach can lead to higher energy savings than the ramped approach, as it uses higher set points for mechanical cooling in warmer climates. The results from Figure 6 showed that the operative temperatures in Palermo and Tokyo were higher for the conserving approach, compared to the ramped approach. However, both methods reached similar median and maximum operative temperatures, which indicates that the adaptive ramped approach was not able to mitigate the periods with the highest temperatures. A few studies were able to evaluate the energy savings potential of mixed-mode buildings operated based on the adaptive comfort model. Barbadilla-Martín et al. [39] tested a comfort-based control framework in three mixed-mode buildings located in Sevilla, Spain, achieving a reduction of energy use between 11 % and 27 % compared to a control strategy with fixed set points. They used a control strategy based on a local adaptive comfort model [6], which differed from the control framework proposed in the present study. In the controller from Barbadilla-Bartín et al., windows were opened manually and the optimal operative
temperature of the adaptive model was defined as the room temperature set point for the air conditioning system. In the present study, windows were opened automatically and the set points were defined as the upper and lower bounds of the adaptive comfort model and PMV model, as shown in Section 2.3.2. Yun et al. [40] estimated that the energy use with an adaptive comfort control was 22% lower than using MC in a mixed-mode building located in Seoul, South Korea. The results from field studies were probably influenced by human-related factors (i.e., occupants’ adaptation and behavioural adjustment). This limited the energy savings potential of such studies compared to the higher estimations observed in this study. The study from Torcellini et al. [41] identified energy savings within 22% to 77%, which were obtained from a large-scale field study in six mixed-mode buildings located in different parts of the United States. However, they evaluated control systems that optimized energy use only, without considering thermal comfort. The control approach proposed in the present study considered that the limits of the adaptive comfort zone were applicable when the running mean outdoor temperature was within 10 °C to 25 °C. Larger energy savings could have been obtained if a wider applicability range for the adaptive comfort zone was applied.

In the mixed-mode control strategies analysed in the present study, the ventilation system was turned off when windows were opened. Despite the lack of control over the air flow rate through the window openings, all control strategies provided an adequate indoor air quality. The annual indoor CO₂ concentration from all the cases studied was within the limits of the indoor environmental Category I from EN 16798-1. These results could be however different from an operational office building, where some occupants are able to override the automatic window opening control and offices could have a higher occupant density than those considered in the present study.

The night cooling operation strategy with natural ventilation showed a reduction of energy use and operative temperatures in Palermo, compared to the case with daytime operation only. This approach reached an energy use 61% lower than the MC building when a night cooling set point of 19 °C was used. That corresponds to additional energy savings of 10% compared to the savings obtained with the adaptive conserving approach. In Tokyo, the heating energy use and HVAC auxiliary energy use were higher when opening windows during night-time due to overcooling. The office building considered for this study was conditioned with an all-air VAV system. Therefore, a higher energy requirement for heating also increased the requirement for auxiliary energy due to an increase of the fan speed when heating or cooling were applied. Implementing the proposed night cooling operation strategy in buildings with other HVAC systems could lead to a lower requirement for auxiliary energy, especially when having overcooling. The results showed that using night cooling with mechanical ventilation reduced the energy use for cooling in Palermo, Tokyo, and Zurich, compared to the daytime operation. However, the savings were exceeded by a higher electricity use for the fans when operating during night-time.

When comparing the results from the different outdoor reference temperatures (i.e., running mean temperature and monthly average temperature) to calculate the adaptive comfort limits, it was not possible to determine which configuration had the best performance. Using the monthly mean outdoor temperature or the running mean outdoor temperature yielded similar results in terms of operative temperatures, indoor air quality and energy use. Carlucci et al. [42] compared the comfort-related implications of using different outdoor reference temperatures, considering different calculations of the running mean outdoor temperature. Their study highlighted that the predictions from the adaptive comfort model are highly dependent on the period considered for the calculation of the running mean temperature. Using the simplified formula to calculate the running mean outdoor temperature (Eq. (2)), will allow calculating the running mean outdoor temperature in a simple manner without significant differences in energy use, compared to the standard equation. This method could reduce the complexity of the controller and minimize the time used to operate the climatic system.

5. Limitations

The simulation-based nature of this study did not allow to assess the subjective thermal comfort of occupants when operating a mixed-mode building. Future studies should include the implementation of the proposed mixed-mode control approach in a real building. This will allow to verify the applicability of the adaptive comfort model from EN16798-1 to characterize thermal responses or the need to implement specific models.
for mixed-mode building developed at regional level [6] [15] [40] [43]. A field study will also allow to evaluate the thermal comfort implications of switching between NV and MC, and the effects of thermal adaptation when windows are both automatically and manually controlled. The present study considered the simulation of an office building module without considering different building types (e.g. schools, dwellings). This was because the focus of the study was on the development of the algorithm and the developed algorithm could be applied to other building types with modifications. Factors such as occupancy level, human behaviour, and building design may lead to different results between office buildings and other building types.

The evaluation of thermal comfort was only performed through the analysis of operative temperatures. Other parameters that influence thermal comfort were not considered in the evaluation to provide a simple comparison between the different cases studied.

6. Conclusions

A simulation-based analysis of control strategies for mixed-mode buildings was made with the aim of defining an optimal operation in terms of energy use and thermal comfort. A control approach for mixed-mode buildings was proposed, which applies the adaptive model of thermal comfort and the PMV-PPD method. The main conclusions are as follows:

- The mixed-mode operation based on the adaptive comfort model had a 12 % to 51 % lower primary energy use than a mechanically cooled building.

- The adaptive comfort control using the upper limit of the adaptive comfort zone instead of the upper limit of the PMV-PPD method as set point for mechanical cooling led to nearly 20 % more energy savings and fewer switchovers between operation modes. This applied only for Palermo and Tokyo, which are warm and humid climates. For the other locations both configurations of the adaptive comfort control led to similar energy use.

- Mixed-mode office buildings using the proposed adaptive comfort control were observed to reach lower median operative temperatures compared to mechanically cooled buildings. The maximum operative temperature was higher for the adaptive comfort control in the warmest locations since it considers that occupants may tolerate higher temperatures given the possibility to open windows.

- Night cooling with natural ventilation improved the overall performance of the adaptive comfort control only in Palermo. This strategy led to additional energy savings of 10 % as well as a reduction of the operative temperature and the number of switchovers, compared to only daytime operation. For the other locations analysed, night cooling led to an increase of the energy use, which indicates that the benefits of night cooling vary depending on the climate.

- The proposed control for mixed-mode buildings was enough to provide sufficient natural ventilation to have CO₂ concentration levels within Category I from EN16798-1 during occupied hours.

- Minor differences regarding energy use, air quality and thermal comfort were found when using different outdoor reference temperatures to calculate the limits of the comfort zone from the adaptive model.

- The proposed control framework could be applied in different climates and in different buildings with slight modifications.

Acknowledgements

This study was financially supported by Mitsubishi Electric R&D Centre Europe BV.
References


**Appendix 1 – Control diagram for daytime operation**

![Control diagram for daytime operation](image)

Figure A1. Mixed-mode operation scheme during daytime; \(T_{op}\): operative temperature; \(T_{out}\): outdoor air temperature; \(T_{rm}\): running mean outdoor air temperature; \(T_{ACM,UL}\) and \(T_{ACM,LL}\): upper and lower limits of the adaptive comfort model.

As an example of the scheme from Figure A1, if \(T_{op}, T_{out}, T_{rm}\) and \(T_{ACM,UL}\) were equal to 30 °C, 32 °C, 24 °C and 27 °C, respectively, the mechanical cooling set point for the CA approach would be 27 °C and for the
RA would be 26 °C (upper limit of the PMV-based comfort zone for the cooling season). In this case, \( T_{rm} \) is within the applicability range of the adaptive comfort model and \( T_{op} \) is above \( T_{ACM,UL} \), therefore, the ZCS would keep the windows closed and open the dampers in the ventilation system, whereas the CCS would activate the cooling coil and increase the fan speed, as described in Section 2.2.1.

Appendix 2 – Control diagram for night-time operation

Figure A2. Operation scheme of the night cooling strategy with mechanical ventilation (red box) and natural ventilation (green box).

As an example of the scheme from Figure A2, if the operation takes place on a weekday, then \( T_{out} \) is applied to calculate \( T_{rm} \). If \( T_{op}, T_{out}, T_{rm}, T_{sp,nct} \) were equal to 30 °C, 28 °C, 20 °C, 15 °C, then the night cooling strategy with mechanical ventilation would activate the ventilation system to supply a constant airflow during night-time. If the night cooling strategy used natural ventilation, then the system would open the windows during night-time, as described in Section 2.3.3.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:
Highlights

- A control framework for mixed-mode buildings was proposed
- Different framework configurations were tested using dynamic simulations
- Energy use, thermal comfort and air quality were analyzed for five locations
- The proposed framework used between 12 to 51 % lower energy than mechanical cooling
- Using the proposed framework led to satisfactory thermal comfort and indoor air quality