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Energy simulation of traditional vs. adaptive thermal comfort for two moderate climate regions

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Abstract
The original intent of this paper was to quantify the implications for energy demand of indoor temperature requirements based on a proposed adaptive thermal comfort standard (7) relative to a more traditional thermal comfort approach. The study focuses on a typical office situation in a moderate climate such as in The Netherlands or in the Czech Republic. The paper starts with a brief introduction of the concepts of traditional and adaptive thermal comfort models. This is followed by a description of the research method, i.e. computer modeling and simulation. The building model, the required indoor temperature ranges and the simulation results are described in some detail.
Since the scope of applicability of the proposed adaptive thermal comfort standard has been extremely limited lately (13, 14) the energy demand results have become largely irrelevant other than that they may be interpreted as indications for the time integrated degree of indoor conditions beyond the temperature limits of the respective comfort models should the office not have a mechanical heating or cooling system at all.
The main conclusion of the current work is that for moderate climate countries such as The Netherlands and the Czech Republic there is no apparent reason for rushing to adopt the proposed adaptive thermal comfort standard in its current form.

Preamble
The research for – and the initially submitted version of – the current paper was based on the adaptive thermal comfort standard as proposed in 1998 by De Dear and Brager (7). Due to overseas mailing delay, Brager and De Dear’s October 2000 paper (13) only came to our attention very late. However, because the latter paper presents new analysis and describes how the adaptive standard is actually being incorporated in the ANSI / ASHRAE 55 standard, some of the points in the initial version of the current paper became moot. Since we feel that it might still make an interesting contribution to the discussions at the conference, we have retained much of the material which was in the initial version of the current paper and added relevant information from (13) and ultimately from (14).

Keywords:
thermal comfort, adaptation, energy demand, computer simulation

Introduction
Thermal comfort can be defined as that condition of mind, which expresses satisfaction with the thermal environment (1). The main criteria for thermal comfort for the human body as a whole can be divided to environmental parameters: air temperature, radiant temperature, humidity, air velocity and personal parameters:
clothing and activity. In addition there are other environmental parameters that can cause local thermal discomfort such as draught, a high vertical temperature difference between head and ankles or too high radiant temperature asymmetry.

**Traditional vs. adaptive thermal comfort models**

Current comfort standards such as ISO/EN 7730 (1) and ANSI/ASHRAE 55-92 (2) are based on a more or less static model of human thermal comfort. The physiological and psychological response to the thermal environment is basically the same throughout the year. The only thing that changes is clothing and this results in different preferred temperatures in winter and in summer. Although ISO/EN 7730 presents a generic model according to Fanger (3), which will probably also be included in the upcoming revision of ANSI/ASHRAE 55 (4), in common usage the standards divide recommended comfort requirements into two categories: winter (heating season) and summer (cooling season) with parameters such as in Tables 1 and 2.

**Table 1.** Recommended operative temperature levels predicting an acceptable thermal sensation for 90 % of the occupants during light, mainly sedentary activity with other environmental parameters within specified limits according to ISO/EN 7730 (1)

<table>
<thead>
<tr>
<th>Season</th>
<th>Clothing insulation (clo)</th>
<th>Activity level (met)</th>
<th>Optimum operative temperature (^{\circ}\text{C})</th>
<th>Operative temperature range (^{\circ}\text{C})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>1.0</td>
<td>1.2</td>
<td>22</td>
<td>20 - 24</td>
</tr>
<tr>
<td>Summer</td>
<td>0.5</td>
<td>1.2</td>
<td>24.5</td>
<td>23 - 26</td>
</tr>
</tbody>
</table>

**Table 2.** Optimum and acceptable ranges of operative temperature for people during light, primarily sedentary activity, 50 % relative humidity and mean air speed \(\leq 0.15\) m.s\(^{-1}\) according to ANSI/ASHRAE 55-1992 (2)

<table>
<thead>
<tr>
<th>Season</th>
<th>Typical clothing</th>
<th>Clothing insulation (clo)</th>
<th>Activity level (met)</th>
<th>Optimum operative temperature (^{\circ}\text{C})</th>
<th>Operative temperature range (^{\circ}\text{C})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>heavy slacks, long-sleeve shirt and sweater</td>
<td>0.9</td>
<td>1.2</td>
<td>22</td>
<td>20 – 23.5</td>
</tr>
<tr>
<td>Summer</td>
<td>light slacks, short-sleeve shirt</td>
<td>0.5</td>
<td>1.2</td>
<td>24.5</td>
<td>23 – 26</td>
</tr>
<tr>
<td>Minimal</td>
<td></td>
<td>0.05</td>
<td>1.0</td>
<td>27</td>
<td>26 – 29</td>
</tr>
</tbody>
</table>

Experience shows that the most important factor determining human thermal comfort is the general feeling of warmth. “Get the warmth right and only then worry about any remaining causes of discomfort. They may well have disappeared”, according to McIntyre (5). The optimum operative temperature for comfort is a function of metabolic rate and clothing insulation. It is possible to predict the activity level of people in a particular environment and subsequently their metabolic rate. It is however very difficult to predict what people will wear. People usually change clothing according to outside temperatures; i.e. people choose clothes more for
outdoor than for indoor climate. In practice, women are able and tend to adapt (the insulation level of) their clothing more to the outside temperature than men (4). And in addition to this, individual people are different not only in choosing their clothes but in thermal responses and thermal adaptation to the environment as well.

According to the adaptive hypothesis of De Dear and Brager (6, 7, 13, 14), contextual factors and past thermal history modify building occupants’ thermal expectations and preferences. One of the predicted consequences is that people in warm climate zones prefer warmer indoor temperatures than people living in cold climate zones. This is contrary to the static assumptions underlying the current ASHRAE comfort standard (2).

De Dear and Brager published in (7) a draft proposal for a thermal comfort standard that would – unlike (1) and (2) - take thermal adaptation into account. They make a distinction between two types of buildings: 1) buildings with centralized (i.e. centrally controlled) HVAC (heating, ventilation and air-conditioning) and 2) buildings with natural ventilation. The reason for this distinction appears to be that people have different expectations in these two types of buildings. When people have a possibility to control their environment (for example just being able to open a window) they are more easily thermally satisfied than when they perceive not to have control. In addition there might be higher room air speeds in naturally ventilated buildings in warm periods. The result is apparently that in a building without centrally controlled HVAC the occupants will accept a wider range of operative temperature over the year.

The above draft proposal was the initial starting point for the current study. Before discussing our work it might be useful to briefly elaborate some of the terminology used.

Adaptive model: a linear regression model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters; e.g. the outcome of ASHRAE research project RP-884 as reported in (7).
Static model: a model that relates the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) to environmental and personal parameters; e.g. (1).
Thermal neutrality ($T_n$): the indoor thermal index value (usually operative temperature) corresponding with a mean vote of neutral on the thermal sensation scale by a sample of building occupants (it does not necessarily coincide with ‘preferred temperature’ in case of buildings with centrally controlled HVAC systems).
Thermal sensation: a conscious feeling commonly graded into the categories – cold, cool, slightly cool, neutral, slightly warm, warm and hot; it requires subjective evaluation. An individual’s ideal thermal comfort does not necessarily correspond with a thermal sensation vote of neutral.

Outdoor effective temperature ($ET^*$); in the adaptive comfort approach (6, 7, 13), optimum comfort temperatures depend on outdoor $ET^*$. The $ET^*$ concept has been developed using the ‘two-node model’ (8). It is defined as the dry-bulb temperature ($DBT$) of a uniform enclosure at 50 % relative humidity, which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question. In principle, radiation can be taken into account by using operative temperature instead of $DBT$ (9, 10). In the absence of radiation, $ET^*$ lines coincide with $DBT$ values at the 50% relative humidity curve; see Figure 1.
\[ ET^* = t_o + w i_m LR (p_a - 0.5 p_{ET^*,s}) \]  \[1\]

Where:
\( t_o \) = operative temperature
\( w \) = skin wettedness
\( i_m \) = moisture permeability index
\( LR \) = Lewis ratio (at typical indoor conditions, equals approximately 16.5°C/kPa)
\( p_a \) = ambient partial vapor pressure
\( p_{ET^*,s} \) = saturated vapor pressure at ET*

In the adaptive comfort approach the optimum comfort temperature for buildings with centrally controlled HVAC systems is calculated from equation [2].

\[ T_n = 22.6 + 0.04ET^* \ldots with \ldots -5 < ET^* < 33, ^\circ C \]  \[2\]

The 90% acceptability range is between \( T_n - 1.2^\circ C \) and \( T_n + 1.2^\circ C \)

Equation [2] is shown together with the comfort temperature according to the static PMV model in Figure 2. The adaptive model results are based on experimental findings in a large number of buildings in a range of climate zones. The static model’s comfort temperature for each building was derived by inputting the buildings mean room air speed, relative humidity, clothing and activity level into the PMV model and then iterating for different operative temperature until PMV=0.
In the adaptive comfort approach the optimum comfort temperature for buildings with natural ventilation is calculated from equation [3] and shown in Figure 3. The static model’s comfort temperature for each building was again derived as indicated above.

\[ T_n = 18.9 + 0.255ET^* \text{ with } 5 < ET^* < 33^\circ C \]  

The 90% acceptability range is between \( T_n - 2.5^\circ C \) and \( T_n + 2.5^\circ C \)
Computer modeling and simulation

The objective of our current research was to predict energy demand implications by analyzing the space heating and cooling energy demands of ‘a standard office’ using both concepts of thermal comfort. Currently the most powerful technique available for the analysis and design of complex systems (like buildings and their environment) is computer modeling and simulation. The current study made use of ESP-r (Environmental Systems Performance - research) (12), which is a transient energy simulation system, capable of modeling the energy and fluid flows within combined building and plant systems when constrained to conform to control actions.

![Building Model](image)

**Figure 4.** Model of test office used for simulations

**Building model**

The simulations were carried out for a “standard office” (11); a typical cellular office for two occupants as schematically shown in Figure 4. Further details of the office model are as follows.

- **3.5 x 5.4 x 2.7 m or floor area = 19.44 m² and volume = 52.5 m³**
- Default orientation is window facing west. Other orientations were considered as well.
- **Constructions:**
  - **external wall:** U-value 0.39 W/m²K
  - **window:** U-value 2.75 W/m²K, transparency: 0.76
- **Activity:** mainly sedentary
- **Internal gains:** 2 people (total 140 W sensible plus 140 W latent) equipment (300 W)
- **Occupancy:** week days from 8 a.m. to 6 p.m.
- **Ventilation:** fresh air supply by either natural or mechanical ventilation during occupancy hours: 1.2 ACH; i.e. 30 m³/h/person (8.3 l/s/person)

1 In reality, the amount of fresh air supply will not be constant in natural ventilated buildings. However, since we wanted to focus on energy demand implications of different approaches to required indoor temperatures, variable infiltration and ventilation rates due to natural ventilation have not been taken into account.
when not occupied: 0.2 ACH

Outdoor climate: two moderate climate cases were considered:
- **The Netherlands (Eindhoven)**: Latitude: 51.45° N, Longitude: 5.40° E, Altitude: 20 m above sea level and annual mean air temperature: 10.1°C
- **Czech Republic (Prague)**: Latitude: 50.0° N, Longitude: 14.40° E, Altitude: 303 m above sea level and annual mean air temperature: 8.8°C

**Required indoor temperature ranges**

The required (or design) indoor temperature ranges are based on the thermal comfort approaches as described above. The numerical values of the indoor temperature mid points are summarized in Table 3, and the temperature ranges for 90% acceptability are graphically shown in Figure 5 for The Netherlands and in Figure 6 for the Czech Republic. From these figures it is immediately clear that there are relatively large differences between the different required indoor temperature approaches.

In the heating season, the minimum indoor temperatures would be about 1.5°C higher when the adaptive comfort approach would be adopted for buildings with centrally controlled HVAC systems relative to the current standards. In the heating season, the minimum indoor temperatures could be about 2°C lower when the adaptive comfort approach would be adopted for buildings with natural ventilation relative to the current standards.

**Table 3. Monthly indoor temperature range mid points according to:**

<table>
<thead>
<tr>
<th>Month</th>
<th>ISO</th>
<th>The Netherlands</th>
<th>Czech Republic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.0</td>
<td>0.7</td>
<td>20.2</td>
</tr>
<tr>
<td>2</td>
<td>22.0</td>
<td>3.4</td>
<td>20.2</td>
</tr>
<tr>
<td>3</td>
<td>22.0</td>
<td>2.8</td>
<td>20.2</td>
</tr>
<tr>
<td>4</td>
<td>22.0</td>
<td>8.5</td>
<td>21.1</td>
</tr>
<tr>
<td>5</td>
<td>22.0</td>
<td>13.9</td>
<td>22.4</td>
</tr>
<tr>
<td>6</td>
<td>24.5</td>
<td>15.3</td>
<td>22.8</td>
</tr>
<tr>
<td>7</td>
<td>24.5</td>
<td>16.4</td>
<td>23.1</td>
</tr>
<tr>
<td>8</td>
<td>24.5</td>
<td>16.0</td>
<td>23.0</td>
</tr>
<tr>
<td>9</td>
<td>22.0</td>
<td>14.0</td>
<td>22.5</td>
</tr>
<tr>
<td>10</td>
<td>22.0</td>
<td>8.1</td>
<td>21.0</td>
</tr>
<tr>
<td>11</td>
<td>22.0</td>
<td>6.6</td>
<td>20.6</td>
</tr>
<tr>
<td>12</td>
<td>22.0</td>
<td>2.2</td>
<td>20.2</td>
</tr>
</tbody>
</table>

In the middle of the cooling season, the maximum indoor temperature would be about 1.5°C lower when the adaptive comfort approach would be adopted for buildings with
centrally controlled HVAC systems relative to the current standards. The maximum indoor temperature would be about 0.5°C lower when the adaptive comfort approach would be adopted for buildings with natural ventilation relative to the current standards.

![Graph](image-url)

**Figure 5.** Required temperature ranges - according to the approaches in Table 3 - for 90% acceptability in The Netherlands.

![Graph](image-url)

**Figure 6.** Required temperature ranges - according to the approaches in Table 3 - for 90% acceptability in the Czech Republic.
As can be seen from Figure 5 and Figure 6, during the intermediate season the situation may reverse; i.e. the maximum indoor temperatures may be higher than according to the current standards. It actually depends on whether May and September would be treated as heating or cooling season.

Results & discussion

The following section presents our results in terms of energy demand for heating and cooling of a typical office. These results may alternatively be interpreted as indications for the time integrated degree of indoor conditions beyond the temperature limits of the respective comfort models should the office not have a heating or cooling system at all.

Table 4 summarizes the absolute and relative total annual energy demands for heating and cooling of the office for two different geographical locations, facing different orientations, and for the various required indoor temperature ranges.

Table 4. Absolute and relative annual energy demand for heating and cooling of the office when facing different orientations (O) and for the 3 types of required indoor temperature ranges (Ti) as specified in Table 3.

<table>
<thead>
<tr>
<th>O</th>
<th>T_i</th>
<th>The Netherlands</th>
<th>Czech Republic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heating (kWh)</td>
<td>Cooling (kWh)</td>
<td>Total (kWh)</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>586</td>
<td>134</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>468</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>761</td>
<td>164</td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>547</td>
<td>309</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>430</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>709</td>
<td>341</td>
</tr>
<tr>
<td>S</td>
<td>1</td>
<td>389</td>
<td>430</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>430</td>
<td>287</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>534</td>
<td>452</td>
</tr>
<tr>
<td>W</td>
<td>1</td>
<td>464</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>355</td>
<td>565</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>611</td>
<td>607</td>
</tr>
</tbody>
</table>

Since the required temperatures during the heating season would be lower (see Figure 5 and Figure 6), it comes as no surprise that the energy demand for heating would be lower when adopting the adaptive comfort approach for naturally ventilated buildings. Similarly, since the required temperatures during the heating season would be higher (see Figure 5 and Figure 6), the energy demand for heating would be higher when adopting the adaptive comfort approach for buildings with centrally controlled HVAC systems.
Since the required temperatures for both adaptive comfort model cases (i.e. $T_i[2]$ and $T_i[3]$ in Table 4) would be lower during the cooling season (see Figure 5 and Figure 6), one would expect the energy demand for cooling to be higher for the adaptive comfort model cases. The reason this is not the case can be seen in Figure 7, which shows the energy demand for heating and cooling per month for the office when facing west and when located in The Netherlands. From this Figure it is clear that there would be a considerable amount of cooling needed in May and September; i.e. months in which – in our assumption – the temperature according to the current standards would be similar to that for the heating season period (see Figure 5).

If May and September would be considered as summer months in terms of required indoor temperature ranges according to the current standards (i.e. $T_i[1]$), then the energy demand for cooling would be considerably lower when the current comfort standard would be applied. In other words the energy demand for cooling would be higher if the adaptive comfort approach would be adopted. Figure 8 shows similar results but now for the Czech Republic. Since the climate in the Czech Republic is fairly similar to The Netherlands, the above conclusion can be drawn as well.
Some questions and issues

During the work summarized above some questions and issues were encountered which are briefly discussed below.

Outdoor ET* and solar radiation

As indicated above the effective temperature is an imaginary temperature of a uniform enclosure at 50% relative humidity, which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question. However, when calculating the outdoor ET*, the solar radiation is actually not taken into account; neither in ASHRAE RP-884 (7) nor in the current work (where outdoor ET* was calculated as suggested in (7)).

According to Brager and De Dear (14) it was agreed by the ASHRAE committee in charge of Standard 55 that ET* is primarily an index used by researchers, and that practitioners would be more likely to use the adaptive comfort model if the meteorological input data was a more familiar and accessible index. The adaptive comfort model was, therefore, reformulated in terms of mean monthly outdoor air temperature, defined simply as the arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry bulb) temperatures for the month in question. This climate data is readily available and familiar to engineers.

An implicit justification seems to be that either the outdoor dry bulb temperature is dominant in terms of people’s clothing behavior and/or thermal adaptation, or that the cross-correlation between dry bulb temperature and solar radiation is so strong that there is no need to account for solar radiation separately. According to us this is an issue which has not yet been quantified.

Mean To based on daily or monthly mean values

In our current study, the required indoor temperature ranges according to the adaptive comfort approach were established per month; i.e. based on the monthly mean To. This also conforms to the current draft standard; see (14)). However, according to the originally proposed standard (7) it would be allowed to establish To on a daily basis. Figure 9 shows the difference for the required temperature range in The Netherlands during July of a climatic reference year. It is clear that if the daily approach would be used, the allowable indoor temperatures would be considerably higher during the warmer days, especially for buildings with natural ventilation.

The underlying issue is of course whether the time constant of human thermal adaptation is in the order of one day or in the order of one month. It seems more reasonable to assume the former. Subsequently it would seem more reasonable for the adaptive comfort standard to start from daily outdoor To, and – perhaps – to allow monthly mean outdoor To only in those cases where daily weather data is not available. This seems to be an issue that needs to be resolved.
Figure 9. The required temperature range based on either daily or monthly mean outdoor temperatures according to the adaptive comfort approach for naturally ventilated buildings in The Netherlands during July.

Definition of building category

Finally there seems to be an issue in defining the two categories of building. The scope definitions in the originally proposed standard (7) state the following.

- **Standard for buildings with centrally controlled HVAC** – The standard applies exclusively to indoor environments with HVAC systems over which the occupants have no control. The occupants of such buildings are presumed to have no option to open/close windows.

- **Standard for naturally ventilated buildings** - The standard applies exclusively to indoor environments without centralized HVAC systems. Such buildings are presumed to have operable windows that the occupants have some degree of control over. They may have some form of heating installed, but it would be controlled by the building occupants, either individually or in small groups.

Many buildings in temperate climates have so-called mixed mode cooling systems. In some cases this means that either the mechanical cooling or the natural ventilation can be active at any point in time. In other cases these systems may work simultaneously. Very often these systems consist of centralized and local components and controls. Presumably these systems would mostly fall in the second category because the occupants have some form of control, however this is not immediately clear from the above scope definitions.

Then there is the very common case of a naturally ventilated building with centrally controlled heating system. Strictly according to the above definitions such a building would fall in the centrally controlled HVAC category; but is this reasonable? Or should the standard be interpreted such that a particular building can be in the first category during the heating season and in the second category during the cooling season, or vice versa?

The ASHRAE committee in charge of Standard 55 has already addressed many of the above questions. As reported by Brager and De Dear (14) the scope of applicability was one of the biggest contested issues in this committee. The current state is that the
adaptive comfort approach will be included in Standard 55 as an option to be used only for the following conditions:

- naturally conditioned spaces where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows. It is specifically noted that the windows must be easy to access and operate.
- spaces can have a heating system, but the method doesn’t apply when it is in operation.
- spaces cannot have a mechanical cooling system (e.g., refrigerated air-conditioning, radiant cooling, or desiccant cooling).
- spaces can have mechanical ventilation with unconditioned air, but opening and closing of windows must be the primary means of regulating thermal conditions.
- occupants of spaces must be engaged in near sedentary activity (1-1.3 met), and must be able to freely adapt their clothing to the indoor and/or outdoor thermal conditions.

**Conclusions**

As reported by Brager and De Dear (13, 14) the originally proposed (7) adaptive comfort model for buildings with centrally controlled HVAC systems is not relevant any longer. If it had been, then the indoor temperature requirements for The Netherlands and the Czech Republic would have been stricter – and the energy demand higher - than according to the current thermal comfort standard.

Using the originally proposed adaptive comfort standard (7) for buildings with natural ventilation would result in moderate climates such as in The Netherlands and in the Czech Republic in considerable lower energy demands for heating in comparison to the current thermal comfort standard. However, how realistic would it be to allow indoor temperatures down to 18°C operative temperature, which is the lower limit for 90 % acceptability when outside ET* ≤ 5°C?

Presumably similar considerations led several members of the ASHRAE committee in charge of Standard 55 to feel that the lower end of Equation [3] was too extreme. Brager and De Dear (14) report that consequently the adaptive comfort approach in Standard 55 will have a lower limit of 10°C mean outdoor air temperature; i.e. not 5°C as still reported in (13).

As follows from Table 3, for moderate climate regions such as The Netherlands and the Czech Republic this means that the adaptive comfort approach will not be applicable for any building during the main part of the year; i.e. typically from October through to April.

Based on monthly mean outdoor air temperatures in The Netherlands and the Czech Republic, the currently proposed adaptive thermal comfort standard for naturally ventilated buildings will be more strict than the current standard during the major part of the summer period. Since it will not be allowed to use the adaptive approach in case there is any mechanical cooling system, there will not be an energy penalty. It will, however, be easier for a designer to comply with the current standard thus making the adaptive comfort standard moot.

As demonstrated in Figure 9, the use of daily – instead of monthly - mean outdoor temperatures would effectively widen the acceptable temperature range thus making
the adaptive comfort standard for naturally ventilated buildings beneficial even in moderate climate regions such as The Netherlands and the Czech Republic.

Based on the current work it may be concluded that for moderate climate countries such as The Netherlands and the Czech Republic there is no apparent reason for rushing to adopt the proposed adaptive thermal comfort standard in its current form.

References