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Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones

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Abstract

Standards governing thermal comfort evaluation are on a constant cycle of revision and public review. One of the main topics being discussed in the latest round was the introduction of an adaptive thermal comfort model, which now forms an optional part of ASHRAE Standard 55. Also on a national level, adaptive thermal comfort guidelines come into being, such as in the Netherlands. This paper discusses two implementations of the adaptive comfort model in terms of usability and energy use for moderate maritime climate zones by means of literature study, a case study comprising temperature measurements, and building performance simulation. It is concluded that for moderate climate zones the adaptive model is only applicable during summer months, and can reduce energy for naturally conditioned buildings. However, the adaptive thermal comfort model has very limited application potential for such climates. Additionally we suggest a temperature parameter with a gradual course to replace the mean monthly outdoor air temperature to avoid step changes in optimum comfort temperatures.

Keywords:
Adaptive Thermal Comfort, Moderate Climates, Standards, Energy Use

1 Introduction

People have always been in pursuit of creating comfort in their environment. It is still one of the most important matters taken into account in a building's design process. The indoor environment includes all physical, chemical and biological factors of a building that influence the health and well being of its occupants [1]. This paper deals with thermal comfort in particular, which can be defined as '*the state of mind, which expresses satisfaction with the thermal environment*' [2]; a definition quickly comprehended, but hard to capture in physical parameters.

In European countries ISO 7730 [3] is the current standard for evaluating thermal comfort, together with CR 1752 [4] -a technical report on ventilation- which covers thermal comfort as well as other indoor environmental parameters. ANSI/ASHRAE Standard 55 [2] is the counterpart in North-America. These documents specify comfort zones in which a large percentage of occupants with given personal parameters will regard the environment as acceptable.

Standards are established to assist the industry and the public by offering a uniform method of testing for rating purpose [2]. The creation of standards is determined by the need for them, and conformance to them is completely voluntary, unless legislation requires otherwise. Standards are on a constant cycle of revision and public review [5,6]. This process is based on reaching consensus, which is the substantial agreement reached by concerned interests according to the judgement of a duly appointed authority, after a concerted attempt at resolving objections. It implies much more than the concept of a single majority but not necessarily unanimity [2]. An important matter during the latest round of standard revisions was the incorporation of an adaptive thermal comfort evaluation method. Such an adaptive model has been introduced in the revised ASHRAE Standard 55 for the evaluation of the indoor environment in naturally conditioned buildings [2]. Contrary to the North-American standard, the revised ISO 7730 does not incorporate such a model [6].

The hypothesis of adaptive thermal comfort predicts that contextual factors and past thermal history modify the occupant's thermal expectations and preferences [7]. People in warm climate zones would prefer higher indoor temperatures than people living in cold climate zones, which is in contrast to the assumptions underlying comfort standards based on the comfort model by Fanger [7]. Adaptation is defined as the gradual lessening of the human response to repeated environmental stimulation [7], and can be both behavioural, physiological as well as psychological [7,8,9]. De Dear et al. [7] showed that occupants of fully air-conditioned buildings are twice as sensitive to changes in temperature as occupants of naturally conditioned buildings. Occupants of air-conditioned buildings tend to adapt less, and this makes their thermal sensation more sensitive to changes in temperature. They become finely tuned to the narrow range of comfort temperatures and develop high expectations for homogeneous, cool environments. Occupants of naturally conditioned buildings turn out to be more active in thermoregulatory adaptation through changes in activity level and clothing (behavioural adaptation), and appear more tolerant to a wider range of temperatures (psychological adaptation). In short, the indoor temperature regarded as most comfortable increases significantly in warmer climatic contexts, and decreases in colder climate zones, due to adaptation [10]. De Dear and Brager concluded that, because of this phenomenon, considerable energy savings are possible in large parts of the United States of America, particularly the south [9], whereas energy savings in New England and along the northern Pacific coast are negligible.

Besides the international developments in the field of adaptive thermal comfort evaluation methods, there are also local initiatives. One example is the introduction of an adaptive guideline in the Netherlands, a country characterised by a moderate thermal climate. The objectives are better thermal conditions for occupants along with a possibility to save energy

[11]. Such local initiatives raise the question if models of adaptive thermal comfort should be introduced in moderate thermal climate zones since they obviously have most impact in hot climate zones [9]. Therefore this paper focuses on the impact of the introduction of adaptive thermal comfort evaluation criteria in moderate thermal climate regions, especially the marine climates labelled Cfb and Cfc according to the Köppen-Geiger-Pohl classification [12], in terms of usability and energy use. Such climates are found in low and mid latitudes, such as most of western and central Europe, along the North-American Pacific coast from Oregon to Alaska, New Zealand, the States of Victoria and Tasmania (Australia), parts of South Africa, southern Chile and Argentina. The Cfb climates are characterised by cool summers ($\overline{T}$ <22°C), mild winters, and low diurnal and annual temperature ranges due to high cloud cover and ocean influence. Cfc climates are known for brief summers [12].

The objective of this study is to (i) summarise the standard changes proposed, (ii) to investigate improvements to the usability of adaptive thermal comfort models, and (iii) to quantify the impact of these models to energy use for moderate maritime climate zones.

2 Background. Standard revisions and the introduction of models of adaptive thermal comfort

This chapter provides a short overview of relevant standard changes to the standards ISO 7730 and ANSI/ASHRAE 55, as well as an introduction to the evaluation methods of the new adaptive guideline for the Netherlands.

2.1 Revisions to ISO 7730 and ASHRAE Standard 55

An important change to the (inter)national standards ISO 7730 and ASHRAE Standard 55, is the specification of three different levels of acceptability for general thermal comfort and local thermal discomfort parameters after CR 1752 [4]. The background is that it may be desirable to establish different targets of thermal satisfaction (category A for 90% acceptability, B for 80% and C for 70%) based on technological possibilities, economy and politics, environmental considerations and occupant performance [5,6]. Criteria set to category B correspond to criteria currently stated in ISO 7730, except for the current draught rating (DR) criterion, which complies with category A. Moreover the revised standard will include diagrams showing the relation between the percentage of dissatisfied (PD) and various local comfort parameters [5,6], as well as a diagram to estimate the air velocity required to offset an increase in temperature. In order to apply this diagram, it is essential that occupants have some degree of personal control over the air velocity for reasons of acceptability.

If criteria for good general thermal comfort have to be met 100% of occupancy time, even in extreme weather conditions, the heating and cooling capacities required would be prohibitive. Economic and environmental considerations lead to allowing thermal conditions to exceed the recommended ranges for a limited amount of time. For long-term evaluations -using computer simulation tools- the revised ISO 7730 will incorporate weighted hours (WH) [5,6]. The time during which the Predicted Mean Vote (PMV) [1,3] exceeds the comfort boundaries is weighted with a factor that is a function of the Predicted Percentage of Dissatisfied (PPD). Starting from a PMV-distribution on a yearly basis, and the corresponding PPD-values, a weighting factor (WF) can be calculated from Equation 1. The summation of weighting factor multiplied by time is called “weighted time” (Equation 2). This weighted time is then added for a characteristic working period during one year and is an overall index of indoor environmental quality.

$$\mathrm{WF} = \frac{\mathrm{PPD}_{\mathrm{actualPMV}}}{\mathrm{PPD}_{\mathrm{PMVlimit}}} \quad (1)$$

$$\text{Warm/cold period: } \sum \mathrm{WF} \cdot \mathrm{time} \qquad (|\mathrm{PMV}| > |\mathrm{PMV}_{\mathrm{limit}}|) \quad (2)$$

ASHRAE Standard 55-2004 includes an adaptive comfort standard for occupant-controlled naturally conditioned spaces. This model can be applied when the mean monthly air temperature (T_{month}) is between 10 and 33°C. It is presented as an optional method since the PMV/PPD-model is still accepted as universally applicable for all conditions. Although there has been much debate as to whether the adaptive comfort standard should be applicable to hybrid buildings, this type of buildings is excluded in the latest revision to ASHRAE Standard 55 [10]. Fully air-conditioned buildings are also excluded from the standard. The comfort standard has a mean comfort zone band of 5K for 90% acceptance, and another of 7K for 80% acceptance, both centred around the optimum comfort temperature (T_{comf}) (Equation 3) [9].

$$\mathrm{T}_{\mathrm{comf}} = 17.8 + 0.31 \cdot \mathrm{T}_{\mathrm{month}} \quad (3)$$

The adaptive comfort standard for naturally conditioned spaces is only applicable when there are operable windows that open to the outdoors and can be readily opened and adjusted by the occupants. There must be no mechanical cooling system in the space, although mechanical ventilation with unconditioned air may be utilised as long as operable windows are the primary means of regulating the indoor thermal environment. The comfort standard is not applicable for spaces with a heating system in operation. Moreover, occupants must be engaged in near sedentary activity (1 to 1.3 met) and must be able to freely adapt their clothing.

The revised ISO 7730 does not incorporate any adaptive model, but allows the thermal indoor environment in naturally conditioned buildings with a high degree of personal control to be within the limits of category C [6].

2.2 Local initiatives: an adaptive guideline in the Netherlands

The WTEH method (weighted temperature excess hours), developed in the 1980s by the Dutch Government Building Agency [13], is the current method used in the Netherlands to assess a building's comfort performance over time. This method is described in detail by Van der Linden et al. [14]. The method has shown to be a feasible tool in designing and evaluating building services in practice. A new method based on the results of De Dear et al. [7] was developed for the Netherlands to replace the WTEH method [11,15]. This Adaptive Temperature Limit method (ATL) [11,16] should be used for evaluating design phase simulations as well as assessing existing buildings for regular activity and clothing levels. The PMV/PPD-model remains in use for situations with high metabolism or clothing insulation. The ATL method can be used only for office buildings and workspaces. It distinguishes between two different types of office buildings; type Alpha with a high degree of occupant control and type Beta with a low degree of occupant control [11] (Figure 1). The adaptive comfort standard in ASHRAE Standard 55 is comparable to the Dutch Alpha model (Figure 2), although the criteria for designating a building as a type Alpha building are more defined but less strict than criteria for naturally conditioned buildings. The method can be used for characterising the instantaneous comfort performance in a certain space as well as the long-term comfort performance. The ATL method is based on an adjusted version of the running mean outdoor temperature by Morgan et al. [17] called weighted mean outdoor temperature ($T_{e,ref}$). The same comfort criteria apply to both Alpha and Beta buildings during the heating season when $T_{e,ref}$ is below 12°C (Figures 2 & 3). The reason is that personal control of the indoor environment by opening windows is limited and almost every office is being heated. When $T_{e,ref}$ exceeds 12°C, the upper comfort limits are allowed to increase stronger in Alpha than in Beta buildings.

ABOUT HERE, INSERT FIGURES 1,2,3 and TABLE 1

When assessing the instantaneous comfort performance, the operative temperature in a given space is compared to comfort limits for type Alpha or Beta buildings, which are certain bandwidths based on categories of 90, 80 and 65% acceptability, centred around a neutral temperature that is calculated based on $T_{e,ref}$ (Table 1). The comfort performance during a specific period is qualified by the percentage of occupation time, during which the operative temperature lies within certain bandwidths depending on the category of acceptability. If the operative temperature never travels outside certain acceptability regions, the performance is identified as the category corresponding to the criterion. In order to estimate the number of excess hours, results of short measurements (1 or 2 weeks) can be extrapolated for the summer period. These short measurements provide a sufficient amount of data for a risk inventory to see if the building complies with the performance desired. A true evaluation can only take place based on a building performance simulation fitted to measurements, using a certain reference year.

Since the adaptive model is based on field measurements, where people are naturally integrating general plus local sensations, field votes already account for both general and local discomfort. The latter is thus not considered separately, together with fluctuations in air velocity since these are dependent on outdoor air temperature. No criteria are set to relative humidity as well. It turns out that these parameters are sufficiently accounted for in the underlying model [11] and the assertion that local discomfort comprises a large percentage of complaints in practice needs verification [8].

3 The impact of input temperatures on usability and energy use

In order to assess the usability of, and differences between, the various input parameters of both the adaptive comfort standard of ASHRAE Standard 55-2004 and the Dutch ATL method, as well as the consequences of these evaluation methods to energy consumption compared to using standards based on the PMV/PPD-model by Fanger, temperature measurements were carried out during the summer of 2003, as well as climate research making use of databases of the Royal Netherlands Meteorological Institute [18]. The outdoor air temperature was registered every quarter hour from June 16th to September 21st 2003 in downtown Eindhoven, the Netherlands. Maximum (T_{max}) and minimum (T_{min}) outdoor air temperatures were determined on a daily 24 hours basis for calculating the mean daily outdoor air temperature (T_{24h}) in accordance to Equation 4. Based on the mean daily outdoor air temperatures of 4 consecutive days, each decreasing in weighting with the progress of time, the weighted mean outdoor temperature [11] was determined according to Equation 5. The mean air temperature over a period of 30 days (T_{30d}) was determined according to Equation 6. The long-term mean monthly air temperature ($T_{month\ long\text{-}term}$) for the town of De Bilt, the Netherlands, was determined for the period 1901-2003 [18]. For the assessment of energy use, neutral temperatures and the corresponding 90 and 80% acceptability bandwidths, were calculated from $T_{e,ref}$ (Table 1) and compared to comfort zones stated in ISO 7730.

$$T_{24h} = \frac{T_{min} + T_{max}}{2} \qquad (4)$$

$$T_{e,ref} = \frac{T_{24h,1} + 0.8 \cdot T_{24h,2} + 0.4 \cdot T_{24h,3} + 0.2 \cdot T_{24h,4}}{2.4} \qquad (5)$$

$$T_{30d} = \frac{\sum_{i=1}^{30} T_{24h,i}}{30} \qquad (6)$$

ABOUT HERE, INSERT FIGURES 4,5,6 and TABLES 2 and 3

Figure 4 shows $T_{e,ref}$ in comparison to the mean monthly air temperature, T_{24h} and T_{30d}. The course of $T_{e,ref}$ follows that of the mean daily air temperature but is less extreme and fluctuating. It allows the neutral temperature to increase by up to 3K more, than when using mean monthly temperatures (both long-term and 2003). The $T_{e,ref}$ was particularly high due to the official heat wave [18] recorded from 31st June to 13th July when temperatures exceeded 25.0°C on a daily basis, and 30.0°C on 7 days. T_{30d} shows a subtler course than $T_{e,ref}$, since it an mean over 30 days. It accounts for temperatures to gradually rise and decrease over a month, while mean monthly temperatures are stable throughout the month in question and suddenly rise or drop at the end. The adaptive model in ASHRAE Standard 55, which is based on mean monthly air temperature, could be more in pace with adaptation of the human body when adopting T_{30d} as input parameter in case sufficient weather data are present for evaluations.

Figures 5 and 6 show neutral temperatures for type Alpha and Beta buildings based on $T_{e,ref}$ measured in Eindhoven. The indoor operative temperatures for 90 and 80% satisfaction criteria in Alpha buildings exceeded the current upper limits on a more or less daily basis throughout June, July and August 2003 by 1.5K on average, and a maximum of 3.0 to 3.5K (Figure 5). The indoor operative temperatures for 90 and 80% satisfaction criteria in Beta buildings hardly exceed the current upper limits of 25.5 and 26.0°C respectively (categories A and B in the revised ISO 7730) (Figure 6). Figure 5 also shows that neutral temperatures for Beta buildings, even in periods of consecutive hot days, are lower than the optimum temperature based on criteria of the revised ISO 7730. This might imply that more cooling capacity is required for type Beta buildings in summer, since the neutral temperature and upper comfort limits are lower than when applying ISO 7730. For both Alpha and Beta buildings, one needs to consider that periods of consecutive hot days leading to high $T_{e,ref}$ values are very limited in number in the Netherlands (Table 2). The same is also true for other moderate thermal climate zones that have similar weather patterns as the Netherlands (Table 3), mainly nations in North-Western Europe. The fact that very high indoor temperatures were allowed in the summer of 2003, was due to the persistent character of the long periods of warm weather [18]. The summer of 2003 was the warmest in Europe in over 5 centuries [18]. The mean European temperature in summer 2003 was 2K above the long-term average of 17.5°C, in Central Europe and the Alps it was even 5K above. Especially in buildings with possibilities for personal indoor climate control, one could turn up cooling on extremely hot days, which would lead to extra energy consumption. Of course, the indoor temperature is not only dependent on outdoor temperature, but also on solar gains and the distribution over the day [5].

In regard to overall applicability of adaptive thermal comfort models, the outdoor temperature needs to be within a certain range. The mean monthly outdoor air temperature of ASHRAE

Standard 55 needs to be within the range of 10 to 33.5°C, and $T_{e,ref}$ of the ATL method within the range of –5 to 30°C [2,11,15]. These parameters will hardly exceed 23 to 25°C in summer in most moderate thermal climate zones (Tables 2 & 3) An extension of these models beyond 25°C is not strictly necessary. The ASHRAE model for naturally conditioned buildings can only be applied when outdoor temperatures exceed 10°C. This weather condition is present in moderate temperate climates roughly from May to September (Northern Hemisphere), and from September to April (Southern Hemisphere) based on long-term mean air temperatures (Table 3). The distinction between Alpha and Beta type buildings in the Netherlands (Figure 2) is also made when the outdoor temperature parameter exceeds 10°C (from May to September). The largest amounts of energy could be saved on warm days (preferably $T > 20°C$) since higher operative temperatures are permitted inside naturally conditioned buildings compared to air-conditioned office spaces, implying a decreased demand for cooling. Table 3 shows that such weather is common from December to March in South Africa, and can also be found in summer in Northern Spain and in Southern Australia, but in the case of the Netherlands (Table 2) such weather occurs up to 35 days a year, based on recent and standard reference years.

Using a model based on $T_{e,ref}$ can lead to higher permissible indoor temperatures in summer time, compared to a model based on mean monthly outdoor air temperature. When using T_{month}, a period of consecutive hot days gets levelled away against a colder period in the same month or is even ignored when a long term mean is used. Moreover, the term neutral temperature is not necessarily the same as optimum comfort temperature, since a number of people prefer thermal conditions somewhat warmer or cooler than thermal neutrality.

4 Building performance simulations

Two building performance simulation studies are considered in order to estimate the amount of energy needed to provide optimum comfort to occupants of office buildings using indoor climate controls based on both the PMV/PPD-model and adaptive approaches.

The first simulation study [19] analyses the energy consumption for a standard office (Table 4) for two moderate climate cases, namely Eindhoven in the Netherlands and Prague in the Czech Republic, using the tool ESP-r [20]. The indoor temperature control set-points (Table 5) are based on three thermal comfort approaches: (i) the PMV/PPD-model by Fanger [1] and the adaptive thermal comfort models by de Dear and Brager [7] for (ii) buildings with centrally controlled HVAC systems, and (iii) buildings without centrally controlled HVAC systems. These set-points were calculated based on the mean monthly (or daily) outdoor effective temperature (ET*), which is an arithmetic average of 06:00 and 15:00 hours outdoor ET* for a calendar month or a particular day, for a 90% satisfaction criterion.

In the heating season, the minimum indoor temperatures will be about 1.5 K higher when the adaptive comfort model would be adopted for buildings with centrally controlled HVAC systems, and about 2 K lower for buildings without centrally controlled HVAC systems, compared to the PMV/PPD-method. In middle of the cooling season, the maximum indoor temperature will be about 1.5 K lower for buildings with centrally controlled HVAC systems, and about 0.5 K lower for buildings without centrally controlled HVAC systems. During the intermediate season the situation may reverse, which means that the maximum indoor temperatures may be higher than according to the PMV/PPD-method. It depends on whether May and September are treated as heating or cooling season [19].

Given the required temperature ranges for the heating season, it is no surprise that the energy consumption for heating is higher for buildings with centrally controlled HVAC systems and lower for buildings without centrally controlled HVAC systems, if the adaptive comfort model would be adopted in both the Netherlands and the Czech Republic (Table 6). Using the adaptive comfort model for buildings with centrally controlled HVAC systems would lead to an increase of over 10% in energy needed for heating and cooling in comparison to the PMV/PPD-model. On the other hand, it is not very realistic to heat a building just up to the lower operative temperature limit for 90% acceptability in winter (18°C, when outside ET*≤ 5°C). Using the adaptive comfort model for buildings without centrally controlled HVAC systems would result in approximately 10% more energy for heating and cooling relative to using the current thermal comfort standard [19]. However, when calculating the outdoor ET*, the solar radiation was actually not taken into account, which results in relatively low outdoor ET* in summer in moderate climates. Hence, the required indoor temperatures according to the adaptive comfort model are lower than according to the PMV/PPD-model, and the energy consumption for cooling will thus be higher [19].

The results of this simulation study can be easily compared to the Dutch ATL method for Alpha and Beta buildings, but in case of ASHRAE's adaptive comfort standard one should only consider the unconditioned office space for the months May until September.

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The second simulation study quantifies the differences in energy consumption between the WTEH and ATL methods in the Netherlands [21]. The building performance simulations were carried out using the VABI tool VA114 [22]. Since the majority of office buildings in the Netherlands are equipped with building services to control the indoor environment [23], the simulations focus on a type Beta building. The 16 design variants include two office rooms (Table 4) with type A and type B HVAC systems, for the reference years 1964 and 1994, with 4 orientations (north, east, south and west). The type A HVAC system includes mechanical ventilation with centralised warm water heating with local post-control, as well as centralised heating and cooling of ventilation air with centralised control. The type B HVAC system includes centralised warm water heating & cold water cooling systems with local post-control, as well as a centralised heating and cooling system of ventilation air with centralised control [21].

The results of the flow rate and cooling capacity calculations (Table 7) are based on the assumption that the HVAC systems are dimensioned in compliance with the WTEH method (maximum of 150 weighted excess hours; PMV ≥ 0.5) and the ATL method (category B; 80% acceptability; 0 excess hours per year). Results of the simulation (Table 8) show that HVAC systems, which have been designed based on the WTEH method, do not meet the criteria of the ATL method, regardless of the year, type of HVAC system or orientation of the building. This means that buildings, of which the indoor climate previously complied with criteria, do not longer meet the criteria set by the ATL method. The new method appears to be stricter than the WTEH method, while due to adaptation less strict a criterion was to be expected. The simulations also show that HVAC systems designed based on the WTEH method also do not even meet the criteria set for the lowest category (category C) of indoor environmental quality of the ATL method. When HVAC systems are designed based on the ATL method (category B), it turns out that in a large number of simulated cases, type A HVAC systems can not guarantee an indoor environment that meets the criteria, because the air flow rate needed exceeds the amount of air exchanges by six times, and PMV too often falls below -0.5. This is not only economically disadvantageous, but also leads to draughts and cold discomfort. In case of type B HVAC systems the criteria of the ATL method can only be met if a large local cooling capacity is installed. The cooling capacity needed is more than double in some situations compared to the WTEH method, and can in some cases not be realised since maximum capacities are exceeded. Moreover, the optimisation of set-points and pure time delay between heating and cooling, and minimising the number of times PMV falls below -0.5, are important. It is remarkable that is some cases the winter situation is decisive; not the summer situation [21].

Simulations also show that type Beta buildings, in combination with high capacity conventional cooling, can hardly meet the criteria set by the ATL method's category B. When a category A indoor environment is desired, this is even more problematic. The implementation of the ATL method implies using more advanced building services with local radiant cooling and heating [21].

5 Discussion

A great arithmetic advantage of adaptive models is their relative simplicity, compared to the PMV/PPD-model [1] that requires 6 input parameters and iterative calculations. One of the great disadvantages of adaptive models is their application range, which is limited to offices and workspaces only, while the PMV/PPD-model can be applied throughout most types of buildings. The omission of the assessment of local thermal discomfort and the parameters influencing the human heat balance is a weakness, as was also discussed by Fanger and Toftum [24]. The omission of air velocity as input parameter in the adaptive model can be critical, particularly when operative temperature is calculated as the average of mean radiant temperature and air temperature at high air velocities. ASHRAE Standard 55 therefore still recommends building consultants to assess local discomfort separately when necessary [2]. Because the adaptive models are valid only for regular levels of metabolism and clothing insulation, the PMV/PPD-model will remain in force for situations with high levels. This is conflicting with the findings of Nicol and Humphreys [25], who showed that particularly for high met- and clo-values the PMV/PPD-model is not valid. Perhaps future guidelines and standards will be based on an improved PMV/PPD-model that allows for adaptation, such as a model proposed by Fanger and Toftum [24].

In periods, when mean daily outdoor temperatures range between 12°C and 28°C, outcomes of the PMV/PPD and adaptive model [9] differ less than 1K. De Dear and Brager [9] found that when mean outdoor temperatures rose above 23°C, indoor operative temperatures of naturally conditioned buildings frequently exceeded the upper comfort limits, clustering around 30°C. While neutral temperatures for these buildings were calculated to be in the range of 26 to 27°C, data suggest that such buildings are not able to guarantee thermal comfort for many hours of the day. If, due to global climate change, there would be in increase in temperature [26], this could imply a greater demand for cooling for places with (personally controlled) air-conditioning, given the outcomes of the measurements and building performance simulations. This increased energy consumption is unwanted given the ever increasing energy prices [26]. Nicol and Humphreys [27] stated that a "low energy" standard which increases discomfort may be no more sustainable than one which encourages energy use because of the adaptive principle that occupants may well use energy to alleviate their discomfort. Moreover, Olesen [28] raises the important question if air-conditioning at home could influence the adaptation process of working in a naturally conditioned office? Many unsolved but relevant matters still remain.

As for the Dutch ATL method, when comparing type Alpha buildings to naturally conditioned buildings [2,7], and type Beta buildings to fully air-conditioned buildings [7] (Figure 2), it turns out that the ATL method deviates from international consensus. The lower limits for operative temperature of Alpha buildings are equal to those of Beta buildings, while the adaptive model in ASHRAE 55-2004 has its own lower limits. By introducing a special model for Beta buildings in the Netherlands, ISSO publication 74 [11] deviates from international consensus. The research report of De Dear et al. [7] contained a model for fully air-conditioned buildings, but this model was not incorporated into ASHRAE Standard 55-2004. For both naturally conditioned and fully air-conditioned buildings, the PMV/PPD-model will remain in use internationally. The PMV/PPD-model is shown to be valid for predicting thermal comfort in fully air-conditioned buildings in near-comfort conditions [25], the kind of buildings it was originally created for by Fanger [1]. The question arises why this model does not stay in force in the Netherlands for the great number of Beta buildings that can be categorised as fully air-conditioned. In addition the estimated number of large Alpha office buildings in the Netherlands is small, since most consist of open space offices, which are equipped with some form of air-conditioning without offering the occupants personal control options. About 50% of the small (home) offices are estimated to be type Alpha. The main question, of course, is if the process of generating initiatives on a local or national level should be stimulated if there is much variance in methodologies, which can actually lead to an increase in energy consumption, while on a global scale engineers and politicians are trying hard to obtain more uniform, energy-saving methods.

6 Conclusions

The introduction of various implementations of the adaptive thermal comfort model, such as the adaptive comfort standard for naturally conditioned buildings in ASHRAE Standard 55 [2] and the Dutch Adaptive Temperature Limit guideline [11], in moderate maritime climate zones, permits indoor operative temperatures of naturally conditioned offices spaces to slightly rise on summer days. Differences in optimum indoor temperatures, resulting from implementing traditional and adaptive thermal comfort models, can be found roughly from May to September on the Northern Hemisphere, and from September to April on the Southern Hemisphere. In winter the adaptive models cannot be used due to low outdoor air temperatures. Even though indoor temperatures are allowed to increase on hot days, it remains the question if unconditioned buildings can maintain an optimum indoor environment without the use of air-conditioning if solar gains further increase the indoor temperatures. Using mean monthly outdoor air temperature as input parameter for ASHRAE's adaptive comfort standard leads to step changes in optimum indoor temperature at every turn of the month. Replacing this monthly temperature with a parameter that allows for a more gradual course of indoor temperatures is more appropriate and fitting to the concept of adaptation.

In moderate maritime climates, the introduction of adaptive models can lead to a 10% reduction in energy consumption on an annual basis for naturally conditioned buildings or building with a high degree of occupant control, and a 10% increase in energy for heating and cooling on an annual basis for buildings with centrally controlled HVAC systems. The number of office buildings that comply with the requirement for applying the adaptive comfort standard are small in number since most office buildings are equipped with some form of air-conditioning these days. It seems that the two major world standards in the field of thermal comfort, ASHRAE Standard 55 and ISO 7730, are aware of this. Even though de Dear and Brager [7] originally came up with two adaptive models, one for buildings with centrally controlled HVAC systems and another for naturally conditioned buildings, the North-American ASHRAE Standard 55 only incorporated a model for the latter category of buildings as an optional method, since in the southern parts of the USA hot days are frequent, whereas the European standard ISO 7730 does not introduce any adaptive model at all.

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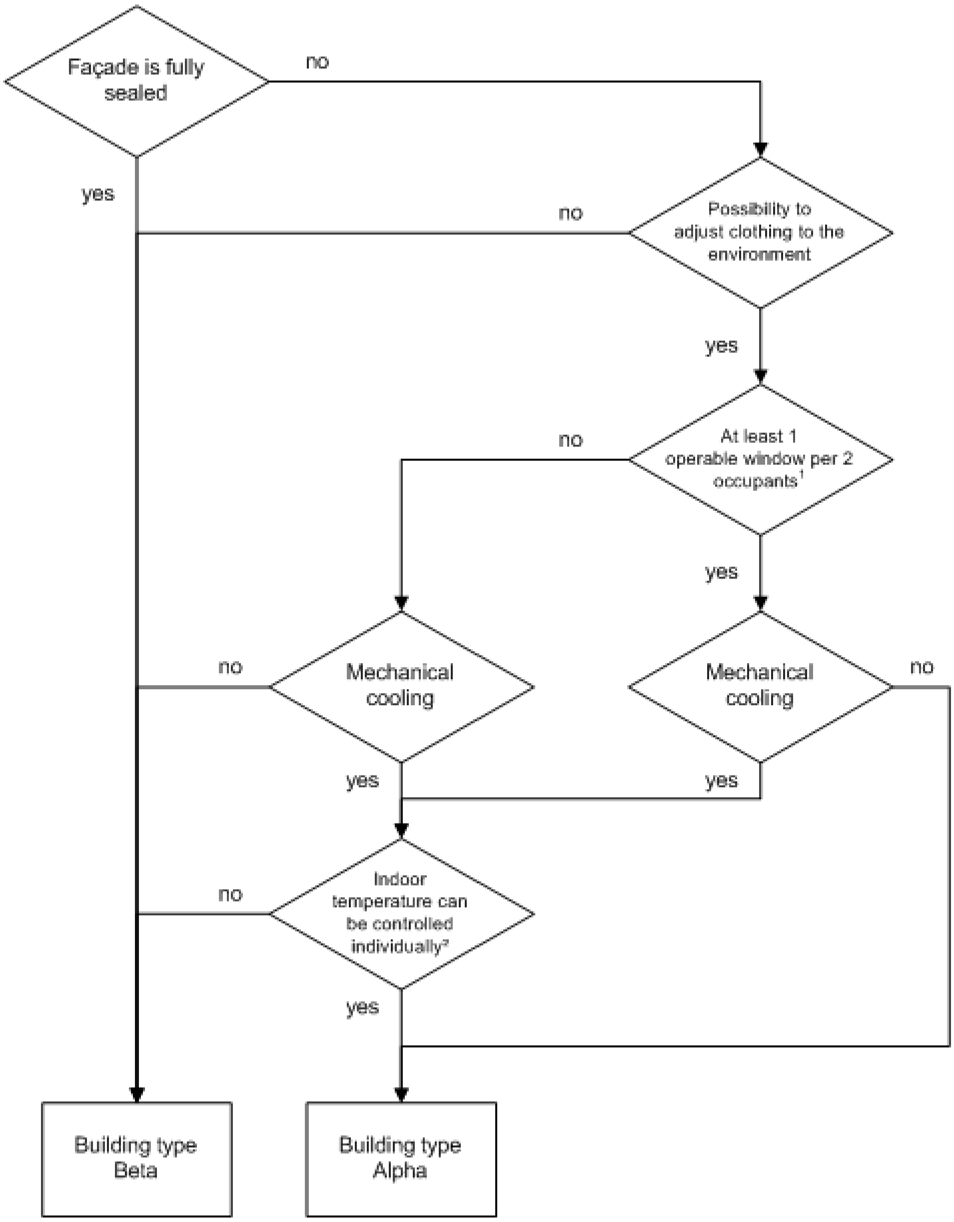
Figures

Figure 1. Flowchart for determining type Alpha / Beta building or space [11].



1.) Conditions: (i) Per bay at least one operable window of 0.5 m^2, for buildings with mechanical ventilation, or buildings where the frequent use of operable windows to allow for displacement ventilation is not feasible due to high sound, wind or pollutions levels, (ii) windows can be controlled independently by occupants, (iii) the window should be equipped with a wind proof window shutter with a controllable crack width.

2.) Conditions: (i) Control range of ±3K centred around the design value, (ii) feedback when set-point temperature is altered, (iii) effective response time of at least 1K per 30 minutes, (iv) feedback when altered set-point temperature has been reached.

Figure 2. Overview of operative temperature zones in office situations for building types Alpha [11]. The grey zones show bandwidths of operative temperature for 90, 80 and 70% acceptability in winter and summer (based on 0.5 / 1.0 clo and 1.2 met) in compliance with the revised ISO 7730 [6]. Moreover the figure shows the adaptive model from ASHRAE 55-2004 and bandwidths of 90 and 80% acceptability [2]. The Dutch ATL method deviates from ASHRAE's adaptive comfort standard since its application range is extended to winter periods and the lower boundaries in summer are higher.

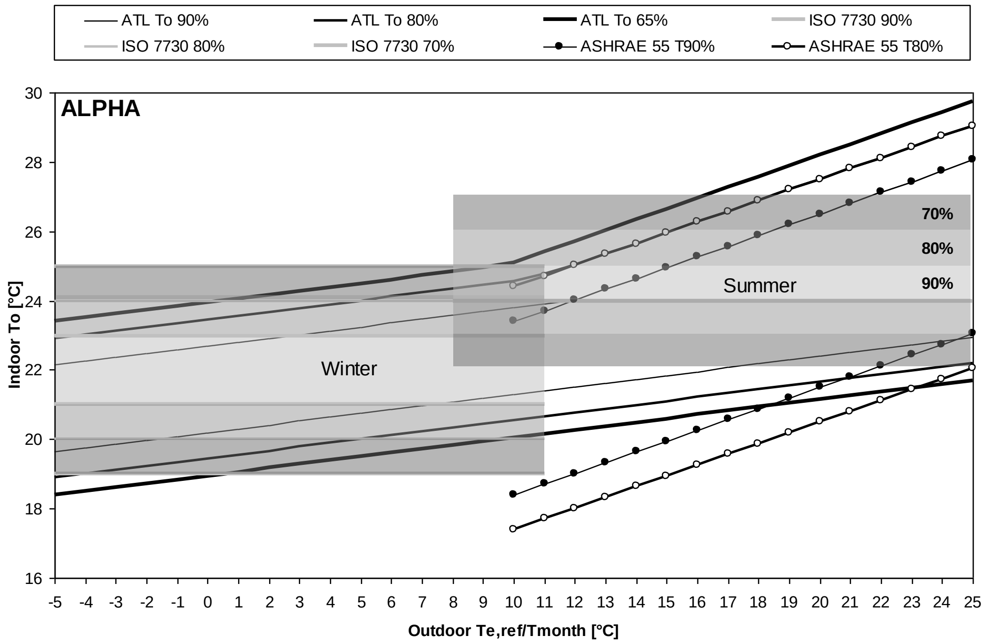


Figure 3. Overview of operative temperature zones in office situations for building types Beta [11]. The grey zones show bandwidths of operative temperature for 90, 80 and 70% acceptability in winter and summer (based on 0.5 / 1.0 clo and 1.2 met) in compliance with the revised ISO 7730 [6]. The neutral temperature of the ATL model is lower than the optimum temperature of ISO 7730, implying the need for extra cooling in summer when buildings are confronted with extra solar gains.

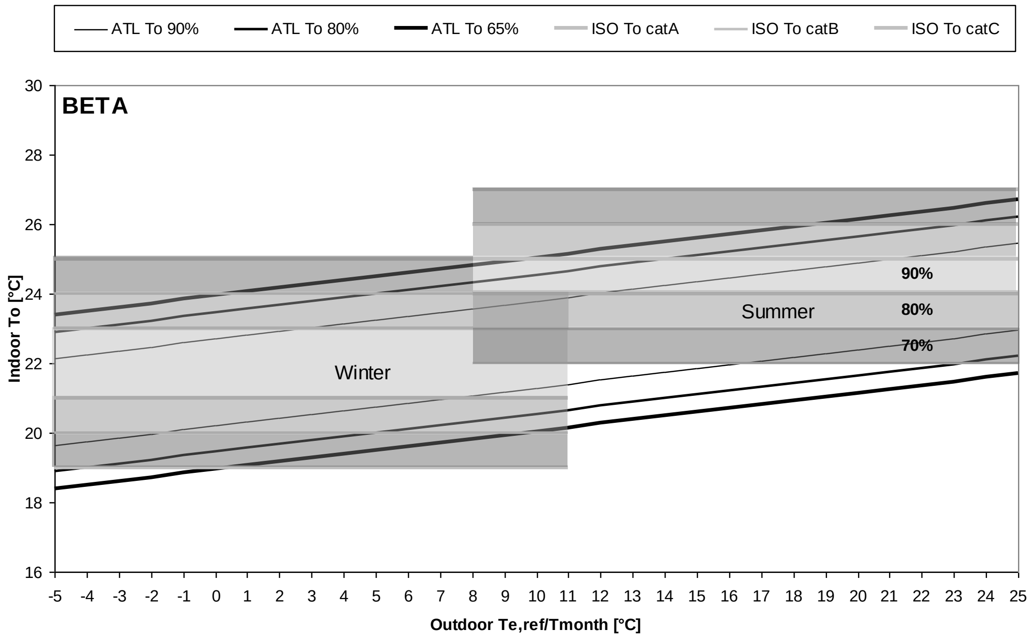


Figure 4. Outdoor air temperatures for Eindhoven from June to September 2003 ($T_{\text{month long-term}}$, $T_{\text{month 2003}}$, taken from [18], and $T_{e,\text{ref}}$, T_{24h}, T_{30d}, which were measured).

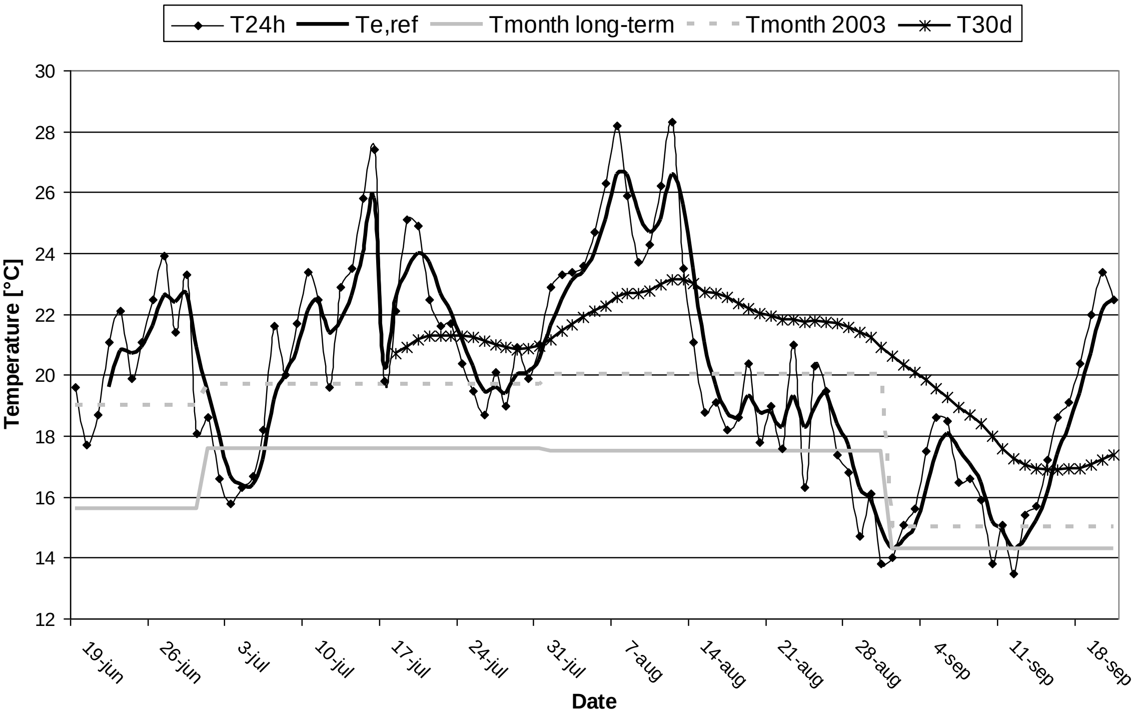


Figure 5. Neutral temperatures (T_n), and indoor operative temperature bandwidths for 90 and 80% acceptability ($T_{o\ 90\%}$ & $T_{o\ 80\%}$) for type Alpha buildings (comparable to ASHRAE's adaptive comfort standard) calculated from $T_{e,ref}$ measured in Eindhoven in 2003, shown together with the operative temperature bandwidths for category A and B spaces ($T_{o\ catA}$ & $T_{o\ catB}$) according to the revised ISO 7730. The adaptive model provides much broader bandwidths of thermal comfort than a standard based on the PMV/PPD-model, implying that both cooler and warmer temperatures are still acceptable. Neutral temperatures are up to 1 K higher than optimum comfort temperatures of the adaptive comfort standard that is based on mean monthly outdoor air temperature.

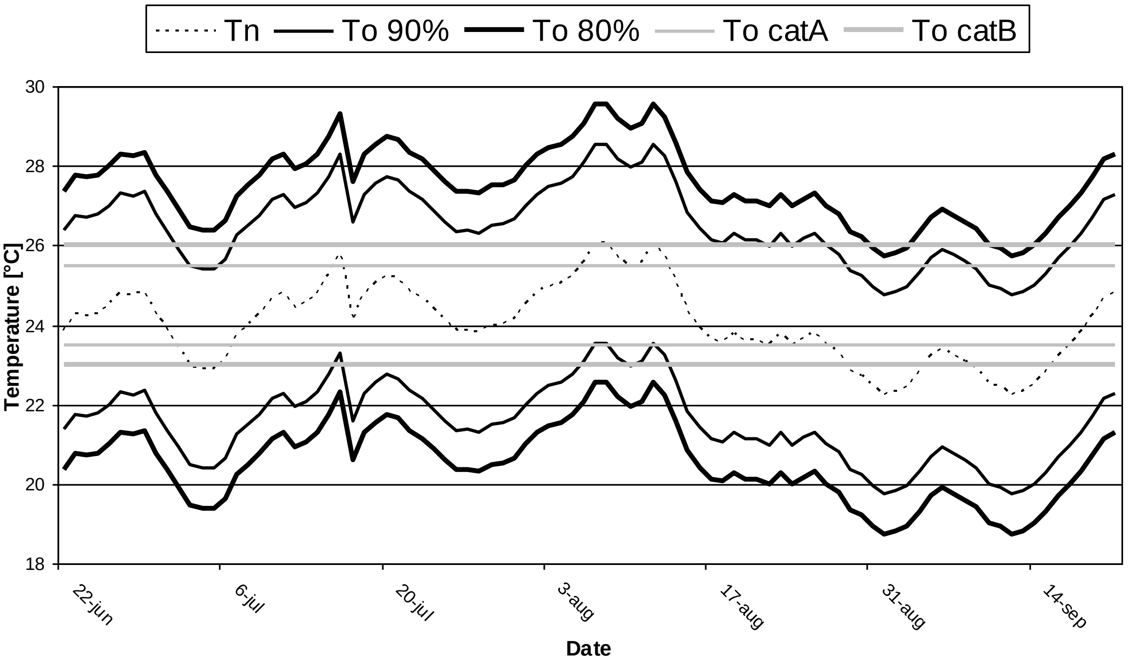
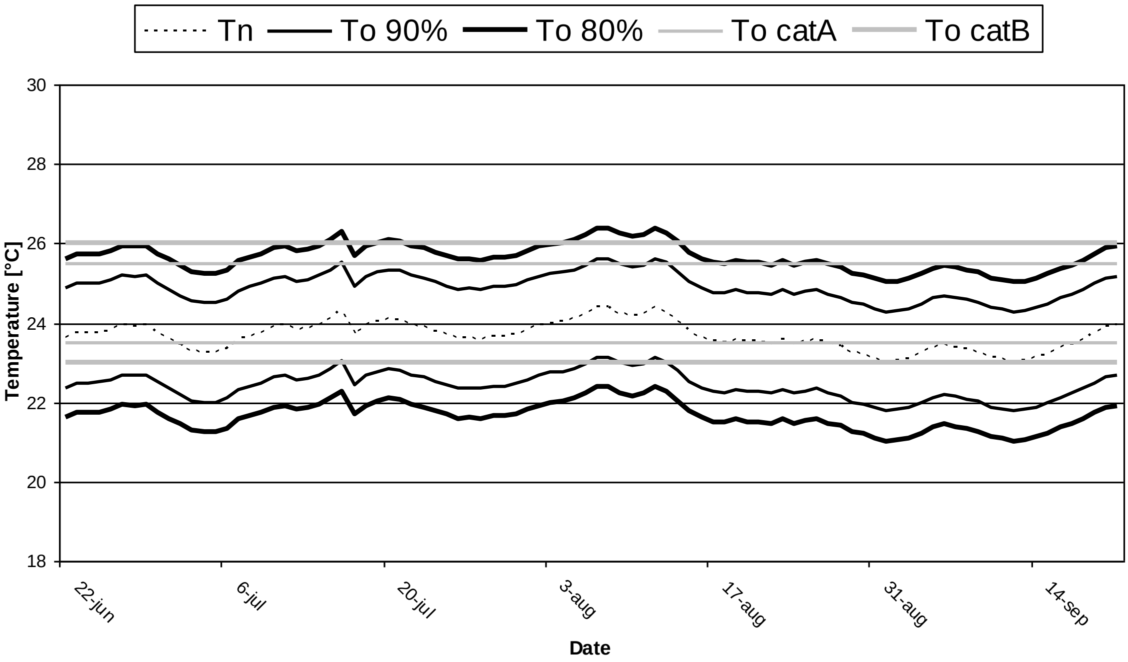


Figure 6. Neutral temperatures (T_n), and indoor operative temperature bandwidths for 90 and 80% acceptability ($T_{o\ 90\%}$ & $T_{o\ 80\%}$) for type Beta buildings calculated from $T_{e,ref}$ measured in Eindhoven in 2003, shown together with the operative temperature bandwidths for category A and B spaces ($T_{o\ catA}$ & $T_{o\ catB}$) according to the revised ISO 7730. For type Beta building the adaptive model shows comfort temperatures to be on the cooler side compared to the PMV/PPD-model. This could indicate the need for more cooling, and thus a higher need for energy.



Tables

Table 1. Intervals of acceptable operative temperature for classes of preference per building category [11].

Category	Acceptability [%]	Building type and indoor temperature ranges‡	
		Alpha ($T_{e,ref} < \pm 12°C$) & Beta	Alpha ($T_{e,ref} > \pm 12°C$)
		$T_{neutral} = 21.45 + 0.11 \cdot T_{e,ref}$	$T_{neutral} = 17.8 + 0.31 \cdot T_{e,ref}$
A	90	$T_{neutral} \pm 1.25$ K	upper limit† = $T_{neutral} + 2.5$ K
B	80	$T_{neutral} \pm 2.0$ K	upper limit† = $T_{neutral} + 3.5$ K
C	65	$T_{neutral} \pm 2.5$ K	upper limit† = $T_{neutral} + 4.2$ K

‡ Based on $1.0 < M < 1.4$ met and $0.5 < I_{cl} < 0.9$ clo. In exceptional conditions, such as laboratories and washing-up kitchens, the upper limits may be corrected with a factor $\Delta T = -6(I_{cl} - 0.7) - 8(M - 1.4)$, if $1.4 < M < 4.0$ met, and if $0.7 < I_{cl} < 2.0$ clo.

† For type Alpha buildings ($T_{e,ref} > \pm 12°C$) lower operative temperature limits are described by criteria for type Alpha buildings ($T_{e,ref} < \pm 12°C$)!

Table 2. Cumulative distribution of $T_{e,ref}$ in °C in the Netherlands in the computer simulation reference years 1964 and 1976, as well as the years 1989 to 2000 [11].

$T_{e,ref}$ >	1964	1976	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
10	172	171	194	198	171	171	176	190	173	185	176	190	195	200
11	157	160	175	179	149	154	172	165	162	157	165	171	183	181
12	136	147	155	154	1320	148	161	140	150	128	147	156	168	165
13	125	130	136	127	110	138	134	116	138	107	135	138	148	147
14	99	113	118	98	93	131	104	90	127	85	118	118	123	130
15	79	94	101	77	77	117	83	75	100	67	97	99	108	103
16	57	68	86	57	63	105	51	60	83	49	76	67	87	76
17	34	59	65	40	44	76	30	49	57	34	65	36	62	49
18	21	52	47	27	32	49	9	40	52	20	47	20	45	24
19	11	42	30	18	21	27	4	35	42	9	28	12	24	14
20	6	23	10	12	13	11	2	27	35	5	23	9	17	5
21	4	20	5	4	6	5	1	19	21	2	13	5	11	2
22	1	10	3	2	4	1	0	17	14	2	7	2	4	2
23	0	7	0	2	2	0	0	9	6	1	4	0	0	2
24	0	6	0	1	0	0	0	3	3	0	1	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 3. Overview of long term mean monthly temperatures for various cities in Cfb and Cfc climate zones [18].

City, country	Climate type	January	February	March	April	May	June	July	August	September	October	November	December
Northern Hemisphere													
London Heathrow, United Kingdom	Cfb	3.5	3.8	5.7	8.0	11.3	14.4	16.5	16.1	13.8	10.7	6.4	4.5
Paris, France	Cfb	3.4	4.2	6.6	9.5	13.2	16.4	18.4	18.0	15.3	11.4	6.7	4.2
De Bilt, the Netherlands	Cfb	2.2	2.5	5.0	8.0	12.3	15.2	16.8	16.7	14.0	10.5	5.9	3.2
Frankfurt, Germany	Cfb	0.5	1.7	5.0	9.2	13.6	17.1	18.6	17.9	14.5	9.4	4.8	1.7
Prague, Czech Republic	Cfb	-2.0	-0.6	3.1	7.6	12.5	15.6	17.1	16.6	13.2	8.3	3.0	-0.2
Ljubljana, Slovenia	Cfb	0.8	0.6	5.0	9.9	14.4	17.9	20.3	19.7	16.1	10.6	5.2	1.4
Santander, Spain	Cfb	9.7	10.3	10.8	11.9	14.3	17.0	19.3	19.6	18.6	16.1	12.5	10.5
Bergen, Norway	Cfb	1.5	1.6	3.3	5.9	10.5	13.5	14.5	14.4	11.5	8.7	4.7	2.6
Port Hardy, Canada	Cfb	3.0	4.1	5.1	6.8	9.4	11.8	13.7	13.9	11.8	8.6	5.2	3.3
Cold Bay, Alaska USA	Cfc	-1.8	-2.5	-1.1	0.7	4.2	7.6	10.3	10.8	8.7	4.2	1.3	-0.5
Reykjavík, Iceland	Cfc	-0.5	0.4	0.5	2.9	6.3	9.0	10.6	10.3	7.4	4.4	1.1	-0.2
Southern Hemisphere													
Melbourne, Australia	Cfb	19.9	19.7	18.4	15.1	12.5	10.2	9.6	10.5	12.4	14.3	16.2	18.4
Hobart, Australia	Cfb	16.3	16.1	15.1	12.4	10.5	8.3	7.8	8.8	10.6	11.8	13.6	15.1
Auckland, New Zealand	Cfb	19.5	19.8	18.7	16.2	13.4	11.4	10.5	11.3	12.7	14.3	16.1	18.0
Invercargill, New Zealand	Cfb	14.0	13.7	12.6	10.3	7.7	5.5	5.3	6.4	8.3	9.9	11.4	13.0
East London, South Africa	Cfb	21.6	21.6	20.8	18.9	17.1	15.4	15.1	15.4	16.3	17.2	18.7	20.4
Port Elizabeth, South Africa	Cfb	21.3	21.2	20.3	18.2	16.1	14.3	13.9	14.3	15.4	16.7	18.2	20.1
Valdivia, Chili	Cfb	15.8	15.2	13.2	10.5	9.3	7.4	7.0	7.4	8.6	10.4	12.7	14.9
Punta Arenas, Chili	Cfc	10.5	10.1	8.2	6.0	3.4	1.5	1.1	2.0	4.0	6.4	8.2	9.7

Table 4. Properties of the offices used in the simulations

	Hensen & Centnerová, 2001	‘t Hooft et al., 2005
Type of office space	Standard office space	Intermediate office space on intermediate floor
Dimensions	3.5 x 5.4 x 2.7 m^3	3.6 x 5.4 x 2.7 m^3
U-value external wall	0.39 $W/(m^2K)$	0.37 $W/(m^2K)$
Percentage of glass in façade		35 %
U-value of panes	2.75 $W/(m^2K)$	1.1 $W/(m^2K)$
Solar factor		0.32
Transparency factor	0.76	0.61
Internal gains (people)	2 people (total 140 W sensible plus 140 W latent)	8 W/m^2
Internal gains (equipment)	300 W	20 W/m^2
Internal gains (lighting)		12 W/m^2
Occupation ratio		100%
Infiltration number		0.3 $m^3/(hm^3)$
Flow rate of local cooling		2.0 $m^3/(hm^3)$
Ventilation system	Natural or mechanical supply. During occupancy hours: 1.2 ACH; i.e. 30 m^3/h/person (8.3 l/s/person), when not occupied: 0.2 ACH	Mechanical supply and exhaust during occupancy hours
Occupancy	08:00 - 18:00 hours	08:00 - 18:00 hours
Supply air temperature		16 °C (in summer)
Supply air temperature (after occupancy)		T_e + ventilator- and duct heating
Ventilator- and duct heating		1.5 K
Night ventilation		When temperature difference between inside and outside exceeds 2K, in at T_{room} = 23°C, out at T_{room} = 20°C
Minimal T_{room} during occupancy		22°C
Minimum T_{room} after occupancy		18°C
Activity level	mainly sedentary (1.2 met units)	1.2 met units
Clothing insulation	0.5 clo	0.7 clo (in summer)

Table 5. Monthly indoor temperature control set-points based on ISO 7730 and adaptive neutral temperature (T_n) (comparable to T_{comf}) for buildings with and without centrally controlled HVAC systems [19].

Month	ISO 7730 [3]	Adaptive thermal comfort [7]					
		the Netherlands			Czech Republic		
	T_n [°C]	ET* [°C]	$T_{n,without}$[1] [°C]	$T_{n,with}$ [°C]	ET* [°C]	$T_{n,without}$[1] [°C]	$T_{n,with}$ [°C]
January	22.0	0.7	20.2	22.6	-1.5	20.2	22.5
February	22.0	3.4	20.2	22.7	2.5	20.2	22.7
March	22.0	2.8	20.2	22.7	4.3	20.2	22.8
April	22.0	8.5	21.1	22.9	9.3	21.3	23.0
May	22.0	13.9	22.4	23.2	13.9	22.4	23.2
June	24.5	15.3	22.8	23.2	17.1	23.3	23.3
July	24.5	16.4	23.1	23.3	17.5	23.4	23.3
August	24.5	16.0	23.0	23.2	17.1	23.3	23.3
September	22.0	14.0	22.5	23.2	15.4	22.8	23.2
October	22.0	8.1	21.0	22.9	9.5	21.3	23.0
November	22.0	6.6	20.6	22.9	4.5	20.2	22.8
December	22.0	2.2	20.2	22.7	-0.2	20.2	22.6

[1] for ET* < 5°C, T_n is calculated as if ET* = 5°C

Table 6. Absolute and relative annual energy consumption for heating and cooling of the office when facing different orientations and for the 3 types of indoor temperature control as specified in Table 5 [19]. Extra energy is needed for heating and cooling buildings with centralised HVAC systems, while the annual energy consumption is lower for naturally conditioned buildings.

Orientation	Indoor temperature control according to:	the Netherlands				Czech Republic			
		Heating [kWh]	Cooling [kWh]	Total [kWh]	Total [%]	Heating [kWh]	Cooling [kWh]	Total [kWh]	Total [%]
N	ISO 7730	585.8	133.7	719.5	100	541.4	232.0	773.4	100
	Without HVAC	467.5	124.5	592.0	82	421.5	192.3	613.9	79
	With HVAC	761.2	163.6	924.8	129	704.2	260.1	964.3	125
E	ISO 7730	546.8	309.3	856.1	100	449.5	512.4	962.0	100
	Without HVAC	429.7	279.9	709.7	83	341.9	455.9	797.8	83
	With HVAC	709.3	341.2	1,050.5	123	581.6	527.4	1,109.0	115
S	ISO 7730	389.3	429.6	818.9	100	365.0	606.8	971.9	100
	Without HVAC	429.8	286.7	716.5	87	270.4	540.5	811.0	83
	With HVAC	533.7	452.2	985.9	120	477.9	609.0	1,086.8	112
W	ISO 7730	463.8	599.5	1,063.3	100	414.5	882.0	1,295.5	100
	Without HVAC	354.6	565.0	919.6	87	321.1	813.1	1,134.2	88
	With HVAC	611.1	606.6	1,217.7	115	530.3	887.6	1,417.9	109

Table 7. Flow rates and cooling capacities needed for buildings designed in accordance with WTEH and ATL methods [21]

Design method	Type of HVAC system	Year	Flow rate/ Cooling capacity	Orientation			
				N	E	S	W
WTEH method	A	1964	m^3/h	172	249	293	262
		1994	m^3/h	193	213	298	371*
	B****	1964	W	212	496	636	551
		1994	W	325	395	685	995
ATL method	A	1964	m^3/h	230	420*	***	***
		1994	m^3/h	240	275	***	***
	B****	1964	W	380	1,040	1,430**	1,200**
		1994	W	460	580	1,430**	2,200**

*Exceeding the amount of air exchanges by 6 times

**Exceeding of maximum local HVAC system capacity of approx. 55 W/m^2

***No design possible (ventilation rate too large, PMV often falls below -0.5)

****Ventilation rate at local cooling (by fan coil units or induction devices): 2 m^3/(hm^3), corresponding to 110 m^3/h, T_i = 16 ºC (in summer).

Table 8. Overview of simulation results of the design based on the WTEH method, with a maximum of 150 weighted hours (PMV ≥ 0.5), and the design based on the ATL method (category B) with 0 exceeding hours per year [21].

Type of HVAC system	Year	Orientation	Overview of simulation results of the design based on the WTEH method, with a maximum of 150 weighted excess hours							Overview of simulation results of the design based on the ATL method (category B) and 0 excess hours per year						
			WTEH method				ATL method			WTEH method				ATL method		
			Excess hours [y^{-1}]		$T_{air,max}$ [°C]	Number of weighted hours	Excess hours, upper limit [y^{-1}]			Excess hours [y^{-1}]		$T_{air,max}$ [°C]	Number of weighted hours	Excess hours, upper limit [y^{-1}]		
			$T_{air} \geq$ 25° C	$T_{air} \geq$ 28° C			Category A (90%)	Category B (80%)	Category C (65%)	$T_{air} \geq$ 25° C	$T_{air} \geq$ 28° C			Category A (90%)	Category B (80%)	Category C (65%)
A	1964	N	500	0	26.9	145	950	462	191	3	0	25.2	0	176	0	0
		E	188	0	26.6	150	621	272	136	0	0	23.9	0	35	0	0
		S	86	0	26.4	148	624	323	172	-	-	-	-	-	-	-
		W	131	0	27.0	148	379	207	131	-	-	-	-	-	-	-
	1994	N	257	0	26.8	144	462	160	52	60	0	25.6	5	107	0	0
		E	243	0	26.9	147	387	173	51	10	0	25.5	1	45	0	0
		S	109	0	26.3	148	493	228	120	-	-	-	-	-	-	-
		W	74	0	26.8	150	269	165	110	-	-	-	-	-	-	-
B	1964	N	471	0	26.8	148	958	428	180	14	0	25.3	0	273	0	0
		E	182	0	26.6	150	740	271	141	0	0	24.0	0	37	0	0
		S	86	0	26.3	149	793	338	174	0	0	22.9	0	45	0	0
		W	126	0	26.9	150	489	206	130	0	0	23.7	0	59	0	0
	1994	N	244	0	26.7	150	430	153	49	54	0	25.6	17	149	0	0
		E	218	0	26.7	148	399	164	52	10	0	25.4	2	57	0	0
		S	96	0	26.2	148	556	233	114	0	0	22.9	0	40	0	0
		W	62	0	26.7	149	396	177	105	0	0	22.7	0	30	0	0