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# Potential for free-cooling by ventilation

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**Abstract**

Natural ventilation is one of the most effective techniques for cooling. Its potential for cooling may be assessed by using a method based on the indoor–outdoor temperature difference of the free-running building, the adaptive comfort criteria and the outdoor temperature. It is demonstrated that the free-running temperature may be used instead of the balance temperature in energy estimation methods. The indoor–outdoor temperature difference of the free-running building becomes a characteristic of the thermal behavior of the building which is decoupled from comfort range and outdoor temperature. A measure related to the energy saved and the applicability of free-cooling is given by the probabilistic distribution of the degree-hours as a function of the outdoor temperature and time. Weather data for this method are available in public domain from satellite investigation. The method can be applied when buildings similar to existing ones are constructed in a new location, when existing buildings are retrofitted or when completely new buildings are designed. The method may be used to interpret the results of building simulation software or of the field measurements.


*Keywords:* Natural ventilation; Energy; Building design; Free-running temperature

## 1. Introduction

The most important decisions that affect the thermal performance of buildings are taken in the initial stages of design (Holm, 1993; de Wilde et al., 2002). Design evaluation may be supported by the results of building simulation, by simplified guidelines or by expert advice based on experience (deWit and Augenbroe, 2002). Building simulation programs are based on first principles and require as inputs the geometry of the building, the comfort criteria and even the specification of the HVAC technology. These prerequisites make simulation more adapted for evaluations in the final stages of design rather than a support for decisions when the building is sketched (Clarke, 1985; Shaviv, 1998; Al-Homoud, 2000; Hong et al., 2000; Olsen and Chen, 2003; Clarke et al., 2004). In the initial design, the architects have many important issues on which the project is evaluated and investing more in thermal design would make them less competitive. The thermal analysis is done usually by engineers after the

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## Nomenclature

| | |
|---|---|
| $dh_c$ | degree-hour for cooling (K h) |
| $dh_{fr}$ | degree-hour for free-cooling (K h) |
| $DH_c$ | frequency distribution of degree-hour for cooling |
| $DH_{fc}$ | frequency distribution of degree-hour for free-cooling |
| $DH_{mc}$ | frequency distribution of degree-hour for mechanical cooling |
| $f$ | relative density |
| $K_{tot}$ | total cooling loss coefficient of the building (W/K) |
| $N$ | total number of samples |
| $P_{df}$ | probability distribution |
| Pr | probability density |
| $q_c$ | energy rate needed for cooling (W) |
| $q_{gain}$ | total heat gains from sun and internal sources (W) |
| $Q_c$ | energy needed for cooling (J) |
| $T_b$ | balance temperature (K) |
| $T_{bin}$ | temperature interval for a bin (K) |
| $T_{cl}$ | lower limit of comfort temperature (K) |
| $T_{cu}$ | upper limit of comfort temperature (K) |
| $T_{diff}$ | temperature difference between indoor and outdoor in free-running (K) |
| $T_{fr}$ | free-running temperature (K) |
| $T_o$ | outdoor temperature (K) |

*Greek letters*

| | |
|---|---|
| $\delta_c$ | condition for cooling (−) |
| $\delta_{fr}$ | condition for free-cooling (−) |
| $\delta_{mc}$ | condition for mechanical cooling (−) |

building is designed in order to estimate the heating and cooling loads. Energy consumption can be estimated and checked if it is within accepted limits, complying thus with minimal requirements (Mihalakakou et al., 2002; CSTB, 2003). But these calculations have practically no influence on the building design (Ellis and Mathews, 2001). Since the thermal calculations are not done in the initial stages of design, it is essential that the architects are able to take decisions that affect the thermal design. They can use simplified models (Ellis and Mathews, 2001), a combination of simplified models and expert knowledge (Yezioro and Shaviv, 1996; Shaviv, 1999), or just rules of thumb based on acquired experience. Although these results are not optimal, the heuristic rules indicate design solutions for building orientation, geometry, and thermal mass (Shaviv et al., 1996; Shaviv, 1999).

Another approach would be to consider the building as a system that should have the potential to ensure indoor comfort. The indoor temperature is the result of the balance of energy fluxes and accumulation. Then, from a thermal point of view, the aim of the architectural design is to provide the potential to implement the control of the energy fluxes through the envelope and to allow energy storage in the building structure. Arguably, the main gains are solar and internal (Givoni, 1991; Littlefair, 1998), the main losses are by advection and conduction (Florides et al., 2002), and the energy storage is in the thermal mass (Zalba et al., 2003; Khudhair and Farid, 2004). Putting the problem in this way allows us to assess the potential of architectural elements, e.g. sun-space for heating and cooling (Argiriou et al., 1994; Mihalakakou, 2002), green roofs (Del Barrio, 1998) and pond roofs (Kishore, 1988; Erell and Etzion, 2000), or methods, such as passive cooling (Belarbi and Allard, 2001).

The potential of free-cooling represents a measure of the capability of ventilation to ensure indoor comfort without using mechanical cooling systems. A way to measure this ability is by using a variant of the bin method in which the annual energy consumption is evaluated for different temperature intervals and time periods. The energy consumption is estimated for several values of the outdoor temperature, called bins, and then the total is obtained by multiplying by the number of hours in the temperature interval (ASHRAE, 2001a,b). The bin method employs the balance temperature for calculating the degree-hours in a bin. Balance temperature concept supposes that the indoor temperature is constant which implies the use of a heating or air conditioning system. In buildings that use natural ventilation, the indoor temperature varies making the concept of balance temperature unsuitable. In order to estimate the relative influence of the building design, of the comfort criteria and of the climate, it is important to have a method that decouples these three characteristics.

## 2. Thermal comfort zone

Thermal comfort standards specify the range of conditions or comfort zones where 80% of sedentary or slightly active people feel the environment thermally acceptable. ASHRAE Standard 55 indicates summer and winter comfort zones that correspond to typical clothing level of 0.5 and 0.9 clo, respectively. ASHRAE comfort range is 3 °C, with a seasonal shift of 3 °C (ASHRAE, 2001a,b). Field studies showed that indoor temperature in fully HVAC controlled buildings is maintained in narrower ranges, with the mean temperature of 23 °C, standard deviation of 1–1.5 °C and seasonal shift of 0.5–1 °C (Fountain et al., 1996). But because people adapt themselves to the environment, thermal comfort in naturally ventilated buildings has larger seasonal ranges than assumed by ISO 7730 and ASHRAE 55 Standards (de Dear et al., 1997; Brager and de Dear, 1998; Nicol and Humphreys, 2002).

Fig. 1 shows a comparison of the comfort zones for the European climatic conditions. The comfort range in real HVAC controlled buildings (Fountain et al., 1996) is compared to the ASHRAE comfort zone (ASHRAE, 2001a,b) and the standard for natural ventilation (Brager and de Dear, 2000). The approximate parameters of the comfort zones are given in Table 1. According to the comfort standard for natural ventilation, the indoor mean temperature in summer is considered to be 25 °C, corresponding to the mean monthly temperature of 22 °C (Fig. 2). This comfort standard may be used for thermal adaptive control of buildings (McCartney and Nicol, 2002).

## 3. Balance temperature and the free-running temperature

A common way to compare the energy consumption of buildings is by applying the bin method (ASHRAE, 2001a,b). The estimation of the degree

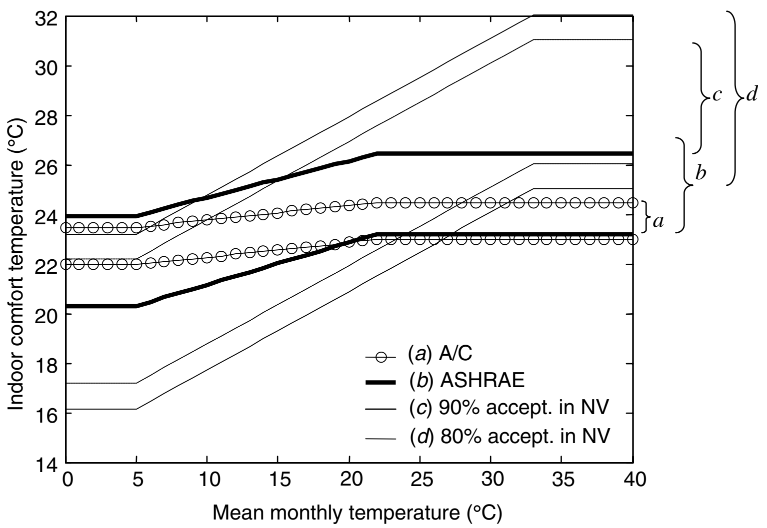


Fig. 1. Comfort range for air conditioning and for natural ventilation: (a) air conditioning; (b) ASHRAE comfort range; (c) natural ventilation, 90% acceptability limits; (d) natural ventilation, 80% acceptability limits (Table 1).

Table 1
Comfort zones

| | Mean (°C) | Winter mean (°C) | Summer mean (°C) | Range (°C) | Seasonal shift (°C) |
|---|---|---|---|---|---|
| (a) Air conditioned buildings | 23.0 | 22.5 | 23.5 | 1.5 | 1.0 |
| (b) ASHRAE comfort zone | 23.5 | 22.1 | 24.9 | 3.5 | 2.7 |
| (c) Standard for natural ventilation, 90% acceptability limits | 23.9 | 19.5 | 25.0 max 28.3 | 5.0 | 8.8 |
| (d) Standard for natural ventilation, 80% acceptability limits | 23.9 | 19.5 | 25.0 max 28.3 | 7.0 | 8.9 |

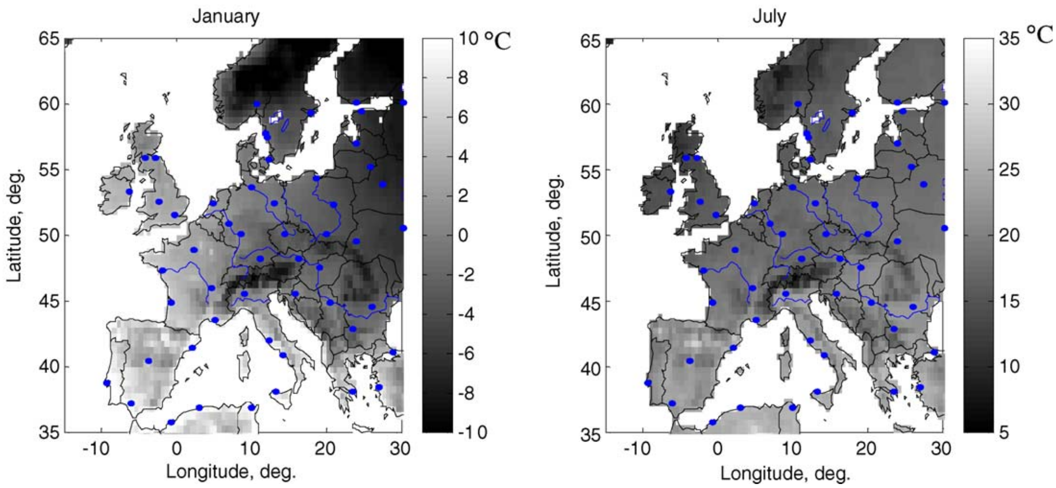


Fig. 2. Mean monthly temperature in Europe during January and July (data from IIASA, 2001).

hours in the bin method is done by using the concept of balance temperature. The balance temperature for cooling, $T_b$, is the outdoor temperature for which the building having a specified indoor temperature, $T_{cu}$, is in thermal balance with the outdoors. For this temperature, the heat gains (solar, internal) equal the heat losses (ASHRAE, 2001a,b):

$$q_{gain} = K_{tot}(T_b - T_{cu}), \tag{1}$$

where $q_{gain}$—total heat gains [W]; $K_{tot}$—total cooling loss coefficient of the building [W/K]; $T_{cu}$—upper limit of comfort temperature [K]; $T_b$—balance temperature [K].

The balance point temperature is then

$$T_b = T_{cu} + \frac{q_{gain}}{K_{tot}}. \tag{2}$$

The energy rate needed for cooling is

$$\begin{cases} q_c = K_{tot}(T_o - T_b), & \text{if } T_o > T_b, \\ 0, & \text{if } T_o \leqslant T_b, \end{cases} \tag{3}$$

where $T_o$ is the outdoor temperature. The energy needed for cooling is

$$Q_c = \int_{t_{init}}^{t_{fin}} K_{tot}(T_o - T_b)\delta_c \, dt, \tag{4}$$

where $\delta_c$ is the condition for cooling.

$$\delta_c = \begin{cases} 1, & \text{if } T_o > T_b, \\ 0, & \text{if } T_o \leqslant T_b. \end{cases} \tag{5}$$

The total cooling loss coefficient of the building is a function of outdoor temperature and time. The discrete equivalent of the integral (4) is

$$Q_c = \sum_i \sum_j K_{tot}(i,j)[T_o(i,j) - T_b(i,j)]\delta_c \Delta t(i), \tag{6}$$

where summation indexes $i$ and $j$ refer to time interval and bins of the outdoor temperature, respectively. If the time interval, $\Delta t(i)$, is one hour, the factor

$$dh_c \equiv [T_o(i,j) - T_b(i,j)]\delta_c \Delta t(i) \tag{7}$$

is termed degree-hour for cooling, $dh_c$. The expression (7) has the disadvantage of using the concept of balance temperature which implies that the indoor temperature is controlled at a constant value.

We can demonstrate that the degree-hours as used in the bin method can be expressed as a function of the free-running temperature, $T_{fr}$ (Ghiaus, 2003). The free-running temperature is the indoor temperature of the building when no HVAC system is used; by "system" we mean heating, air conditioning and ventilation for cooling. Practically, this condition means that the building is as tight as during the heating season. The airtightness may be changed by ventilation and it is used for cooling.

From the thermal balance

$$K_{tot}(T_{fr} - T_o) - q_{gain} = 0, \tag{8}$$

it results the free-running temperature

$$T_{fr} = T_o + \frac{q_{gain}}{K_{tot}}. \tag{9}$$

By replacing $T_b$ in Eq. (7) by the expression (2) and by using Eq. (9), we obtain an equivalent expression for degree-hour for cooling:

$$\mathrm{dh_c} = (T_{\mathrm{fr}} - T_{\mathrm{cl}})\delta_{\mathrm{c}}, \tag{10}$$

where the condition for cooling is

$$\delta_{\mathrm{c}} = \begin{cases} 1, & \text{if } T_{\mathrm{fr}} > T_{\mathrm{cu}}, \\ 0, & \text{if not.} \end{cases} \tag{11}$$

The cooling load may be balanced by free-cooling or by mechanical cooling. If the outdoor temperature, $T_{\mathrm{o}}$, is lower than the upper limit of the comfort range, $T_{\mathrm{cu}}$, then free-cooling is possible. The condition for free-cooling is

$$\delta_{\mathrm{fr}} = \begin{cases} 1, & \text{if } T_{\mathrm{fr}} > T_{\mathrm{cu}} \text{ and } T_{\mathrm{o}} < T_{\mathrm{cu}}, \\ 0, & \text{if not,} \end{cases} \tag{12}$$

resulting the degree-hour for free-cooling

$$\mathrm{dh_{fr}} = (T_{\mathrm{fr}} - T_{\mathrm{cu}})\delta_{\mathrm{fr}}. \tag{13}$$

If cooling is needed, i.e. $T_{\mathrm{fr}} > T_{\mathrm{cu}}$, but the outdoor temperature, $T_{\mathrm{o}}$, is higher than the upper limit of the comfort temperature, $T_{\mathrm{cu}}$, then mechanical cooling is required. The condition for mechanical cooling is

$$\delta_{\mathrm{mc}} = \begin{cases} 1, & \text{if } T_{\mathrm{fr}} > T_{\mathrm{cu}} \text{ and } T_{\mathrm{o}} \geqslant T_{\mathrm{cu}}, \\ 0, & \text{if not,} \end{cases} \tag{14}$$

resulting the degree-hour for mechanical cooling

$$\mathrm{dh_{mc}} = (T_{\mathrm{fr}} - T_{\mathrm{cu}})\delta_{\mathrm{mc}}. \tag{15}$$

The conditions expressed by the Eqs. (11), (12) and (14) are shown in Fig. 3. The comfort range is delimited by the lower and the upper comfort limits, $T_{\mathrm{cl}}$ and $T_{\mathrm{cu}}$ as shown in Fig. 1 and Table 1. The free-running temperature, $T_{\mathrm{fr}}$, may be higher or lower than the outdoor temperature, $T_{\mathrm{o}}$; free cooling is feasible when $T_{\mathrm{fr}} > T_{\mathrm{o}}$ (Fig. 3(a)).

By summing the degree-hours given by Eqs. (11), (13) and (15) in bins of outdoor temperature, we obtain the degree-hour distribution as a function of the outdoor temperature for cooling:

$$\mathrm{DH_c}(T_{\mathrm{o}}) \equiv \mathrm{DH_c}(j) = \sum_i [T_{\mathrm{fr}}(i,j) - T_{\mathrm{cl}}(i,j)]\delta_{\mathrm{c}} \tag{16}$$

for free cooling,

$$\mathrm{DH_{fc}}(T_{\mathrm{o}}) \equiv \mathrm{DH_{fc}}(j) = \sum_i [T_{\mathrm{fr}}(i,j) - T_{\mathrm{cu}}(i,j)]\delta_{\mathrm{fc}} \tag{17}$$

and for mechanical cooling,

$$\mathrm{DH_{mc}}(T_{\mathrm{o}}) \equiv \mathrm{DH_{mc}}(j) = \sum_i [T_{\mathrm{fr}}(i,j) - T_{\mathrm{cu}}(i,j)]\delta_{\mathrm{mc}}, \tag{18}$$

where $T_{\mathrm{fr}}(T_{\mathrm{o}})$, $T_{\mathrm{cl}}(T_{\mathrm{o}})$, and $T_{\mathrm{cu}}(T_{\mathrm{o}})$ represent the free-running temperature and the lower and the upper limits of the comfort temperature that correspond to the bin $j$ centered around $T_{\mathrm{o}}$; $\sum_{T_{\mathrm{fr}}}[\bullet]$ is the sum for all the values in the bin centered around $T_{\mathrm{o}}$.

The integral of degree-hour distributions for cooling:

$$\mathrm{DH_c} = \sum_j \sum_i [T_{\mathrm{fr}}(i,j) - T_{\mathrm{cl}}(i,j)]\delta_{\mathrm{c}} \tag{19}$$

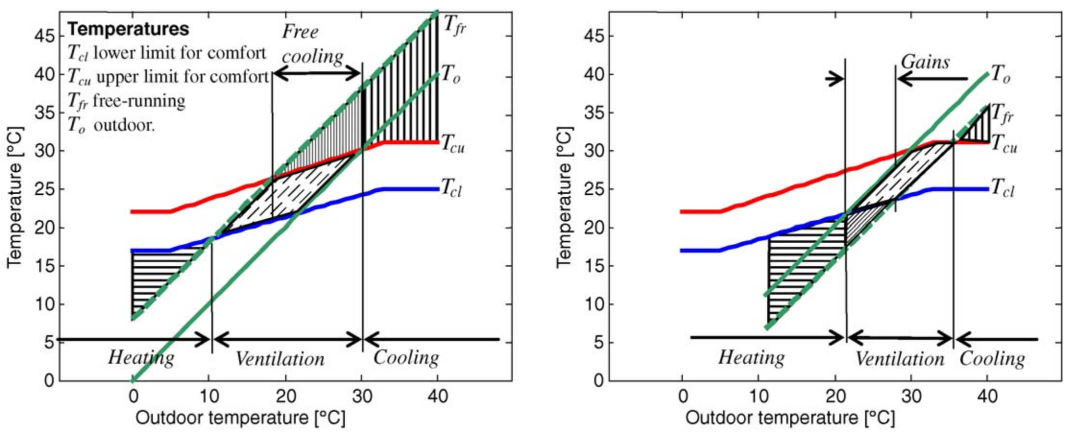


Fig. 3. Ranges for heating, free-cooling and mechanical cooling when the free-running temperature is (a) higher and (b) lower than the outdoor temperature.

for free cooling

$$DH_{fc} = \sum_j \sum_i [T_{fr}(i,j) - T_{cu}(i,j)]\delta_{fc} \quad (20)$$

and for mechanical cooling

$$DH_{mc} = \sum_j \sum_i [T_{fr}(i,j) - T_{cu}(i,j)]\delta_{mc} \quad (21)$$

are mathematically equivalent with the classical definition of degree-hours.

Fig. 4 shows an example of the degree-hour distribution for 12 h and for 18 h obtained from building simulation. The panels in the first row show the comfort zone, the outdoor temperature and the free-running temperature. The panels in the second row show the frequency distribution of the outdoor temperature in bins of 1 °C at 12 and 18 h for a year. The integral of this distribution is the sum of occurrences over a year, i.e. 365. The last row shows the degree-hours obtained with Eqs. (17) and (18). We may notice that free cooling is not possible at 12 h because the free-running temperature is lower than the outdoor temperature. The integrals of degree-hour distribution $DH_{mc}(T_o)$ and $DH_{fc}(T_o)$ represent the degree-hours for mechanical cooling, $DH_{mc}$, and free-cooling, $DH_{fc}$, respectively. At 18 h, about 20% of the energy needed for cooling may be saved by using ventilation.

## 4. Obtaining the degree-hour distribution from the probability distribution

Degree-hours may be calculated when the time variation of the outdoor temperature is known. However, this approach has two disadvantages: the data are not easily available and, if accessible, they should be available for more years (typically 5–20) in order to be statistically significant. An alternative to using time series is to use the probability distribution. The probability distribution is obtained on measurements achieved during long periods of time, more than 5 years (IIASA, 2001).

### *4.1. Number of days in a month with a given temperature*

A histogram shows the distribution of data values. It bins the values of a variable in equally spaced

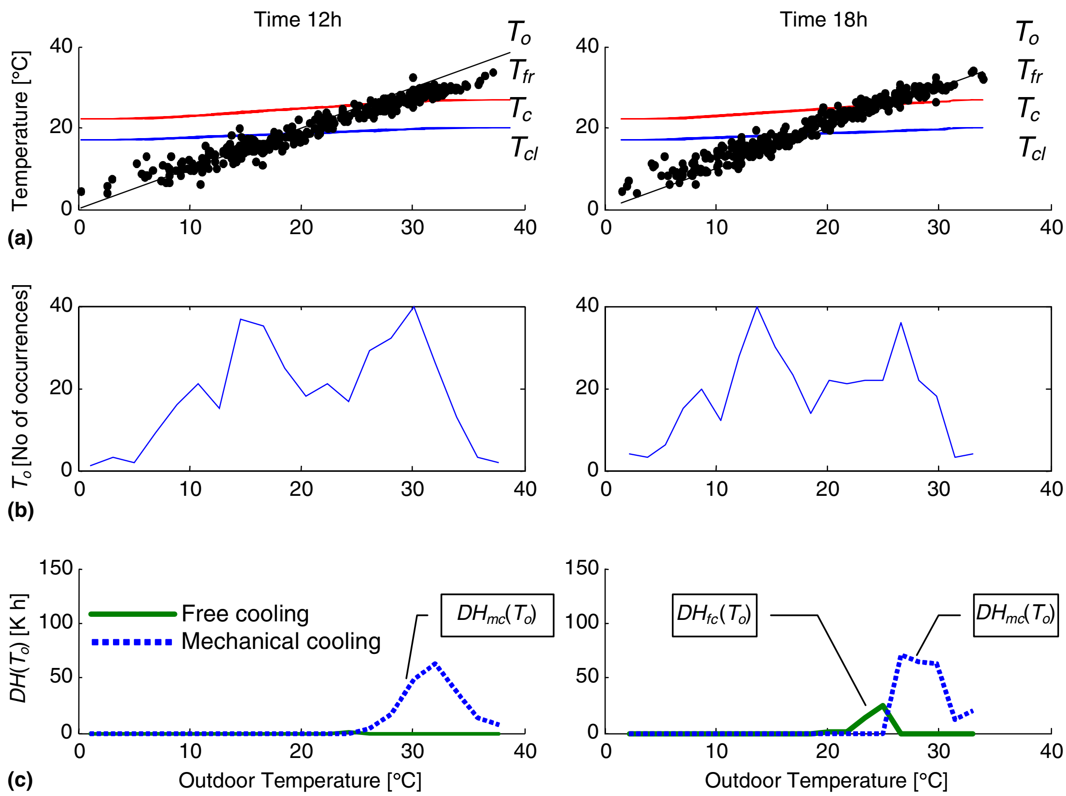


Fig. 4. Degree hour distribution for cooling: (a) Free-running temperature, (b) outdoor temperature distribution (c) degree-hour for free cooling and mechanical cooling.

containers and returns the number of elements in each container. The number of values in an interval (bin) divided by the total number of values represents the relative frequency of that variable for a bin. The probability density is the limit of relative density, when the number of values of the variable is infinity (Fig. 5):

$$\Pr = \lim_{N\to\infty}\left(\frac{f}{N}\right). \tag{22}$$

The probability density function, $P_{\mathrm{df}}$, has a different meaning depending on whether the distribution is discrete or continuous (Fig. 6). For discrete distributions, the probability density function is the probability of observing a particular outcome. Let us consider, for example, that the temperature is measured in discrete values of 1 °C. In the case of the discrete probability density function ($P_{\mathrm{df}}$) represented in Fig. 6(a), the probability that the temperature is 10 °C is given by the value of the $P_{\mathrm{df}}$ at 10. Unlike discrete distributions, the $P_{\mathrm{df}}$ of a continuous distribution at a value is not the probability of observing that value. For continuous distributions, the probability of observing any particular value is zero. To obtain probabilities, the $P_{\mathrm{df}}$ must be integrated over an interval. For example, the probability of the temperature to be between 9.5 and 10.5 °C is the integral of the appropriate $P_{\mathrm{df}}$ from 9.5 to 10.5 °C (Fig. 6(b)).

For a discrete distribution having bins of $T_{\mathrm{bin}}$, the probability of the temperature being between $T - T_{\mathrm{bin}}/2$ and $T + T_{\mathrm{bin}}/2$, $T \in \{T_{\min}, T_{\min} + T_{\mathrm{bin}}, T_{\min} + 2T_{\mathrm{bin}}, \ldots, T_{\max}\}$ is

$$\Pr(T \in [T - T_{\mathrm{bin}}/2, T + T_{\mathrm{bin}}/2]) = T_{\mathrm{bin}} \cdot P_{\mathrm{df}}(T). \tag{23}$$

For a continuous distribution, the probability of the temperature being between $T - T_{\mathrm{bin}}/2$ and $T + T_{\mathrm{bin}}/2$, $T \in \mathbf{R}$, is

$$\Pr(T \in [T - T_{\mathrm{bin}}/2, T + T_{\mathrm{bin}}/2]) = \int_{T-t_{\mathrm{bin}}/2}^{T+t_{\mathrm{bin}}/2} P_{\mathrm{df}}(T)\cdot \mathrm{d}T. \tag{24}$$

Let us consider a random variable, $T$, that has $N$ values. The probable frequency of variable $T$ in the bin $[T - T_{\mathrm{bin}}/2,\ T + T_{\mathrm{bin}}/2]$ is

$$\begin{aligned} &f(T \in [T - T_{\mathrm{bin}}/2, T + T_{\mathrm{bin}}/2]) \\ &\quad = N \cdot \Pr(T \in [T - T_{\mathrm{bin}}/2, T + T_{\mathrm{bin}}/2]). \end{aligned} \tag{25}$$

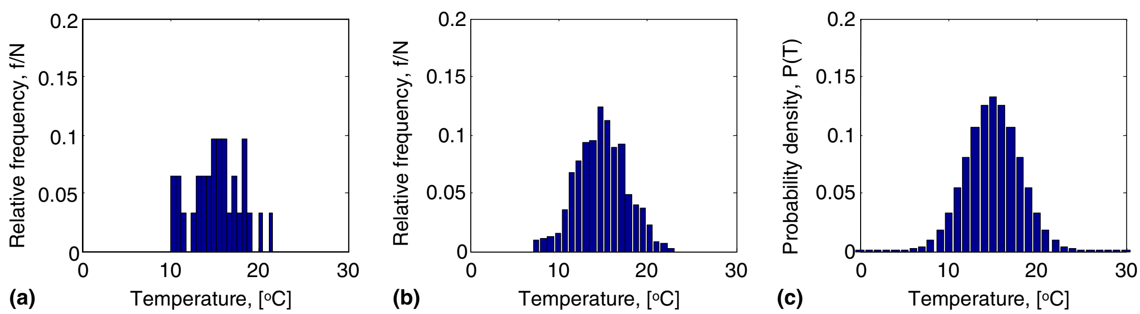


Fig. 5. Relative distribution frequency and probability density for a random process with $m = 15$, $s = 3$. (a) Relative frequency, $N = 31$; (b) Relative frequency, $N = 20 \times 31$; (c) probability density function.

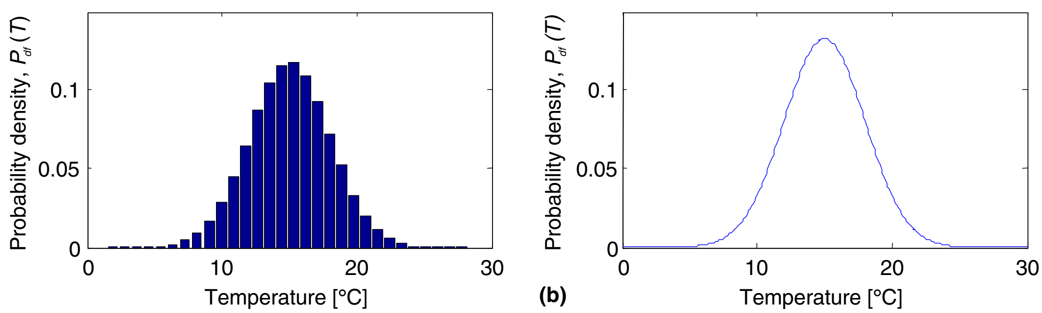


Fig. 6. Probability density functions (a) discrete and (b) continuous.

For a discrete distribution, Eq. (25) becomes

$$f(T \in [T - T_{\text{bin}}/2, T + T_{\text{bin}}/2]) = N \cdot T_{\text{bin}} \cdot P_{\text{df}}(T), \quad (26)$$

and for a continuous distribution it becomes

$$f(T \in [T - T_{\text{bin}}/2, T + T_{\text{bin}}/2]) = N \cdot \int_{T-T_{\text{bin}}/2}^{T+T_{\text{bin}}/2} P_{\text{df}}(T) \cdot \mathrm{d}T. \quad (27)$$

If the random variable $T$ represents the daily mean temperature in a month, then $N$ is the total number of days in a month, $N \in \{28, 30, 31\}$ and $f(T \in [T - T_{\text{bin}}/2,\ T + T_{\text{bin}}/2])$ gives the number of days in a month that have the temperature $T \in [T - T_{\text{bin}}/2,\ T + T_{\text{bin}}/2]$. Having the probable number of days in a month with a given mean temperature, we can calculate the number of degree-hours for that month.

### *4.2. Degree hours for cooling*

The degree-hours are a function of outdoor temperature. For a given outdoor temperature, $T_o$, the degree-hour distribution is obtained as the product of

1. the number of days having the temperature $T_o$, number expressed by $N \cdot T_{\text{bin}} \cdot P_{\text{df}}(T_o)$,
2. and the temperature difference $(T_{\text{fr}} - T_{\text{cu}})$,
3. when there is a need for cooling, condition given by Eq. (11):

$$\text{DH}_c(T_o) = N \cdot T_{\text{bin}} \cdot P_{\text{df}}(T_o) \cdot (T_{\text{fr}} - T_{\text{cu}}) \cdot \delta_c. \quad (28)$$

Similarly, the degree hour distribution for free-cooling is

$$\text{DH}_{\text{fc}}(T_o) = N \cdot T_{\text{bin}} \cdot P_{\text{df}}(T_o) \cdot (T_{\text{fr}} - T_{\text{cu}}) \cdot \delta_{\text{fc}}, \quad (29)$$

and for mechanical cooling is

$$\text{DH}_{\text{mc}}(T_o) = N \cdot T_{\text{bin}} \cdot P_{\text{df}}(T_o) \cdot (T_{\text{fr}} - T_{\text{cu}}) \cdot \delta_{\text{mc}}, \quad (30)$$

where the conditions for cooling, $\delta_c$, free-cooling, $\delta_{\text{fc}}$, and mechanical cooling, $\delta_{\text{mc}}$, are given by Eqs. (11), (12) and (14), respectively. The free-running temperature in Eqs. (28)–(30) depends on the building characteristics and on the outdoor temperature.

In order to obtain a characteristic of the building that is independent of the climate, we define the temperature difference in free-running as

$$T_{\text{diff}} = T_{\text{fr}} - T_o. \quad (31)$$

$T_{\text{diff}}$ is a property of the building that is almost independent of the outdoor temperature. A concept similar to the temperature difference in free-running is the temperature difference ratio used in assessing the potential of cooling by using the thermal mass (La Roche and Milne, 2004).

The free-running temperature can be expressed as the sum of two values that are independent: the temperature difference in free-running and the outdoor temperature. By introducing the relation (31) in Eqs. (28)–(30), we obtain the degree-hour distribution for cooling:

$$\text{DH}_c(T_o) = N \cdot T_{\text{bin}} \cdot P_{\text{df}}(T_o) \cdot (T_{\text{diff}} + T_o - T_{\text{cu}}) \cdot \delta_c, \quad (32)$$

for free-cooling,

$$\text{DH}_{\text{fc}}(T_o) = N \cdot T_{\text{bin}} \cdot P_{\text{df}}(T_o) \cdot (T_{\text{diff}} + T_o - T_{\text{cu}}) \cdot \delta_{\text{fc}}, \quad (33)$$

and for mechanical cooling,

$$\text{DH}_{\text{mc}}(T_o) = N \cdot T_{\text{bin}} \cdot P_{\text{df}}(T_o) \cdot (T_{\text{diff}} + T_o - T_{\text{cu}}) \cdot \delta_{\text{mc}}. \quad (34)$$

The degree-hour distributions expressed by Eqs. (32)–(34) depend on the characteristics of the building, $T_{\text{diff}}$, of the climate, $T_o$, and of the comfort criteria, $T_{\text{cu}}$.

## 5. Obtaining the temperature difference in free-running

The temperature difference in free-running may be an educated guess or it may be calculated by simulation or measured during building operation. Typical values of the daily mean temperature difference in free-running can be obtained from the experience acquired during the heating season, when $T_{\text{diff}}$ has values of 3–10 °C. But since the building inertia has an important influence on the daily variation of $T_{\text{diff}}$, the use of daily mean can be misleading. URBVENT project created a database of daily variations of $T_{\text{diff}}$ based on results of building simulation. Three types of buildings (Table 2) were placed in different conditions (Table 3). The free-running temperature of the three types of buildings located in Rome, Munich and Moscow was obtained for the orientation and occupancy given in Table 3. Then, the mean of the temperature difference between the indoor and the outdoor temperature

Table 2
Types of buildings

| | Surf. ($m^2$) | Vol. ($m^3$) | Occupants no. | Heat gains ($W/m^2$) | | ACH |
|---|---|---|---|---|---|---|
| | | | | Sensible | Latent | |
| House | 20 | 50 | 4 | 7 | 5 | 0.5 |
| Glass façade office | 300 | 750 | 30 | 7 | 5 | 0.5 |
| Brick wall office | 75 | 200 | 10 | 7 | 5 | 0.5 |

Table 3
Conditions for URBVENT database of buildings

| Type of building | Location | Orientation | Occupancy |
|---|---|---|---|
| House | North | North | Full time |
| Glass facade office | Center | East | Working time |
| Brick wall office | South | South | |
| | | West | |

in free-running regime was calculated for each of the hours: 0, 6, 12, and 18 h and for each month. An example of the result for the "glass façade office" with south orientation located in Rome is given in Fig. 7.

## 6. Estimation of potential for energy savings

The energy savings for cooling may be estimated by comparing the integrals of degree-hour distribution. The energy consumption for cooling depends on the adopted standard for comfort. Since the comfort range for natural ventilation is much larger, the need for cooling is lower as compared to the case in which the comfort standard for air conditioning would be used. Let us take the example of a zone in an office building having the dimensions of 10 m long × 7.5m wide × 2.5 m height (75 $m^2$ of floor), occupied by 10 persons and internal sources of 30 $W/m^2$. The results of the degree-hours for Europe are given in Fig. 8. The first row shows the results for the case of the comfort range found in real air conditioned buildings for which the comfort range is indicated in Fig. 1(a). The second row shows the results for the ASHRAE comfort range as presented in Fig. 1(b). The third and the fourth rows show the results for the comfort range found in buildings with natural ventilation, as indicated in Fig. 1(c) and (d).

Comparison of the rows of Fig. 8 reveals that the distribution is almost the same but the energy consumption in air conditioned buildings would be almost halved if ASHRAE comfort range were used. The reduction would be even more important if the standard for natural ventilation were used. The pat-

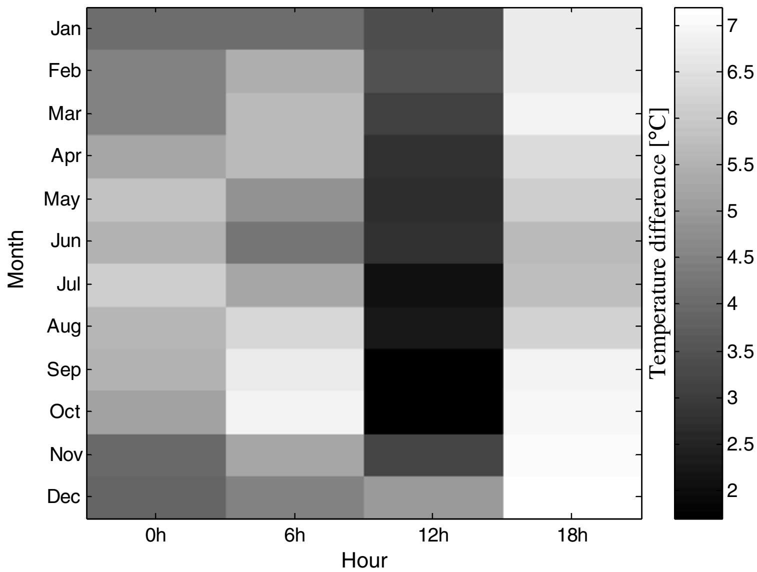


Fig. 7. Example of temperature difference of a free-running building.

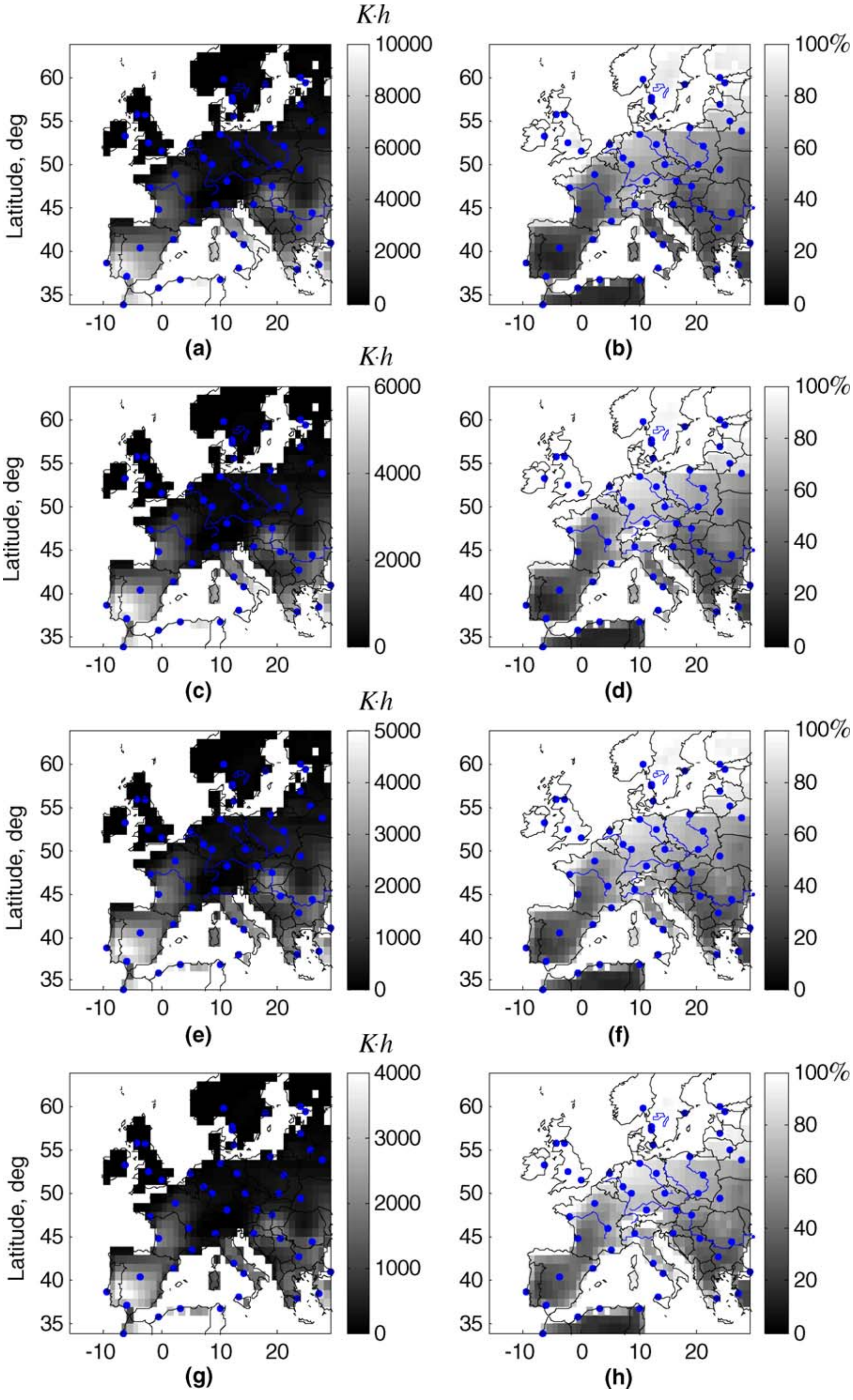


Fig. 8. Energy consumption and savings for an office building as a function of comfort standards. Case of comfort range of fully HVAC buildings: (a) degree-hours for cooling; (b) percentage of free-cooling. Case of ASHRAE comfort range: (c) degree-hours for cooling; (d) percentage of free-cooling. Case of natural ventilation with 90% acceptance: (e) degree-hours for cooling; (f) percentage of free-cooling. Case of natural ventilation with 80% acceptance: (g) degree-hours for cooling; (h) percentage of free-cooling.

tern of energy savings is also similar. For all comfort ranges, free-cooling may save more than 50% for regions located northern Danube and Loire but the need for cooling is much lower in these regions.

## 7. Conclusions

The free-running temperature may be used instead of the base temperature to define the degree-hours in the bin method. The two definitions are equivalent, but the use of the free-running temperature has the advantage that it can be applied when the indoor temperature varies, which is the case for non-air conditioned buildings in summer.

The method proposed has the advantage that the three important aspects that influence the results of the building simulation, i.e. building type, comfort range and local climate, are decoupled. The building is characterized by the temperature difference in free-running; the comfort is characterized by the temperature mean, range and seasonal shift; the local climate is characterized by the time series of outdoor temperature or by the probabilistic distribution of outdoor temperature for different hours of the day (0, 6, 12 and 18 h) of each month.

Based on this method, we can obtain quick estimations of energy need for cooling and of the potential of energy savings for cooling by using ventilation. In Europe, ventilation has the potential to be used for cooling especially in north. However, the need for cooling in these regions is also much smaller. Free-cooling alone can cover only a small part of the need for cooling in southern Europe.

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