Thermal Load and Application

2. Degree-days: Theory and Application

The two main uses for degree-days in buildings are:

1. To estimate energy consumption and carbon dioxide emissions due to space heating and cooling for new build and major refurbishments.
2. For on-going energy monitoring and analysis of existing buildings based on historical data.

Degree-days are essentially the **summation** of **temperature differences** over time, and hence they capture both **extremity** and duration of outdoor temperatures. The **temperature difference** is between a **reference temperature** and the **outdoor air temperature**. The reference temperature is known as the **base temperature** which, for buildings, is **a balance point temperature, i.e. the outdoor temperature at which the heating (or cooling) systems do not need to run in order to maintain comfort conditions.**

When the **outdoor temperature** is below the **base temperature**, the **heating system** needs to provide heat. Since **heat loss** from a building is directly proportional to the **indoor-to-outdoor temperature difference**, it follows that the **energy consumption** of a heated building over a period of time should be related to **the sum** of these **temperature differences** over this **period**. The usual time period is **24 hours**, hence the term degree-days, but it is possible to work with **degree-hours. (Degree-days are in fact mean degree-hours, or degree-hours divided by 24)**. In order to appreciate the use of degree-days for building energy applications it is important to address some of the key concepts of this seemingly simple idea.

It must be stressed that, particularly for estimation purposes, degree-day techniques can only provide **approximate** results since there are a number of simplifying **assumptions** that need to be made. These **assumptions** particularly relate to the use of average conditions (**internal temperatures, casual gains, air infiltration rates etc**), and that these can be used in conjunction with each other to provide a good approximation of building response. The advantage to their use, therefore, lies in their relative ease and speed of use, and all of the information required to conduct estimation analysis is available from the building design criteria. Unlike full thermal simulation models degree-day calculations can be carried out manually or within computer spreadsheets; they have a transparency and repeatability that full simulations may not provide.

2.1 Degree-days Calculations

The simplest (**heating**) degree-day calculation is when, on a given day, the **outdoor temperature** never rises above the base temperature. In this case degree-days for that day are simply equal to **the base temperature** minus the **daily mean outdoor temperature**. Figure 1.1 shows a variation in hourly temperature over two days, together with a base temperature (in this case 14 °C). **Each outdoor temperature can be subtracted from the base temperature to give a temperature difference, as represented by the columns for each hour. For each day the summation of these differences would give daily degree-hours; dividing this by 24 gives a value in degree days. The same result can be obtained by subtracting the mean daily outdoor temperature from the base temperature as indicated in the Figure. From Figure 1.1, on day 1 a base temperature of 14 °C and a mean outdoor temperature of 7.3 °C will give 6.7 degree-days (or K.day) for that day. On day 2 the mean outdoor temperature is 9.4 °C to give 4.6 K·day. For these two days there is a total of 6.7 + 4.6 = 11.3 K·day.** It is usual to use **degree-day** sums over suitable periods, for example **monthly**, **seasonally** or **annually**. The daily degree-days are simply summed for each day for the appropriate period. The higher the total of heating degree-days the colder the weather in that period, while a lower number indicates **milder** weather.

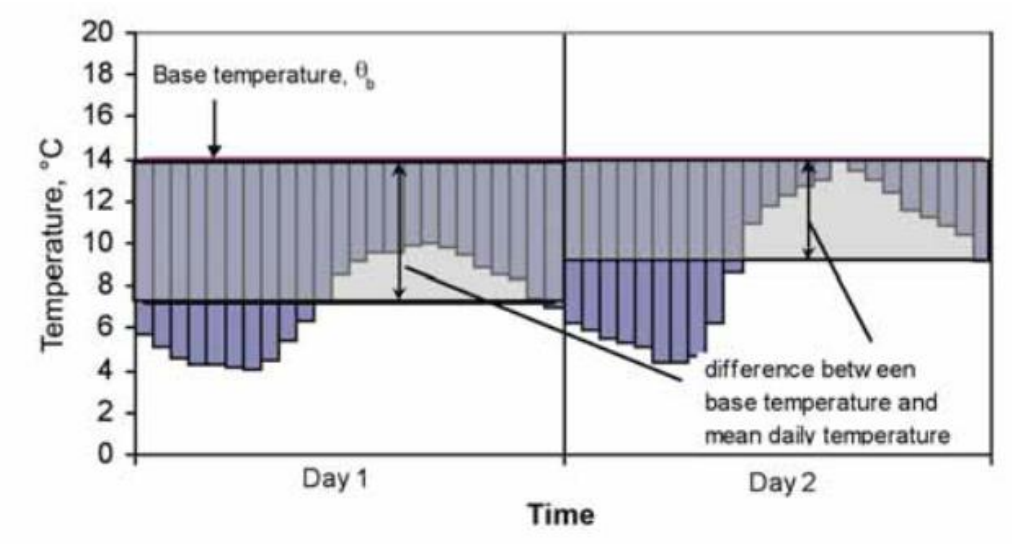

Figure 1.1 The basic definition of degree-days as the difference between the base temperature and the mean daily outdoor temperature

However, in practice it is more complex as the outdoor temperature may **fluctuate around** the base temperature. In building heating applications this happens in the **warmer months** or when the base temperature is particularly low. In this case calculation methods are required that capture the fact that degree-days are positive when the temperature falls below the base for part of the day, but ignore the times when it rises above the base (**there can be no negative degree-day values**). Ideally this can be calculated from continuous (i.e**. hourly or**

even shorter interval) temperature data if it is available. **Positive** temperature differences are taken and **negative** ones set to **zero**; these are summed over the day and divided by the number of readings (24 in the case of hourly data).

2.2 Base Temperature

The **base temperature** is central to the successful understanding and use of degree-days. In a heated building during **cold** weather **heat** is **lost** to the **external** environment. Some of this heat is replaced by **casual heat gains** to the space from **people**, **lights**, **machines** and **solar gains** while the rest is **supplied** by the **heating system**. Since the **casual gains** provide a **contribution** to the heating within the building, there will be some outdoor temperature, below the **occupied set point temperature**, at which the heating system will not need to run. **At this point the casual gains equal the heat loss.** This temperature will be the **base temperature** for the building (sometimes called the **balance point temperature** [ASHRAE 2001]).

When the outdoor temperature is below the base temperature heating is required from the heating system. Heating degree-days are a measure of the amount of time when the outside temperature falls below the base temperature. They are the **sum** of the **differences** between **outside** and **base temperature** whenever the **outside** temperature **falls** *below* the **base** temperature. For an actively **cooled** building the **base** temperature is **the outdoor temperature** at which the **cooling** plant need not run, and is again related to the **casual heat gains** to the space (which now **add** to the **cooling load**). In this case **cooling degree-days** are related to **temperature differences** *above* this **base**.

The difficulty that **arises** is that **casual gains** vary throughout the **day**, from **day** to **day**, and throughout the **season**. In addition the **base temperature** depends on the building's thermal characteristics such as its **heat loss coefficient**, **thermal capacity**, and **heat loss mechanisms** such as the **infiltration** rate that may **vary** with **time**. This means that to define the **base temperature** it is necessary to take **average values** of these **variables** over a **suitable** time period (for example a **month**). The **uncertainty** in the **accuracy** of the results therefore increases with **decreasing** time scale, i.e. **daily** energy estimates are likely to be less accurate than **monthly** ones [Day 1999].

2.3 Calculating degree-days

Degree-days are the summation (or integral) of the differences between outdoor temperatures and a defined base temperature. Figure 2.1 shows four days with typical **diurnal** temperature fluctuations together with a notional base temperature.

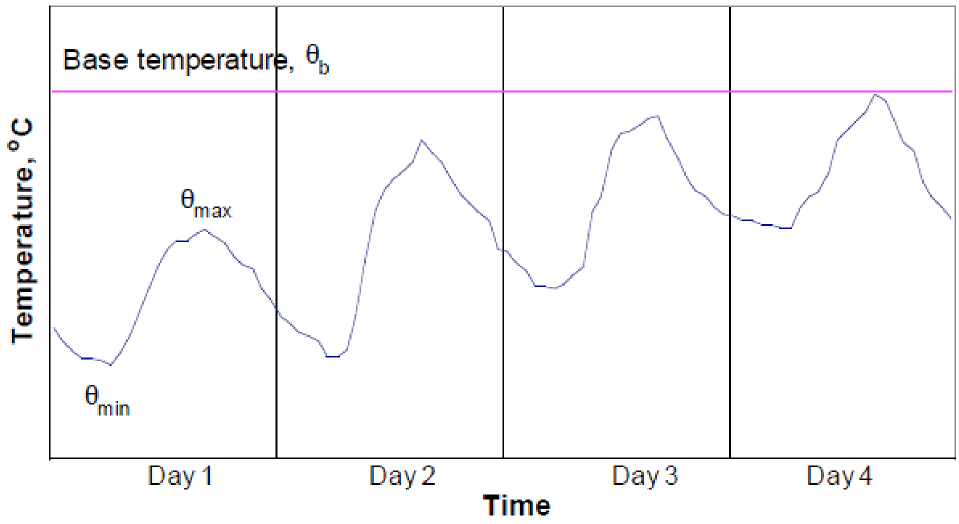

Figure 1.2 Four days of outdoor temperature variation where the maximum daily temperature is always less than the base temperature.

In each case the maximum daily temperature, θ_{max}, is less than the base temperature, in which case the (heating) degree-days are the total area bounded by the two temperature curves.

2.4 Mean degree-hours

The most rigorous (and most mathematically precise) method of calculating degree-days is to sum hourly temperature differences and divide by 24. (Smaller time increments may be used if the data exists, but there is little to be gained in terms of accuracy.) It is important that only positive differences are summed; in the case of heating degree-hours when the outdoor temperature exceeds the base temperature the value is set to zero for that hour. Equation 1 shows the general formula for this process for heating degree-days:

$$D_d = \frac{\sum_{j=1}^{24} \left(\theta_b - \theta_{o,j}\right)_{\left(\left(\theta_b - \theta_{o,j}\right) > 0\right)}}{24} \tag{2.1}$$

Where D_d is the daily degree-days for one day, θ_b is the base temperature and $\theta_{o,j}$ is the outdoor temperature in hour **j.** The subscript denotes that only positive values are taken. For cooling degree-days this simply becomes:

$$D_d = \frac{\sum_{j=1}^{24} \left(\theta_{o,j} - \theta_b\right)_{\left(\left(\theta_{o,j} - \theta_b\right) > 0\right)}}{24} \tag{2.2}$$

Daily degree-days are then summed over the appropriate period — usually over a month, a season or a year. However, this method of calculation requires a great deal more data handling and storage capability than other methods, although this is not a significant problem for electronic data systems. Using hourly temperatures to calculate degree-days does not imply that hourly energy estimates can be produced accurately — it is the summation of degree-days over a suitably long period of time that is of any real value in building energy analysis

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2.5 McVicker - The British Gas formulae & Hitchin's formula

Sometimes referred to as the 'McVicker' or the 'British Gas' formulae, due to the sources that have presented them in the past, these equations have been the standard method for calculating degree-days in the UK since 1928. They are an attempt to approximate the integral:

$$D_{\mathrm{d}} = \int (\theta_{\mathrm{b}} - \theta_{\mathrm{o}})\, dt \tag{2.3}$$

There have been a number of attempts to calculate degree-days from reduced weather data, for example Thom [1952, 1954, and 1966] and Erbs [1983] in the USA, based on the **statistical** analysis of **truncated** temperature distributions. These are usually based on mean monthly temperature and the standard deviation throughout the month, and thus are location-sensitive. Hitchin [1983] proposed a relatively simple formula for heating degree-days that showed a better correlation with the UK climate than Thom's method. Hitchin's formula states:

$$D_{\mathrm{m}} = \frac{N_{\mathrm{m}}\,(\theta_{\mathrm{b}} - \bar{\theta}_{\mathrm{o,m}})}{1 - e^{-k(\theta_{\mathrm{b}} - \bar{\theta}_{\mathrm{o,m}})}} \tag{2.4}$$

Where D_m is the monthly degree-day value, N_{m} is the number of days in the month, $\boldsymbol{\theta}_{\mathrm{o,m}}$ is the mean monthly temperature, and $\boldsymbol{k}$ (mean) is equal to (0.71).

3. Heating

There are a number of ways of interpreting the degree-day concept with respect to simplified heating analysis, for example as discussed by Hitchin and Hyde [1979]. However, these are all predicated on the notion that heating energy demand is directly proportional to the indoor-to-outdoor temperature difference, such that:

Heat loss (kW) = Overall heat loss coefficient (kW·K^{-1}) × Temperature difference (K)

The overall heat loss coefficient is made up of two components: the fabric coefficient, and the air infiltration rate. (It is also legitimate to combine ventilation air with the infiltration rate to give an overall loss coefficient for these components.

Heating energy demand (kW·h) = overall heat loss coefficient (kW·K^{-1}) × degree-days (K·day) × 24 (h·day^{-1})

(The 24 is included to convert from days to hours.)

It remains to define properly the indoor-to-outdoor temperature difference. While the total heat loss from a building is related to the actual indoor temperature, it does not follow that all of this heat loss is replaced by the heating system — some is met from incidental heat gains arising from solar insolation, people, lights and equipment. There is an energy balance whereby the sum of the heat inputs to the building equals the overall loss (see Figure 1.3), and the degree-day approach assumes that all of the incidental gains can be averaged out over time to give some representative indoor temperature which relates to the heating system contribution.

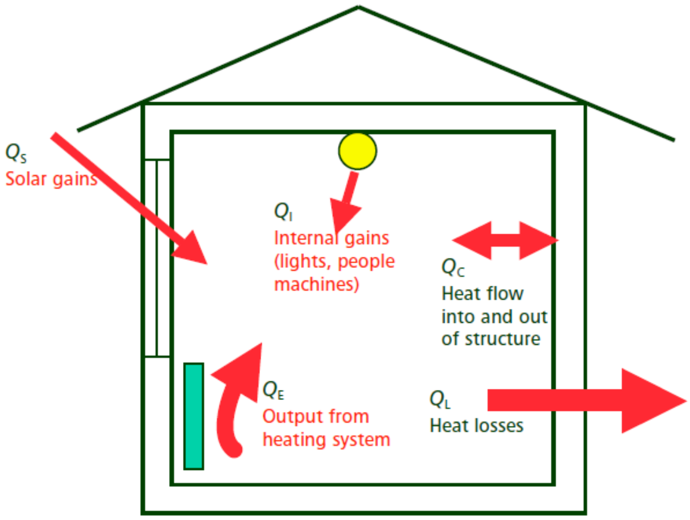

Figure 3.1 Energy balance on a heated building

3.1 Heating applications

The heat demand of a building comprises fabric transmission losses, air exfiltration losses and mechanical ventilation loads. (This publication does not consider hot water and other process loads). Taking the fabric and infiltration loads, the instantaneous load on the heating system, *Q*E, in kW is given by:

$$Q_E = U'\left(\theta_{sp} - \theta_o\right) + Q_C - Q_G;\ \text{for}\ Q_E > 0\ , \tag{3.1}$$

Where θ_{sp} is the indoor set point temperature (°C), θ_o is the outdoor temperature (°C), Q_G is the useful heat gain to the space (kW), Q_C is a term to account for building thermal storage effects (kW) and U` is the overall building heat loss coefficient ($kW \cdot K^{-1}$), given by:

$$U' = \frac{\sum A\ U + \frac{1}{3} N\ V}{1000} \tag{3.2}$$

Where *U* is the fabric *U*-value ($W \cdot m^{-1} \cdot K^{-1}$), *A* is the component area (m^2), *N* is the air infiltration rate in air changes per hour (h^{-1}) and *V* is the volume of the space (m^3). (*Note*: the numerical factor 1/3 arises from typical values of density and specific heat of air, and the conversion to air changes per hour [CIBSE 1999b]).

The energy demand on the heating system, E, is the summation of these instantaneous loads over time, in other words the integration of equation 3.1.

$$E = \int Q_E \, dt = \int U'(\theta_{sp} - \theta_o)\,dt + \int Q_c \,dt - \int Q_G \,dt;\ \text{for } Q_E > 0 \tag{3.3}$$

In the case of a continuously heated building, the Q_C term is equal to zero in which case the terms can be rearranged to bring the gains into the temperature integral:

$$E = U' \int \left(\theta_{sp} - \theta_o - \frac{Q_G}{U'}\right) dt \tag{3.4}$$

The term Q_G / U' has the units of temperature difference (K) and can be considered the internal temperature rise due to gains. Subtracting this gain-related temperature rise from the internal temperature gives rise to the concept of a base temperature, thus:

$$\theta_b = \theta_{sp} - \frac{Q_G}{U'} \tag{3.5}$$

Giving the energy demand on the heating system as:

$$E = U' \int (\theta_b - \theta_o)\,dt \tag{3.6}$$

Where the temperature integral is the degree-day total as previously defined in equation 2.3, i.e.:

$$D_d = \int (\theta_b - \theta_o)\,dt$$

This is calculated from the methods set out over the appropriately defined timescale, typically taken as a heating season or a month. The estimated *fuel* consumption, F (kW·h) is then found from:

$$F = \frac{24\, U' D_d}{\eta} \tag{3.7}$$

Where η is overall seasonal heating system efficiency and 24 is the conversion factor from days to hours.

From the above it can be seen that the use of a ‘standard’ base temperature of 15.5 °C is not appropriate for all buildings. Over the years changes to Building Regulations have had the effect of reducing the value of U' significantly, while internal gains have greatly increased. It is not uncommon to have buildings with base temperatures of 10 °C or less. The need to determine the correct base temperature has further implications for intermittent heating.

Example 3.1: Monthly space heating energy consumption of a continuously heated building. A building with an overall heat loss coefficient U' of 20 kW K^{-1} experiences average (useful) gains of 130 kW. The building is maintained at 19 °C with an average heating system efficiency of 75%. Calculate the expected energy consumption for the month of November when the mean outdoor temperature is 8 °C.

The building base temperature is found from equation 3.5:

$\theta_b = 19 - (130 / 20) = 12.5$ °C

Monthly degree-days can be found using Hitchin's formula (equation 2.4). In this case the constant k will be assumed to be 0.71:

$$D_m = \frac{30 \times (12.5 - 8)}{1 - e^{-0.71 \times (12.5 - 8)}} = 140.8 \text{ K} \cdot \text{day}$$

The expected fuel consumption is found from equation 3.7:

$F = 24 \times 20 \times 140.8/0.75 = 90\ 112$ kWh

3.2 Intermittent heating

It has been usual in the past to ignore the QC term entirely. However, this term is related to the thermal properties of the building which dictate how it will respond to changes in external and internal conditions, which is particularly important for intermittently operated buildings. While it is true that over a heating season the net flow of energy into and out of the building storage will be negligible, it must be stressed that on a day-to-day basis this has a strong bearing on overall heat loss from the building. A 'heavyweight' building will store more heat and, on average, be warmer than a 'lightweight' building; this has the effect of a higher overall rate of heat loss over time. Any simplified energy model needs to take such influences into account.

In order to maintain the inherent simplicity of degree-day methods, this factor can be accounted for by adjusting the base temperature. This can be done by taking the mean internal temperature of the building, instead of the set point temperature [Day and Karayiannis 1999a]. The base temperature is calculated by subtracting the mean gains divided by the heat loss coefficient from this mean internal temperature as illustrated in Figure 3.2.

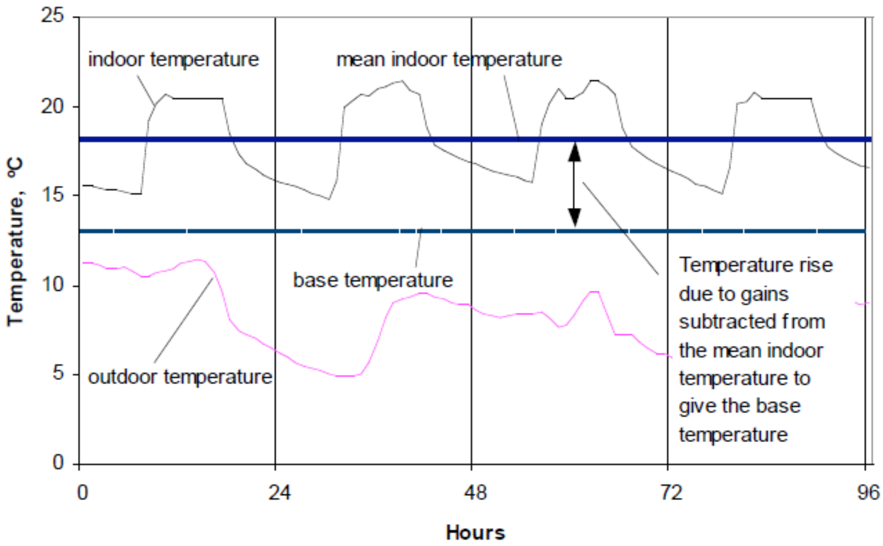

Figure 3.2 For intermittent heating the base temperature is related to the mean internal temperature of the building, not the set point temperature.

It has been shown that taking the mean monthly internal temperature is a good compromise with respect to accuracy and reducing the number of calculations [Day and Karayiannis 1999a]. This can be found by considering a notional average day within a month and determining the mean internal temperature for that day. Figure 3.3 shows an idealised indoor temperature profile over a 24-hour period (starting from when the occupants leave and the plant shuts down). This also shows the 24-hour mean internal temperature and a representative base temperature relative to the actual internal temperature. The calculation of the mean temperature depends on the thermal properties of the building (heat loss coefficient and thermal capacity), the plant output capacity, the length of the unoccupied period and the set point and outdoor temperatures.

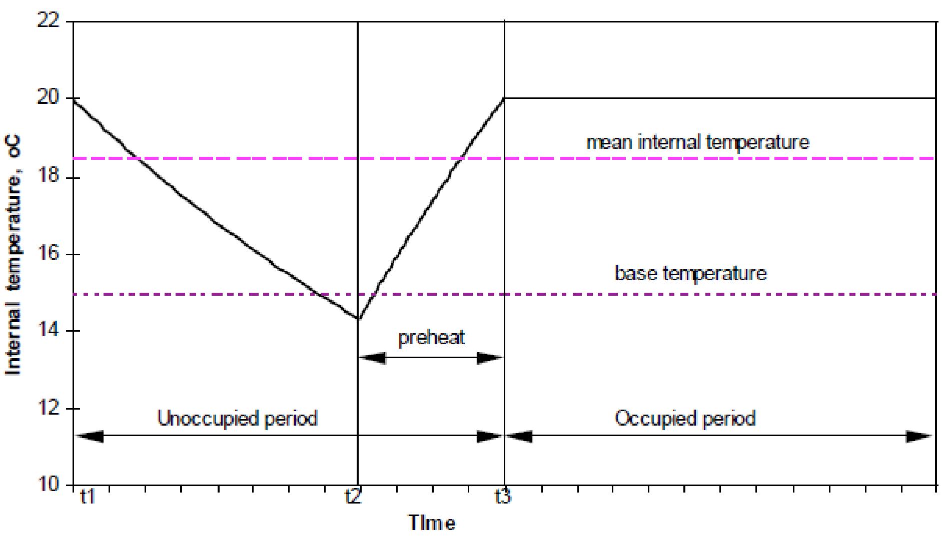

Figure 3.3 Internal temperature variations in an intermittently heated building; the mean internal temperature is determined by summing the hourly temperatures over the day and dividing by 24.

These key variables can be incorporated into a simplified first order thermal response model of the building. Similar approaches have been used by others to show the behaviour of buildings under intermittent heating [Levermore, 1992]. Two classical equations for the cooling and heating of a structure are:

For cooling:

$$-C\frac{\mathrm{d}\theta_i}{\mathrm{d}t} = U' \ (\theta_\mathrm{i} - \theta_\mathrm{o}) \tag{3.8}$$

For heating:

$$C\frac{\mathrm{d}\theta_\mathrm{i}}{\mathrm{d}t} = Q_\mathrm{p} - U' (\theta_\mathrm{i} - \theta_\mathrm{o}) \tag{3.9}$$

Where Q_p is the heating system output (at full load), $\mathrm{d}\theta/\mathrm{d}t$ is the rate of change of the building temperature. C is the effective thermal capacitance of the building given by:

$$C = \sum_n c_\mathrm{p}\, \rho\, V_\mathrm{f} \tag{3.10}$$

Where V_f is the volume of the structural element that is thermally responsive (m3), ρ is the density of the element ($\mathrm{kg.m^{-3}}$) and C_p is the specific heat of the element ($\mathrm{kJ.kg^{-1}.K^{-1}}$) for (*n)* active elements. The main difficulty is in assessing the effective depth of mass that should be chosen. BS EN ISO 13790 [2004] recommends that for each internal element the depth should be taken up to the first insulating layer, up to a maximum depth of 30 mm. Thus for a concrete slab 30 mm depth should be used to calculate the volume of the element, but for a wall dry lined with plasterboard only the thickness of the plasterboard should be taken.

Example 3.2: Calculation of thermal capacitance

A three-storey building of plan area 30 m × 20 m has lightweight concrete blocks as the inner element of the external walls. Glazing constitutes 30% of the external walls. The floors are cast concrete, and the space is partitioned using plasterboard. Table 3.1 shows the areas of each component, together with typical values of density and specific heat. The effective depth of mass is set to 30 mm for the external walls and ground and internal floors, and 12 mm the plasterboard partitions. The thermal capacitance, *C*, is the product of the four preceding columns. This gives a value of *C* for the building of 1.638×10^5 $\mathrm{kJ{\cdot}K^{-1}}$.

Table 3.1 Example 3.2: calculation of thermal capacitance

	Component area / m^2	Fabric density / (kg/m^3)	Fabric specific heat / (J/kg·K)	Effective depth of mass / m	*C* / (J/K)
External walls	630	1400	1000	0.03	26460000
Ground floor	600	2100	840	0.03	31752000
Roof	600	2100	840	0.03	31752000
Internal partitions	1080	950	840	0.012	10342080
Internal floors	1200	2100	840	0.03	63504000
				Total:	163810080

Equations 3.8 and 3.9 can be solved for a constant outdoor temperature to calculate the indoor temperature at any time in the unoccupied period. The solutions will also reveal the theoretical optimum start time for the plant. Thus the cooling and pre-heat curves of Figure 3.3 can be determined, from which it is possible to calculate the mean 24-hour temperature (i.e. the summation of the hourly temperatures over the day divided by 24):

$$\bar{\theta}_i = \frac{\sum_{t_1}^{t_3} \theta_i + \left(\theta_{sp} \times \text{hours of occpancy}\right)}{24} \tag{3.11}$$

Where θ_{sp} is the set point temperature and $t1$ and $t3$ define the occupancy leaving and arrival times respectively as defined in Figure 3.3.

Example 3.3: Determining the 24-hour mean internal temperature

Using Figure 3.3 as an example, the overnight temperatures can be read off the graph for each hour and added together (after 1 hour the temperature is 19 °C, after 2 hours it is 18.3 °C etc) to obtain the summation. The result for Figure 3.3 is 204.2. There are 12 hours during which the building is at the set point temperature of 20 °C, which must be added to the overnight total, such that:

24-hour summation of temperatures = 204.2 + (12 × 20) = 444.2

24-hour mean internal temperature = 444.2 / 24 = 18.5 °C

However, the summation of overnight hourly temperatures can be found analytically using equation 3.12 below, which has been developed from the solutions of equations 3.8 and 3.9 (see Appendix A4 for derivation).

$$\sum_{t_1}^{t_3} \theta_i = \theta_o (t_3 - t_1) + \tau \left(\theta_{sp} - \theta_o\right) \left[e^{\left(\frac{t_3 - t_2}{\tau}\right)} - e^{-\left(\frac{t_2 - t_1}{\tau}\right)} \right] + \frac{\tau\, Q_p}{U'} \left[1 + \left(\frac{t_3 - t_2}{\tau}\right) - e^{\left(\frac{t_3 - t_2}{\tau}\right)} \right] \tag{3.12}$$

Where $\boldsymbol{\tau}$ is the building time constant (h), obtained from:

$$\tau = \frac{C}{3600\,U'} \tag{3.13}$$

t_2 is the optimum switch-on time, obtained from:

With the plant switch-on temperature, θ_{so} (°C), obtained from:

$$t_3 - t_2 = -\frac{C}{3600\,U'}\ \ln\left[\frac{Q_p - U'(\theta_{sp} - \theta_o)}{Q_p - U'(\theta_{so} - \theta_o)}\right] \tag{3.14}$$

$$\theta_{so} = \theta_o + \frac{Q_p\left(\theta_{sp} - \theta_o\right) e^{-\left(\frac{t_3 - t_1}{\tau}\right)}}{Q_p + U'\left(\theta_{sp} - \theta_o\right) e^{-\left(\frac{t_3 - t_1}{\tau}\right)} - U'\left(\theta_{sp} - \theta_o\right)} \tag{3.15}$$

A full derivation of these expressions can be found in Appendix A4, with further discussions about their applicability in Appendix A5. In theory, the value of θ_o used in equations 3.12, 3.14 and 3.15 should be the mean overnight temperature. This can range between 0.2 °C to 1.5 °C below the mean monthly temperature depending on location and time of year. In practice, using the overall mean monthly temperature makes very little difference (generally less than 1%) to the final energy calculations. This has the advantage of needing to know only one outdoor temperature. (*Note*: equation 3.14 probably overestimates the length of pre-heat times for most medium to heavyweight buildings, and too much credence should not be given to the absolute value obtained. More important, however, is the overall mean internal temperature determined from the procedure, which can be seen as the mean 24-hour internal temperature that drives the average rate of heat loss. This has been shown to be reasonably consistent with temperatures obtained from simulations of buildings [Day 1999] for all but the most heavyweight buildings. However, the errors in forecasting mean temperatures are of secondary importance, as the degree-day energy forecasts have been shown to correspond well with simulations.) The base temperature can be found as for the continually heated case (equation 3.5) with the set point temperature replaced by the mean internal temperature, i.e:

$$\theta_b = \bar{\theta}_i - \frac{Q_G}{U'} \tag{3.16}$$

Calculation of degree-days and fuel consumption follow the same procedure as for the continuously heated case with this revised base temperature. While appearing to contain a good deal of complex calculation the method has the advantage of removing the need for correction factors, and allows for all of the input assumptions to be tested for their impact on the results. It is recommended that the equations be entered into a spreadsheet, which allows rapid and repeatable calculations to be made. An example calculation procedure is shown in section 4.1. The method set out above determines the monthly fuel consumption of the building. This can be repeated for all months of the heating system and the total seasonal fuel demand determined by summing these values. The length of the heating season is chosen by the user by selecting those months that the heating system is switched on. There is no need to try to fix the precise start and finish times of the heating season, as these are effectively accounted for by the degree-day approach. The method presented here is also only possible using a time-based approach such as degree-days; alternative methods, such as frequency of occurrence (or bin) methods [ASHRAE 2001], cannot readily take thermal capacity effects into account.

3.3 Carbon dioxide emissions

The fuel consumption can be converted to carbon dioxide (CO2) emissions by multiplying by the relevant carbon dioxide factor; C_f. Table 3.2 gives these factors for a range of fuels. Note that the factor for electricity will change with the change of generation mix.

Table 3.2 CO2 factors for various fuels [Source: Building Regulations 2006]

Fuel	CO_2 factor C_f / (kg/kW·h)
Natural gas	0.194
Oil (average)	0.265
Coal (typical)	0.291
Electricity	0.422

The carbon dioxide emissions, in tonnes, are then given by:

$$Carbon\ emission = \frac{C_f F}{1000} \qquad (3.17)$$

Heating energy estimation step-by-step procedure

This procedure will calculate the expected heating energy consumption for a given month, together with costs and CO_2 emissions and the expected uncertainty (an indication of accuracy). It should be repeated for different mean monthly outdoor temperatures and solar gain for each month of the heating season. The procedure is best suited to a spreadsheet which can then be used to vary the different input parameters to rapidly assess their relative importance on energy consumption. A full worked example is given in section 4.1.

Input information

Building heat loss coefficient	$U^{`}$ (kW K^{-1})	(see equation 3.2)
Building thermal capacity	C (kJ K-1)	(see equation 3.10)
Plant output capacity	Q_p (kW)	
Plant average efficiency	η	
Average casual gains to the space	Q_G (kW)	
Occupied set point temperature	θ_{sp} (°C)	

Mean monthly outdoor temperature $\bar{\theta}_{o,m}$ (°C)

Length of unoccupied period $(t3 - t1) = 24 -$ occupied period (hours)

Step 1

Calculate the building time constant τ (hours) (equation 3.13)

Step 2

Calculate the optimum plant switch-on temperature

Θ_{so} (°C) (equation 3.15)

Step 3

Calculate the length of the preheat time $(t_3 - t_2)$ (hours) (equation 3.14)

And the length of time the plant was off $(t_2 - t_1) = (t_3 - t_1) - (t_3 - t_1)$

Step 4

Calculate the mean 24-hour internal temperature, which involves two stages:

Step 4a

Calculate the sum of the overnight internal temperatures

$\sum\theta_i$ (equation 3.12)

Step 4b

Add this to the sum of the occupied period temperatures and divide the total by 24

$\bar{\theta}_i$ (equation 3.11)

Step 5

Calculate the base temperature θ_b (equation 3.16)

Step 6

Calculate monthly degree-days D_m

The way this is done will depend on the type of temperature data that is available. Unless hourly or daily temperature temperatures are available in a suitable form for rapid calculation (i.e. in a spreadsheet or database), then the most practical method is to use Hitchin's formula, which requires only the mean monthly outdoor temperature, which is obtainable from the Meteorological Office website.

(equation 2.4)

Alternatively, published monthly degree-days to base 15.5°C can be obtained and Hitchin's formula used to convert to degree-days for the building-specific base temperature calculated in step 5.

Step 7

Calculate the monthly fuel consumption F (kW· h) (equation 3.7)

Step 8

Convert to cost $F \times$ cost of fuel (£)

Convert to CO_2 CO_2 emission (tonnes) (equation 3.17)