

Comparison of multi-year and reference year building simulations

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Running Head: Multi-year and reference year building simulations.

Buildings are generally modelled for compliance using reference weather years. In the UK these are the test reference year (TRY) used for energy analysis and the design summer year (DSY) used for assessing overheating in the summer. These reference years currently exist for 14 locations around the UK and consist of either a composite year compiled of the most average months from 23 years worth of observed weather data (TRY) or a single contiguous year representing a hot but non-extreme summer (DSY). In this paper we compare simulations run using the reference years and the results obtained from simulations using the base data sets from which these reference years were chosen. We compare the posterior statistic to the reference year for several buildings examining energy use, internal temperatures, overheating and thermal comfort. We find that while the reference years allow rapid thermal modelling of building designs they are not always representative of the average energy use (TRY) exposed by modelling with many weather years. Also they do not always give an accurate indication of the internal conditions within a building and as such can give a misleading representation of the risk of overheating (DSY).

Keywords: reference year, building simulation, overheating, thermal comfort, energy.

Practical Implications: An understanding of the limitations of the current reference years is required to allow creation of updated reference years for building simulation of future buildings. By

comparing the reference years to the base data sets of historical data from which they were compiled an understanding of the benefit of multiple simulations in determining risk can be obtained.

Introduction

Reference weather years are used by the building simulation community to model the likely internal environment within a building or its energy use. These reference years consist of data files that contain a list (usually on an hourly time step) of measured common weather parameters such as atmospheric pressure, temperature and wind speed. Reference weather years are published for many parts of the world with the exact detail depending on the professional body or national institute that has assembled them; however, in all cases they attempt to represent many years worth of weather with a single year. In the UK these take the form of the Chartered Institute of Building Services Engineers (CIBSE) Test Reference Year (TRY) and the Design summer Year (DSY). These reference years are used to estimate values for energy usage (TRY) and estimate potential carbon emissions, or to estimate potential overheating risk (DSY). The use of a reference year would seem a sensible approach as it greatly reduces the computational effort required in modelling a building (as only one year need be considered) and hence the cost of the design process.

Since this approach was first used, computers have become a lot faster but models and codes more complex, thus the method has remained the standard way of assessing building performance. Unfortunately it does suffer from at least four potential problems. (i) There is a tendency for the external statistic to be confused with the internal. So, for example, if the DSY reference year is said to contain the third hottest summer in the complete data set (as measured by external average summertime temperature), it is common to postulate that a simulation of the building will produce

the third hottest internal year (as measured by internal temperature). Unfortunately there is no guarantee that this is true as the internal temperature also depends on other variables such as wind speed and cloud cover. (ii) The method can not be used to compute risk: Given a single representative year it is impossible to assess quantitatively how likely any conditions are, nor the return periods of extreme events. (iii) It does not allow more complex statistical questions to be addressed, such as “what is the likelihood of the building being above 32°C for four days with a diurnal cycle of less than 3°C?”. These are exactly the type of questions that it would be most useful to be able to discuss with clients as they best represent the concerns of the client. The reason the answer to such questions cannot be provided by use of a reference year is that the reference year will not have been assembled with such questions in mind. So, for example, a reference year might be the warmest on record, but this might be from a generally warmer than typical spring. Whereas when addressing the question of mortality or morbidity from thermal stress it is peak temperatures sustained over several days that is important and the reference year may not be extreme in this regard at all. (iv) Reference years are usually assembled from a consideration of around 20-30 years of observed data. This is a relatively short period for the identification of means and very short for the identification of extremes.

In this work we make a direct comparison between the conditions within a series of buildings when modelled by a continuous twenty to thirty year record of weather to those produced by using single reference years selected from the same data set, i.e. we are comparing the posterior statistic (for example energy consumption) with the statistic generated by using a climatologically representative year. The years considered are the CIBSE TRY and DSY reference years for Plymouth and Edinburgh, these were chosen since the data was easily obtained and they allow us to examine data from very different climates in the UK. This allows us to assess how well the reference years reflect the base data from which they were chosen, we can also examine the spread of the base set and

draw conclusions about the level of risk in terms of overheating and energy usage that the use of a reference year masks.

Climate Change

One of the reasons for completing this work is the question of climate change. By definition we do not have a record of future weather, and therefore files to allow the simulation of buildings under future climates must be obtained by other means. One method^{1,2} is by using mathematical transformations of current reference years, another is to use a weather generator to produce hourly results given knowledge of future climate typically expressed as monthly changes to the current climate³. This second method has the ability to produce a vast number of example years, which could either be used to produce one or more reference years, or a reasonably sized sub-set could be used to study a wide range of questions about the energy consumption and internal environment. Potentially such a sub-set, because it is drawn from a large number of years would include extreme years that would thereby allow one to address return periods for extreme events solving problem (iv) above).

Given the implied increase in computation time and cost, before such an approach could be justified there is the need to obtain a reasonable idea of how much of an advantage such multi-year runs offer over that of reference years. Much of this work has been completed within the reference of the UK's building regulations and the reference weather files used in the UK. However the method and results are general in nature and transferable to other locations outside the UK.

The Building Regulations

The UK's building regulations, like much legislation, start from a position of pragmatism. For overheating this means that (a) a certain amount is allowed, and (b) it is a computer model of the building that is assessed not the building itself. If occasional overheating were not allowed or the requirement was for the building to pass in use, then a particularly hot summer, or the later placing of a large amount of heat producing equipment in a building could be presented as a failure of the architecture.

Schools for example are allowed, when modelled, to overheat for 120 of the occupied hours over the summer period, where overheating is defined as an air temperature in excess of 28°C. There is also the need for the maximum temperature not to exceed 32°C and the mean internal/external temperature difference during occupied hours not to exceed 5°C during the summer period (strictly speaking meeting any two of these three requirements is enough for compliance). Although the choice of 28°C and 120 hours was based on some consideration of human psychology and thermal comfort, it was also known at the time that it was possible to design buildings that meet this requirement without the use of air conditioning in most spaces, or the use of expensive materials or construction techniques, for example one-metre thick stone walls. However, this doesn't mean that almost any architectural form or construction is likely to pass. Building regulations are also designed to encourage good practice and to meet other agendas such as sustainability. The corollary of this has been that computer simulations of designs often indicate a building will be perilously close to the overheating limits. This position begs the question, what is the likelihood that a building would breach similar requirements if it were modeled over a number of years?

Weather Files

The conditions within a building will depend on: the size and form of the design, including the size and position of the windows; the choice of materials and constructions; the number and density of internal heat gains, such as metabolic, lighting and computer equipment; the ventilation provided; the design of the heating and cooling system; and the weather the building is exposed to. As discussed above in modelling work the latter is represented by some form of standard weather files for a location near where the building will be sited. In the UK, either a Test Reference Year (TRY) or a Design Summer Year (DSY) is used, drawn from one of 14 locations. We have only examined two locations in this paper but the method of choosing the reference years from the base set remains the same and so the results obtained from the two locations chosen (Plymouth and Edinburgh) should be generally representative of all 14 locations when compared to their respective base data sets.

The TRY is composed of 12 separate months of data each chosen to be the most average month from 23 years of observed weather (1983 to 2005). The most average months were chosen based on the cumulative distribution functions of the daily mean values of three parameters: dry bulb temperature (DryT), global solar horizontal irradiation (GI_{Rad}) and wind speed (WS). The daily mean values were determined from the hourly values of each of the parameters for all the months in the years considered. The most average months are chosen using the Finkelstein-Schafer (FS) statistic to compare the cumulative distribution functions. The FS statistic compares the absolute difference between the values for each day in an individual month's cumulative distribution function and the overall cumulative distribution function for all the months considered. The months with the smallest FS statistic are chosen as the most average. The FS method is believed to be superior to just using means to choose the most average months as it selects months with less extreme values that have a cumulative distribution function closer to that of all the years considered. Hence, the average month chosen using the FS statistic could be considered representative of all the

years in the range observed. This process is followed for each month of the year (January, February, etc) for each parameter in turn for the whole base set of data.

The candidate, most average months for the TRY are chosen using the sum, FS_{sum} , from their minimum FS statistics, FS_{min} . This gives a weighted index for selection combining all three parameters (DryT, GlRad and WS)⁴.

$$\text{eqn. 1 } FS_{sum} = w_1 FS_{min}(\text{DryT}) + w_2 FS_{min}(\text{GlRad}) + w_3 FS_{min}(\text{WS})$$

where w_1 , w_2 and w_3 are weighting factors for each weather parameter. The weighting factors add up to unity and the exact values are chosen depending on each parameter's relative importance for the climate under consideration. Since the candidate month with the lowest FS_{min} for WS might not have the lowest FS_{min} for DryT the sum is taken and each candidate most average month is input into eqn. 1. The most average month is the one with the lowest FS_{sum} , and hence the most average for the three parameters considered. This is done for each month of the year in turn; hence the TRY is a composite year with the most average (lowest FS_{sum}) January, February etc chosen from all the 23 years considered. For the TRY files created for the UK a value of 1/3 was chosen for each weighting factor. For comparison the ASHRAE International Weather Years for Energy Calculations (IWECs) used nine different parameters, with different weightings dependant upon their relative importance. Since natural ventilation is possibly less common in North America and humidity is more important than in the UK the equal weightings for the CIBSE⁵ data were believed adequate for the UK, as natural ventilation, solar gain and fabric heat transmission were all considered equally important factors. However, it is difficult to justify the use of any particular weighting for the different parameters since different architectural designs will have different

sensitivities to each parameter, hence their relative importance varies and such sensitivities may change with a changing climate.

In order to create a TRY, the 12 most average months need to be combined. Often there is a mismatch in the parameters at the join between different months. The method used to overcome this discontinuity simply removes the middle four values for each parameter in the weather file between 21:00 on the last day of the month and 02:00 on the 1st day of the next month and replaces with a linear interpolation for 22:00, 23:00, 00:00 and 01:00.

In contrast to the relatively complex method of assembling a TRY, the method of selecting a DSY is very simple. The DSY is a single contiguous year rather than a composite one made up from average months. The CIBSE procedure for selecting a DSY is to calculate the daily mean DryT in the period April to September for each of the 23 years. The DSY is the year with the third hottest April to September period, i.e. a hot but non-extreme summer.

Further details on the creation and data selection procedures for the TRY and DSY data files can be found in a paper by Levermore and Parkinson⁴.

Method

The test reference and design summer years can easily be obtained from CIBSE for all fourteen locations, this is not so of the full set of years from which they are assembled, which we term the *base set* (or BS). We obtained the base set from the British Atmospheric Data Centre (BADC)⁶. Unfortunately these data contain many missing points and, as mentioned above, mathematical algorithms had to be produced to fill in missing values and to validate the data in line with the

methods used by Levermore⁴. This is common practice when compiling weather years as there are usually some gaps in the data. For small gaps in the data interpolation can generally be used to fill in the gaps, for larger gaps or where more than a certain amount of data is missing from a single month that month is discounted in the case of a TRY or the whole year is discounted in the case of a DSY. More details on methodology of compiling weather years can be found in Levermore⁴.

The impact of modelling using the full base set was compared to the use of a TRY and DSY for two locations in the UK (Plymouth and Edinburgh) by simulating 15 buildings. These buildings included a school, a typical house and two types of office all of varying construction. These buildings were studied to give a range of different building uses, internal gains, fenestration and ventilation. The range of building parameters and floor areas studied, along with the defining variable is shown in Table 1, with full details of constructions included in the appendix. All were designed to 2002 building regulations, use gas central heating and most are naturally ventilated. The buildings were modelled using a fully dynamic thermal simulation software (IES virtual environment), which models occupant behaviour such as opening of windows at set temperatures, and includes calculations of ventilation based upon wind pressure difference across the building and buoyancy effects.

Results

Figure 1 shows the results for one of the buildings (building 7: medium weight house) with respect to the DSY (1990) and base set data for Plymouth, this is a fairly typical result as seen when compared to the data shown in tables 2 and 3. Years that are absent in the figure such as 1991 contain large gaps in the data for one or more variables and hence are not included in the base set when choosing the DSY. We see that although the DSY is (by default) the 3rd warmest summer

externally, it is only the 5th hottest internally, as measured by mean internal temperature over the summer period. As shown in Figure 1 the difference is 0.4°C, which might seem little, however the difference between the warmest summer (in terms of mean external air temperature) in the base set and the coldest in the set is only 2.5°C with a standard deviation of 1.2°C. This failure of the DSY is an indication that the reference year method of testing a particular form of architecture is not always accurate and could lead to the construction of buildings that produce an internal environment that is both uncomfortable to inhabit and suffers from overheating possibly leading to larger cooling energy bills or costly refurbishments. The internal temperature in buildings is dependent on more than just the external air temperature and this reflected here in the fact that the DSY is not the 3rd warmest internally as it is externally. Figure 2 shows similar data to figure 1 but for Edinburgh and building 1 (heavy weight office). Here we see that again the DSY under estimates the internal conditions, the DSY (1997) produces the 4th warmest internal environment despite being 3rd warmest externally. Note that the BS for Edinburgh is larger than for Plymouth. There are several other years with very similar internal temperatures to the DSY (e.g. 1983, 1989) implying that the DSY while not intended to be an extreme year could be viewed as a typical year rather than a relatively warm one.

Figure 3 shows the level of thermal discomfort in terms of percentage of people dissatisfied (PPD) for all the non-airconditioned buildings studied in this paper. Shown is the maximum PPD generated by the BS data for each building, the 3rd highest PPD in the BS and the PPD generated by the DSY. The data shows that the DSY consistently underestimates the PPD experienced in each building, sometimes by a significant amount.

Table 2 presents summary statistics for all the buildings; mean heating energy is shown for the TRY, the mean of the BS and the range of values generated by the BS data (data shown is for

Plymouth). The mean and maximum internal temperatures are shown for the DSY, the 3rd warmest (internally) in the BS as well as the range of values exhibited by the BS. The hours of overheating (>28°C) for each building is also shown for the DSY, 3rd warmest (internally) in the BS and the maximum in the BS. Table 3 shows a breakdown of the monthly heating energy requirements for building 1 for the TRY and all the years in the base set for Edinburgh. Table 4 shows the rank orderings of the TRY and DSY within the BS in terms of heating energy use mean / max internal temperature. The data show that the TRY generates a figure for the heating energy use only a few percent different from that of the average of the BS values. However the TRY gives no indication of the range of possible values that are used to create the average, in some cases the maximum heating energy used by the BS is >40% greater than that predicted by the TRY. This is important since the BS gives an indication of the range of possible values whereas the TRY is just a single data point, this means that heating and energy requirements could be substantially under/oversized. The data also shows that the DSY is generally not the 3rd warmest year internally and produces results that are lower in terms of mean and maximum internal temperatures. While the differences in internal temperatures are small, the values generated for hours of overheating show a much larger variation. The DSY regularly underestimates the overheating within a building when compared to the 3rd warmest internally in the BS and the maximum amount of overheating generated by the BS can be triple that indicated by the DSY. Furthermore it was noted that when comparing occupied hours above 25°C during the summer term for one of the schools studied (building 10) that the DSY came 14th in the 19 available base years. In this case the DSY only had 19% of the overheating of the hottest year. Again, here the single snap shot of a warm year generated by the DSY fails to give an indication of the overheating risk of a particular building. Closing an office block or a school due to inadequate cooling provision can be far more costly than performing several thermal simulations.

The cooling energy used by the air-conditioned office building is shown in Table 5, from which we see that the DSY slightly overestimates the average total energy use of the cooling plant for the office block. In fact the DSY here is third in the BS in terms of the amount of total cooling energy used, which is the result which should be expected considering that the DSY is the 3rd warmest year (externally) in the BS. We also see that the peak load experienced by the cooling plant for the DSY is different to the extremal values for peak load from the BS. This could have implications for the sizing and efficiency of cooling plants within buildings, particularly if the plant is significantly oversized for the majority of the time.

Discussion

In this paper we have compared the conditions within a series of buildings modelled using a climatologically representative year against the posterior statistic of the same buildings modelled using the base data sets used to compile the reference year. We find that while the TRY allows rapid thermal modelling of building designs it is not always representative of the average energy use (compared to the average of the BS) and gives no indication of the expected range of energy usage for a particular form of architecture. We have also studied the DSY which is generally used to assess the whether a building design is likely to overheat or not. We find that the DSY year while the 3rd warmest in terms of average external temperatures over the summer period is typically not the 3rd warmest internally over the same period. As a result the DSY consistently underestimates the levels of overheating and thermal discomfort within the building. Using some statistics (in this case occupied hours over 28°C) for overheating the DSY produces a signal which is less than 1/3 of the maximum produced by the warmest year in the BS, and is ranked 14th within the BS. This underestimation of internal temperatures can lead to higher than expected levels of overheating in

newly constructed buildings, especially with the current trends towards a warmer climate, which then require costly remedial work or the addition of air-conditioning to solve the problem.

Therefore we conclude that the TRY in general does produce representative average data for a building in a given location, but there is a benefit in running simulations with the base set historical data to give an indication of the likely range of energy uses, this would allow for a more risk based analysis of likely energy usage and comfort levels.

We also conclude that the DSY generally underestimates the levels of human discomfort (PPD) as well as overheating risk. This is maybe due to the choice of using only one weather parameter to choose a DSY. It is clear from the data in figures 1 and 2 that it is not only external temperature that influences the internal environment of the building. In light of this perhaps a year chosen using more than one weather variable would provide better results, variables that seem most appropriate are cloud cover (and hence solar gains) and wind speed as low cloud cover and wind speed as these can have a profound effect on the internal environment, especially naturally ventilated buildings with large windows. Also given the trend of a warming climate is taking the 3rd warmest average summer over a period of 20-30 years the best way of estimating overheating? Perhaps using the warmest summer from that period and allowing slightly more generous building regulations would be a better way to perform overheating analysis. Or perhaps overheating analysis should only be performed with future weather files that incorporate the results of future estimates of climate change. Another option worth considering would require the creation of a composite year similar to the TRY rather than a single contiguous year. Since one could envisage overheating occurring during periods of high temperature, low cloud cover and low wind speeds a composite year with weightings similar to the TRY (i.e 1/3), made up of the 3rd most extreme months from the 20-30

period could be a viable option for a replacement for the DSU. However, if any of these were adopted current building regulations would have to be reviewed in light of this.

Appendix

Details of building designs used for thermal modeling:

Building 1: Heavy-Weight Office,

Floor areas = 876.00 m², Ext wall area = 702.00 m², glazed area = 66.00 m².

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m²K, SBEM thermal capacity 155.20 kJ/m²K.

Ceiling/floor:- carpet (0.01m), screed (0.05m), cast concrete (0.1m), cavity (0.25m), ceiling tile (0.01m). U-Value = 1.0687 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Internal walls:- plaster (0.013m), concrete block (0.1m), plaster (0.013m). U-Value = 1.9306 W/m²K, SBEM thermal capacity 83.06 kJ/m²K.

External walls:- Vermiculite Insulating block (0.0585m), EPS slab (0.117m), concrete block (dense) (0.1m), plaster (0.015m). U-Value = 0.1937 W/m²K, SBEM thermal capacity 210.57 kJ/m²K.

Flat Roof:- U-Value = 0.2497 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Glazing:- 4mm glass, 12mm cavity (argon), 4mm glass, 12mm cavity (argon), 4mm glass U-Value (including frame) = 1.2938 W/m²K

Building 2: Medium-Weight Office,

Floor areas = 876.00 m², Ext wall area = 702.00 m², glazed area = 66.00 m².

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m²K, SBEM thermal capacity 155.20 kJ/m²K.

Ceiling/floor:- carpet (0.01m), screed (0.05m), cast concrete (0.1m), cavity (0.25m), ceiling tile (0.01m). U-Value = 1.0687 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Internal walls:- plaster (0.013m), concrete block (0.1m), plaster (0.013m). U-Value = 1.9306 W/m²K, SBEM thermal capacity 83.06 kJ/m²K.

External walls:- Vermiculite Insulating block (0.0585m), EPS slab (0.117m), concrete block (medium) (0.1m), plaster (0.015m). U-Value = 0.1887 W/m²K, SBEM thermal capacity 135.07 kJ/m²K.

Flat Roof:- U-Value = 0.2497 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Glazing:- 4mm glass, 12mm cavity (argon), 4mm glass, 12mm cavity (argon), 4mm glass U-Value (including frame) = 1.2938 W/m²K

Building 3: Light-Weight Office,

Floor areas = 876.00 m², Ext wall area = 702.00 m², glazed area = 66.00 m².

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m²K, SBEM thermal capacity 155.20 kJ/m²K.

Ceiling/floor:- carpet (0.01m), screed (0.05m), cast concrete (0.1m), cavity (0.25m), ceiling tile (0.01m). U-Value = 1.0687 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Internal walls:- plaster (0.013m), cavity (0.1m), plaster (0.013m). U-Value = 1.6598 W/m²K, SBEM thermal capacity 10.37 kJ/m²K.

External walls:- Vermiculite Insulating block (0.0585m), EPS slab (0.117m), concrete block (light weight) (0.1m), plaster (0.015m). U-Value = 0.1777 W/m²K, SBEM thermal capacity 66.07 kJ/m²K.

Flat Roof:- U-Value = 0.2497 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Glazing:- 4mm glass, 12mm cavity (argon), 4mm glass, 12mm cavity (argon), 4mm glass U-Value (including frame) = 1.2938 W/m²K

Building 4: Mechanically Ventilated Office,

Floor areas = 876.00 m², Ext wall area = 702.00 m², glazed area = 66.00 m².

As Building 1.

Building 5: Buoyancy Driven Ventilated Offices,

As Building 1.

Building 6: Heavy-Weight New Build House

Floor areas = 135.29 m², Ext wall area = 178.56 m², glazed area = 11.98 m².

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m²K, SBEM thermal capacity 155.20 kJ/m²K.

Ceiling/floor:- carpet (0.01m), cast concrete (0.1m). U-Value = 2.2826 W/m²K, SBEM thermal capacity 97.02 kJ/m²K.

Internal walls:- plaster (0.013m), concrete block (0.1m), plaster (0.013m). U-Value = 1.9306 W/m²K, SBEM thermal capacity 83.06 kJ/m²K.

External walls:- brickwork (0.1m), EPS slab (0.0625m), concrete block (dense) (0.1m), plaster (0.015m). U-Value = 0.3465 W/m²K, SBEM thermal capacity 210.57 kJ/m²K.

Flat Roof:- U-Value = 0.2497 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Glazing:- 4mm glass, 12mm cavity (argon), 4mm glass, U-Value (including frame) = 1.6453 W/m²K

Building 7: Medium-Weight New Build House

Floor areas = 135.29 m², Ext wall area = 178.56 m², glazed area = 11.98 m²

Ground floor:- soil (0.75m), brickwork (outer leaf), cast concrete (0.1m), EPS slab (0.0635m), chipboard (0.025m), carpet (0.01m). U-Value = 0.2499 W/m²K

Ceiling/floor:- carpet (0.01m), chipboard (0.025m), cavity (0.25m), plasterboard (0.013m). U-Value = 1.2585 W/m²K

Internal walls:- plasterboard (0.013m), cavity (0.1m), plasterboard (0.013m). U-Value = 1.6598 W/m²K

External walls:- brickwork (0.1m), EPS slab (0.0585m), concrete block (0.1m), plaster (0.015m). U-Value = 0.3495 W/m²K

Flat Roof:- U-Value = 0.2497 W/m²K

Glazing:- 6mm glass, 12mm cavity, 6mm glass, U-Value (including frame) = 1.9773 W/m²K

Building 8: Light-weight New Build House

Floor areas = 135.29 m², Ext wall area = 178.56 m², glazed area = 11.98 m².

Ground floor:- soil (0.75m), brickwork (outer leaf), cast concrete (0.1m), EPS slab (0.0635m), chipboard (0.025m), carpet (0.01m). U-Value = 0.2499 W/m²K, SBEM thermal capacity 45.86 kJ/m²K.

Ceiling/floor:- carpet (0.01m), chipboard (0.025m), cavity (0.25m), plasterboard (0.013m). U-Value = 1.2585 W/m²K, SBEM thermal capacity 10.37 kJ/m²K.

Internal walls:- plasterboard (0.013m), cavity (0.1m), plasterboard (0.013m). U-Value = 1.6598 W/m²K, SBEM thermal capacity 10.37 kJ/m²K.

External walls:- timber board (0.025m), cavity (0.09m), plywood (0.01m), mineral wool (0.075m), cavity (0.06m), plasterboard (0.013m). U-Value = 0.3364 W/m²K, SBEM thermal capacity 10.37 kJ/m²K.

Flat Roof:- U-Value = 0.2497 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Glazing:- 4mm glass, 12mm cavity (argon), 4mm glass, U-Value (including frame) = 1.6453 W/m²K

Building 9: School - Big Windows.

Floor areas = 2813.65 m², Ext wall area = 2275.87 m², glazed area = 941.23 m². (openable area 10%)

Ground floor:- soil (0.75m), EPS slab (0.09m), cast concrete (0.1m). U-Value = 0.2455 W/m²K, SBEM thermal capacity 200.00 kJ/m²K.

Ceiling/floor:- cast concrete (0.2m). U-Value = 2.9167 W/m²K, SBEM thermal capacity 176.40 kJ/m²K.

Internal walls:- concrete block (0.215m) U-Value = 2.5517 W/m²K, SBEM thermal capacity 230.00 kJ/m²K.

External walls:- EPS slab (0.058m), concrete block (dense) (0.215m), U-Value = 0.3435 W/m²K, SBEM thermal capacity 140.00 kJ/m²K.

Flat Roof:- U-Value = 0.2324 W/m²K, SBEM thermal capacity 176.40 kJ/m²K.

Glazing:- 6mm glass, 16mm cavity, 6mm glass, U-Value (including frame) = 2.1739 W/m²K

Building 10: School – Large Opening Big Windows.

Floor areas = 2813.65 m², Ext wall area = 2275.87 m², glazed area = 941.23 m². (openable area 40%)

As Building 9.

Building 11: School – Small Windows.

Floor areas = 2813.65 m², Ext wall area = 2275.87 m², glazed area = 299.74 m². (openable area 10%)

As Building 9.

Building 12: Light-Weight Studio Flats:

9 studio flats and adjoining corridor, Floor areas = 1170.00 m², Ext wall area = 619.20 m², glazed area = 54.00m².

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m²K, SBEM thermal capacity 155.20 kJ/m²K.

Ceiling/floor:- carpet (0.01m), cast concrete (0.1m). U-Value = 2.2826 W/m²K, SBEM thermal capacity 97.02 kJ/m²K.

Internal walls:- plasterboard (0.013m), cavity (0.1m), plasterboard (0.013m). U-Value = 1.6598 W/m²K, SBEM thermal capacity 10.37 kJ/m²K.

External walls:- timber board (0.025m), cavity (0.09m), plywood (0.01m), mineral wool (0.075m), cavity (0.06m), plasterboard (0.013m). U-Value = 0.3364 W/m²K, SBEM thermal capacity 10.37 kJ/m²K.

W/m²K Flat Roof:- U-Value = 0.2497 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Glazing:- 6mm glass, 12mm cavity, 6mm glass, U-Value (including frame) = 2.0713 W/m²K

Building 13: Medium-Weight Studio Flats:

9 studio flats and adjoining corridor, Floor areas = 1170.00 m², Ext wall area = 619.20 m², glazed area = 54.00m².

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m²K, SBEM thermal capacity 155.20 kJ/m²K.

Ceiling/floor:- carpet (0.01m), cast concrete (0.1m). U-Value = 2.2826 W/m²K, SBEM thermal capacity 97.02 kJ/m²K.

Internal walls:- plasterboard (0.013m), cavity (0.1m), plasterboard (0.013m). U-Value = 1.6598 W/m²K

External walls:- brickwork (0.1m), EPS slab (0.0585m), concrete block (0.1m), plaster (0.015m). U-Value = 0.3495 W/m²K

Flat Roof:- U-Value = 0.2497 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Glazing:- 6mm glass, 12mm cavity, 6mm glass, U-Value (including frame) = 2.0713 W/m²K

Building 14: Heavy-Weight Studio Flats:

9 studio flats and adjoining corridor, Floor areas = 1170.00 m², Ext wall area = 619.20 m², glazed area = 54.00m².

Ground floor:- soil (0.75m), stone chippings (0.15m), EPS slab (0.075m), cast concrete (0.15m), screed (0.01m), carpet (0.01m). U-Value = 0.2383 W/m²K, SBEM thermal capacity 155.20 kJ/m²K.

Ceiling/floor:- carpet (0.01m), cast concrete (0.1m). U-Value = 2.2826 W/m²K, SBEM thermal capacity 97.02 kJ/m²K.

Internal walls:- plaster (0.013m), concrete block (0.1m), plaster (0.013m). U-Value = 1.9306 W/m²K, SBEM thermal capacity 83.06 kJ/m²K.

External walls:- brickwork (0.1m), EPS slab (0.0625m), concrete block (dense) (0.1m), plaster (0.015m). U-Value = 0.3465 W/m²K, SBEM thermal capacity 210.57 kJ/m²K.

Flat Roof:- U-Value = 0.2497 W/m²K, SBEM thermal capacity 3.80 kJ/m²K.

Glazing:- 6mm glass, 12mm cavity, 6mm glass, U-Value (including frame) = 2.0713 W/m²K

Building 15: Air Conditioned Office,

Floor areas = 876.00 m², Ext wall area = 702.00 m², glazed area = 66.00 m².

As building 1.

Other Details:

Heating set points: Buildings 1-5 22°C, Buildings 6-8, 12-14 18°C, Buildings 9-11 18°C, Building 15 19°C

Window opening temperature: Buildings 1-3 22°C, Building 5 23°C, Buildings 6-8, 12-14 21°C Buildings 9-11 26°C

Mechanical ventilation rate: Building 4, 2 ach⁻¹ from external air supply. Building 15, 1 ach⁻¹ from air-conditioning.

Cooling set point: Building 15 21°C.

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Table 1. Building type, building parameters and floor areas studied. All buildings were considered for both Edinburgh and Plymouth. Details of the constructions used can be found in the appendix.

| Building | Building type | Floor area (m²) | Defining variable |
|-----------------|----------------------|-----------------------------------|-----------------------------|
| 1 | Office | 876 | Heavy weight construction |
| 2 | Office | 876 | Medium weight construction |
| 3 | Office | 876 | Light weight construction |
| 4 | Office | 876 | Mechanically ventilated |
| 5 | Office | 670 | Buoyancy driven ventilation |
| 6 | House | 135 | Heavy weight construction |
| 7 | House | 135 | Medium weight construction |
| 8 | House | 135 | Light weight construction |
| 9 | School | 2814 | Big windows |
| 10 | School | 2814 | Larger opening big windows |
| 11 | School | 2814 | Small windows |
| 12 | Studio Flats | 1170 | Light weight construction |
| 13 | Studio Flats | 1170 | Medium weight construction |
| 14 | Studio Flats | 1170 | Heavy weight construction |
| 15 | Office | 876 | Air conditioned |

Table 2. Results. (Diff. = difference in percent). Data shown is for Plymouth.

| Building | Mean annual heating energy use, MWh | | | Min / max energy use, MWh | Internal Mean T (°C) (Dry Bulb) | | | Internal Max T (°C) (Dry Bulb) | | | Occupied Hours over 28°C | | |
|----------|-------------------------------------|-------|---------|---------------------------|---------------------------------|-----------------------|---------------|--------------------------------|-----------------------|---------------|--------------------------|-----------------------|-----|
| | TRY | BS | Diff. % | BS | DSY | 3 rd in BS | Min / Max | DSY | 3 rd in BS | Min / Max | DSY | 3 rd in BS | Max |
| 1 | 191 | 195 | -2 | 173 / 253 | 23.67 | 24.11 | 22.99 / 24.18 | 31.22 | 31.50 | 26.21 / 31.82 | 37 | 71 | 113 |
| 2 | 213 | 216 | -2 | 192 / 276 | 23.73 | 24.17 | 23.02 / 24.24 | 31.87 | 32.04 | 26.72 / 32.51 | 48 | 83 | 113 |
| 3 | 236 | 239 | -1 | 212 / 303 | 23.57 | 24.00 | 22.86 / 24.07 | 32.57 | 32.66 | 27.34 / 33.45 | 60 | 97 | 147 |
| 4 | 32.3 | 34.8 | -8 | 24.6 / 47.1 | 24.10 | 24.20 | 22.25 / 24.78 | 33.26 | 33.26 | 28.04 / 33.47 | 267 | 427 | 441 |
| 5 | 665 | 640 | 4 | 556 / 727 | 19.20 | 19.27 | 18.15 / 19.53 | 31.05 | 30.69 | 25.56 / 31.57 | 16 | 16 | 21 |
| 6 | 8.91 | 9.07 | -2 | 7.23 / 10.4 | 20.40 | 20.54 | 19.90 / 20.62 | 26.00 | 26.00 | 22.44 / 26.67 | 0 | 0 | 0 |
| 7 | 26.7 | 26.7 | 0 | 19.9 / 37.2 | 20.49 | 20.81 | 20.02 / 20.90 | 28.50 | 28.50 | 23.78 / 28.79 | 3 | 3 | 4 |
| 8 | 28.0 | 31.2 | -11 | 23.2 / 40.3 | 20.46 | 20.76 | 19.83 / 20.82 | 30.28 | 30.28 | 25.28 / 31.21 | 20 | 20 | 37 |
| 9 | 71.8 | 70.9 | 1 | 56.4 / 85.8 | 24.17 | 24.17 | 22.17 / 24.39 | 31.27 | 31.88 | 28.01 / 32.15 | 30 | 30 | 56 |
| 10 | 74.4 | 73.6 | 1 | 58.8 / 89.3 | 23.66 | 23.66 | 21.90 / 23.84 | 30.48 | 31.02 | 27.50 / 31.41 | 28 | 37 | 52 |
| 11 | 62.1 | 64.3 | -4 | 48.3 / 81.5 | 21.99 | 21.99 | 20.25 / 22.26 | 29.25 | 29.04 | 24.42 / 29.80 | 7 | 7 | 13 |
| 12 | 40.2 | 41.0 | -2 | 32.7 / 49.2 | 19.09 | 19.32 | 18.57 / 19.48 | 25.89 | 25.89 | 21.83 / 26.25 | 0 | 20 | 0 |
| 13 | 36.06 | 37.00 | -3 | 28.96 / 44.49 | 19.18 | 19.40 | 18.65 / 19.59 | 25.19 | 25.09 | 21.40 / 25.54 | 0 | 0 | 0 |
| 14 | 51.68 | 53.16 | -3 | 42.87 / 64.13 | 18.97 | 19.18 | 18.36 / 19.40 | 23.97 | 23.92 | 20.77 / 24.21 | 0 | 0 | 0 |

Table 3 Table of monthly heating energy usage for building 1 for the TRY and all the base set years. Data shown is for Edinburgh.

| | | | | | | | | | | | | | | |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Date | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 |
| Jan | 32.96 | 38.40 | 30.28 | 29.44 | 33.10 | 37.17 | 37.90 | 31.82 | 34.31 | 33.83 | 28.78 | 25.39 | 27.34 | 31.62 |
| Feb | 29.49 | 34.25 | 21.60 | 28.92 | 25.43 | 30.55 | 25.60 | 28.76 | 32.97 | 24.96 | 28.53 | 29.60 | 31.14 | 27.43 |
| Mar | 30.54 | 43.06 | 28.55 | 25.16 | 31.75 | 27.46 | 27.47 | 26.28 | 32.23 | 28.82 | 28.05 | 28.93 | 31.56 | 21.91 |
| Apr | 24.03 | 25.80 | 16.72 | 20.17 | 17.78 | 22.29 | 20.06 | 22.37 | 28.59 | 16.54 | 18.34 | 21.69 | 22.79 | 25.33 |
| May | 12.69 | 16.73 | 12.94 | 10.64 | 15.48 | 16.12 | 12.68 | 14.48 | 21.69 | 15.59 | 12.32 | 10.70 | 8.16 | 12.12 |
| Jun | 8.97 | 8.80 | 6.29 | 8.29 | 9.56 | 10.23 | 7.01 | 8.80 | 9.13 | 8.64 | 4.45 | 5.08 | 4.80 | 8.32 |
| Jul | 6.50 | 5.25 | 3.67 | 3.75 | 2.20 | 2.54 | 0.74 | 5.58 | 5.10 | 3.17 | 4.78 | 1.38 | 3.86 | 2.68 |
| Aug | 3.36 | 4.06 | 3.15 | 1.97 | 7.34 | 1.14 | 1.98 | 6.50 | 7.31 | 2.95 | 3.81 | 4.17 | 3.03 | 2.52 |
| Sep | 13.35 | 12.13 | 7.81 | 7.50 | 9.64 | 11.68 | 8.65 | 10.78 | 11.74 | 9.93 | 9.76 | 7.92 | 9.50 | 9.18 |
| Oct | 13.64 | 13.01 | 20.79 | 22.77 | 16.76 | 22.38 | 16.70 | 11.63 | 17.42 | 16.36 | 16.46 | 13.19 | 15.28 | 18.36 |
| Nov | 26.95 | 27.51 | 26.62 | 26.15 | 27.20 | 18.72 | 21.96 | 25.89 | 26.22 | 20.76 | 20.92 | 21.50 | 21.98 | 26.91 |
| Dec | 32.48 | 29.36 | 30.72 | 37.07 | 30.56 | 25.25 | 24.63 | 24.96 | 27.79 | 23.77 | 23.98 | 28.26 | 29.28 | 28.04 |
| Total | 234.96 | 258.37 | 209.13 | 221.82 | 226.82 | 225.52 | 205.40 | 217.85 | 254.48 | 205.31 | 200.18 | 197.80 | 208.71 | 214.42 |
| | | | | | | | | | | | | | | |
| Date | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | TRY |
| Jan | 28.98 | 34.91 | 33.86 | 32.95 | 28.94 | 25.06 | 25.04 | 28.43 | 31.14 | 29.44 | 29.58 | 31.13 | 26.64 | 29.12 |
| Feb | 25.85 | 23.74 | 29.31 | 29.16 | 30.26 | 30.95 | 24.49 | 28.87 | 29.67 | 27.28 | 27.95 | 26.19 | 23.74 | 24.88 |
| Mar | 29.07 | 30.73 | 38.16 | 32.77 | 28.05 | 25.71 | 22.97 | 22.82 | 24.46 | 30.07 | 27.39 | 20.26 | 24.46 | 25.16 |
| Apr | 24.04 | 18.16 | 23.97 | 20.64 | 18.83 | 16.78 | 23.39 | 18.90 | 19.79 | 20.09 | 17.93 | 16.33 | 16.72 | 22.50 |
| May | 15.72 | 19.50 | 20.64 | 12.23 | 18.65 | 15.55 | 13.80 | 16.51 | 12.19 | 8.85 | 12.42 | 11.85 | 7.90 | 15.45 |
| Jun | 4.26 | 7.77 | 10.62 | 4.79 | 5.74 | 7.55 | 8.24 | 5.96 | 7.64 | 8.69 | 7.45 | 2.52 | 4.72 | 5.97 |
| Jul | 4.06 | 5.80 | 1.28 | 2.35 | 2.60 | 1.77 | 4.35 | 2.49 | 2.37 | 2.35 | 2.46 | 0.59 | 2.61 | 2.63 |
| Aug | 6.14 | 4.05 | 3.66 | 0.84 | 0.70 | 0.84 | 4.58 | 3.74 | 0.96 | 1.31 | 0.79 | 1.11 | 1.41 | 3.18 |
| Sep | 11.72 | 9.85 | 10.25 | 7.67 | 6.29 | 7.33 | 5.48 | 3.62 | 4.63 | 7.18 | 3.23 | 4.33 | 8.18 | 9.52 |
| Oct | 18.05 | 17.94 | 13.84 | 11.98 | 13.55 | 13.86 | 19.89 | 13.93 | 17.05 | 10.76 | 16.63 | 15.68 | 16.96 | 16.52 |
| Nov | 25.28 | 24.45 | 15.89 | 20.99 | 27.96 | 16.23 | 23.26 | 22.47 | 23.26 | 21.93 | 18.44 | 18.98 | 20.96 | 23.32 |
| Dec | 27.74 | 31.03 | 27.08 | 29.00 | 27.77 | 24.77 | 23.60 | 30.88 | 27.82 | 28.34 | 23.97 | 26.57 | 28.22 | 29.27 |
| Total | 220.92 | 227.94 | 228.55 | 205.36 | 209.34 | 186.40 | 199.07 | 198.61 | 200.98 | 196.30 | 188.23 | 175.53 | 182.54 | 207.52 |

Table 4. Rank orderings in energy use (of TRY) or mean, or maximum temperatures (of DSY) within the base set (19 complete years). Data shown is for Plymouth.

| Building | Heating energy use | Mean internal temp. | Max internal temp. |
|----------|--------------------|---------------------|--------------------|
| 1 | 12 th | 5 th | 4 th |
| 2 | 12 th | 5 th | 4 th |
| 3 | 11 th | 5 th | 4 th |
| 4 | 12 th | 4 th | 3 rd |
| 5 | 7 th | 4 th | 2 nd |
| 6 | 14 th | 5 th | 3 rd |
| 7 | 10 th | 5 th | 3 rd |
| 8 | 15 th | 5 th | 3 rd |
| 9 | 9 th | 3 rd | 5 th |
| 10 | 9 th | 3 rd | 5 th |
| 11 | 10 th | 3 rd | 2 nd |
| 12 | 8 th | 6 th | 3 rd |
| 13 | 10 th | 4 th | 2 nd |
| 14 | 10 th | 6 th | 2 nd |

Table 5. Total cooling energy used (MWh) by the air-conditioned office block (building 15) and peak cooling energy load (kW) of the DSY compared to values generated by the BS data. Data shown is for Plymouth.

| DSY (MWh) | Average of BS (MWh) | Range (MWh) | DSY (kW) | Range (kW) |
|-----------|---------------------|---------------|----------|---------------|
| 18.66 | 16.32 | 13.21 / 19.90 | 18.62 | 13.29 / 19.24 |

Figure 1. Mean internal and external summertime temperatures for typical new build house (building 7 in Table 1). Although the DSY is the 3rd hottest in terms of external mean temperature, it is only the 5th hottest in terms of the internal mean temperature. Years that are absent (eg. 1991) contain large gaps in one or more variables and were not included in the base set when choosing the DSY.

Figure 2. Mean internal and external summertime temperatures for an office building (building 1 in Table 1). Although the DSY is the 3rd hottest in terms of external mean temperature, it is only the 4th hottest in terms of the internal mean temperature.

Figure 3. Plot showing percentage of people dissatisfied (PPD) for each of the non-airconditioned buildings studied, showing maximum PPD, the 3rd highest PPD in the base set and the PPD generated by the DSY.