

## AN INVESTIGATION INTO THE ROLE OF THERMAL MASS ON THE ACCURACY OF CO-HEATING TESTS THROUGH SIMULATIONS & FIELD RESULTS

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### ABSTRACT

To successfully meet emissions targets and reduce energy demand in the built environment, high targets have been set for building fabric performance. However, field measurements to date have indicated that the measured as-built fabric heat loss of tested UK buildings is consistently and sometimes considerably higher than design values. Many of these results stem from co-heating tests – an in situ measurement of the heat loss across the entire building envelope. Widespread implementation of the co-heating method is however restricted due to its invasive nature, long testing duration and uncertainty in the result. The test's reliability and accuracy are embedded in the available mix of weather and in the tested building's characteristics. This paper presents the results of both simulated and field co-heating tests, showing how changing external temperatures and high incident solar radiation interact with the thermal mass and glazing characteristics of a dwelling and can reduce the accuracy of the test and often lead to systematic underestimation of heat loss.

### INTRODUCTION

Space heating accounts for 60% of domestic energy use, which itself makes up around a quarter of final UK energy consumption. (DUKES, 2011). As such to reach binding emission targets the UK government must reduce this demand and has declared that all new homes should be 'Zero Carbon' by 2016 (Zero Carbon Hub, 2010). To tackle the extensive existing stock the Green Deal has been launched to encourage a deeper and more extensive retrofit programme. Whilst large reductions are technically feasible, ensuring they are achieved in practice is more difficult. A so-called performance gap, between designed and actual performance, has raised its head and could undermine reduction strategies. Understanding building performance in practice is therefore crucial to informing strategy and controlling quality.

The performance gap can result from issues regarding the fabric performance, from heating system underperformance, from occupant behaviour and combinations of the three. Assessing or disentangling these is a difficult proposition, such that they are often evaluated in isolation. The performance of the building fabric can be examined

using a small selection of post-construction testing tools. Whilst building elements can be tested individually in a lab, it remains important to test in the field, in situ, to derive a full picture of performance in real conditions and as a result of the full construction process.

In its role as a post-construction tool infrared thermography allows areas of heat loss to be visually identified on site and can therefore be used to diagnose many problems present in the building fabric. The qualitative nature of this tool does however limit its application and use, as do the requirements for suitable weather and the skill and experience of the user.

Point in situ u-value measurements can be made fairly unobtrusively using heat flux sensors (EN ISO 9896, 1994). This measurement suffers from its own uncertainties but perhaps its strongest limitation is the small sensor measurement area, and the consequent difficulty in accurately measuring variations in heat flow across the fabric and in characterising areas of complex geometry.

These more complex heat loss mechanisms and the variations in the fabric due to the 'buildability' of the structure are of key practical importance so they need to be captured. Co-heating is an in situ measurement tool that measures the heat loss across the entire fabric, in a quantity known as the heat loss coefficient (*HLC*). At its simplest, this is achieved by holding the test dwelling at a constant internal temperature and measuring all heat inputs.

Despite being theoretically relatively undeveloped, in situ measurements have yielded considerable evidence that a performance gap, in the building fabric, does exist. Of 34 co-heating tests conducted by Leeds Metropolitan University under the co-heating method, over 60% have had measured heat losses more than 20% higher than design with nearly half over 50% worse (Stafford et al., 2012). Amongst further examples, Doran (2011) reports an average in situ measured u-value for cavity walls 30% higher than predicted.

Calls have been made that reduction targets need to be met not only in theory but also in practice. The Zero Carbon Hub has recently recommended that 95% of new buildings should perform as well, or better than, design by 2020 (ZCH, 2011). For this

target to be realised, robust and appropriate tools are needed to provide quality assurance and feedback on designs, materials, construction methods and processes.

### THE CO-HEATING METHOD

The co-heating method dates back to work at a number of locations in the late 1970s and early 1980s including at the US Solar Energy Research Institute (Balcombe, 1992), and at ECRC in the UK (Siviour 1981). The method was explored and developed by Subbarao et al., (1988) and Everett (1988). In the UK, sporadic use of the method through the 1990s (e.g. Bell & Lowe, 1996) was followed by an intense period of activity at Leeds Metropolitan University, which resulted in the development of the current UK experimental guidelines (Wingfield et al., 2010).

The co-heating method is based on an energy balance at an approximated steady state, approximated because the internal conditions cannot be held precisely constant and the external conditions will vary, subject to the actual weather during the test. The test building is held at a constant internal temperature, in the UK typically 25°C, through the use of electric fan heaters and mixing fans. Heat input to electrical equipment is recorded through the use of kilowatt-hour meters and uncontrolled heat input from solar radiation is measured via a local pyranometer. Regressions, either with heating power,  $Q$ , and  $\Delta T$ , or multiple regressions which also include solar radiation,  $S$ , are used to evaluate the building heat loss coefficient and solar aperture,  $R$ , see equation 1.

The key numerical output from the co-heating tests is the heat loss coefficient  $HLC$  in units of W/K. The  $HLC$  is a measure of the total heat loss across the envelope in relation to external air temperature, incorporating conduction, ventilation and radiation losses. The second output is the solar aperture,  $R$ , a measure of the conversion of local solar radiation into effective solar gains inside the dwelling.  $R$  can also be estimated by calculation from the building's glazing characteristics, although this can introduce further uncertainties based on these assumed characteristics.

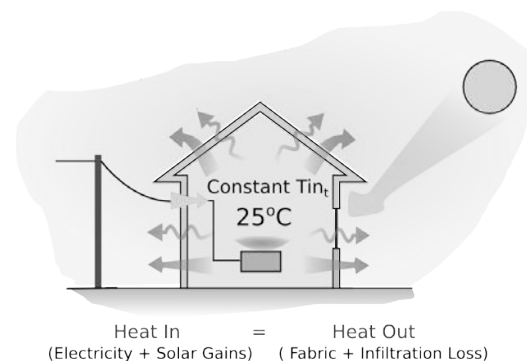


Figure 1 The co-heating principal

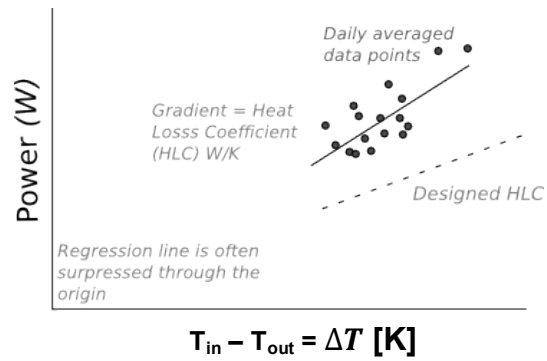


Figure 2 An example of co-heating analysis

$$Q + R.S = HLC \cdot \Delta T \quad (1)$$

Three major limitations in the co-heating method have restricted its application to date:

- For this method to work, the test dwelling needs to remain sealed and unoccupied during the test.
- Daily averaging is needed in an attempt to smooth over dynamic effects throughout the course of the day. The independence of data points for successive days does not always hold true, and is a key source of uncertainty, as is shown in this paper.
- The results of the method turn out to be highly weather dependent. A suitable range of  $\Delta T$  and hence in external temperatures, and solar radiation is needed to perform the regression analysis and accurately determine the heat loss coefficient and solar aperture.

These three factors all result in a typical test duration 2-3 weeks during a testing season of October to March. However, even with such long testing periods an accurate result is not guaranteed and importantly the uncertainty in a given result is not well understood or easily defined.

This has led to the limited use of the co-heating method with only approximately 100 tests carried out in the UK to date. There are good examples how co-heating and additional evaluation tools can improve both our fundamental understanding of building heat loss (Lowe, 2007), and also provide effective feedback to developers to improve actual performance (Wingfield et al., 2011; Miles-Shenton et al., 2011). However, to perform post-construction evaluation on the scale needed to ensure 2050 and intermediate emissions targets are met within the built environment this type of testing method needs to become much more applicable and reliable.

### RESEARCH METHOD

Only a limited number of co-heating tests have been performed to date and the data from these is rarely

available publically. The use of real co-heating data to evaluate the method and its uncertainties is also limited as one data set will only give an indication for that particular dwelling, under the weather conditions experienced under that particular test. Whilst prolonged co-heating data can be useful, simulated co-heating tests allow a much more rapid and extensive evaluation of the reliability across a wider range of conditions and building types. Therefore, the method adopted here is to use simulated co-heating tests whilst changing the thermal mass of the building. Crucially, simulation allows the test procedure to be exposed to simulated measurement uncertainties with precisely known statistical characteristics. The aim of this paper is to explore the impacts on estimates of *HLC* from interactions between weather and thermal mass.

Simulated co-heating tests were performed in Energy Plus software where a constant 25°C was maintained inside the dwelling following the co-heating field method. An advantage of the simulated method is that the parameters we wish to extract from the test, i.e. the heat loss coefficient, are inputs into the building model so are therefore known. This makes gauging uncertainty and error easier in comparison to field tests where the as-built state is impossible to know precisely. A typical Gatwick, UK, weather file (London Gatwick 037760 IWEC) was used in the simulations in which a simple detached house was modelled, with two floors, glazing on the north and south facades and an unheated attic, figure 3.



Figure 3 Test house used in simulations and field work. Construction materials are changed but the basic building form remains the same in all cases.

This paper specifically focuses on the effect on the co-heating test of varying external temperatures and solar radiation, and their interaction with the thermal mass of the test building. These are key sources of uncertainty in the co-heating method but little is yet understood of their direct effects. Using the simulation framework, co-heating tests are explored

whilst changing the construction of the test dwelling. For example, the results and uncertainty generated in simulated co-heating tests on a lightweight construction can be compared to those of a heavyweight construction under the same weather conditions.

The test house in figure 3 is based upon a test house upon which prolonged real co-heating tests were performed (NHBC Co-heating Steering Group Project, 2012). This large dataset allows the effects seen in the simulated co-heating tests to be compared to real data. This house, built to Swedish standards in 1995, is externally brick clad with an internal timber frame – corresponding closest to the external heavyweight, internal lightweight simulated test set-up.

### EFFECT OF THE THERMAL MASS OF THE TEST DWELLING

The effect of the building's thermal mass was explored by varying the *external mass* (material outside the insulation layer) and *internal mass* (material inside insulation layer, including partition walls) whilst the building form remained constant. Heavyweight and lightweight options for external and internal mass create four combinations of construction, which were all tested under identical weather conditions.

Heavyweight and lightweight wall constructions were based upon 2010 UK Building Regulation notional *lightweight* (cladding-insulation-plaster) and *heavyweight* (brick-insulation-block) constructions. Whilst the mass of the walls was changed the U-value was maintained at the same level so the overall heat loss and *HLC* were not altered. Fully heavy and lightweight options precisely followed these constructions whilst the heavy and lightweight mixes adopted appropriate hybrids of the two. The internal partition wall construction also changed between lightweight (plasterboard-air-plasterboard) to heavyweight (plaster-brick-plaster) structures, coming under the internal mass label.

Four histograms, one for each possible construction, are shown in figure 4. These display the derived heat loss coefficient from simulated two-week co-heating tests across the entire UK testing season (October-March). As may be expected the distribution of the fully lightweight construction is tighter around the true 70 W/K *HLC* when compared to the fully heavyweight combination. The heavyweight construction is more dispersed but also shows a trend to occasionally underestimate the *HLC*. The hybrid combinations show a similar trend to underestimate the *HLC*. Comparing the two hybrid combinations it appears in this case that the internal thermal mass has a stronger effect than the external mass.

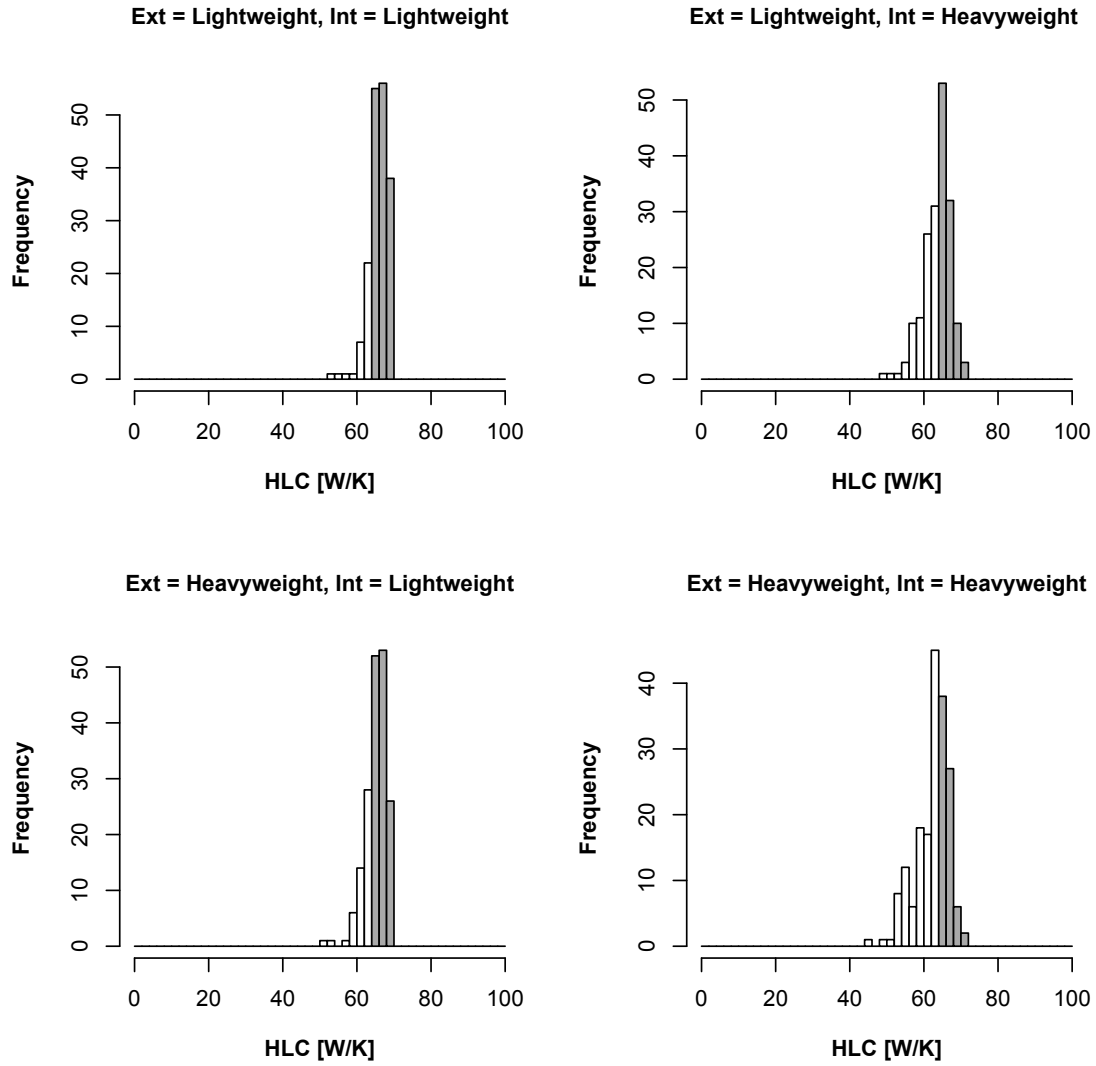
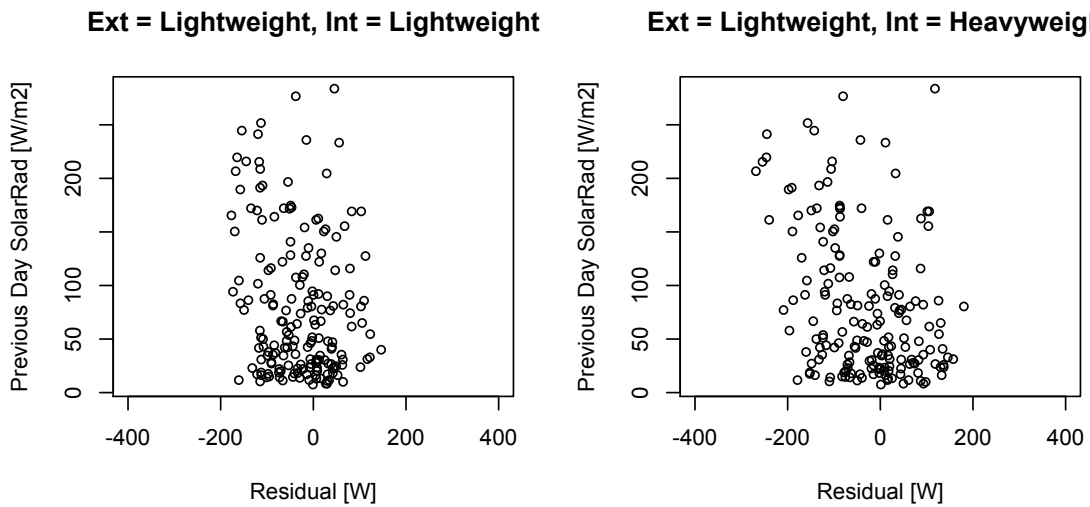


Figure 4 Histograms of derived HLC from simulated co-heating tests, throughout the testing season, on four construction types. Note the solid bars represent results within +/- 10% of the true value.



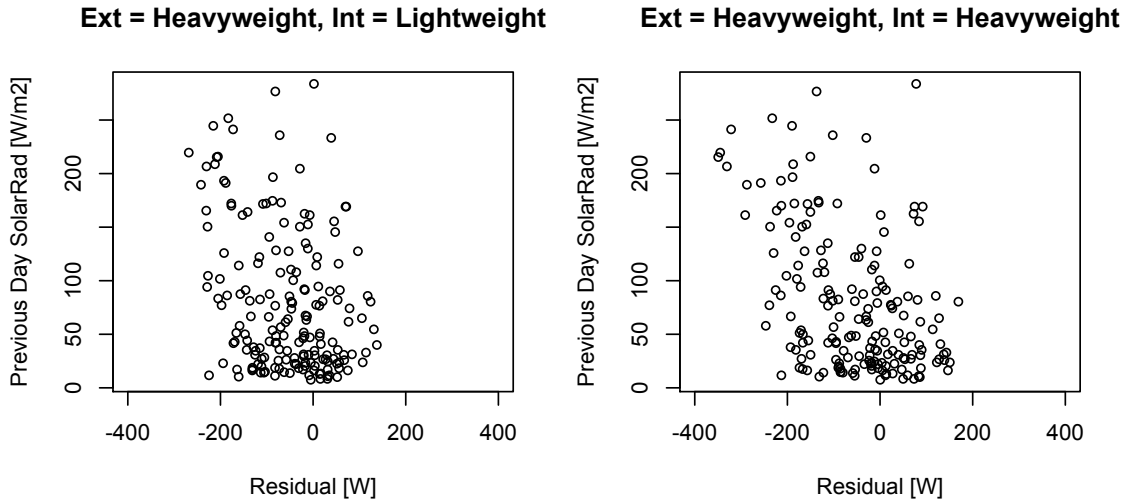


Figure 5 Plots of previous day solar radiation vs. residual power for the four construction types.

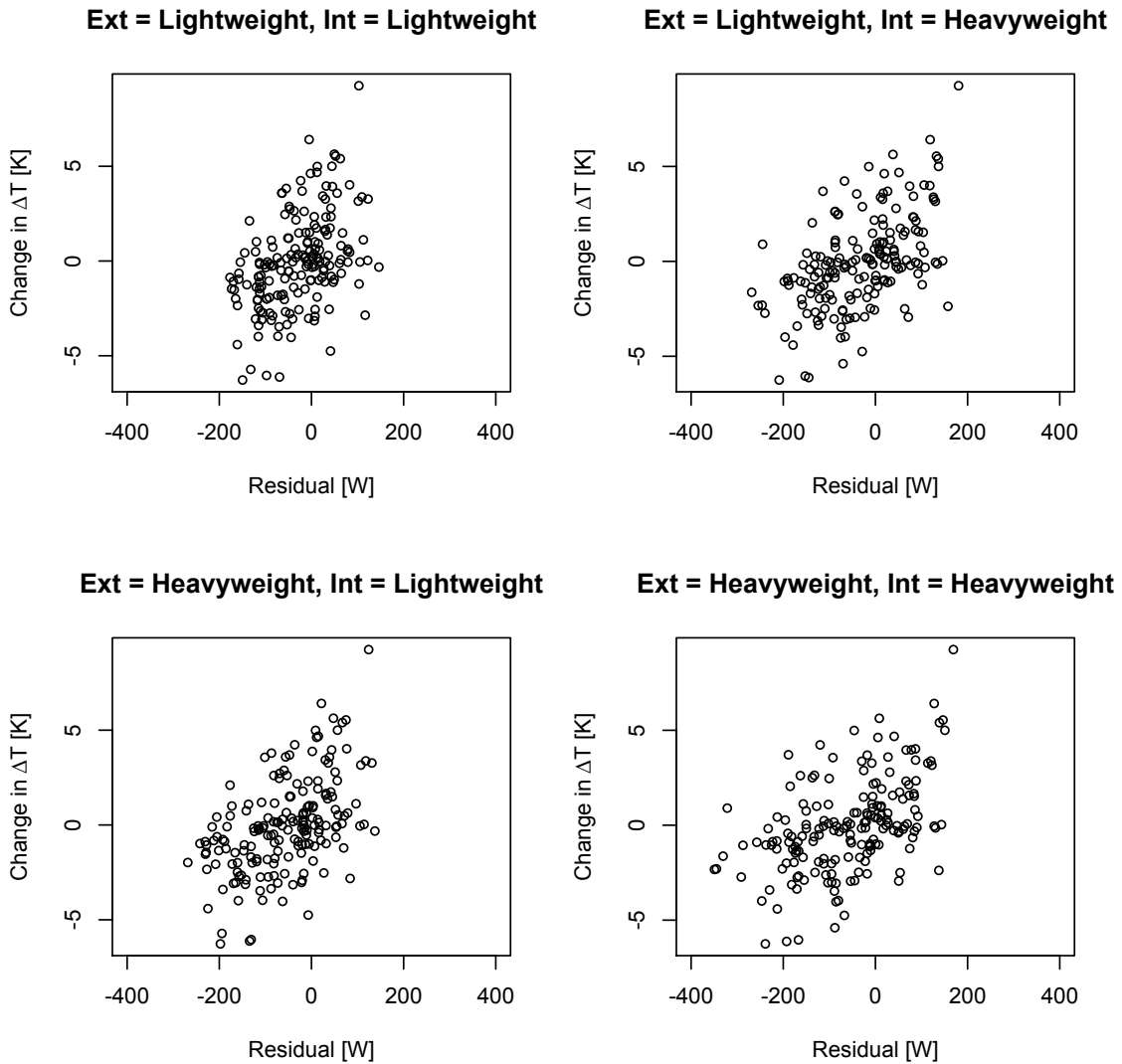


Figure 6 Plots of change in  $\Delta T$  between successive days vs residual power for the four construction types.

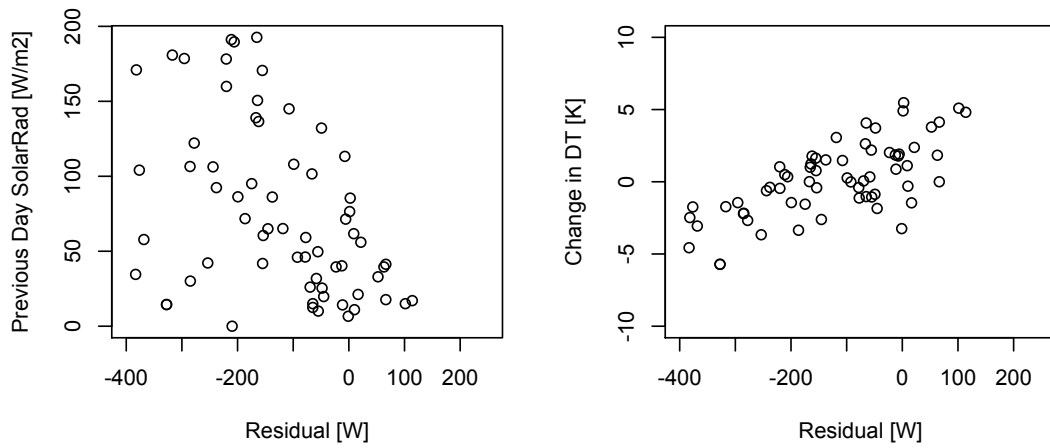


Figure 7 Plots of previous day solar radiation and change in  $\Delta T$  between successive days vs residual power for the real co-heating data.

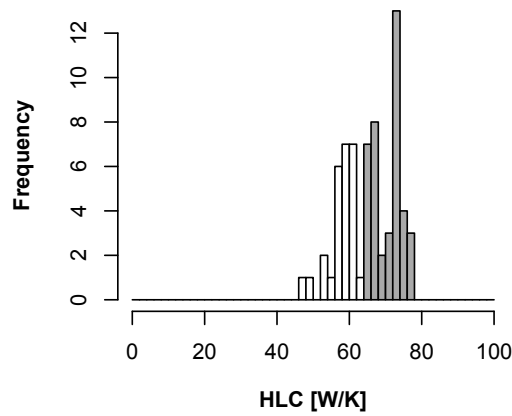


Figure 8 Histogram of derived HLC from real co-heating data.

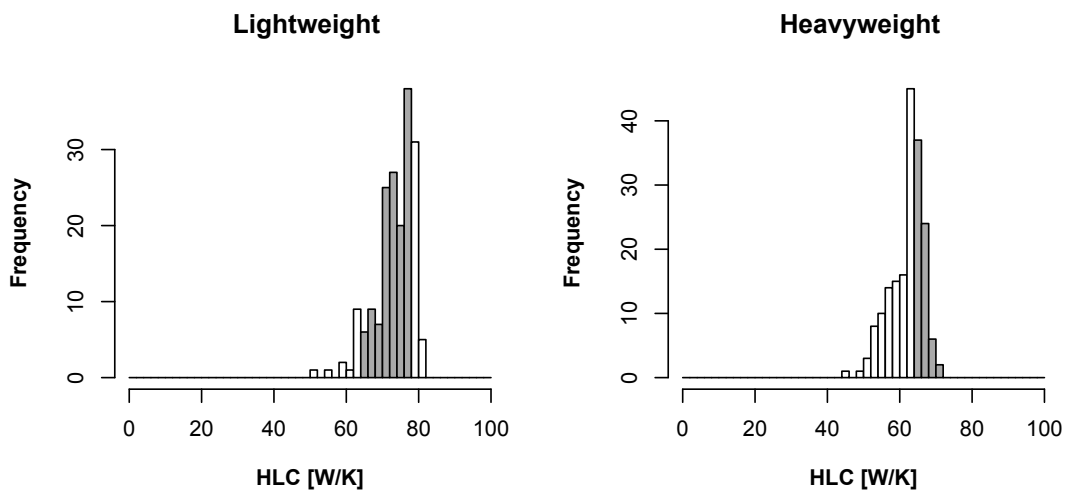


Figure 9 Histogram of derived HLC from simulated co-heating data with increased solar glazing.

### **Response to solar radiation and temperature changes**

The larger distribution of derived *HLC* in higher mass constructions is, in part, expected to be a result of the stronger influence successive days can have on each other. The higher storage potential and thermal time constant mean that a large change in external temperature between successive days could result in less/more power being required on the subsequent day, dependent on the direction of the magnitude of change. Equally, large amounts of solar radiation heating the thermal mass on one day are likely to result in a lower power requirement the subsequent day.

These two effects are demonstrated in the two sets of plots in figures 5 and 6. Again, the magnitude of the residuals increases significantly with the heavier external construction, where the independence of each daily data point from one another is reduced. Both effects have a general trend towards a negative residual, or a lower power needed than expected by the heat loss model. This bias and error is outside the steady-state assumptions and can lead the regression model to underestimate the *HLC* parameter, figure 4.

The implication here is that a heavyweight construction is more likely to result in a co-heating derived *HLC* lower than the true value. Co-heating tests performed in such heavyweight dwellings under weather conditions with high incident solar radiation or highly changing external temperatures are more likely to result in such an underestimate.

### **Comparison to real field data**

These same effects can be seen in real co-heating data from field tests on a dwelling of the same form and similar construction as figure 3. Figure 8 shows the bias in the derived *HLC* in the form of a histogram and the relationships between the previous day's solar radiation and the change in day-to-day  $\Delta T$  are shown in figure 7.

### **GLAZING FRACTION OF THE TEST DWELLING**

As an extension to demonstrate the interaction between the thermal mass of a building and its glazed fraction, the glazed area in the test building was increased. This was performed in an effort to begin to understand the uncertainties in parameter estimation in highly glazed, highly insulated and massive dwellings, such as passivhaus, due to interactions with solar radiation.

The south facing glazing of the test dwelling shown in figure 3 was doubled, for both a fully heavyweight and lightweight construction. Again, histograms of the derived result are shown in figure 9. This time the result in the lightweight dwelling, with limited ability to retain heat, remains distributed evenly around the true *HLC*, albeit more dispersed than in the previous

case. The heavyweight case, now far more exposed to solar radiation through the glazing, shows a greater potential to underestimate the *HLC*.

It should also be noted that whilst analysis presented here only uses weather from the co-heating test season, when looking throughout the year the increased glazing models, particularly heavyweight, overheat for a greater proportion of the year. When more heat is supplied in the form of solar gains than is required to maintain the building at 25°C it will overheat. Buildings that experience overheating during co-heating will have highly uncertain results with significant likelihood of underestimation of *HLC*.

### **CONCLUSIONS**

The results indicated here show how the heat loss coefficient measured through co-heating in a lightweight building can be more reliable and accurate than in a heavyweight building. Data from both simulated and real world co-heating tests show a trend in co-heating measurements to underestimate the heat loss coefficient. This is driven, in part, by both the presence of high solar radiation in previous days and large day-to-day changes in external temperature.

Increasing the glazing fraction did not significantly upset the result in the lightweight case but served to increase the probability of bias in the heavyweight case. This in particular points out the dangers in testing highly glazed, and high thermal mass dwellings under conditions of high solar radiation.

Correcting this bias may require longer averaging periods to maintain the 'steady-state' energy balance equation used in co-heating. This however is unlikely to be feasible in a test already regarded as taking too long. Therefore a different approach may be required to either limit or account for thermal mass contributions.

### **NOMENCLATURE**

$Q$  = the heat input from electric heaters or other heating device [W]  
 $R.S$  = the Solar Gains [W], where  $S$  is the solar radiation [ $W/m^2$ ] and  $R$  is the solar aperture [ $m^2$ ]  
 $\Delta T$  = the temperature difference [K] between the internal and external conditions  
 $HLC$  = the heat loss coefficient [W/K], a measure of the total building heat loss across the entire envelope.

### **ACKNOWLEDGEMENT**

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