Cavity Party Walls: Measuring U-values

For the Department for Business, Energy and Industrial Strategy

FINAL
REPORT

21 December 2018

CAR
Cambridge Architectural Research

LEEDS BECKETT UNIVERSITY

BRIDGEWATER SURVEYORS

Contents

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Executive Summary

CAR, Leeds Beckett University and Bridgewater Surveyors worked jointly together to carry out detailed measurements of heat loss through party walls in English homes for BEIS. The work started in November 2016 and ran until July 2018.

Key Message

This research indicates that most party walls have in-situ U-values at least as good as insulated cavity walls. A small proportion of dwellings have higher heat loss through the party wall – where interventions would be justified to save energy – but these cannot be identified without complex and expensive expert scrutiny.

Over the course of two winters, we collected and analysed data from 284 sets of equipment, installed in 54 homes with uninsulated cavity party walls. The equipment in each case comprised as a minimum of a heat flux plate, wall and air temperature sensors, an external temperature sensor and a temperature sensor in the dwelling next door (the other side of the party wall). We trialled and used different methods of installing and arranging equipment in homes – ranging from three to 30 sensors installed on party walls of different homes.

For a subset of five homes, we carried out 'invasive' measurements that included drilling holes into the party walls and measuring air velocities in the cavities. We also depressurised these homes using a blower door, and used thermographic imaging and a smoke generator to examine air paths exiting the party wall. Where possible, in these homes we also raised floorboards or removed skirting boards to examine the junction of the party-wall with the floor.

For a separate subset of five homes, we also instrumented both sides of the party wall, providing heat-flux measurements from both the main house and the neighbouring dwelling. This provided an opportunity to validate our methods.

Separately, in addition to these scientific measurements, we also carried out statistical work using drawings submitted in planning applications to identify whether homes built since 1980 had solid or cavity party walls.

This report describes our experience of recruiting households into a scientific study, how we carried out measurements, and the new and innovative methods we used for analysing these measurements. It also summarises findings from all of the homes we instrumented, as well as the statistical work we carried out using planning applications.

Findings

Given that temperatures vary over time in real homes, and because heat moves between neighbouring dwellings as well as from inside to outside, U-values in real homes cannot be measured directly[1]. The in-situ U-values cited in this report have been estimated through modelling based on detailed measurements taken in occupied homes.

Spot measurements of in-situ party wall U-values varied significantly from location to location even in the same dwelling. This indicates there are considerable local factors (including proximity to external walls, the floor, the roof, as well as construction anomalies such as mortar 'snots' and wall ties bridging the party cavity) that affect measured in-situ U-values. There was up to a four-fold difference between measured U-values in a single dwelling (from 0.3 to 1.3 W/m^{2}K). There were even larger differences between measured spot U-values in different homes (more than 100-fold).

For homes with un-insulated cavity party walls the mean was 0.21 W/m^{2}K. The highest average value for a property, from 284 measurements in total, was 0.81 W/m^{2}K, and this was a bungalow with an uncapped full-height cavity in the party wall, cavity-wall insulation in the external walls, a suspended timber floor, and blockwork cavity wall construction. There were six properties with un-insulated

[1] This is implicit in Building Regulations, where U-values are taken to be under steady-state conditions with building components in equilibrium.

party walls with an in-situ U-value less than 0.05 W/m^{2}K. These were a mixture of mid-terrace and semi-detached homes, with three different types of party cavity wall construction, with blockwork or brick party walls, and five out of six of them had solid concrete ground floors. This emphasises the finding, unknown previously, that the construction of the party wall is not a good indicator of its thermal performance.

The range of in-situ U-values is significant, indicating that heat loss from seemingly similar homes with cavity party walls may be four times greater in one than another – or even more if the home with a higher in-situ U-value has a larger party wall area. This means that the benefit of installing insulation in the party cavity can be four times or more beneficial from one home to another.

We could find no statistically significant correlations between heat loss through the party wall and dwellings being located in the North or South of England, or different construction in terms of block or brick, floor construction, external cavity-wall insulation or other characteristics that are discernible without carrying out detailed measurements. This suggests that other factors, including missing bricks or holes in the party wall, poor seals at the floor-wall, party wall-external wall and party wall-roof junctions, are more important than the construction type.

Using the mean in-situ party-wall U-values and taking the English Housing Survey average wall area for a semi-detached house (33m^2) allows an approximate estimate of typical savings from insulating party walls. This suggests that insulating an average cavity party wall would bring savings in the region of 0.8% of gas use for a typical semi-detached property: from around 72 to 152 kWh a year, depending on the house, heating and controls. This compares with typical savings from cavity wall insulation of 6.5%, or from around 580 to 1240 kWh a year (based on actual reductions in gas bills analysed in the National Energy Efficiency Data Framework). [2,3]

We examined in detail the effect of wind speed on heat loss through the party wall in a subset of five dwellings. This did not support our hypothesis that higher wind speeds correlate to greater heat loss, which does not support carrying out interventions in dwellings in windy areas – based on the evidence we collected.

Segmenting homes

We identified four types of party wall:

- Type 1: Solid wall (not of interest to this research, and specifically excluded from our sample)
- Type 2: Full-height cavity – with the cavity in the party wall extending all the way up to the ridge of the roof
- Type 3: Capped cavity – with a cavity wall built up to the floor joists in the loft, then a single-skin or block (or more commonly brick) extending up to the ridge in the roof
- Type 4: Capped full-height cavity – with the top of the cavity capped with damp-proofing membrane, insulation, blocks laid sideways or other material where the party wall meets the roof.

However, we could find no statistically significant relationship between heat loss through the party wall and construction Types 2 to 4.

It is very difficult to say how many homes overall may be classified into these four categories. We examined planning applications for more than 2000 new homes built since 1980, in the North and the South of England. This suggested that a majority, 85%, of homes with party walls built since 1980 have cavity party walls (Types 2-4), but it was not possible to disaggregate further because the detailed party wall construction was not described in planning drawings.

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[2] BEIS (2018) NEED Framework Report: Summary of analysis 2018. London: BEIS. https://www.gov.uk/government/statistics/national-energy-efficiency-data-framework-need-report-summary-of-analysis-2018

[3] Compared to average gas use of 14,000 kWh a year.

Our physical inspections from inside the roofs of a smaller sample of homes in the North and the South – 110 homes in total, all built from 1940 to 2010 – suggested that half had solid party walls (Type 1), with the remainder divided into 63% full-height cavity (Type 2), 17% capped at the roof joists (Type 3), and 20% capped at the ridge (Type 4). If this modest sample is representative of the whole English housing stock, then there are around 7.3 million dwellings with potential for insulating party walls. This estimate should be treated with some caution, and the likely range is 6.6 to 8.0 million homes.[4] The theoretical 'technical potential' from insulating all cavity party walls in England would be 0.5-1.2 TWh.[5]

Recruitment

Despite paying incentives from £50 to £400 to participant households, it was extremely difficult to recruit homeowners and people renting social housing to participate in the study. We used multiple approaches to recruitment – approaching social landlords, posters, social network recruitment drives, website advertisements, cold-call knocking on doors in targeted areas, distributing leaflets, in-house company staff bulletin boards, and university and school mailing lists. The most successful method of recruitment was by face-to-face meetings with existing social, family or professional connections.

This could be evidence of a low level of interest in energy efficiency among householders. There was limited awareness among households of energy efficiency more broadly: either opportunities for improving energy efficiency, or how to set heating controls for optimum efficiency. It appeared that energy efficiency upgrades of homes to save energy or improve comfort seldom take priority over other pressures on people's time.

[4] The range is estimated based on a sampling error of up to 10% for homes identified as having cavity party walls. The 10% figure is based on the sampling error from the much larger English Housing Survey, which has annual inspections of 6,200 dwellings, with two years of inspections data combined, and where the sampling error for house type ranges from 2% to 24%. (Table 7.3B, 2016-17 English Housing Survey Technical Report – Standard error tables).

[5] This is derived from a simple multiplication: savings of 72-152 kWh per dwelling x 6.6-8.0 million homes. In reality it would be inordinately difficult to insulate party walls in this number of homes – even aside from the difficulty identifying homes with cavity-party walls.

1. Introduction

BEIS commissioned this research in 2016 to collect robust evidence about heat loss through cavity party walls. The Department needed sound scientific measurements and as large a sample as possible, accepting that it can be difficult to recruit households into such studies. This was to build on more limited studies of small numbers of homes carried out previously.

Key Message

This work set out to estimate in-situ U-values of real, occupied homes, and to estimate how many English homes have cavity party walls. It characterised four types of party wall: solid, full-height cavity, capped at the ridge, and capped at the level of the loft joists.

The objectives of the work were:

1. to estimate in-situ U-values of cavity party walls in real homes when they are occupied.
2. to estimate how many homes, nationally, have cavity party walls.

The aims were not to carry out lab-based measurements in very strictly controlled conditions (as happens with conventional U-value measurements, undertaken using a hot box), with no air movement and heat transfer in only one direction. This project undertook real-world measurements, which are subject to the complexities of real homes, heat moving in different directions and changing in direction and magnitude over time, and the realities of neighbouring homes, which can have very different heating regimes.

Previous work carrying out in-situ U-value measurements had indicated that the U-value near the edges of a cavity party wall can be as much as 0.9 W/m^2K – significantly higher than the U-value of an insulated external cavity wall. [6] The prospect of a new opportunity for the Government to intervene to encourage a different method of insulating homes is all the more significant now that most homes with easy-to-treat external cavity walls have already insulated them, and most homes with inadequate loft insulation (say less than 100mm) and accessible lofts have also already been treated. The Government needed more evidence to decide whether adding insulation to cavity party walls is a worthwhile intervention to support.

Heat loss through cavity party walls is important not so much because of heat passing from one house to its neighbour (because this is a very small proportion of heat loss through party walls, likely to be less than 5%), but more because of heat loss to the outside – see Figure 3.3, page 13. If there is evidence of significant heat loss through the cavity party wall to the outside, there may be a case for Government incentives or subsidies to encourage homeowners, registered social housing providers and private landlords to insulate cavity party walls.

Context: History of Party Wall Construction in the UK

The construction of party walls in the UK has evolved over time, and quite likely geographically, as a result of local by-laws introduced as a result of the Local Government Act of 1858, which gave local authorities the power to regulate buildings, and also local builder preferences. Nearly all party walls constructed before 1945 are solid, so do not bring the risk of thermal bypass through walls like cavity party walls, or offer potential for insulating a cavity. From 1945 to 1965, some homes have solid and others cavity party walls, but when the party wall is constructed from blockwork, cavities appear to dominate.

From 1965 onwards, to reduce noise from one home to the next, party walls were typically of cavity construction. Typically, the cavities were built 50 to 80 mm wide. The first UK-wide Building

[6] Farmer, D., Miles-Shenton, D., Glew, D., & Fletcher, F. 2016. Quantifying the Effect of Approved Document L1a Party Wall Thermal Bypass Mitigation Methods in Retrofit. Research Report to BEIS. Leeds: Leeds Sustainability Institute.

Regulations[7], published in 1965, and the revised set in 1972, allowed three forms of construction for party walls:

- solid brick or blockwork party walls, with mass of at least 415 kg/m^2
- a cavity of at least 50mm, with two leaves of brick or block with mass of at least 415 kg/m^2
- a cavity of at least 75mm, with two leaves of lightweight concrete with mass of at least 250 kg/m^2.

There is nothing in the 1972 Building Regulations about capping party walls or different party wall construction above the joists in the loft. However, a cavity wall to the level of these joists, capped with a single-skin brick wall above, is likely to have been more economical to build than either a full-height cavity or a heavyweight solid wall.

For homes built from 1945 to 1965, there is some evidence from the chimney location and construction about the nature of the party wall. If the chimney is located on the line of the party wall (often apparent from outside), and the chimney is narrow (five 'stretcher' bricks wide or less), the party wall cannot have a full-height cavity. If the chimney is set back from the party wall line, it is much more likely there is a cavity wall. A wide chimney is also evidence of a cavity party wall, and a chimney width of more than five bricks indicates that the dwelling may have a cavity party wall.

Types of Party Wall

This research has identified four construction types of party wall, see Figure 1.1 overleaf:

- Type 1: Solid wall (not of interest to this research, and specifically excluded from our sample)
- Type 2: Full-height cavity – with the cavity in the party wall extending all the way up to the ridge of the roof
- Type 3: Capped cavity – with a cavity wall built up to the floor joists in the loft, then a single-skin or block (or more commonly brick) extending up to the ridge in the roof
- Type 4: Capped full-height cavity – with the top of the cavity capped with damp-proofing membrane, insulation, blocks laid sideways or other material where the party wall meets the roof.

[7] HMSO (1972) The Building Regulations 1972. London: HMSO. Schedule 12, page 185.

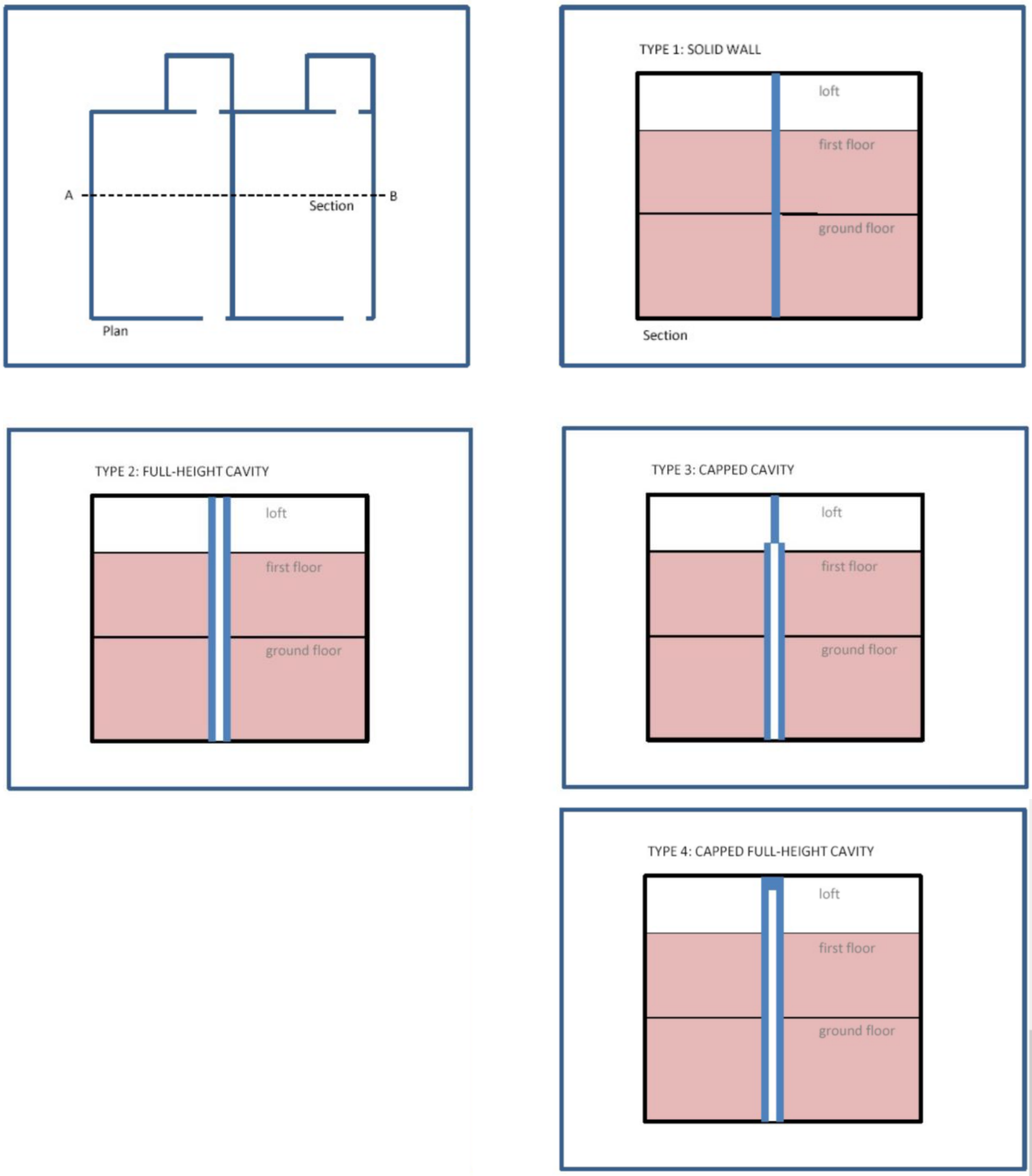


Figure 1.1: The four types of party wall

2. Previous Work on Heat Loss through Party Walls

Key Message

Previous research suggested that heat loss through party walls could be significant and that insulating party walls could make a major contribution to energy efficiency.

Past research work [6,8] indicated that filling party walls can reduce the whole house heat-loss coefficient (measuring overall heat loss, in Watts per Kelvin) by around 24%, on average, see below. Some studies also showed that heat flux measurements vary at different locations along the party wall, for example higher towards the edges. [5] However, these studies were usually restricted to one house and control over conditions on the other side of the wall was not always perfect.

In this project we developed a method to estimate heat loss to outside under varying conditions on both sides of the wall. As well as clarifying how much heat is lost to outside, this enabled us to perform monitoring in a much larger sample of homes: a total of 54 homes. We also performed much higher-resolution intensive monitoring in four cases to further our understanding of the pattern of heat loss to outside through the party wall.

Past work by Leeds Beckett University

Leeds Beckett University (LBU) has carried out research of heat loss from cavity party walls since 2003 (both insulated and uninsulated), including the Stamford Brook field trial. [8] The Stamford Brook study identified significant heat losses via party wall cavities (thermal bypasses) in new-build terraced and semi-detached masonry houses, and proposed various techniques to measure, eliminate or minimise the effect.

In 2008, EURISOL (now MIMA) commissioned LBU to quantify the thermal bypass effect in more detail and to evaluate whether insulating the party wall cavity with mineral wool would eliminate or significantly reduce this. LBU and MIMA continued this work, investigating different layouts and construction types, and expanding from new build dwellings to existing dwellings with cavity party walls. Other projects undertaken by LBU also provided evidence about the proportion of dwelling heat loss attributable to party walls, although full-scale party wall testing (with precise control of environments on both sides of the party wall) usually proved cost-prohibitive.

The Stamford Brook field trial measured the energy performance of dwellings, comparing designed energy efficiency and as-built building fabric efficiency. Whole house aggregate heat loss measurements of dwellings were conducted from 2005 to 2007, and initial results showed the greatest disparities between designed and realised fabric efficiencies in mid-terraced dwellings. The gaps were narrower (but still significant) for end-terraced/semi-detached dwellings.

A second phase of whole house fabric tests was conducted on two pairs of properties with horizontal cavity socks built into the party wall cavities at loft insulation level. These cavity socks were then removed midway through an electric ‘co-heating test’ (based on maintaining constant even and elevated temperatures in empty homes, for up to three weeks, using fan heaters and fans). In both cases, a pseudo internal-to-external steady-state one-sided U-value (effective U-value) was derived for the party walls to allow comparisons to be made with standard steady-state heat loss models.

The effective U-values with the socks in place were 0.18 and 0.26 W/m^{2}K, and with the sock removed these rose to 0.63 and 0.50-0.64 W/m^{2}K, respectively. These values were broadly similar to those reported on by Siviour (1994) of between 0.44 and 0.85 W/m^{2}K for masonry cavity party walls, in a paper largely forgotten by the house-building industry. [9]

[8] Wingfield, J., Bell, M., Miles-Shenton, D., South, T. & Lowe, R. 2011. Evaluating the impact of an enhanced energy performance standard on load-bearing masonry domestic construction - Understanding the gap between designed and real performance: lessons from Stamford Brook. HMSO, London. ISBN: 978 1 4098 2891 4

[9] Siviour, J.B. 1994.Experimental U-values of Some House Walls. BSERT, 15, 1. Pp 35-36

The initial MIMA study measured the whole-house heat loss of a masonry, end-terrace property from January to April 2009, where the party wall was filled with blown mineral wool insulation midway through the period. [10] Extensive measurement and monitoring equipment was installed in the test house and the adjacent mid-terrace property to ensure accuracy and prevent misinterpretation of observations and findings. LBU also monitored:

- external atmospheric conditions (air temperature, wind speed, relative humidity, solar insolation)
- electrical energy input using in-line kWh meters (more accurate than current clamps)
- external temperature and relative humidity
- party wall surface and cavity temperatures
- external wall surface and cavity temperatures
- differential pressures between inside/outside and inside/cavities
- CO_2 concentrations (using a pulsed-release system) to monitor ventilation, and
- air movement in the party wall cavity, using hot-wire anemometers.

LBU also used heat flux sensors fixed internally on party and external walls, carried out thermal imaging, used a borescope to view inside the cavity, and ran blower door tests at strategic stages. The results showed that with the only intervention being filling the 57 m^2 party wall cavity with blown fibre insulation, the heat loss coefficient of the end-terrace reduced from 229.1 W/K to 191.4 W/K, resulting in a reduction in the effective U-value of the party wall of 0.66 W/m^2K. Heat flux measurements confirmed that post-fill, the heat flow measured into the party wall had been reduced to that attributable to conduction (due to temperature differences across the party wall) and thermal bridging alone, with the party wall bypass mechanism effectively eliminated.

Subsequent MIMA studies investigated cavity party wall heat losses of different new-build construction types and build forms. [11] These studies included timber-framed dwellings and a variety of masonry cavity dwelling forms, with samples of both fully-filled and partially-filled external walls. Results from the Eurisol/MIMA test dwellings are shown in the table below. It was not possible to measure or estimate U-values before or after the interventions directly. Consequently, the reductions in effective U-value were obtained by establishing steady-state conditions on either side of the party wall and measuring the whole house heat loss (with a co-heating test), then measuring the same heat loss after the party wall was insulated, with no other changes to either building envelope or adjacent zones.

[10] Wingfield, J., Miles-Shenton, D., Bell, M. & South, T. 2009. Investigations of the Party Wall Thermal Bypass in Masonry Dwellings. Final Report. Report to Eurisol. Leeds Beckett University.
[11] Wingfield, J. & Miles-Shenton, D. 2011. Performance of Cavity Wall Insulation & Insulated Party Wall Cavities: Field Trial Investigations. Final Report. Report to MIMA. Leeds Beckett University.

Table 2.1: Predicted, measured and improved fabric heat loss from insulating party walls

<table>
<tr><th>Test House</th><th>Predicted Fabric Heat Loss† (W/K)</th><th>Measured Fabric Heat Loss† (W/K)</th><th>Reduction due to PW Filling (W/K)</th><th>Party Wall Area (m^2)</th><th>Reduction in PW effective U-value (W/m^2K)</th></tr>
<tr><td>BD1 (PW empty)</td><td>88.9</td><td>186.2</td><td rowspan="2">45.1</td><td rowspan="2">64</td><td rowspan="2">0.70</td></tr>
<tr><td>BD1 (PW filled)</td><td>88.9</td><td>141.1</td></tr>
<tr><td>BD2 (PW empty)</td><td>63.2</td><td>186</td><td rowspan="2">35.6</td><td rowspan="2">64</td><td rowspan="2">0.56</td></tr>
<tr><td>BD2 (PW filled)</td><td>63.2</td><td>150.4</td></tr>
<tr><td>DA1 (PW empty)</td><td>96.8</td><td>107.7</td><td rowspan="2">13.1</td><td rowspan="2">25.76</td><td rowspan="2">0.51</td></tr>
<tr><td>DA1 (PW filled)</td><td>96.8</td><td>94.6</td></tr>
<tr><td>DA2 (PW empty)</td><td>110</td><td>122</td><td rowspan="2">13.6</td><td rowspan="2">25.76</td><td rowspan="2">0.53</td></tr>
<tr><td>DA2 (PW filled)</td><td>110</td><td>108.4</td></tr>
<tr><td>LA1 (PW filled)</td><td>99.4</td><td>125.2</td><td colspan="3">No intervention</td></tr>
<tr><td>LB1 (PW empty)</td><td>79.6</td><td>168.7</td><td rowspan="3">57.5</td><td rowspan="3">44</td><td rowspan="3">1.31</td></tr>
<tr><td>LB1 (PW filled)</td><td>79.6</td><td>111.2</td></tr>
<tr><td>LB1 (PW + external wall filled)</td><td>77.2</td><td>86.8</td></tr>
<tr><td>LB2 (PW empty)</td><td>63.3</td><td>186.8</td><td rowspan="3">92.6</td><td rowspan="3">88</td><td rowspan="3">1.05</td></tr>
<tr><td>LB2 (PW filled)</td><td>63.3</td><td>94.2</td></tr>
<tr><td>LB2 (PW + external wall filled)</td><td>62.3</td><td>70.2</td></tr>
<tr><td>DE1 (PW empty)</td><td>104.2</td><td>148.5</td><td rowspan="2">24</td><td rowspan="2">47.7</td><td rowspan="2">0.50</td></tr>
<tr><td>DE1 (PW filled)</td><td>104.2</td><td>124.5</td></tr>
</table>

†Excluding ventilation heat losses

Both the Stamford Brook and Eurisol/MIMA projects used electric co-heating tests[12] to specifically measure changes in whole house performance due to an intervention to the cavity party wall, thus obtaining a reliable thermal characteristic of the entire party wall. These studies resulted in academic papers, with Lowe et al. (2007)[13] possibly the most cited and influential. The results also stimulated changes to UK energy policy, with the 2010 Building Regulations introducing heat loss from cavity party walls into subsequent dwelling heat loss and emissions evaluations. Other projects by LBU since have allowed some measurement of heat loss via the entire party wall, and most have relied on point measurements based on heat flux sensor readings accrued to provide indicative *in situ* "whole-wall" values.

Studies undertaken in Manchester between 2011 and 2015[9], in conjunction with Knauf Insulation, measured the party wall as part of a whole-house analysis, but were not tests designed specifically to determine the effective U-values of party walls. The results produced a range of values (see Table 2.2

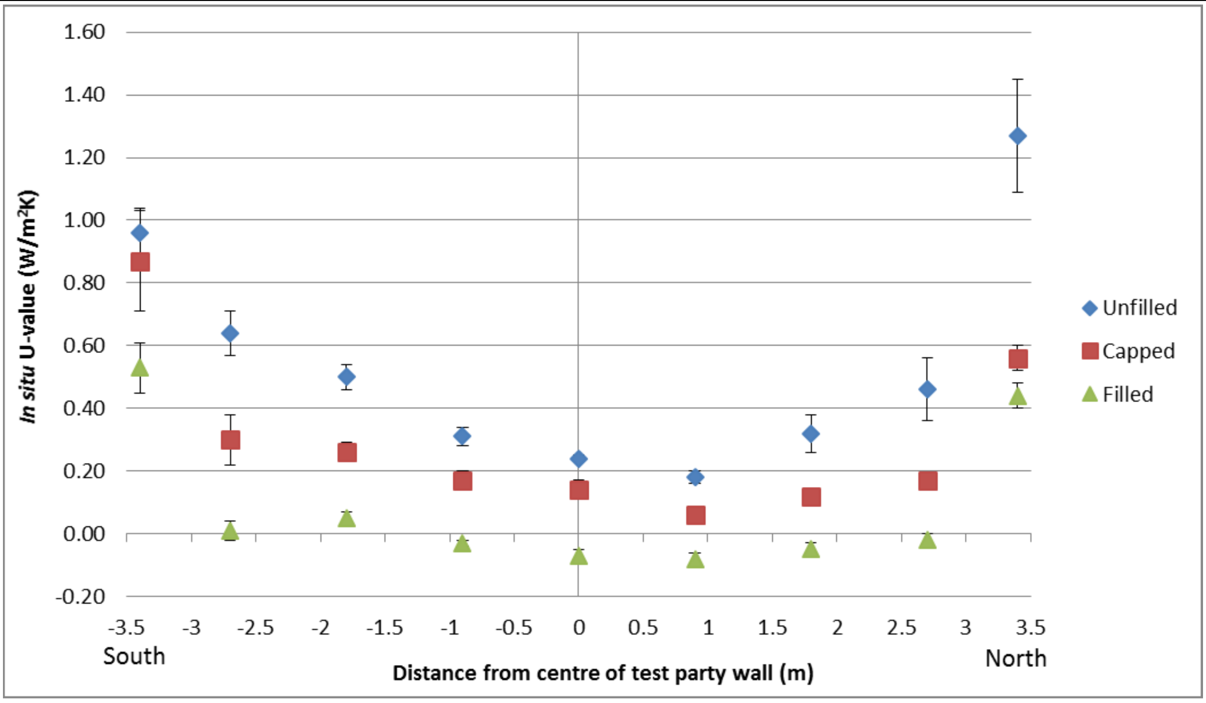
[12] Johnston, D., Miles-Shenton, D., Farmer, D and Wingfeld, J., 2013. Whole House Heat Loss Test Method (Coheating). Leeds Beckett University, Leeds.
[13] Lowe, R.J., Wingfield, J., Bell, M. & Bell, J.M. 2007. Evidence for heat losses via party wall cavities in masonry construction. BSERT 28.2, pp.161-181.

and Figure 2.1 below) due to heterogeneous internal conditions in neighbouring dwellings, caused by radiator placement, stratification, solar impingement and heat sources (electrical appliances) next to the party walls. These used point heat flux density measurements to confirm that similar in-situ effective U-values were exhibited in existing masonry dwellings with full height (ground floor to ridge) cavity party walls. In a number of cases electric co-heating tests were performed on one side of the party wall, with room temperatures on the opposite side of the party wall used in combination with measured heat flux density to calculate effective party wall U-values.

Table 2.2: Effective U-values of unfilled and filled party walls in Manchester (Source: Farmer et al, 2017)

Dwelling Detail	**Measured Effective Party Wall U-value - Unfilled**	**Measured Effective Party Wall U-value - Capped**	**Measured Effective Party Wall U-value - Filled**
1. 1960s Existing terrace house, 60mm cavity, concrete brick, wet plastered, 2 storey	0.62 ~ 0.73 W/m^{2}K		0.0 ~ 0.05 W/m^{2}K
2. 1950s Existing terrace house, 65mm cavity brick, wet plastered, 2 storey	0.7 ~ 1.2 W/m^{2}K		0.0 ~ 0.2 W/m^{2}K
3. 1965 Existing terrace bungalow, 70mm cavity, concrete block, wet plastered	0.6 ~ 1.0 W/m^{2}K		0.0 ~ 0.1 W/m^{2}K
4. 1970s Existing terrace house, 60-65mm cavity, concrete brick, wet plastered, 2 storey	0.24 ~ 0.40 W/m^{2}K		0.02 ~ 0.03 W/m^{2}K
5. 1957 Existing terrace house, 50-55mm cavity, concrete brick, wet plastered, 2 storey†	0.18 ~ 1.27 W/m^{2}K	0.05 ~ 1.05 W/m^{2}K	0.0 ~ 0.75 W/m^{2}K

†Large range in values is potentially misleading, measurements were taken in a horizontal line across the first floor, with highest values measured near the external walls.



(Source: Farmer et al. (2017) Quantifying the Effect of Approved Document L1a Party Wall Thermal Bypass Mitigation Methods in Retrofit)[14]

Figure 2.1: Distribution of in-situ U-values along a section through the party wall. From the front of the house to the back

A similar investigation of a warm-roof, closed-panel timber frame property in York identified lower effective U-values for the cavity party wall – between 0.25 and 0.44 W/m^{2}K (depending on location, away from junctions and bridges) – but this identified air exchange between the party wall cavity and sub-floor void as the bypass mechanism, rather than interaction with the party wall cavity in the loft space as reported elsewhere. [15]

The residual problem, taking into account all of this past work, is threefold:

1. To assess how representative these small samples are of the larger population of all English homes with party walls – do these results reflect in-situ U-values of all English homes?

2. To develop ways of estimating U-values in-situ, with real-world fluctuating temperatures – do such measurements represent true heat losses through party walls more effectively than standard hot box measurements?

3. To estimate the energy savings that might be possible from insulating cavity-party walls with these in-situ U-values – what difference does party-wall insulation make to overall energy efficiency?

[14] Farmer, D., Miles-Shenton, D., Glew, D., & Fletcher, F. 2016. Quantifying the Effect of Approved Document L1a Party Wall Thermal Bypass Mitigation Methods in Retrofit. Research Report to BEIS. Leeds: Leeds Sustainability Institute.
[15] Wingfield, J., Bell, M., Miles-Shenton, D. & Seavers, J. 2011. Elm Tree Mews Field Trial - Evaluation and Monitoring of Dwellings Performance. Final Technical Report. Leeds: Leeds Metropolitan University.

3. Methods

Key Message

We invested considerable effort into recruiting households into the study, and even with a cash incentive it proved difficult to attract participants. It was also hard to definitively identify different party-wall types, and sometimes we had to drill a hole in the wall to be certain. Our standard measurements required up to 15 different sensors to be installed for at least three weeks.

This part of the report is divided into three sections. First, we describe our approaches to recruiting households to participate in the study, including insights we acquired about how best to recruit for scientific research, and whether this applies to householder motivations and barriers to energy efficiency work. Second, we describe the standard approach to instrumenting homes, used for the majority of party walls where we took measurements. Third, we explain the 'intensive' and 'invasive' methods of instrumenting we used where we obtained special consent to take more detailed measurements.

Recruitment

We used a variety of different methods to recruit households into the study:

- Contacts with five housing associations (estimated reach: 10 people, responsible for 10,000 homes).
- Advertising through sustainability oriented groups, such as Transition Cambridge (nearly 2000 recipients) and Cambridge Carbon Footprint (estimated reach: 2500 people).
- Advertising through large local employers, like the European Bioinformatics Institute, the British Antarctic Survey, the University of Cambridge and Leeds Beckett University, using electronic noticeboards and emails (estimated reach: 2600 people).
- Leaflets and door-to-door visits in Ely, Cambridge and Hatfield (200 each, targeted in areas with housing of the requisite age). (Estimated reach: 600 people)
- Social network advertisements, using Facebook: both personal accounts and a local forum account called 'We are Hatfield'.(Estimated reach: 400 people)
- Word-of-mouth, through personal networks and by asking early recruits if they knew anyone else who would be interested. (Estimated reach: 200 people)

We offered a cash incentive of £100 per home for participants, paid in two stages: £50 on installing the monitoring equipment, and £50 on removal. We paid a smaller incentive of £50 to neighbouring dwellings for accommodating temperature loggers, which are small and less obtrusive than the other measuring equipment. (Larger incentives, but to £400, were paid to participants in invasive tests, see below.) We carried out some pre-filtering of dwellings, by asking only households living in homes built from 1945 to 2010 to volunteer. In most cases, there was some dialogue by telephone or email before participants were recruited. This dialogue included a discussion of the party wall construction, but in most cases households did not know whether their homes had cavity party walls.

We also had access to Bridgewater Surveyors' work for one of the big six energy companies, who had a project underway to insulate the party wall cavities of 300 properties. (This was a pilot project, designed to explore practical aspects of insulating party walls at scale, and how much this really costs.)

By far the most successful method of recruiting households was through existing personal contacts – leading to roughly half of the participants in the study. We believe (based on asking participants about this) that this was because of trust in the contact, and a desire by recruits to be helpful to the friend or family member that suggest they participate. This seemed to be as important a factor in participating as the financial incentives.

The second most effective method of recruiting people was by asking participants in the study to suggest other people they knew who might also be willing to take part. This led to around a quarter of the overall recruitment, and often included family members of the first participant.

Depending on financial and social pressures on a household, we found that sometimes cash incentives were effective as prompts to participate, but on other occasions they were unimportant (people chose to take part simply to contribute to a scientific enquiry, and the cash was a bonus).

Inspecting properties

Before we could install measuring equipment in any of the dwellings, we had to ensure they had cavity party walls. Our prior work suggested that approximately half of homes built from 1945 to 2010 had cavity party walls (either capped or full-height cavities). This meant we had to over-sample the recruitment to be sure of getting enough cases to instrument.

In most but not all cases, it was possible to identify the party wall construction from the loft: the brick pattern in the loft often showed whether the wall was solid or cavity construction. The chimney construction also offered some clues, and in some cases there were gaps in the brickwork (either the pointing or whole bricks missing) that allowed a definitive identification. In other cases, a capped cavity could be definitively identified by examining the junction between the loft party wall and the party wall in the occupied part of the dwelling (below the joists). In these cases there was a clear step from the single-skin wall in the loft to a wider cavity wall below the joists.

Figure 3.1: The brick pattern in the loft often provides clues about construction. Here, photo on the left shows a solid wall construction two bricks thick (notice the short 'header' bricks alternating in each course with longer 'stretchers'). The photo on the right is a full-height cavity-party wall (with all 'stretcher' bricks laid with the long side visible).

However, in some cases it was not possible to identify the wall construction definitively by inspection alone. Thick loft insulation sometimes meant it was not possible to access the wall. Some walls were also impossible to identify definitively even when access was possible – especially block walls that extended all the way to the roof lining, with good pointing. Two lofts also had plasterboard on the party walls, which also made definitive identification impossible.

In three cases we obtained consent to drill the walls to make a definitive diagnosis of the wall construction. Two of these led to exclusions, while the third was a positive identification.
When we obtained a positive identification of a cavity party wall, we tried to recruit the neighbouring household, so we could install measuring equipment on their side of the party wall. There were six instances when the neighbour was not prepared to participate, so both dwellings had to be omitted from the study. (This meant repeating the recruit-inspect cycle again for other households.) There were also two instances of the main householder pulling out even after the inspection and agreement was secured with the neighbour.

The whole process of recruitment ran through five stages, see Figure 3.2 below.

Figure 3.2: Recruitment involved five stages of contact, inspection and instrumentation.

Although we cannot be certain how many householders saw our various methods of advertising, we estimate that more than 6,000 people saw them (see breakdown above). Some of these would have self-selected out of the study because their homes were not built from 1945 to 2010, or because they did not have cavity party walls (in the relatively rare instances when they knew about their party-wall construction). From advertising onwards, we know that there was attrition at each stage of the recruitment, with around a quarter deciding not to participate when we spoke to them and they learned what was involved. Half (56 out of 110) of those we inspected proved not to have cavity party walls (or at least, we were not able to make a definitive identification as a cavity party wall). A minority of homes – around 5% of those positively identified as cavity party walls then dropped out because "they were too busy", or they had family or work commitments that meant they were unable to participate. Two positively identified homes also withdrew because the neighbour was unable or unwilling to participate (both of these were linked to longstanding neighbour disputes). On one occasion a landlord was unwilling for the dwelling he owned to be instrumented, even though the occupant and neighbour were willing to participate.

What does this tell us about householder motivation for energy efficiency?

It would be a mistake to infer from this low level of participation and relatively high levels of attrition – even with a clear financial incentive – that people are disinterested in energy efficiency. However, there is limited evidence from people who expressed interest and then did not participate in the study and the reasons they gave for not following through, and this is revealing about the weight they put onto scientific research and energy efficiency in their own homes relative to other demands on their time. Where possible, we gently probed the reasons why householders decided not to go through with the research.

The clearest barrier to participation was simply that people have busy lives, and consequently they are unable or unwilling to suffer intrusions into family life. They commonly cited inflexible work or family arrangements that made it difficult for people to commit to being at home at specific times as reasons they could not participate. We also picked up on (from both households who dropped out and those who went through with the research) embarrassment about their homes and wariness about allowing strangers in. Some people also made clear there were only indirect and weak links in their minds between insulation measures and energy bills and/or comfort.

For these reasons the sample of households (distinct from dwellings) was biased towards those who were either scientifically orientated – accounting for at least half of recruits in Cambridge – or concerned about energy and climate change – accounting for around half of participants overall. (There was an overlap, with some households both science-orientated and interested in energy and climate change.) There is no evidence that this bias affected the selection of dwellings, or construction types, or party-wall characteristics of the dwellings we instrumented.

The very limited conclusions to be drawn from this relating to energy efficiency interventions generally are a) that energy efficiency currently tends to be low priority for most households compared to other concerns, and b) households that do give attention to energy efficiency and upgrading their homes may tend to be more science-orientated and/or more concerned about energy and climate change than the population at large. The first conclusion is not new. For households that are not strongly motivated by science or energy and climate change, the benefits of learning about potential energy efficiency opportunities are uncertain and apparently insufficient to offset the costs, including the hassle connected with making appointments for equipment installation, and a general dislike of letting strangers into the home.

Instrumenting homes: standard measurements

In all cases, before installing measuring equipment, we inspected each home and obtained the owner's consent to carry out research. The inspection included entering the loft and definitively identifying which type of party wall was involved, then, in each case, we carried out:

- A thermographic survey of each side of the party wall (including the loft) to provide qualitative evidence for any existing thermal bypass. The survey was also used to identify areas suitable for U-value measurement.
- A survey of the neighbouring dwelling to identify the locations of heat emitters (e.g. radiators, cookers) which could compromise U-value measurements in the test house.

Subsequently, we installed the following monitoring devices:

- Three to five Hukseflux HFP01 heat flux plates (HFPs) installed on each party wall in areas considered to be unaffected by thermal bridging at junctions, away from notable thermal anomalies, and away from heat sources. Based on previous research, we installed the HFPs in the middle third of the party wall vertically, and 300mm away from external walls, to avoid extreme measurements from thermal bridging. We recorded heat flux density at 10-minute intervals using Leiderdorp LI19 battery powered data loggers.
- We also installed surface thermocouples (TinyTag TGU-4510s, with integrated thermistor probes) adjacent to each heat flux plate, providing a record of air and wall surface temperatures immediately next to each heat flux plate.
- We also recorded the external air temperature close to each property measured, using a TinyTag weather station encased in a Stevenson screen, mounted 1.5m off the ground, where possible at least the height of the nearest building horizontally away from that building.
- From one to four air temperature sensors in the neighbouring home, installed in locations selected to be representative of the average air temperature of the dwelling.

We left all measurement equipment in place for a minimum of three weeks. (Extended from the fourth set of installations of the first winter because feedback from the first sets of installs suggested a longer monitoring period would be beneficial. We also switched to using two or more additional neighbour temperature sensors, so all three sensors were installed as close as possible to the wall opposite the heat-flux plates in the main house. Again, analysis of the first two sets of installs suggested this would help to improve the reliability of measurements.)

Intensive and invasive measurements

We carried out 'intensive' measurements in four homes that were unoccupied, where it was feasible to install many more heat flux plates and temperature probes than in occupied homes – up to 30 across a party wall (see Figure 3.3 below). 'Invasive' measurements could be carried out in five homes where we had consent to drill holes into the party wall and, in some cases, to remove skirting boards and carpets to inspect the party wall-floor junctions.

Based on learning from the first winter, we used a 'five-on-the-dice' distribution across the party wall of all invasive study homes, in order to take a representative range of measurements including extreme values (likely to be near junctions between the party wall and external walls or close to the interface with the ground floor or the top-floor ceiling) as well as less extreme values (likely around the middle of the party wall, where there is likely to be a weaker link to outside).

Figure 3.3: Unoccupied homes allowed intensive measurements and a far higher resolution of measurements across the party wall.

In five of the 'Invasive' houses, in addition to inspecting the party wall-floor junctions, we were able to carry out pressurisation and smoke tests and identify the main areas of air leakage. On five occasions, we were also able to install flux plates on the other side of the party wall also, which gave the opportunity to log heat loss from both sides of the party wall.

We also installed two weather stations, 800mm above the eaves at the front and back of the house, see Figure 3.4 below.

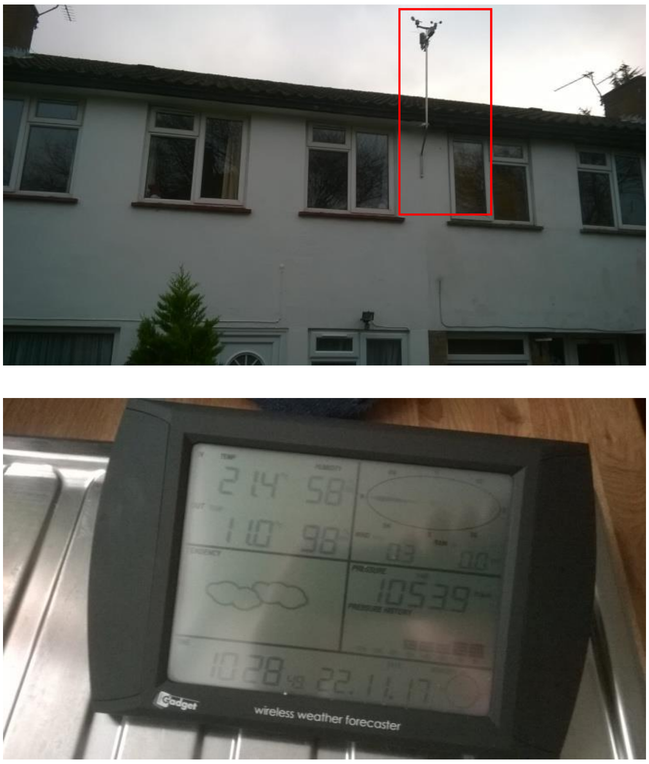


Figure 3.4: The weather stations paired wirelessly to a terminal recording temperature, wind speed and direction, atmospheric pressure and rainfall.

We also drilled two 16mm holes into the party wall at different locations (ground floor, first floor, and front and back) and inserted hot wire anemometers into the holes. The anemometers were connected to tablets using a Bluetooth connection.

In addition, we installed a blower door to depressurise invasive test-houses temporarily and look for evidence of heat loss for half a day. We also carried out smoke tests, injecting smoke into the party wall, to identify obvious air pathways out of the party wall.

Analysis

Measurements alone tell very little, because they need to be interpreted in combination – heat flux with surface, neighbour and external temperature – and because there is considerable noise in the data (due to temperature variations, lag effects, and heat moving in different directions). It is only with appropriate analysis that they become meaningful. Normally a U-value describes the rate of heat transfer across a wall from inside to outside. This is normally a steady-state of thermal equilibrium for the whole structure, with heat passing in only one direction (in reality this only ever happens in the lab). However, in the case of party walls heat transfer occurs both *along* (up and out, towards the roof and external walls) and *through* the wall (to the dwelling next door, see Figure 3.5). We are interested mainly in the heat transfer along the wall from inside to outside, because this is the main opportunity for saving energy and reducing carbon emissions.

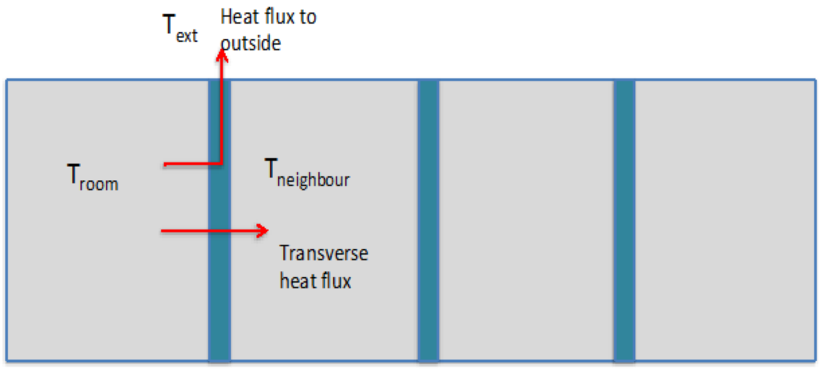


Figure 3.5: In a party wall heat travels both along (upwards and sideways) the party wall, and through it (to the neighbouring property). This makes analysis more complicated and calls for a model in analysis.

The in-situ U-value that we want to measure, which we refer to as U_e, is the heat flux from one side of the party wall to outside (ultimately through the roof and the external walls), divided by the temperature difference between the internal T_{room} and outside T_{ext}. Any difference in air temperature measured between the test dwelling (T_{room}) and the adjacent dwelling (T_{adj}) is also taken into consideration.

To determine the in-situ U-value for the cavity party wall we have developed a new mathematical model, based upon the measured heat flux density and the corresponding temperature conditions. The model has parameters including thermal resistance and capacitance, and we vary these until the model closely matches the measured heat flux[16]. Three thermal resistances are important: from the room to the wall, from one leaf of the party wall to the other leaf, and from the party wall to outside (see Figure 3.6 below). Each of these has corresponding heat flux (again, from room to wall, leaf to leaf, and from the wall to outside). The party wall also has thermal capacitance, and we consider the thermal capacitance of both leaves of the wall together. We use the model to calculate what the heat flux would be if the two homes were always at the same temperature, so there is no transverse heat flux through the party wall, driven by differences in room temperature.

[16] We used a modification of the Levenberg-Marquardt algorithm, as supplied in the statistics package R.

Key

Rr resistance from room to wall

Re resistance from wall leaf to outside

Fc heat flux across the cavity (across Rc)

C thermal capacitance of wall

Rc resistance across cavity from one leaf to the other

Fl heat flux from the room the wall (across Rr on the left)

Fe heat flux from the wall leaf to outside (across Re)

TrL, TrR, room temperatures left and right

Text External temperature

TwL, TwR, wall temperatures left and right

Measured values: TrL, TrR, Text

Modelled and compared with measurement: Fl

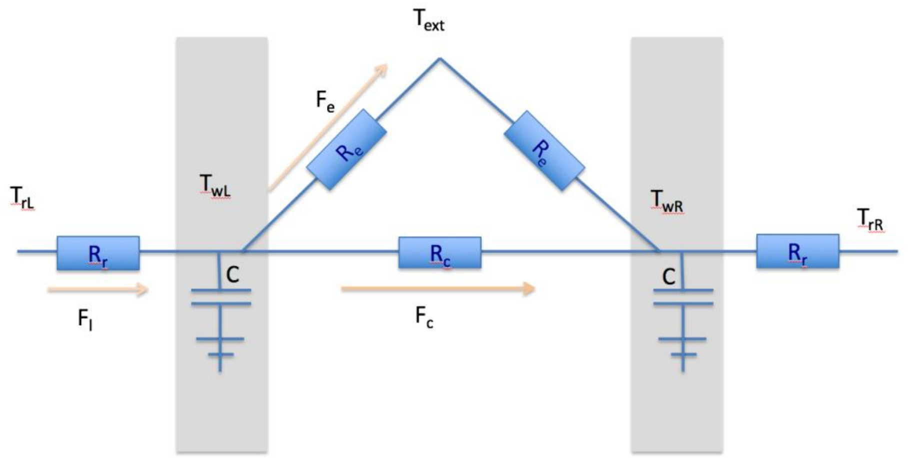


Figure 3.6: A mathematical model is used to calculate heat flux when dwellings on either side of the party wall are the same temperature

We assume that the two sides of the cavity wall are symmetrical in terms of same thermal resistance and capacitance, though not temperatures, as each house has a different heating regime. We ignore the capacitance of the air gap as this is very small. We know the room temperatures and external temperature T_{ext}. We use the model to estimate resistances (R_r, R_e and R_c) and thermal capacitance (C). Then we calculate the in-situ U-value.

$$U = 1/(R_r + R_e).$$

To test each set of parameters, we run the model to see what the heat flux density would be and compare this with the measured value. To run the model, we work in short time steps (our measurement interval is 10 minutes). We use the temperatures to estimate the heat flux density and then the heat flux to estimate the new temperatures. For example, considering the left hand (T_{wL}) wall from Figure 3.4:

Calculate heat flux density:

$$F_l = (T_{rl} - T_{wL})/R_r$$
$$F_e = (T_{wL} - T_{ext})/R_e$$
$$F_c = (T_{wL} - T_{wR})/R_c$$

Calculate next value for TwL (t being the time interval):

$$\text{next } T_{wL} = T_{wL} + (F_l - F_{ext} - F_c) \times t / C$$

In practice, we use the wall surface temperature rather than room temperature where it is known, because it is more reliable. We then apply an adjustment to allow for the surface resistance: 0.13 m^2K/W.[17]

$$F_l = (T_{sl} - T_{wL}) / (R_r - 0.13)$$

Running the model gives a sequence of values for the wall surface temperatures and, importantly, the heat flux density. We optimise the model to get the best fit for flux using the least squares error method. Put technically, this minimises the 'sum of squares residuals' where:

$$S = \Sigma (F_1 - F_{1actual})^2$$

There were 15 cases where optimisation did not converge on a clear best fit set of parameter values. These have been excluded from the analysis.

An alternative approach is to maximise the likelihood function, which tells us how plausible estimated heat flux is, where likelihood is calculated using a probability distribution for the error in the heat flux measurement. However, in this case we found the results are almost identical to the least squares method and take considerably more time to compute. There is more detailed description of the model optimisation and acceptance criteria used in Appendix A.

Analysing Planning Drawings

Alongside our physical measurements, we examined planning applications submitted since 1980 for homes in Cambridge, Welwyn-Hatfield, Leeds and Manchester in considerable detail to establish what proportion of homes built in different decades had cavity party walls. This required us to interrogate large numbers of planning applications in electronic databases and as hard copies in the planning departments of the respective planning authorities, and inspect many different drawings of each site or dwelling.

In many cases, the party walls were not drawn clearly enough to show the wall construction in planning drawings, so although we examined planning applications for more than 2000 new homes in total (all of the available drawings still held in the planning authorities' archive), the party-wall construction was only visible in 1076 cases, see Table 3.1 below. There are regional variations between the planning applications we viewed (for example, many times more common to have cavity party walls in Welwyn-Hatfield and Cambridge, but roughly even split between cavity and solid party walls in Manchester), so we would not suggest that these proportions are nationally representative. The higher prevalence of cavity party walls in the South may suggest that there are proportionately more such dwellings in the South than in the North (indicating greater potential for insulating cavity party walls in the South), but we cannot be confident about this based on just four planning authorities.

Our sample is also skewed towards homes build more recently – since 2010 – because the drawings for these more modern homes are more commonly accessible than older homes. We were unable to obtain planning drawings submitted for any home built prior to 1980, and it is possible that the proportion with cavity party walls is different among homes built from 1940 to 1980.

[17] In the detailed studies, with unoccupied homes, we used circulation fans to mix the internal air and achieve even temperatures around the dwelling. This may have reduced the surface resistance slightly, but we cannot quantify this change so we retained the same simple assumption of surface resistance.

Table 3.1: Evidence from planning drawings since 1980 suggests that many more homes with party walls have cavities in the party wall.

	PCW	Solid
Manchester	35	32
Leeds	55	28
Welwyn-Hatfield	636	57
Cambridge	191	42
Total	**917**	**159**
	85%	15%

5. Findings

Broadly, the findings from this research are of two types. First, evidence about the number of homes with cavity-party walls that could potentially be insulated economically. This helps to understand the number of homes where there is potential for retrofit measures, which could subsequently save energy and reduce carbon emissions. Second, evidence about the actual heat loss through party walls of different types – which helps to quantify what savings could be realised if large numbers of homes have their party walls upgraded.

Key Message

We found that approximately one third of all English homes have cavity party walls that could be insulated. The mean in-situ U-value across our sample of 54 homes was 0.21 W/m^{2}K, and three homes had 'high' U-values from 0.6 to 0.8 W/m^{2}K. Generally, spot measurements near the edges of walls gave higher in-situ U-values.

We begin this section by reporting findings about the number of homes with different types of party wall.

How many homes have cavity party walls?

Viewed logically, most house types apart from detached homes could have one or more party walls. [18] The latest English Housing Survey tells us there were 12.3 million terraced dwellings in 2016-17, 11.3 million semi-detached dwellings, and almost 8 million flats. This compares to 7.9 million detached dwellings.[19] This suggests that close to two-thirds of all homes in England have party walls.

However, only a proportion of these properties have cavity party walls. The English Housing Survey does not record whether dwellings have solid or cavity party walls. However, the recent planning drawings referred to in the previous section suggested that the majority (perhaps as much as 85%) of homes built since 1980 have cavity party walls. Our inspections of planning drawings also indicated regional disparities in the proportion of recent homes built with cavity party walls – 92% in Welwyn and Hatfield, compared to just 52% in Manchester.

It is entirely possible that local preferences, largely driven by volume house-builders and standardised housing designs, dictate whether party walls are solid or have cavities (both are permitted under current Building Regulations[20], although solid party walls are required to use heavy-weight blocks or bricks to achieve acoustic separation between neighbouring dwellings).

It is not possible to determine from planning drawings whether the party wall cavity extends beyond the joists in the roof, or whether it is capped (either at the level of the top-floor ceiling joists, or at roof level). This means that planning drawings alone do not allow us to estimate what proportion of party walls are of the four construction types shown in Figure 1.1.

The only data we have to draw on comes directly from the house and loft inspections undertaken for this project. Table 4.1 below categorises each of the dwellings inspected and monitored in this project. (Two of the properties were measured twice – before and after the party walls were insulated – and one was measured in two different ways, in order to validate our main method.)

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[18] Flats that occupy the whole floor of a building are a special case without party walls, and single-aspect flats with a corridor on one side and no direct neighbour do not have party walls, but most flats do share one or more walls with a neighbouring property.

[19] Ministry of Housing, Communities and Local Government (2018) English Housing Survey headline report 2016 to 2017: Section 2 housing stock tables. London: MHCLG. https://www.gov.uk/government/statistics/english-housing-survey-2016-to-2017-headline-report (Accessed 20 June 2018)

[20] DCLG (2016) Approved Document E: Resistance to the passage of sound. London: DCLG. Page 20.

Table 4.1: All study dwellings and construction parameters

Dwelling	Dwelling type	PW insulation	Capped/ uncapped	Block/ brick	External wall insulation	Floor type
C1	Semi-D	No	Uncapped	Block	Yes	Solid
C2	Upstairs flat	No	Uncapped	Block	Yes	Suspended
C3	Semi-D	No	Uncapped	Brick	Yes	Mixed
C4	Semi-D	No	Uncapped	Block	Yes	Solid
C5	Semi-D	No	Uncapped	Block	Yes	Solid
C6	Semi-D	No	Uncapped	Concrete	Yes	Solid
C7	Semi-D	No	Capped at joists	Brick	Yes	Solid
C8	Semi-D	No	Uncapped	Block	Yes	Solid
C9	Terrace	No	Capped at joists	Brick	Yes	Solid
C10	End-of-terrace	No	Capped at joists	Brick	Yes	Solid
C11	Semi-D	No	Capped at joists	Brick	Yes	Solid
C12	End-of-terrace	No	Uncapped	Brick	Yes	Suspended
C13	Semi-D (offset)	No	Capped at joists	Brick	Yes	Solid
C14	Mid Terrace (passage)	No	Capped at joists	Brick	Yes	Mixed
C15	End-of-terrace	No	Uncapped	Brick	Yes	Solid
C16	Terrace	No	Uncapped	Timber	Yes	Basement
C17	Terrace offset	No	Uncapped	Block	No	Solid
C18	Terrace offset	No	Uncapped	Block	Yes	Suspended
C19	Semi-D	No	Uncapped	Mixed	No	Solid
C20	Semi-D	No	Uncapped	Block	No	Solid
C21	Semi-D	No	Uncapped	Block	No	Solid
C22	Semi-D	No	Uncapped	Block	Yes	Suspended
C23	Semi-D	No	Uncapped	Brick	No	Solid
C24	Semi-D	No	Capped at joists	Brick	Yes	Solid
C25	Mid Terrace (passage)	No	Capped at joists	Brick	Yes	Mixed
C26	Mid Terrace (passage)	No	Capped at joists	Brick	Yes	Mixed
C27	Mid-Terrace	No	Capped at ridge	Brick	Yes	Solid

Dwelling (cont.)	Dwelling type	PW insulation	Capped/ uncapped	Block/ brick	External wall insulation	Floor type
H28	Terrace	No	Not discernible	Block	No	Solid
H29	Terrace	No	Capped at ridge	Block	No	Solid
M30	Terrace	No	Capped at ridge	Block	No	Solid
M31	Terrace	No	Capped at ridge	Block	No	Solid
M32	Terrace	No	Capped at ridge	Block	No	Solid
M33	Terrace	No	Capped at ridge	Block	No	Solid
M34	Terrace	No	Capped at ridge	Block	No	Solid
M35	Terrace	No	Capped at ridge	Block	Yes	Solid
M35-ins	Terrace	Yes	Capped at ridge	Block	Yes	Solid
M36	Terrace	No	Capped at ridge	Block	Yes	Solid
M36-ins	Terrace	Yes	Capped at ridge	Block	Yes	Solid
M37	Terrace	No	Capped at ridge	Block	Yes	Solid
M37-ins	Terrace	Yes	Capped at ridge	Block	Yes	Solid
M38	Terrace	No	Capped at ridge	Block	Yes	Solid
M38-ins	Terrace	Yes	Capped at ridge	Block	Yes	Solid
M43	Terrace	No	Uncapped	Block	Yes	Solid
M44	End-Terrace Bungalow	No	Uncapped	Block	Yes	Suspended
M44-floor	End-Terrace Bungalow	No	Uncapped	Block	Yes	Suspended
M46a	Terrace	No	Uncapped	Block	Partial	Solid
M46b	Terrace	No	Uncapped	Block	Partial	Solid
M48a	Terrace	No	Uncapped	Block	Partial	Solid
M48b	Terrace	No	Uncapped	Block	Partial	Solid
M50a	Terrace	No	Uncapped	Block	Partial	Solid
M50b	Terrace	No	Uncapped	Block	Partial	Solid
M52	Mid-terrace	No	No	Block	Yes	Suspended timber
M53	Mid Terrace (passage)	No	No	Concrete	Yes	Solid concrete slab on ground
M54	Mid Terrace	No	No	Concrete	Yes	Solid concrete slab on ground

Dwelling (cont.)	Dwelling type	PW insulation	Capped/ uncapped	Block/ brick	External wall insulation	Floor type
M55-normal	Mid Terrace	No	Uncapped	Concrete	Yes	Solid
M55-steady	Mid Terrace	No	Uncapped	Concrete	Yes	Solid
M57	Mid Terrace	No	Uncapped	Block	Yes	Solid
W58	Mid-terrace	No	Full-height	Block	No	Solid
W59	End Terrace	No	Full-height	Block	No	Solid

NB. M44 and M44-floor are the same dwelling with floor insulation added – this affected the party wall too, by improving the seal between the floor and party wall cavity. M46, M48 and M50 a and b give measurements from different sides of the same wall. We have removed duplicated cases to ensure that each wall only counts once in aggregate analyses.

Overall our sample included more terrace homes than other house types (see table below). We recruited as widely as possible, with no bias towards any specific dwelling type, age, or construction type, and we instrumented all homes with cavity party walls whose occupants and neighbours agreed to participate. However, the final sample over-represents terraces and under-represents semi-detached houses and flats, compared to national totals (see Table 4.2). Just over half (29 out of 54) had a blockwork party-wall construction, with a quarter (14) having brick construction and the rest concrete or mixed construction. A majority of them (29) were Type 2 full-height cavity party walls. Next most common were Type 4, full-height cavities capped where the wall meets the roof (15), and finally Type 3, with cavities capped at the roof joists (9).

Table 4.2: Dwelling types for instrumented homes

Dwelling type	Number	Comparison with National Totals - Percentage of the stock*
Semi-D	15	25%
Mid-terrace	33	20%
End terrace	4	10%
Bungalow	1	9%
Flat	1	21%
Detached	-	17%
Total	**54**	**100%**

*Source: MHCLG (2018) English Housing Survey 2016-17, Table 2.1. London: MHCLG.

It is open to question whether our modest sample of 110 dwellings in the North and South of England where the loft was inspected to identify the party-wall type is representative of all homes in England. However, in the absence of any stronger evidence, and factoring up to all homes in England with party walls (i.e. excluding detached homes, using data from the English Housing Survey[21]), this suggests that 6.8 to 8.0 million dwellings have the potential for insulating the party wall cavity, see Figure 4.1 below.

[21] MHCLG (2018) English Housing Survey 2016-17, Table 2.1. London: MHCLG.

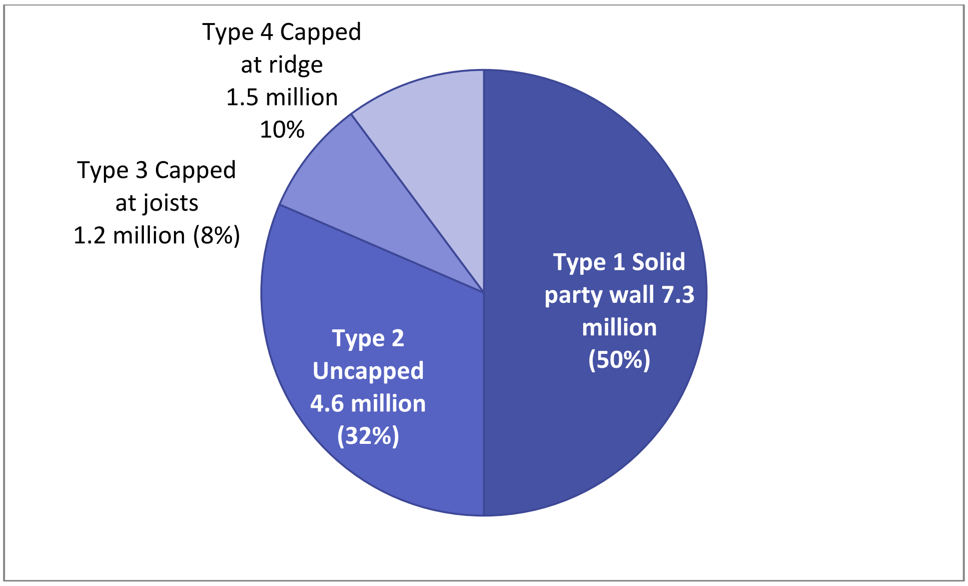

Figure 4.1: Central estimate of number of homes with different party-wall types

Estimating spot in-situ U-values

Overall U-values were estimated based on 284 measurements (comprising heat-flux density, surface temperature and neighbour temperature data) taken across 54 homes. (One of the homes was measured in two different ways to validate our methods, see 'Validation' section below, two had sensors attached to the party walls on either side, and a third had measurements taken before and after the ground floor was insulated.) Our results are shown in Table 4.3 below.

Our method for combining spot measurements of *in-situ* U-values to give an average for the property is described in Section 5 of the report, below. The simple mean across all instrumented homes came out at 0.20 W/m^{2}K (95% confidence interval between 0.153 and 0.25). For homes with uninsulated cavity party walls the mean was 0.21 W/m^{2}K (0.16 to 0.26). The highest average value for a property was 0.81 W/m^{2}K (0.72 to 0.90), for a bungalow with an uncapped full-height cavity in the party wall, cavity-wall insulation in the external walls, a suspended timber floor, and block cavity wall construction (M44a). There were three properties with in-situ U-value less than 0.01 W/m^{2}K (M33, M36-ins, and M38-ins). All three properties were terraces, all with full-height cavities capped at the ridge, all with blockwork party walls and solid concrete ground floors. Two of these (M36-ins and M38-ins) also had retrofit party-wall insulation. (Two of only four homes in the study that had insulated party walls.)

Initially there appeared to be some correlation between the in-situ U-value and whether the party cavity was full-height (Type 2) or capped (Types 3 and 4). Of the 10 dwellings with the highest in-situ U-values, seven are full-height cavities, while of the 10 dwellings with the lowest in-situ U-values, seven were capped – either at the ridge or at the loft joists. However, statistical analyses showed that this was a non-significant relationship, see Appendix C.

Table 4.3: All instrumented homes and in-situ U-values (all simple means)

Dwelling	Number of measure ments	In-situ U-value (W/m²K)	Minimum measured U-value	Maximum measured U-value	Lower uncer-tainty limit	Upper uncer-tainty limit	Con-struct ion	Capped or full height	Visible holes in party wall
C1	3	0.161	0.054	0.262	0	0.359	Block	Uncapped	
C2	2	0.350	0.329	0.370	0.107	0.592	Block	Uncapped	
C3	3	0.100	0.001	0.275	0	0.298	Brick	Uncapped	
C4	3	0.107	0.001	0.164	0	0.305	Block	Uncapped	100x200mm in eaves cupboard
C5	3	0.011	0.001	0.032	0	0.209	Block	Uncapped	
C6	2	0.741	0.175	1.306	0.498	0.983	Con-crete	Uncapped	20x20mm hole at first floor level with floorboards
C7	3	0.116	0.001	0.303	0	0.314	Brick	Capped at joists	
C8	3	0.067	0.001	0.187	0	0.265	Block	Uncapped	
C9	2	0.137	0.055	0.219	0	0.380	Brick	Capped at joists	200x200mm hole in loft
C10	2	0.301	0.149	0.453	0.059	0.544	Brick	Capped at joists	
C11	3	0.220	0.088	0.479	0.022	0.418	Brick	Capped at joists	
C12	3	0.012	0.001	0.024	0	0.210	Brick	Uncapped	
C13	1	0.611	0.611	0.611	0.268	0.954	Undis cer-nible	Capped at joists	
C14	2	0.027	0.005	0.049	0	0.269	Brick	Capped at joists	
C15	3	0.237	0.152	0.319	0.039	0.435	Brick	Uncapped	
C16	3	0.028	0.003	0.045	0	0.226	Tim-ber	Uncapped	
C17	3	0.277	0.075	0.578	0.079	0.475	Block	Uncapped	
C18	2	0.113	0.065	0.160	0	0.355	Block	Uncapped	
C19	3	0.059	0.001	0.116	0	0.257	Mixed	Uncapped	
C20	3	0.286	0.124	0.483	0.088	0.483	Block	Uncapped	
C21	3	0.065	0.001	0.146	0	0.263	Block	Uncapped	
C22	2	0.398	0.001	0.795	0.155	0.640	Block	Uncapped	
C23	3	0.154	0.020	0.239	0	0.351	Brick	Uncapped	
C24	3	0.049	0.019	0.093	0	0.247	Brick	Capped at joists	
C25	9	0.227	0.007	0.412	0.113	0.341	Brick	Capped at joists	
C26	10	0.243	0.001	0.927	0.063	0.424	Brick	Capped at joists	
C27	5	0.203	0.022	0.541	0.029	0.378	Brick	Capped at ridge	
H28	5	0.238	0.024	0.502	0.085	0.391	Block	Unable to see	

Dwelling (cont.)	Number of measurements	In-situ U-value	Minimum measured U-value	Maximum measured U-value	Lower uncer-tainty limit	Upper uncer-tainty limit	Construction	Capped or full height	Visible holes in party wall
H29	6	0.350	0.001	0.996	0.210	0.490	Block	Capped at ridge	Small hole (10 x 30mm) at ridge on neighbour side
M30	3	0.148	0.115	0.205	0	0.346	Block	Capped at ridge	
M31	2	0.144	0.133	0.155	0	0.386	Block	Capped at ridge	
M32	3	0.093	0.022	0.132	0	0.291	Block	Capped at ridge	
M33	1	0.001	0.001	0.001	0	0.343	Block	Capped at ridge	
M34	2	0.434	0.410	0.457	0.191	0.676	Block	Capped at ridge	
M35	2	0.075	0.005	0.145	0	0.317	Block	Capped at ridge	
M35-ins	3	0.060	0.001	0.097	0	0.258	Block	Capped at ridge	
M36	3	0.126	0.014	0.240	0	0.324	Block	Capped at ridge	
M36-ins	3	0.001	0.001	0.001	0	0.199	Block	Capped at ridge	
M37	1	0.027	0.027	0.027	0	0.370	Block	Capped at ridge	
M37-ins	3	0.015	0.001	0.034	0	0.213	Block	Capped at ridge	
M38	3	0.069	0.001	0.170	0	0.267	Block	Capped at ridge	
M38-ins	3	0.001	0.001	0.001	0	0.199	Block	Capped at ridge	
M44	30	0.806	0.429	1.163	0.716	0.897	Block	Uncapped	
M44-floor	30	0.619	0.322	1.271	0.537	0.701	Block	Uncapped	
M46a	3	0.167	0.066	0.329	0	0.365	Block	Uncapped	
M46b	2	0.197	0.120	0.274	0	0.439	Block	Uncapped	
M48a	3	0.328	0.192	0.555	0.130	0.526	Block	Uncapped	
M48b	3	0.351	0.266	0.453	0.153	0.548	Block	Uncapped	
M50a	3	0.080	0.001	0.151	0	0.278	Block	Uncapped	
M50b	3	0.143	0.001	0.311	0	0.341	Block	Uncapped	
M52	5	0.488	0.089	0.982	0.335	0.641	Block	Full-height	20mm diameter hole near ridge AND two 150 x 250mm openings from pantry to party cavity
M53	5	0.088	0.001	0.157	0	0.241	Concrete	Full-height	
M54	5	0.161	0.001	0.277	0.008	0.315	Concrete	Full-height	
M55-normal	14	0.220	0.061	0.470	0.152	0.288	Concrete	Uncapped	
M55-steady	14	0.207	0.028	0.532	0.126	0.289	Concrete	Uncapped	
M57	24	0.187	0.001	0.609	0.100	0.274	Block	Uncapped	

Dwelling (cont.)	Number of measurements	In-situ U-value	Minimum measured U-value	Maximum measured U-value	Lower uncer-tainty limit	Upper uncer-tainty limit	Construction	Capped or full height	Visible holes in party wall
W58	5	0.313	0.124	0.466	0.159	0.466	Block	Full-height	
W59	5	0.198	0.127	0.247	0.023	0.372	Block	Full-height	

Dwellings M30 to M38 all have very similar construction, with M30 to M34 actually in the same terrace block, and M35 to M38 selected from two similar terraces. All of these apart from M37 have similar (low) in-situ U-values. It was not clear why M37 had an in-situ U-value so much higher than the others – possibly because of a poor seal or missing brick(s) in the loft of the neighbouring home.

Conversely, dwellings M46 to M50b – which are also very similar construction, located adjacent to each other in the same street – show a wide range of in-situ U-values, from 0.08 to 0.35 W/m^{2}K (a fourfold difference). This suggests that there is something that is not visible from inspection alone that affects the heat loss through the party wall – possibly concealed openings into the party cavity at the junctions with the floor and/or the external walls.

M35-ins is another anomalous finding – unlike the other homes with retrofit party-wall insulation, this one shows only a small impact on in-situ U-value of insulating the party wall. It is unclear why this should be – perhaps because the insulation was incomplete or poorly installed.

Trends in-situ U-values

We found it is generally the case that in-situ U-values are higher around the edges of a party wall (near external walls) than in the middle, or at least in some parts of the edge, possibly indicating a thermal bypass. Sometimes the U-values are high at the bottom as well as the top and sides. Usually the trends are gradual. The figures below show three examples where we have monitored many locations on the same wall to determine the pattern of heat loss.

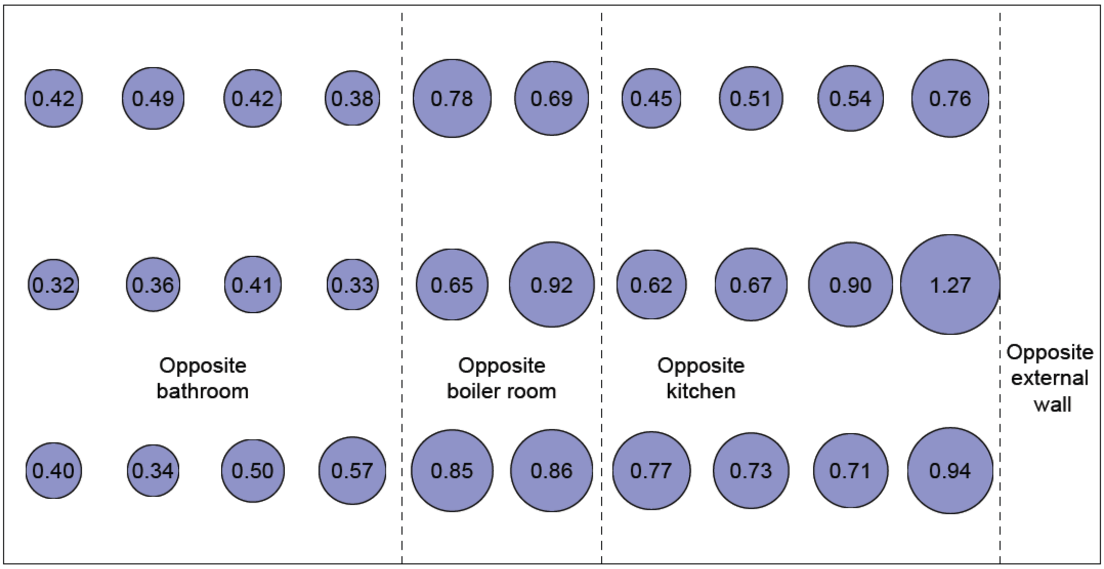

Figure 4.2 In-situ U-values (W/m^2/K) for M44-floor. This house is part of a staggered terrace and part of the wall right of the locations on the far right is actually an external wall. The heat loss is generally high and is higher still towards the right, suggesting there is some kind of thermal bypass there, which affects heat flow in the adjacent parts of the wall.

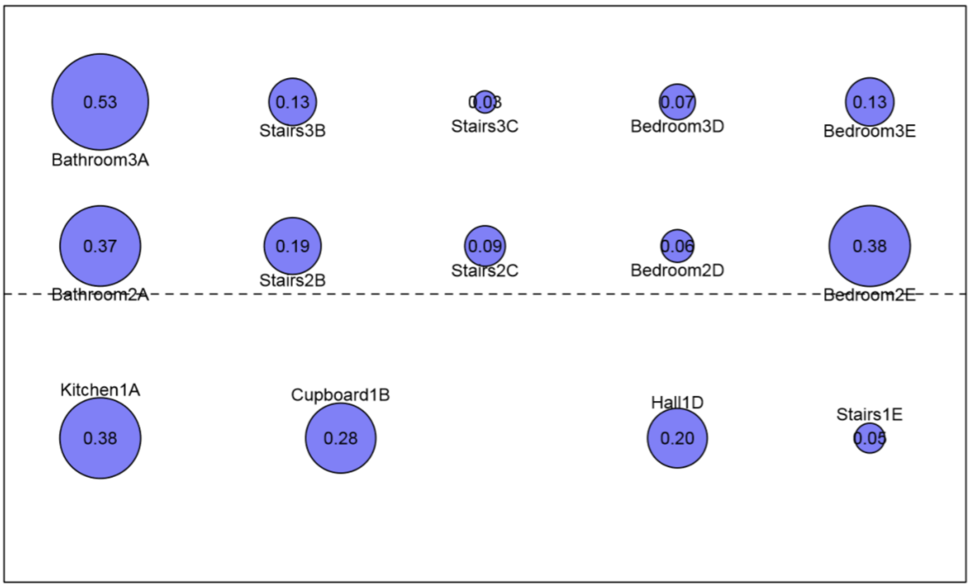

Figure 4.3 In-situ U-values (W/m²/K) for M55-steady temperature. This house has a solid floor slab. Heat loss is generally low, except for some locations on the edges.

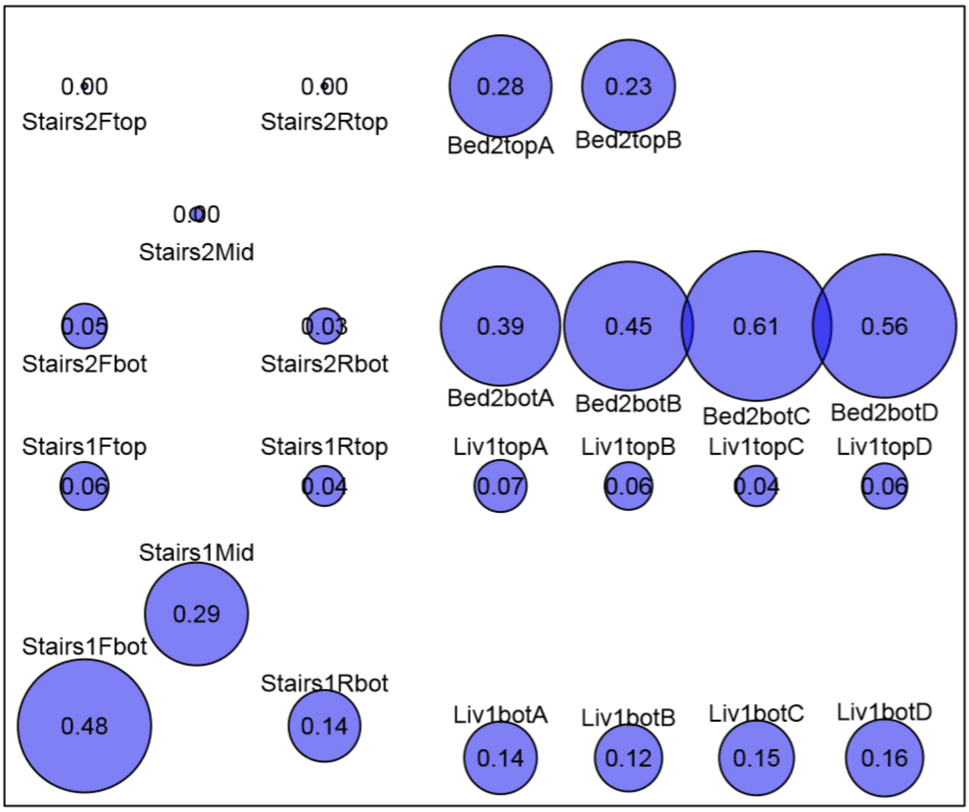

Figure 4.4 In-situ U-values (W/m²/K) for M57. This house has at least one thermal bypass (revealed by thermal imaging) at a location between Bed2botD and Liv1topD on the right hand edge. The data suggests another in the bottom left. This house has a solid floor slab.

Some of the apparent variation in in-situ U-value is likely to be due to limitations in the model, not taking into account heat flow within the wall due to temperature differences in different parts of the house. [22] Heat flows from warmer parts of the wall to the cooler parts. Where these temperature gradients are inconsistent, the measured location gains more or less heat at different times from other parts of the wall. Consequently, the model fit is not as good (lower R-squared). [23] Figure 4.4 below shows this effect, and there is more discussion of this in Appendix B.

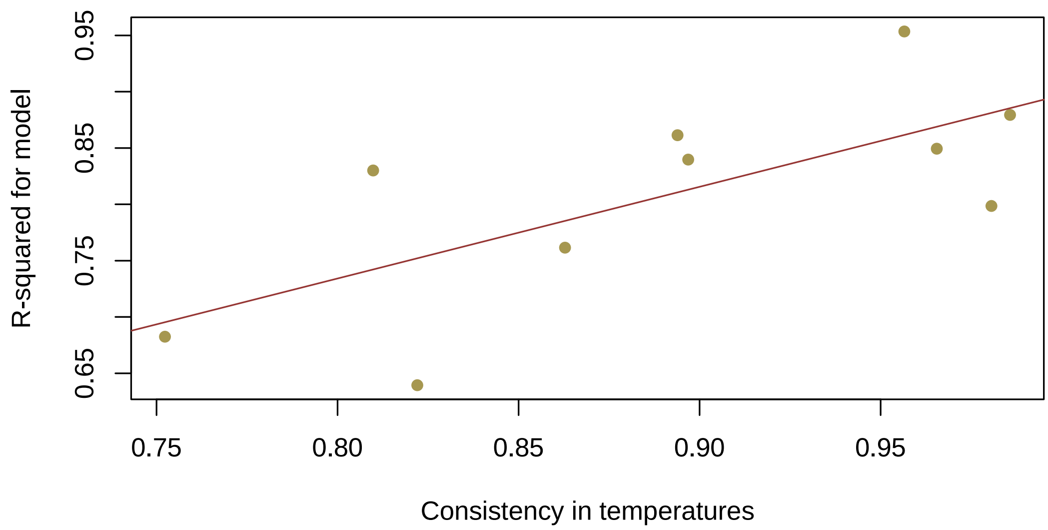

Figure 4.5 R-squared varying with temperature consistency by wall. The red line is the best fit (R-squared is 0.43 and p-value[24] is 0.02). Each dot represents a home where there are at least four locations monitored with both heat flux and temperature and all converged to give clear results. Consistency and R-squared for each home are the average over all locations in the home. Consistency is calculated as the correlation between the temperature at that location and the mean temperature for all locations. Perfect correlation would be 1.0 and 0.0 would mean none.

When there are consistent temperature differences between different parts of a house (i.e. one room kept consistently warmer than the rest) these can lead to bias in the results for each location, though these logically cancel out over the whole wall. Temperature flows within the wall lead to measured local heat flux that is higher or lower than it would otherwise have been. This is discussed in more detail in Appendix B.

Summary

The pattern of heat loss across a wall varies, as can be seen from our intensively monitored walls where we have a large number of measurement locations. Usually the worst places (with highest heat loss) are on the edges. This is also true looking across all of the instrumented homes, although there are exceptions – see Appendix G. This is consistent with previous work undertaken by Leeds Beckett University, see page 8.

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[22] Partly due to using the installed heating system. For the first two cases above (M44 and M55-steady) we used electric fan heaters to reduce this effect.

[23] R-squared is a measure of the extent to which the measured variation in heat flux is accounted for by the model. If R-squared is greater than 0.5, that means our model accounts for at least half the variation in observed heat flux. Most cases are much better than this. Low values for R-squared indicate that there are other effects not included in the model, for example heat transfer within the wall from warmer rooms to cold.

[24] The p-value is the probability of getting the observed, or a more extreme, set of data. A value of less than 0.05 suggests we should reject the null hypothesis (there is no difference). Therefore, in Figure 4.5 obtaining a p-value of 0.02 suggests that it is probable that there is a statistically significant relationship between model outputs (R-squared) and temperature consistency.

Our model does not allow for heat transfer from one part of the wall to another due to temperature gradients between rooms. Where these heat gradients are variable, the model explains less of the observed variation in heat flux (low R-squared). Of greater concern are the cases where the heat gradients are consistent because these lead to model bias. However, if the measured locations are representative, the effect is cancelled out by averaging over the whole wall.

7. Estimating average in-situ U-values

8.

In the first winter of taking measurements for this project we measured heat flux at three locations in each party wall. However, it became apparent that there were often considerable differences across a single wall and it was not possible to get a reliable average from such a small number of locations. However, evidence from the intensive house measurements showed that in-situ U-values generally vary smoothly and if there are severe aberrations they are mainly at the edges (near external walls, the floor or roof). This means a reasonable average can be obtained by interpolation from just one location at the centre and others fairly close to the corners (so the average is not distorted by local effects that affect only a very small fraction of the wall).

Key Message

We updated our methods over the course of the project to incorporate learning from successive measurements – raising the number of sensors used, and lengthening the period of study. We also developed a novel way to extrapolate from a small number of data-points the whole-wall U-value estimate.

We developed a method for estimating the average in-situ U-value across the whole wall using interpolation from a few spot measurements at arbitrary locations. Our method is as follows:

- We create a 5 x 5 grid of points evenly spaced over the wall and estimate the U-value for each grid point, then take the average of these.
- To estimate the in-situ U-value for each grid point, we use the average of all the known points on the wall, weighted by the reciprocal of the distance squared. This means each point is most influenced by its neighbours and less influenced by measurements far away.
- For grid points on the edges, we move them inside such that they are within the bounding box of the known values.

Figure 5.1 below shows an example. The green circles are the measurement points and the blue are the grids, or estimated values.

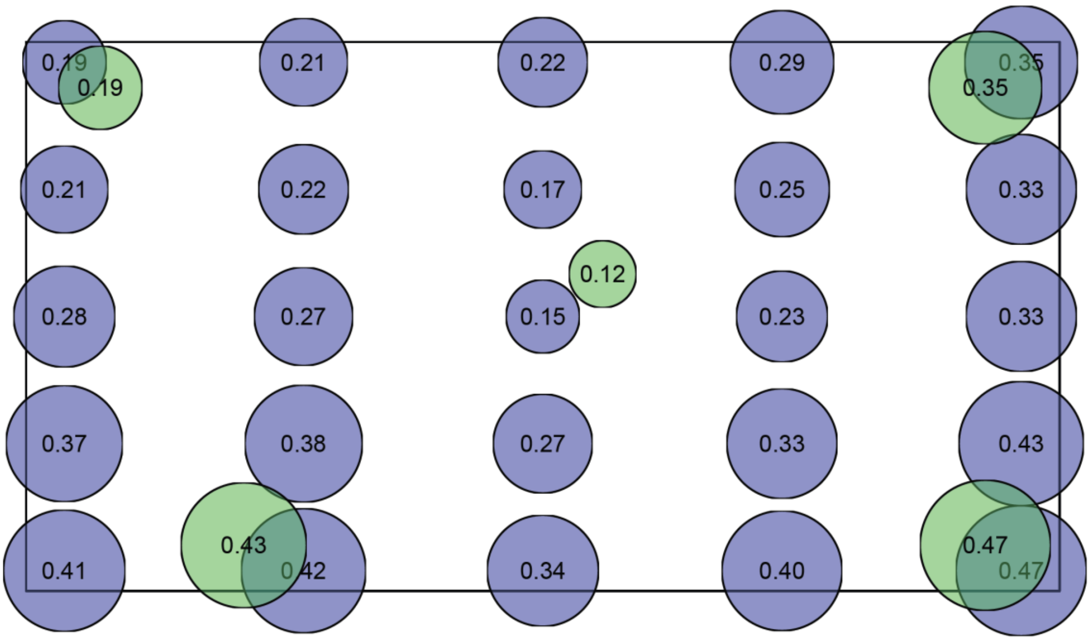

Figure 5.1 Averaging interpolation of the spot estimates for in-situ U-values for house W58. Green circles are spot measurements, blue are interpolated. The average in this case is 0.3 W/m^2/K.

The inverse distance squared weighting method is common in interpolating missing data for geographical information systems [25].

Where there are anomalies right at the edge, this method will underestimate them. However, the area of the wall affected is small. For example, if the measurements are 300mm from the edges (as we did where possible) and the wall is 6 x 8m, then the area outside the measurements is only 18% of the area. If the estimate in this region is 10% lower than the true value, the bias in the overall average is less than 2% (18% × 10% = 1.8%). If heat loss in the extreme edge is double the average elsewhere, this still leads to a bias of only 9%.

On the other hand, if this is a very local effect, then moving our measurement points even closer to the edge will find higher values and bias the overall average upwards.

We have used this method to find average U-values in cases where we have at least five spot estimates on the wall. If there are fewer, then a simple average is just as good (see Figure 5.2 below). Also, in the intensive cases where we have many spot locations, a simple average suffices. The following chart shows the difference between the interpolated mean and the simple mean. In practice it makes little difference, so the interpolated means are not reported here.

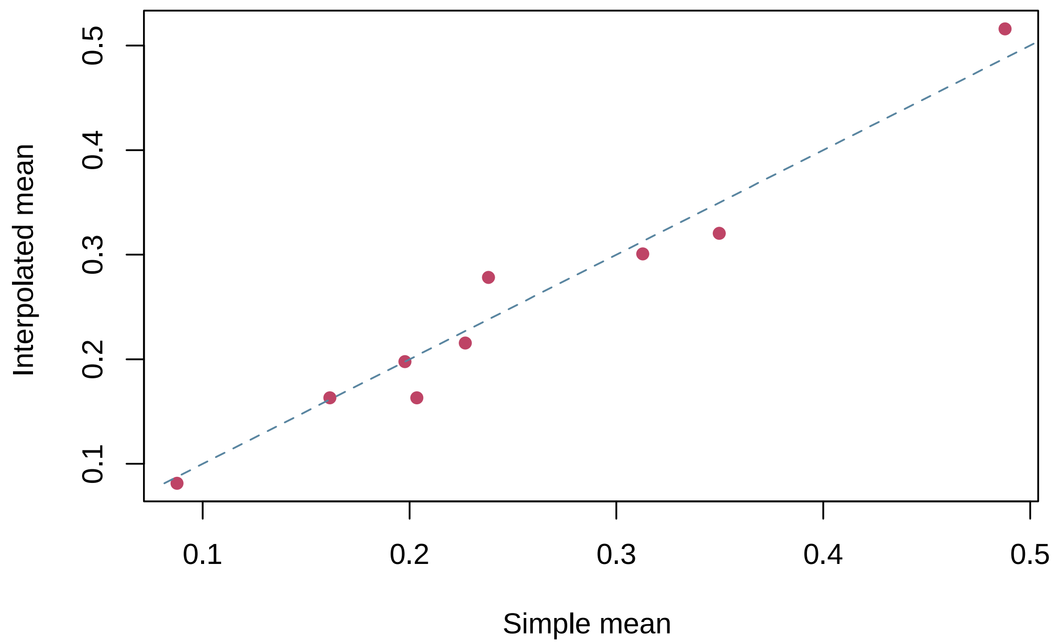

Figure 5.2 Comparison of in-situ U-values by interpolation (inverse distance squared weighting) compared to the simple mean. The dashed line indicates X=Y.

[25] Interpolation: Inverse Distance Weighting from National Centre for Geographic Information and Analysis http://www.ncgia.ucsb.edu/pubs/spherekit/inverse.html

Finding confidence ranges in the in-situ U-value estimates

The method we used to optimise parameters in the model gives uncertainty ranges for each parameter. To determine uncertainty for the U-values, we applied Monte Carlo techniques assuming a normal distribution for each parameter. However, the resulting uncertainty ranges were small compared to the difference in spot values across the wall. From this it was clear that the variation across each wall was the main source of uncertainty and we used this to generate the uncertainty ranges reported below.

There were three different dwellings where we monitored at 14 or more locations. We calculated the average standard deviation (sd) of in-situ U-value estimates from these cases, in the absence of any better distribution data, to represent the standard deviation for the population where there were fewer monitoring locations.

We then calculated confidence ranges based on the standard deviation of the mean as sd/sqrt(N), where N is the number of samples. Where the confidence range included negative values we excluded them, truncating the range to zero because negative U-values values are not possible for heat loss to outside.

These uncertainty ranges are conservative because:

(a) One of the three dwellings had a larger than usual in-situ U-value and large standard deviation
(b) In practice the locations we chose were not random. We selected locations that were well separated on the wall.

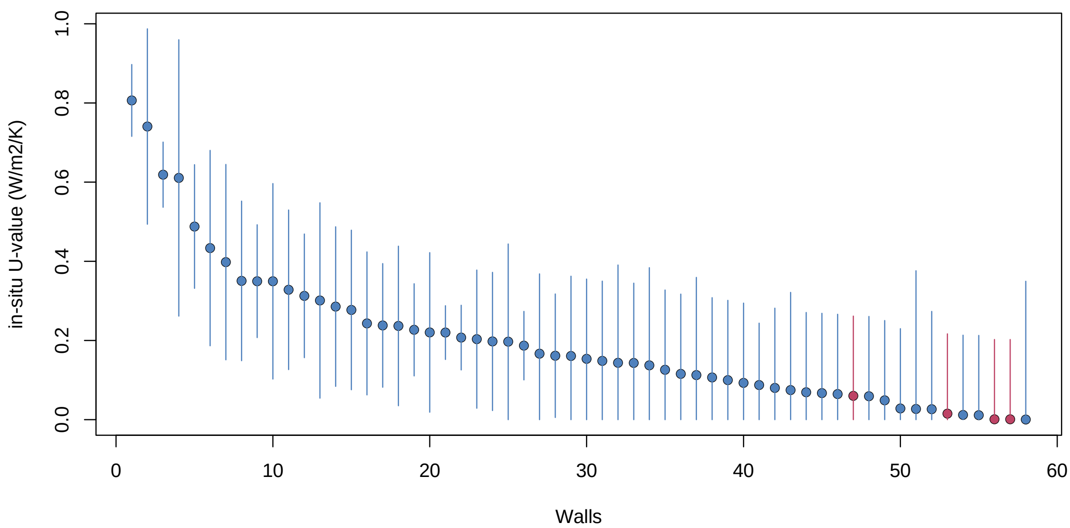

Figure 5.3 In-situ U-value estimates for each dwelling, averaged over all locations on the wall. Un-insulated cases are blue, insulated cases are red. The dots are the estimates and the lines indicate the 95% confidence range. The more monitoring locations, the tighter the confidence interval.

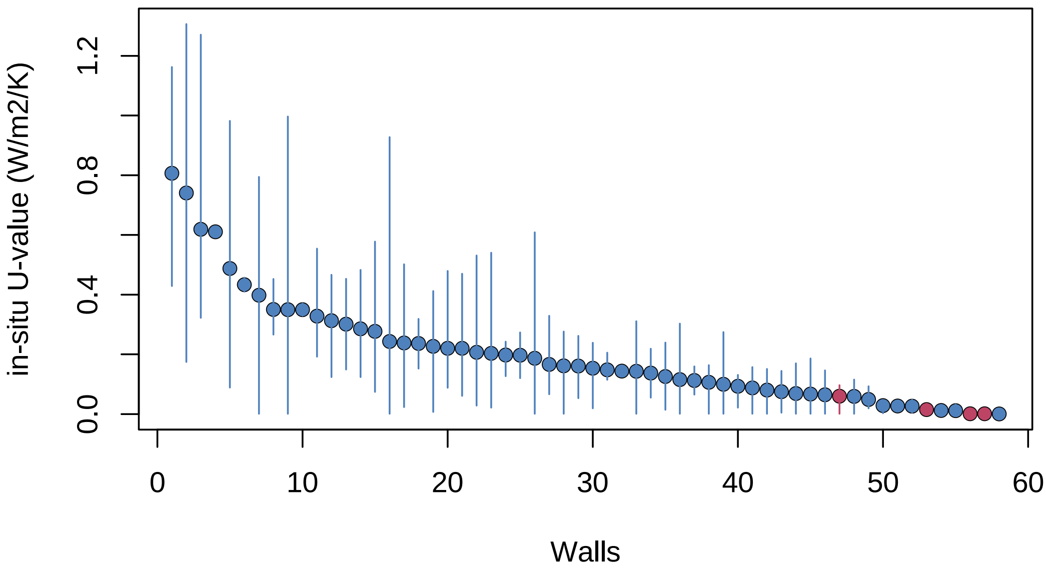

Figure 5.4 In-situ U-value estimates for each dwelling, averaged over all locations on the wall. Un-insulated cases are blue, insulated cases are red. The dots are the estimates and the lines indicate the range between minimum and maximum estimates for the wall.

Excluding uncertainty and the four insulated cases, the overall mean in-situ U-value is 0.21 W/m^2/K. The median is 0.16 and for 77% of the dwellings it was less than 0.30 W/m^2/K.

Differences between different constructions of party wall

We also compared average in-situ U-values for walls of different construction types, as shown in the charts in Appendix C. There were no significant differences between block and brick construction, capped at joists vs. capped at full height vs. uncapped, solid or suspended floor, or with and without external cavity-wall insulation. These were all counter-intuitive findings, and prior to this research it seemed reasonable to think that uncapped party walls would have higher in-situ U-values. The only factor to make a statistically-significant difference was insulation in the party cavity wall, see Figure 5.5 below. All this suggests that other factors, including missing bricks or holes in the party wall, poor seals at the floor-wall, party wall-external wall and party wall-roof junctions, are more important than the construction type.

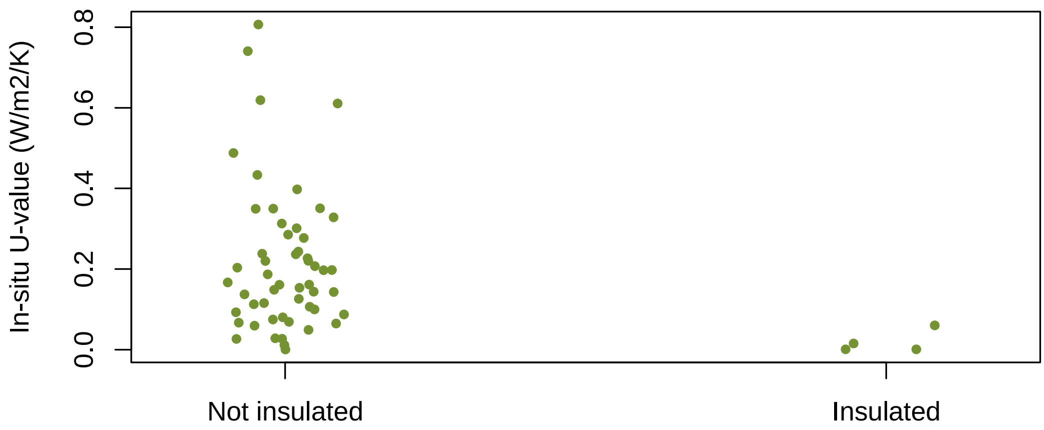

Figure 5.5 The only statistically significant relationship was between in-situ U-value and the presence of insulation in the party cavity. (Other equivalent plots are included in Appendix C.)

8. Air velocities in the cavity and wind speed

Intuitively, you would expect wind speed to have an impact on heat loss through the party cavity as it raises the velocity of air movement in the cavity, and washes heat from the external walls and the roof of the house. This creates a greater temperature difference between the external face of the building components and the internal face. However, none of our approaches to improve the model by incorporating wind speed succeeded in improving model fit, so the evidence did not support our starting hypothesis.

Key Message

We were surprised to find that wind had little effect on cavity air speed or temperature. Even when there was an effect it was not always in the expected direction: there were some high wind speeds associated with low cavity speeds. This suggests that wind interacts with convection in the cavity in complex ways. We found no evidence that high winds increase heat loss.

In order to further our understanding of wind and heat loss, we monitored air flow and temperature within the cavity in five dwellings. Unfortunately this is an invasive technique that involves drilling holes in the party wall to insert air velocity sensors, and once again we were limited to spot measurements, and only in homes where the occupants were prepared to allow invasive tests. The most complete data is for House M57, where we monitored air speed at five separate locations. In four other cases we measured air speed at two places in the cavity.

The results were not at all as we expected. We found evidence that cavity air speed is influenced by wind but the effects are localised, and often high winds drive lower speeds. This suggests that wind interacts with convection in the cavity in a complex way. We found no firm evidence that wind was significantly influencing heat loss in ways that are not accounted for by temperature. This suggests that exchange of air with the external environment is not the primary mechanism of thermal bypass in a majority of homes (which could also explain why there was no significant difference between capped and uncapped cavities). For these five dwellings, openings between the party-wall cavity and outside are not the root cause of heat loss through the party walls.

The five locations in M57 were arranged as shown in Figure 6.1 below.

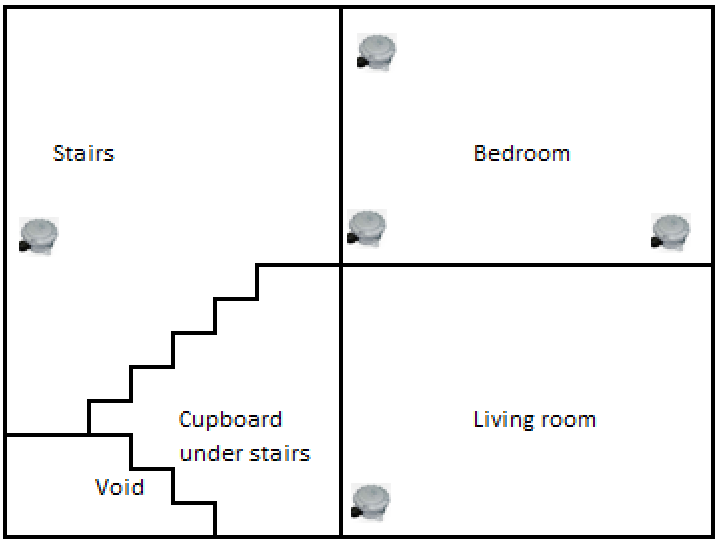

Figure 6.1 Arrangement of cavity air flow measurements in M57. The top and bottom measurements were of vertical wind speeds (Bed2topA and liv1botA) and the three across the middle were horizontal (Stairs2Fbot, Bed2botA, Bed2botD).

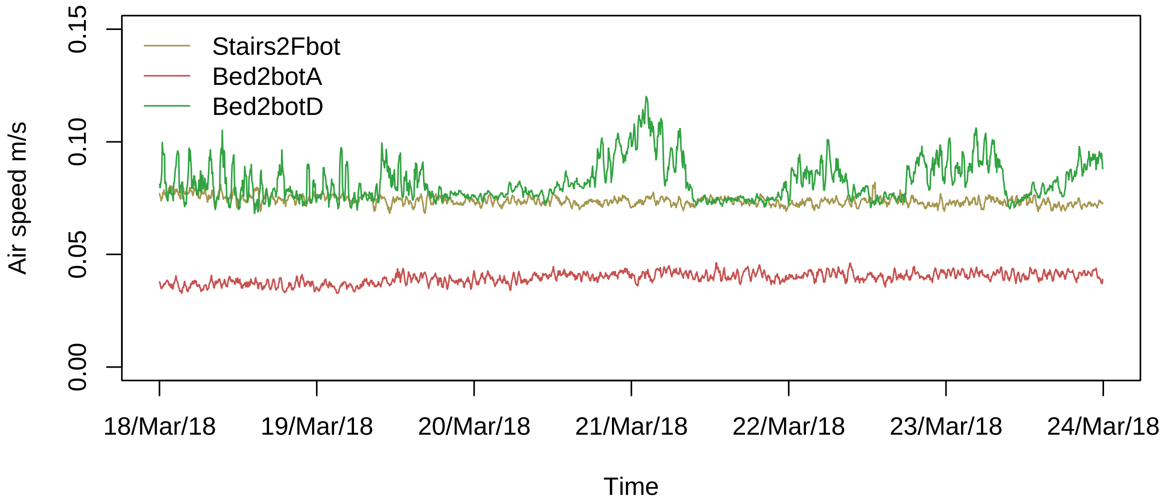

Figure 6.2 Horizontal Cavity air speeds in M57. Bed2bodD (nearest the thermal bypass) is by far the most variable.

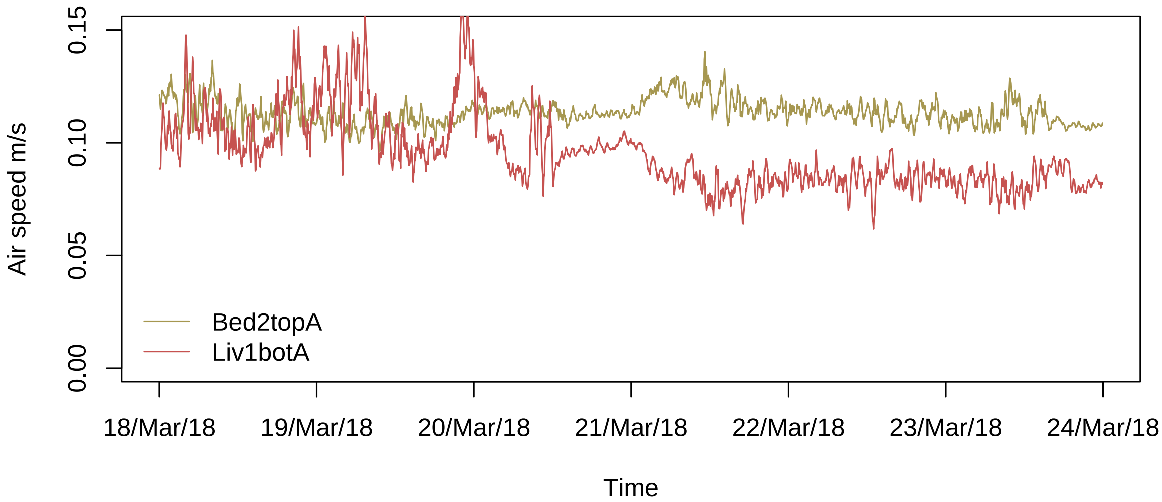

Figure 6.3 Vertical air speeds in M57. These are both variable, but do not correlate with each other.

First, we looked for correlations between wind speed and cavity air speed. We checked for correlations with scalar wind speed (regardless of direction) and also with wind speed in different directions, calculating the component for 18 different directions around a half circle. Wind was significant in all cases, but the correlations were very low. There were also correlations between wind speed and air temperature, so to separate these effects we performed regression analysis to see if wind and external temperature together were better than just external temperature in explaining the cavity air speed. Only in one case did wind improve the analysis by more than 10% (House C27). There was moderate improvement (1% to 10%) in about half the cases. These values are very low, suggesting that factors other than wind are more important.

We were surprised that the wind coefficient was negative in four out of seven cases where there was a discernible effect (possibly because the wind runs counter to the convection currents in the cavity). This implies that cavity air speed was lower when winds were stronger. Also, in all of these cases it did not matter which way the wind was blowing.

Since wind clearly does not make a big difference to cavity air speed in our sample, we continued our investigation to identify the factors that do. By adding modelled values for the wall temperatures (on the average of both sides) and the heat flux from both sides to the cavity/outside we obtained moderately high R-squared values (> 0.3) in about half the cases (for table see Appendix E). As before, wind added little to the regression, even though it was statistically significant. In the best case, the R-squared was 0.63. Usually, high cavity speeds were associated with low external air temperatures and high wall temperatures, but this was not consistent and clearly there are more complex processes involved.

As well as cavity air speeds, we measured cavity air temperatures. (In M57 cavity temperature measurements were taken in more locations than air speed monitors). Using the same regression as for cavity air speed (i.e. mean modelled wall temperature and flux as well as external air temperature and wind) we found these gave a much better explanation of cavity air temperature than air speed. The R-squared values were between 0.72 and 0.98. However, the relative impact of wind was less: at most 0.05.

High cavity temperatures were mostly associated with high external temperature and modelled wall temperatures. However, this was not always the case, suggesting the mechanism linking the two is neither direct nor simple. It may relate to heat transfer between different parts of the wall: a combination of conduction through masonry and convection within the cavity. This could also explain how wind may have an indirect effect on temperatures and cavity air speed that could be either positive or negative: wind may affect some parts of the dwelling more than others and so change temperature gradients and convection patterns within the cavity, but it was not possible to study these effects in detail.

The R-squared values for cavity air temperature in M57 were lower than in other dwellings, probably due to the effects of the thermal bypass (at 1st floor level on the right, see Figure 4.4) complicating the process further. The following chart shows average wall-surface temperature (on the room side) and average cavity-wall temperature at each location in M57. Cavity temperatures are relatively low in the living room. This is especially so at the bottom right, but this is expected from the model which has a high in-situ U-value and low modelled wall temperature at that point. The effect of external temperature was greatest at Bed2botD (for details see the Appendix), where the known bypass is visible by infrared imaging. In some other parts of the dwelling the cavity temperature is actually warmer than the wall surface. This is probably due to heat transfer from other parts of the wall.

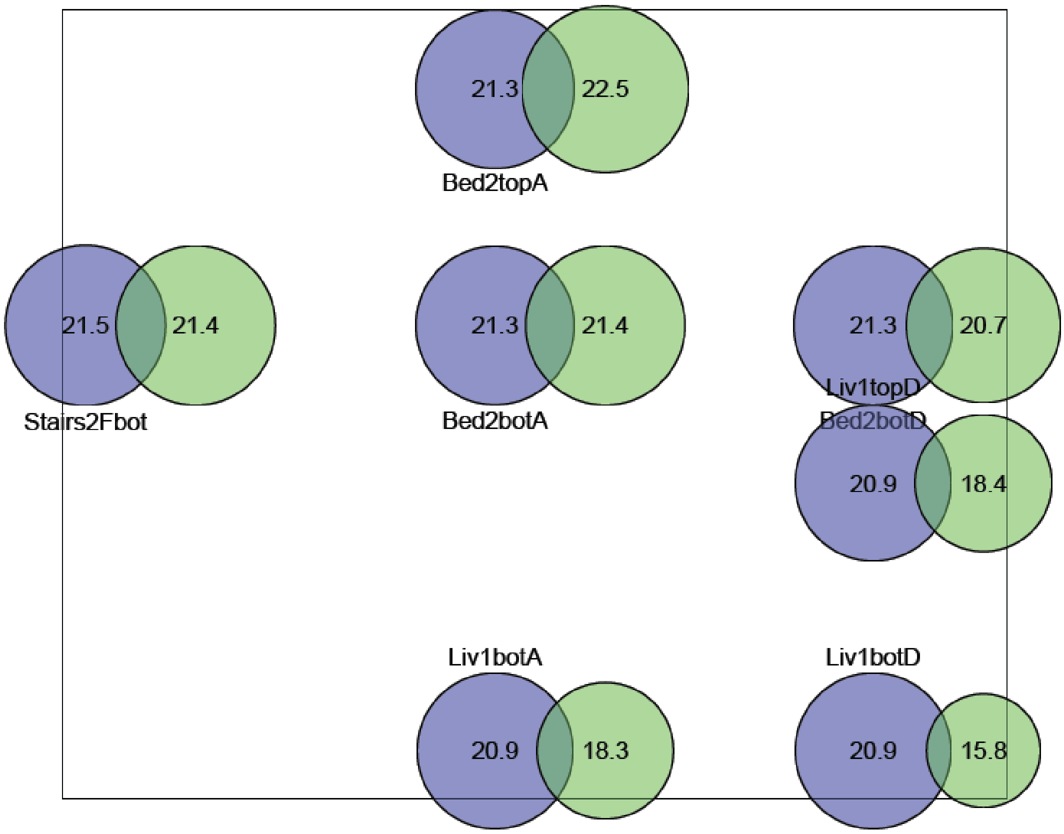

Figure 6.4 Mean wall surface temperature (blue) and cavity air temperature (green) at different locations in the wall for M57. All temperatures are in °C. Circles are scaled for the temperature displayed.

In conclusion, from the limited number of measurements undertaken on a small sample of dwellings, wind appears to have little effect on cavity air speed and when it does, the effects seem to be localised. (Possibly because they all have well sealed party walls.) High winds seem to reduce cavity air speed in four out of seven cases rather than the opposite. The cavity air temperatures are affected by wind even less than air speed, supporting the finding that if wind speed has an impact on heat loss it mostly accounted for the impact on effective external temperature. Wind may have an indirect effect by influencing temperatures in different parts of the house and hence temperature gradients within the wall. Near the known thermal bypass in M57, the external temperature has a stronger effect than at other locations in the wall, and the effect of wind is also discernible.

9. Validating methods

The model we use to determine the party wall in-situ U-values is necessarily simplistic and inexact – the question is, are the U-values sufficiently accurate to be useful? We would argue that spot measurements are not reliable enough, as there is considerable variation from location to location along the wall. Interventions should be based on a series of measurements that can be averaged for one wall, reducing the effect of local variations.

Key Message

We validated the method in several ways. The analysis gives fairly consistent results from different periods with the same heating regime. When the heating regime was changed, the patterns of heat loss across the wall changed but the overall heat loss was similar. This shows that spot measurements can be misleading and averaging over the wall is necessary to get a useful result.

We have used a number of approaches to validate the results of our work.

1) In cases where we have measurements over a sufficiently long period that we can split this into two, we compared estimates for the same location in different time periods.
2) In cases where we were able to carry out back-to-back measurements, we measured the same wall from both sides to see if we could get consistent results.
3) In cases where we were able to maintain a steady temperature in the room, we compared the results with an alternative, simpler model, similar to that used in studies of U-values for external walls.

Consistency over time

For this check we looked at locations where we had measurements over at least 20 days. There were 84 sets of measurements from 30 different dwellings. We divided the monitoring period into two halves, ran the model on each, and compared the results. Figure 7.1 below shows the results. Red dots illustrate cases where there was a good result in both cases. There is one blue circle, for a case which did not converge in the second half. The dashed line represents x=y and ideally every point would lie on this line, with the same result in both time periods.

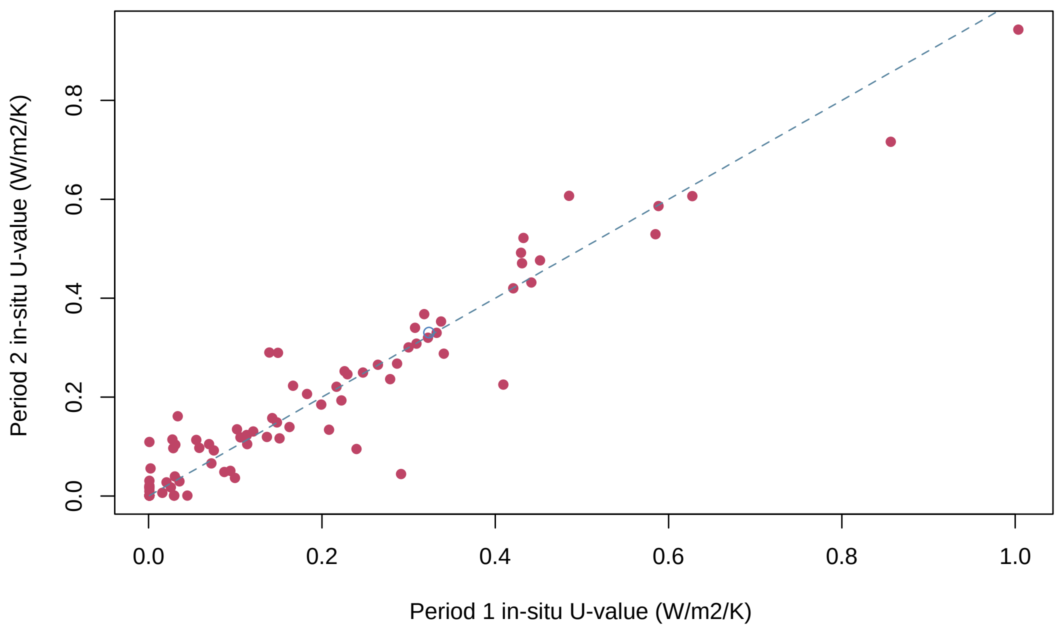

Figure 7.1 Comparing in-situ U-value estimates for the same location over two time periods, not overlapping.

There is no obvious consistency in differences with regard to weather. Five out of 30 dwellings showed an increased U-value at all locations, and four decreased, but these were not obviously correlated in location or time. For example, in the second group of Cambridge homes (monitored Dec/16 to Jan/17) there were two where the in-situ U-value estimate increased at all locations (C11 and C12) and one where it consistently fell (C8).

We monitored House 55 in 14 locations and over two phases. The house was unoccupied throughout and in Phase 1 we maintained a fairly steady temperature regime, while in Phase 2 we simulated a conventional heating regime. Figure 7.2 below shows the two regimes.

In the steady regime, temperatures varied in most locations by no more than 1°C. However, there were differences of up to 4°C between locations. In the conventional regime the differences between locations were slightly reduced, but at any location there were swings of up to 4°C within the daily cycles. Also the patterns of temperature from one part of the wall to another were different. In the conventional regime the coolest location was in bathroom, but in the steady regime the kitchen was the coldest, which was below the bathroom (see Figure 4.3 for a diagram of the layout).

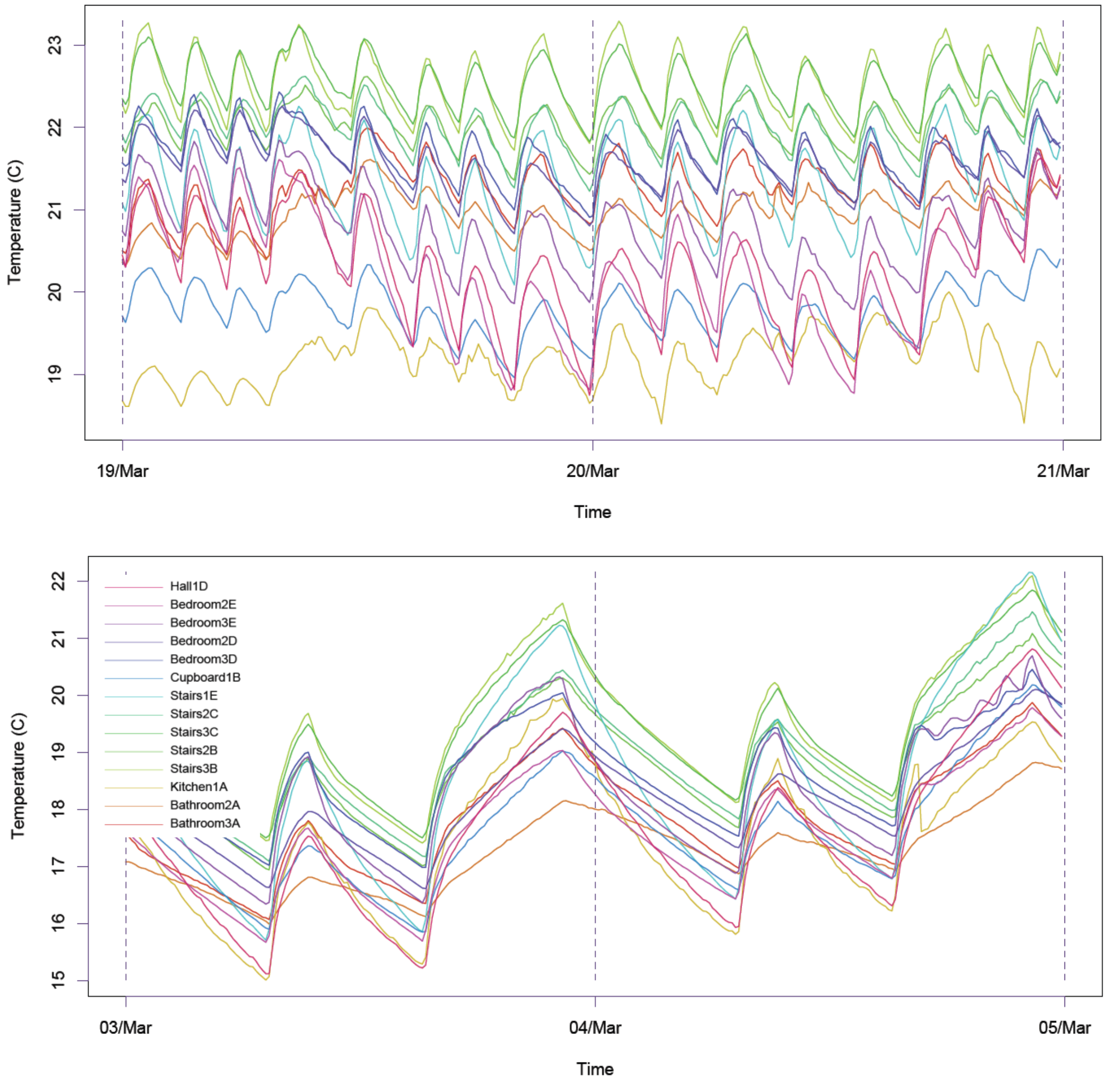

Figure 7.2 Temperatures in Phase 1 ("steady", top) were much more consistent than Phase 2 ("conventional heating", bottom) for House 55, but even Phase 1 was far from constant temperature. There were also considerable variations from room to room.

There is poor agreement in results from the same locations in the two cases. We believe this is due to changes in the rate and pattern of heat transfer within the wall between rooms. (The mechanism for this transfer could be partly conduction within the masonry wall but convective transfer in the cavity is likely to be more dominant). In the steady-temperature phase, the temperature difference between the hottest and coldest parts of the house was smaller, and the temperature changes in different parts of the wall were more consistent. However, the mean in-situ U-value across the whole wall in both cases was similar: 0.22 $W/m^2/K$ in the conventional (dynamic) phase, and 0.21 $W/m^2/K$ in the steady phase. This is as expected given that bias due to temperature flow within the wall should cancel out when measurements over the whole wall is considered. This is a positive finding and gives confidence in the data and analysis.

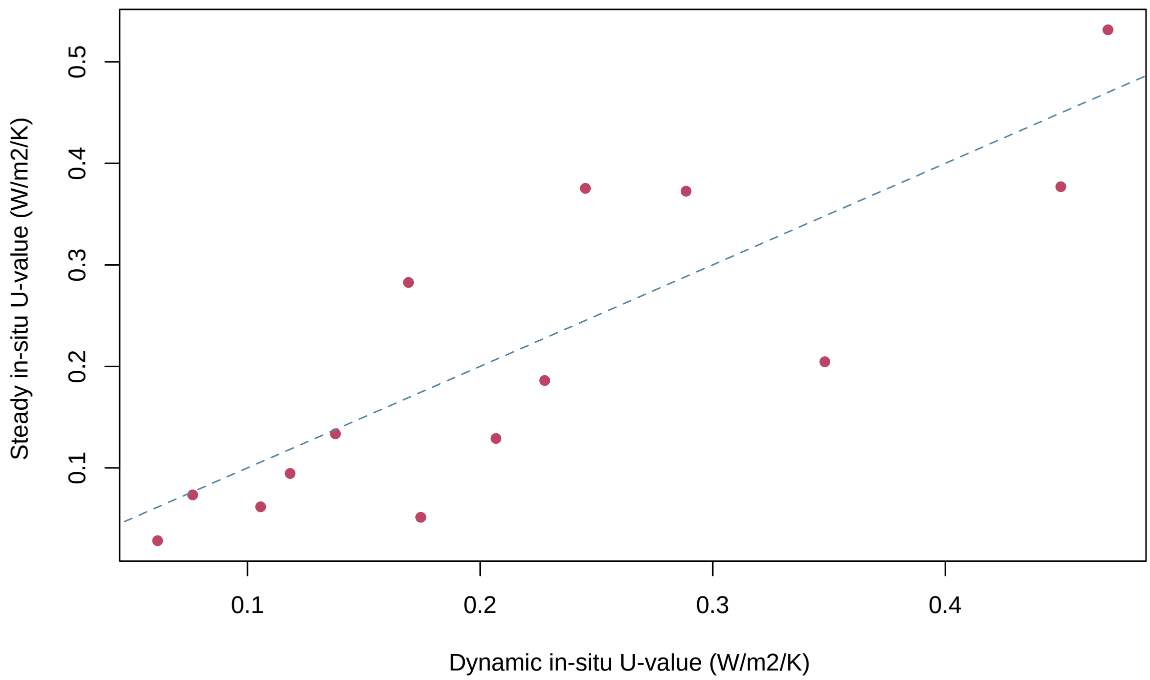

Figure 7.3 Comparing in-situ U-values under different temperature regimes.

Back-to-back measurements

There were two cases where we were successful in taking measurements with heat flux plates and temperatures on both sides of the wall, opposite each other (C25 and C26). Assuming the construction is the same on both sides, with no irregularities, we would expect similar results from either side. We also developed a modification to the model which allowed us to analyse the wall using both sets of data at once (see Appendix F). The following charts show results for the two houses instrumented like this (three locations in one, five in the other).

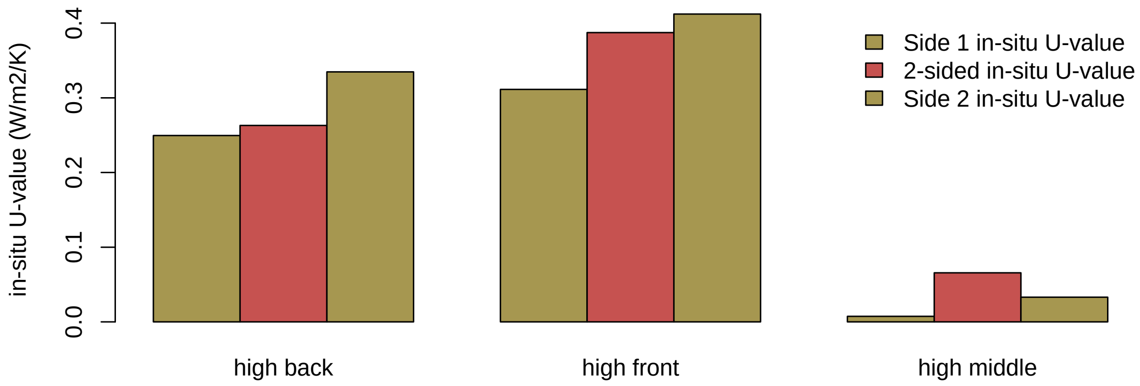

Figure 7.4 Back to back in-situ U-value estimates for C25

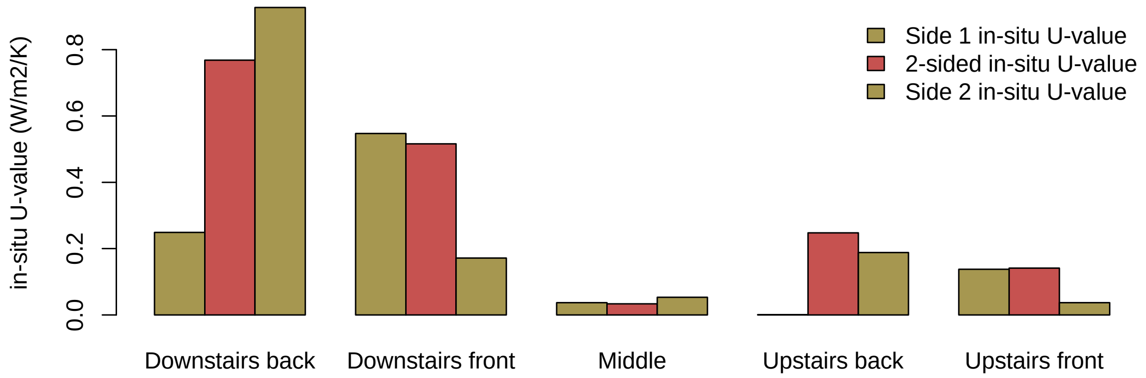

Figure 7.5 Back to back in-situ U-value estimates for C26 (red bars show estimates using data from both sides of the party wall)

For house C25, the results from the two sides are similar and the two-sided case is in between or close. However, for house C26, the results from the two sides are much less consistent. We believe this is due mainly to heat transfer between different locations on each side of the wall (discussed earlier, in the section *Trends in-situ U-values*). This introduced bias in the local heat flux and there is no reason to assume the pattern would be the same on the two sides. In this house there is a difference of 5˚C between the warmest and coolest part of the wall on the main house side and more than 4˚C difference on the neighbour side. Different forms of heat transfer could potentially explain this, but the model fit is not as good in house C25: the mean R-squared for C26 is 0.61, while for C25 it is 0.91. This shows that the results are more reliable when there is a good model fit with high R-squared.

Steady temperatures, using regression

In early analysis work in this study, we estimated the U-value for the cavity wall using daily averages for the heat flux density and the various temperatures (room surface temperature, neighbour temperature, external temperature). This method is a development of the way that U-values for external walls are conventionally measured. It does not take into account the effect of thermal mass and the results are not reliable unless this is minimised; we did this by keeping the room temperature very steady on the side where we could and using daily averages to even out the swings on the other side. Instead of using 10-minute intervals as usual, we used whole days. We used this technique in two cases (M55-steady and M57). Here we compare the estimated in-situ U-values from both methods. The red dots indicate cases where both methods yield good results. (For details see

Appendix F: Validating methods). The results show good agreement in both cases, even when the regression result was not classed as good (blue circles rather than red dots), usually because the U-value coefficient was not significant. (This often occurs when the coefficient is small and so the heat flow to the outside is small.)

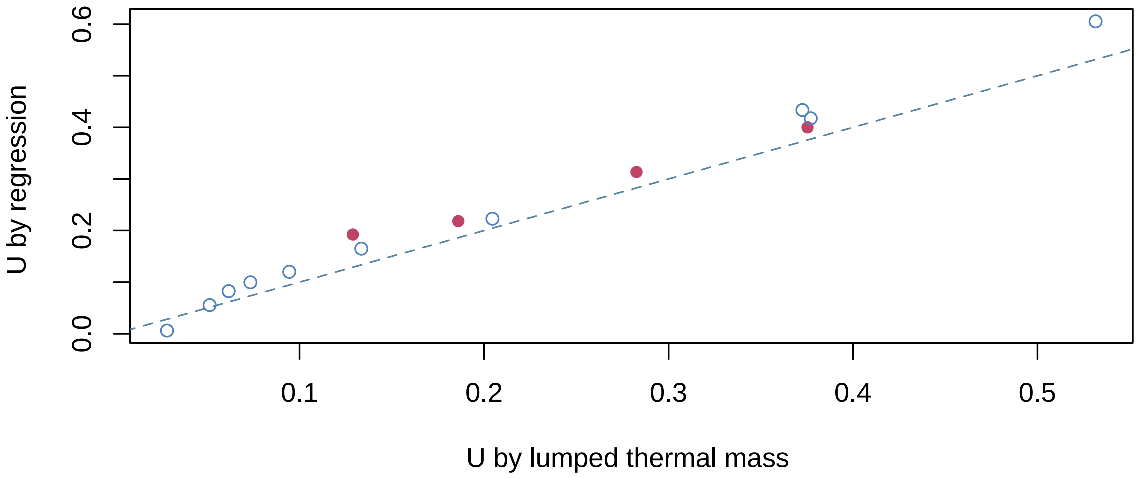

Figure 7.6 Comparing estiimates for in-situ U-values by two different methods for M55-steady. Red dots indicate good results from both methods.

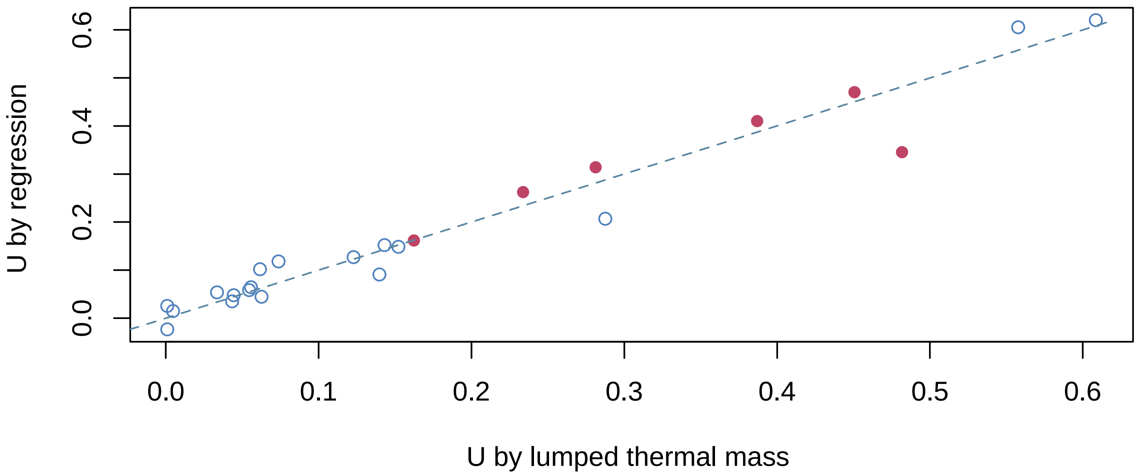

Figure 7.7 Comparing estiimates for in-situ U-values by two different methods for M57. Red dots indicate good results from both methods.

The next chart shows house M55 under a different temperature regime, simulating normal occupancy. This shows very poor agreement because of thermal mass effects – erratic fluctuations of temperature make it harder to model U-values for individual points reliably.

These comparisons show that the lumped thermal mass model gives results consistent with the regression methods used previously, under conditions when they are applicable.

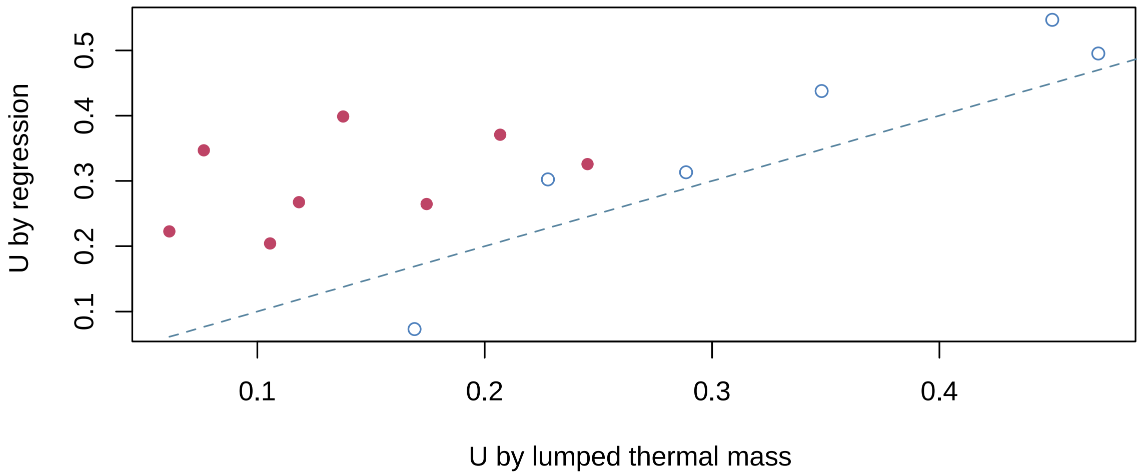

Figure 7.8 Comparing estiimates for in-situ U-values by two different methods for M55 under a normal temperature regime. Thermal mass effects disrupt the regresssion method so that the correlation is poor. Again, red dots indicate good results from both methods.

Summary

In this section we have shown that our model gives results that are reasonably consistent over time – albeit less so in the cases where the in-situ U-value is low or when the temperature regime has been changed.

We have also shown that when the model is used on the same locations on opposite sides of the wall at the same time, the results are consistent when the model has given a good fit. In the case where it did not, we believe the poor fit and inconsistent results were due to heat flux within the wall on each side: heat flowing from warm parts of the house to coolers areas (discussed above).

Finally, we have shown that the model gives results consistent with a more conventional method, which can only be applied in unoccupied homes. This method requires that temperatures are maintained as steady as possible to minimise thermal mass effects in the wall. The model we have developed using lumped thermal mass has much wider application because it can be used in occupied homes.

Conclusions and Recommendations for Further Research

Key Message

This was challenging research that required new methods of analysis that could be applied in other fields. We learned about recruiting households into scientific studies, and categorising party walls, and location and wind effects on heat loss through party walls. We found the mean in-situ U-value for party walls in this study was 0.21 W/m^{2}K.

This research of heat loss through party walls in occupied homes was innovative, and none of the previously-existing methods were adequate for interpreting measurements. Fluctuating temperatures and heat moving between neighbouring dwellings – as well as from inside to outside – made analysis complicated, and the use of these measurements to estimate in-situ U-values required us to develop a new model. This was used with novel instrumentation, including heat-flux measurements linked to weather stations, and invasive in-use tests with instruments monitoring air speeds in party-wall cavities to develop new methods of analysis.

These analysis methods have wide potential application because (unlike alternative methods requiring constant temperatures) they can be used in occupied homes. We validated these novel methods of analysis in three ways and this provided confidence in our results.

This research project took 284 measurements on the party walls of 54 different homes. Our model used this data to estimate the in-situ U-values of each party wall, and we found values from 0.001 to 1.3 W/m^{2}K. The mean in-situ U-value was 0.21 W/m^{2}K. These values are significantly lower than previous research – perhaps because past research has focused on modern homes built since 2000, with dry plastering methods and so potentially larger openings to the party wall.

Recruiting households into scientific research

By far the most successful means of recruiting households into this study was by personal recommendation and word-of-mouth. Having trust in the person suggesting participation (ideally from a friend or family member) seemed to be as important as a financial incentive for many people.

There was some evidence from the recruitment and engagement parts of this study about householders' interest in energy efficiency and learning about their own homes' energy performance, albeit limited evidence. A large majority of householders were not sufficiently interested in these issues to participate in a study – even with a financial incentive between £50 and £400. The minority of households that were sufficiently interested in their homes' energy use to participate in the study (estimated at less than 3%: 110 households out of around 4,000 that saw advertisements and had a home built in the right period) fell into one of three groups. The first group, accounting for around half of participants, were generally interested in energy and climate change.

The second group, accounting for around one third of participants nationally, were interested in science and helping to advance knowledge about household energy use. There was some overlap between this and Group 1, with in the region of 10% of participants interested in both science and energy/climate change. And the final group, accounting for around a quarter of participants, was motivated mainly by the financial incentive (again, with some overlap between Groups 1 and 2).

There may be ways to capitalise on householder interest in energy, climate change or science to help this minority of homes learn more about their energy use. These are questions for further research. However, based on limited evidence from this study, such efforts will have little traction in the majority of households – even when there are clear financial benefits from doing so (here, from the incentive payments, elsewhere, this could be savings from energy bills).

For households that are not strongly motivated by science or energy and climate change, the benefits of learning about potential energy efficiency opportunities are uncertain and apparently insufficient to offset the costs, including the hassle connected with making appointments for equipment installation, and a general dislike of letting strangers into the home.

Categorising the housing stock

One of the most significant findings of this study is that very little can be reported with exactitude about the cavity party walls to be found in English houses. It is very difficult to say how many homes overall may be classified into the four party-wall categories defined on pages 4 and 5 above. We examined planning applications for more than 2000 new homes built since 1980, in the North and the South of England. This suggested that the majority, 85%, of homes built since 1980 have cavity party walls (Types 2-4), but it was not possible to disaggregate any further because the detailed party wall construction was not described in planning drawings.

Our physical inspections of the roofs of a smaller sample of homes in the North and the South – 110 homes in total, all built from 1940 to 2010 – suggested that around half had solid party walls (Type 1), with the remainder divided into 63% full-height cavity (Type 2), 17% capped at the roof joists (Type 3), and 20% capped at the ridge (Type 4). If this modest sample is representative of the whole English housing stock, then there are around 7.3 million dwellings with potential for insulating party walls. This estimate should be treated with some caution, and the likely range is 6.8 to 7.8 million homes.

An analysis of more recently constructed homes, like the homes built since 1980 (and particularly since 2000) where planning drawings were available, suggested that cavity-party walls may be becoming more common, so the proportion of such homes may well be growing slowly over time, as new build dwellings are added to the stock and older dwellings are demolished.

Our work showed that the critical distinction is between homes with solid and cavity party walls. Based on a sample of 54 dwellings where tests have been undertaken, and 284 individual measurements, there is no statistically significant relationship between heat loss through the party wall and construction Types 2 to 4. This means that further research aimed at identifying these sub-groups using other construction clues, or the age or location of properties, appears to be unwarranted for energy-saving motives.

Location effects

It is broadly true, across 54 instrumented homes, that the highest in-situ U-values occur at the edges of the party wall, close to external walls (although there were three exceptions, where very low in-situ U-values were recorded close to external walls). It is likely that this relatively high heat loss from the party wall to the external wall occurs because of poor thermal separation between the party and external wall – either through conduction due to thermal bridging (heat carried by bricks or mortar from the party to the external wall) or convection due to a thermal bypass (air moving from the party wall cavity to the outside wall, or vice-versa and bypassing the thermal insulation).

It may be possible to improve the thermal separation of the party wall from the external wall. This undoubtedly happens if the party wall is insulated completely, but this may also be possible by retrofitting a thermal break like a cavity sock between the party wall and the external wall (perhaps accessed from above, in the loft), or by ensuring that external cavity insulation prevents air from passing from the party cavity into the external wall cavity. These strategies both merit further research.

Across the 54 homes, we also found that none of the very low in-situ U-values occur towards the bottom of the party wall, close to the ground floor-party wall junction. This may also offer potential as an upgrade strategy for new homes, so that floor insulation extends into the cavity of homes with cavity party walls, or an insulated cavity sock is placed in the party-wall cavity where the party wall meets the floor. However, difficult access means this may not be possible as a retrofit upgrade. Again, further research would be valuable.

We could find no statistically significant correlations between heat loss through the party wall and dwellings being located in the North or South of England, or different forms of construction in terms of block or brick, ground floor construction, external cavity-wall insulation or other characteristics that are discernible without carrying out detailed measurements. This suggests that other factors, including missing bricks or holes in the party wall, poor seals at the floor-wall, party wall-external wall and party wall-roof junctions, are more important than the construction type.

Wind effects
The wind/heat loss work we did does not support the hypothesis that higher wind speeds correlate to greater heat loss. Wind did have a small impact on cavity air speed, and to a lesser extent temperature. However, the mechanism was complex, interacting with convection patterns in the wall, and temperature was much more important. Based on this evidence there would be little benefit in targeting interventions in dwellings in windy regions.

Interventions
The four cases in this research where we obtained before-and-after measurements for party walls that were insulated were all party walls that were capped at the ridge. Three of these four witnessed very substantial reductions in the in-situ U-value of the party wall (from an average U-value of 0.07 W/m^2K down to virtually zero). However, the fourth insulated party wall saw a much smaller reduction in in-situ U-value: from 0.075 to 0.06 W/m^2K, and it remains unclear why this was the case. Again, further exploration of this anomalous finding would be justified.

It is very likely that dwellings with an uncapped cavity, or capped at the roof joists, would see similar and significant improvements in in-situ U-values if the party walls were fully insulated. It is also very likely that the other homes in this study, with a mean U-value of 0.21 W/m^2K, would also see in-situ U-values fall close to zero if the party-wall cavities were filled with insulation.

The highest average value for a property was 0.81 W/m^2K, for a bungalow with an uncapped full-height cavity in the party wall, cavity-wall insulation in the external walls, a suspended timber floor, and block cavity wall construction. There were six properties with un-insulated party walls with an in-situ U-value less than 0.05 W/m^2K. These mid-terraces or semi detached homes, with three different types of party cavity wall construction (Types 2, 3 and 4), with blockwork or brick party walls, and five out of six of them had solid concrete ground floors. This emphasises the point that construction type is not a good indicator of party-wall heat loss.

All six almost certainly have a very well sealed party-wall cavity, with no thermal bypass or air movement from the floor into the party wall, or the party wall to the external wall or roof. Although such good seals are almost impossible to detect visually, through this project we developed a simple qualitative field test that could be used when a hole was drilled into the party wall . We used a vacuum cleaner pipe around the hole, with the vacuum cleaner on, which gave audible and 'haptic' (by touch) feedback when the party wall was well sealed. A good seal created a strong suction between the pipe and the wall, and the vacuum cleaner motor worked much harder. This allowed us to distinguish between one very airtight cavity, and three that were tight but not as well sealed.

The high in-situ U-values for a bungalow (0.81 W/m^2K) may justify additional research of bungalows, and it is possible that bungalows offer greater potential savings than other house types – possibly because the ratio of perimeter (i.e. junctions with outside) to area is higher.

Extrapolating energy savings
Using the mean in-situ party-wall U-values from 54 homes instrumented in this study, and taking the English Housing Survey average wall area of 33m^2 for a semi-detached house – the most common English house type – allows an approximate estimate of typical savings from insulating party walls. This suggests that insulating an average cavity party wall would bring savings in the region of 0.8% of gas use for a typical semi detached property: an equivalent reduction in energy terms between 72 and 152 kWh a year.[26] For other kinds of dwelling the savings would approximately scale with the

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[26] This is based on a modelling in the Cambridge Housing Model for a 1950-1966 semi detached dwelling in the North West, with filled external cavities and a party wall area of 33m^2, reducing the U-value from the cavity wall from 0.21 to 0.0 $W/m^2/K$.
https://www.gov.uk/government/publications/cambridge-housing-model-and-user-guide

area of party wall. This compares with typical savings from cavity wall insulation of 6.5%, or from around 580 to 1240 kWh a year (based on actual reductions in gas bills analysed in the National Energy Efficiency Data Framework). [27]

This research did not explore the cost of insulating cavity-party walls, but the methods are similar (and anecdotally the costs are also similar) to external cavity-wall insulation: £480 to £660 per dwelling.[28] Depending on ease of access and the installer, this could cover the costs of insulating two party walls in a mid-terrace home.

Recommendations

Two recommendations for future research come out of this work. First, to explore methods of identifying the minority of homes with higher heat loss through party walls – say those with in-situ U-values of more than 0.5 W/m^{2}K. These may offer cost-effective opportunities for achieving energy and carbon savings, particularly if they are mid-terrace properties where both party walls could be insulated at the same time, and particularly if the party-wall insulation is combined with other work on the house (e.g. a loft conversion).

Second, to investigate the effect of party-wall heat loss and insulation as part of a combination of energy-efficiency upgrades to homes. It is likely that the proportion of heat lost through party walls increases as other thermal elements are improved. Particularly in the case of deep retrofit work – where homeowners try to pare down heat loss to the absolute minimum, improving the thermal efficiency of external walls, floor, roof, windows and doors, and improving air-tightness of the external envelope – the percentage of residual heat loss passing via cavity party walls may become significant

[27] BEIS (2018) NEED Framework Report: Summary of analysis 2018. London: BEIS. https://www.gov.uk/government/statistics/national-energy-efficiency-data-framework-need-report-summary-of-analysis-2018

[28] Palmer et al (2017) What does it cost to retrofit homes? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling. London: BEIS. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/656866/BEIS_Update_of_Domestic_Cost_Assumptions_031017.pdf

Appendices

Appendix A: Optimising the model and acceptance criteria

Figure A.1 below shows the result of a model run with optimised parameters showing a good fit (a better match than most model runs). The top graph shows heat flux density. The model optimisation aims to get the two blue lines showing measured and actual flux as close as possible. The bottom graph shows temperatures. The surface temperature (red dotted line) varies slightly less than the room temperature (red line). The wall surface temperatures vary more slowly because of the wall's thermal capacitance.

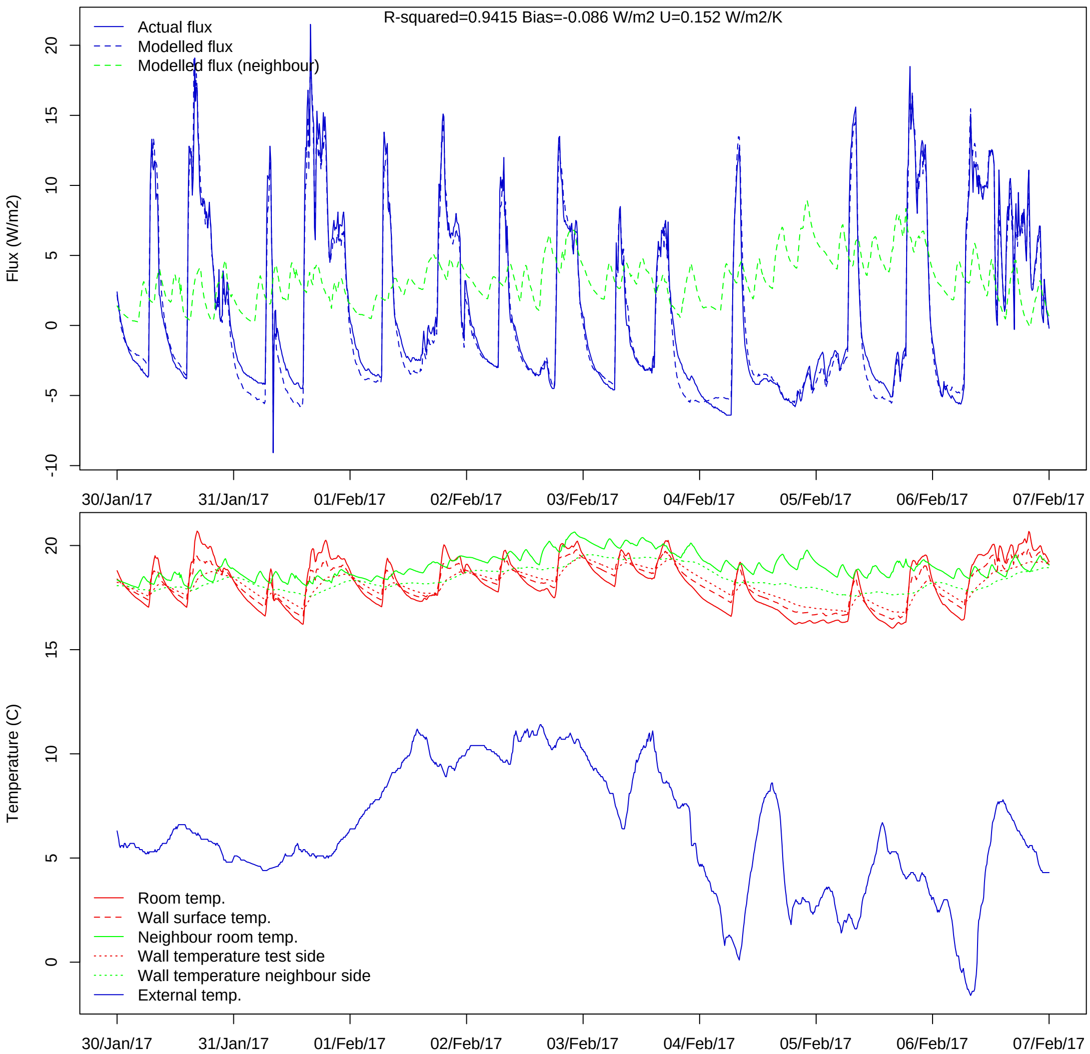

Figure A.1: House C15 flux and temperature measurements. High flux coincides with increasing temperature, when the heating is on.

The model optimiser searches for the combination of parameters that minimise the error as described above and stops when it finds a minimum. However, there were some cases where it failed to find a minimum within the maximum number of trial iterations or failed in some other way. We have excluded those cases: 15 out of 283. The others we have classed as 'good'.

Figure A.2 below shows the spread of R-squared values in both good and bad cases. (Where the optimiser did not converge we used the parameters it reported, even though this was not the minimum). R-squared is a measure of the extent to which the measured flux variation is accounted for. For example, if R-squared is > 0.5, that means our model accounts for at least half the variation in observed heat flux. Usually it is much better than this, as in the example shown above. Low values for

R-squared indicate that there are other effects not in the model, for example heat transfer within the wall from warmer rooms to cold. This effect can also lead to bias, where there is a difference between the average modelled and actual heat flux. In the good cases R-squared is significantly higher but there is little difference in bias between good and bad cases.

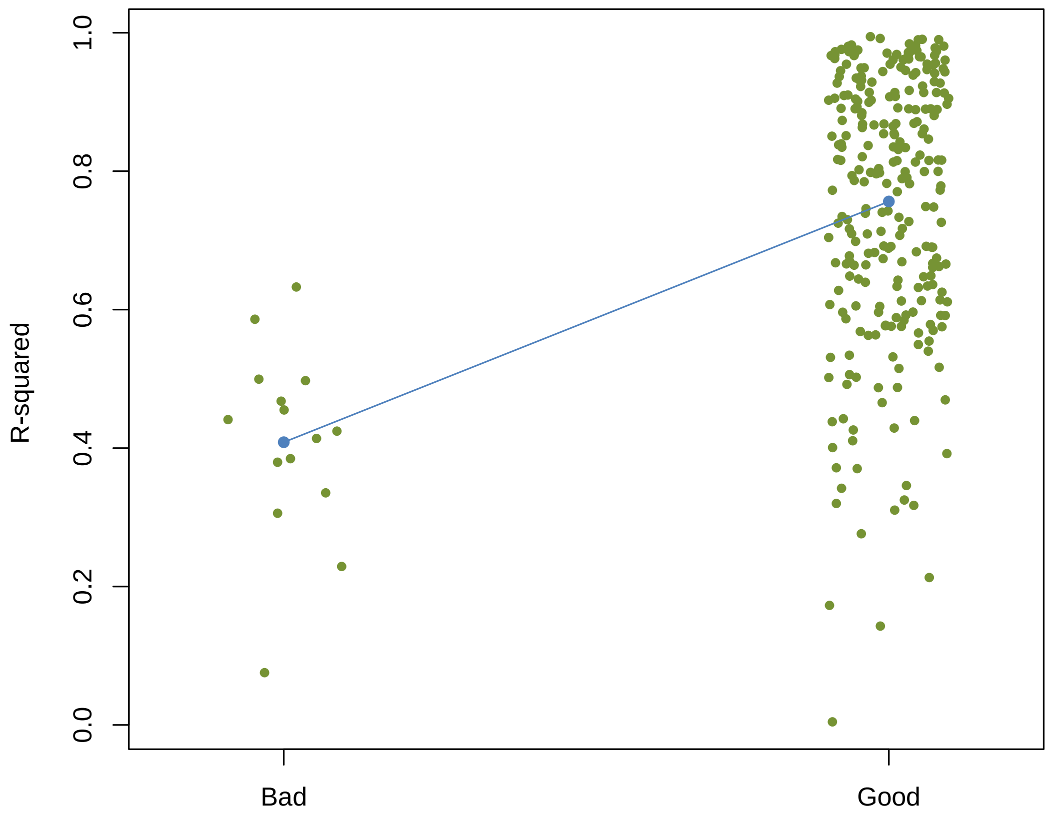

Figure A.2 R-squared for good and bad cases. Bad cases are those were the optimiser failed to find minimum in the error function. We have excluded these from later analysis. The blue line links the mean R-squared in each group: 0.41 (bad) and 0.76 (good).

Appendix B: Bias introduced from uneven temperature in the dwelling

Where temperature gradients are consistent (i.e. where one room is consistently warmer than neighbouring rooms in the same house) it introduces a bias in the result (the mean heat flux in the model is not quite the same as the mean heat flux as measured). These effects cancel out when averaged over the whole wall, but if the monitored locations were not representative, then the resulting bias affects the U-value estimate. High bias leads to low in situ U-value and vice versa. Table B.1 below shows how in situ U-value varies with bias for homes where there were at least six monitored locations and accurate temperatures. The chart shows one typical case.

Table B.1 Variation of in-situ U-value with bias for cases with at least six monitored locations and accurate temperatures. The coefficient is negative, which means that high bias reduces the U-value and vice versa. The low p-values indicate the effect is significant but R-squared is moderate, showing there are other factors not accounted for.

House	Number of locations	Bias coefficient (gradient of graph below)	P-value (low value indicates a relationship)	R-squared (how much variation is explained by the model)
H29	6	-1.58	0.021	0.72
C25	6	-1.16	0.14	0.32
M55-normal	14	-1.18	0.01	0.41
M55-steady	14	-0.61	0.01	0.42
M57	10	-1.3	0.05	0.33

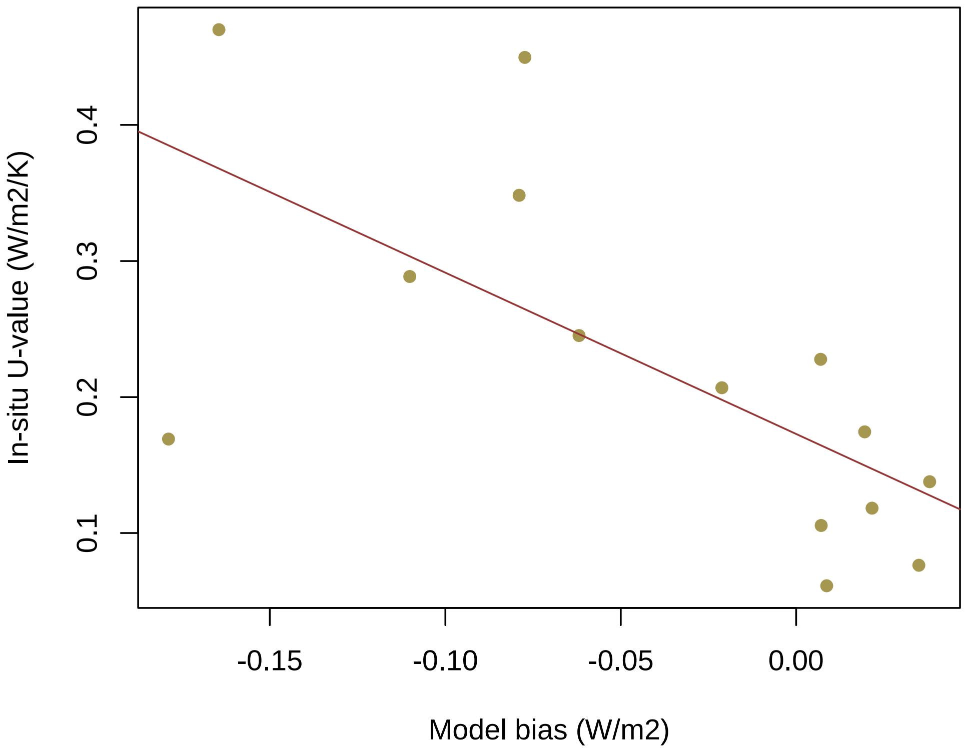

Figure B.1 Variation of In-situ U-value with model bias (the mean difference between the flux predicted in the model and the measured flux) for M55-normal. R-squared is 0.40, p-value is 0.01.

This is not the only reason for variation in the wall (witness the low R-squared values in the table and in some cases relatively high P-values). However, the consistency between homes supports the conclusion that the effect is significant.

Appendix C: Plots of non-significant relationships between construction and in-situ U-value

We looked for correlations between different construction types and materials and in-situ U-values, but we were unable to find any – apart (unsurprisingly) from insulation installed in the party-wall cavity (see Figure C.1 below).

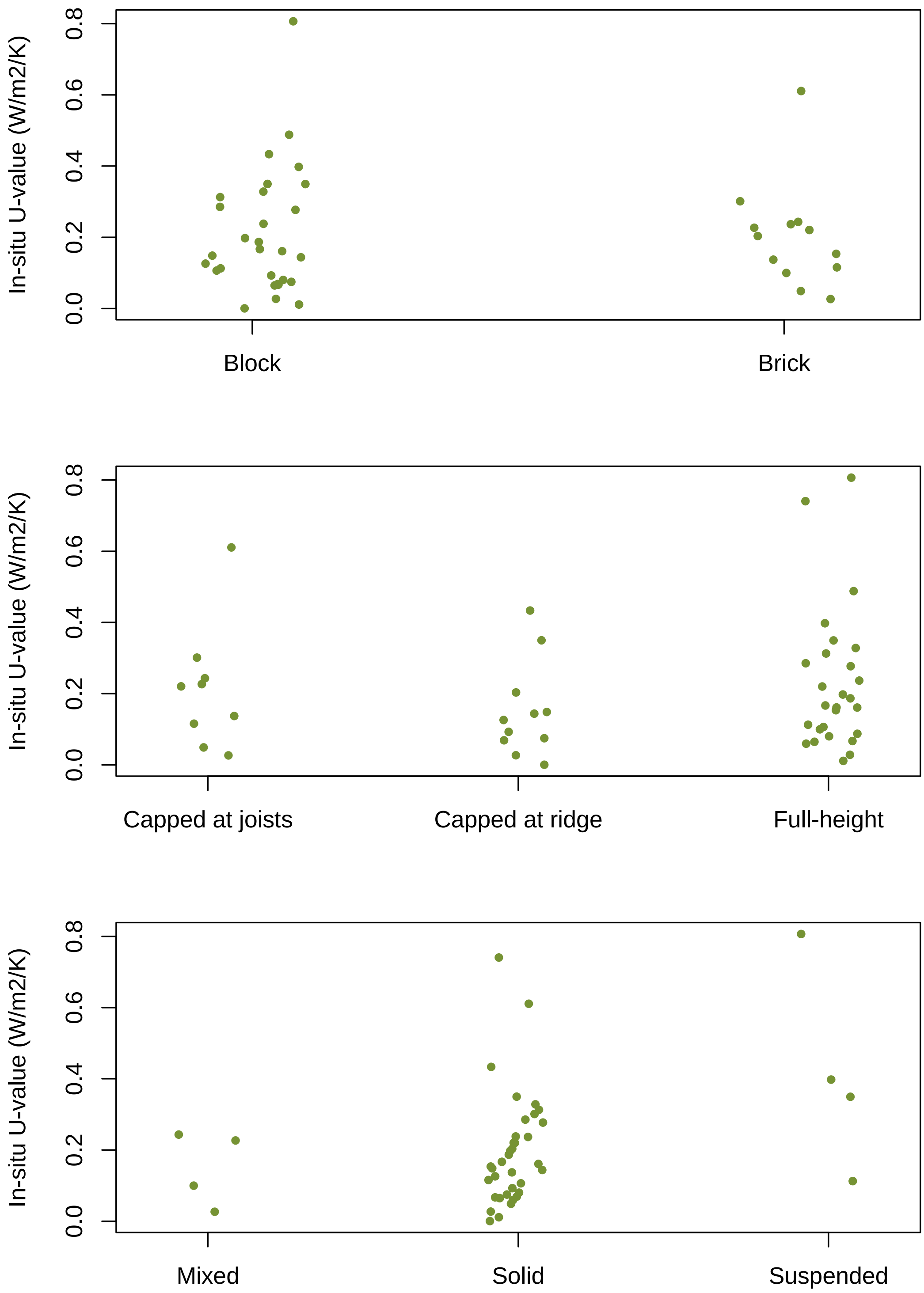

Figure C.1 Comparing in-situ U-values by construction type and materials.

Appendix D: Finding confidence ranges in the in-situ U-value estimates

There were three dwellings monitored at 14 or more locations. Two of them were monitored in two phases, but we used only one phase in this analysis to avoid skewing the sample. We used dwellings M44a, M55-normal and M57. The standard deviations of in-situ U-values were 0.21, 0.13 and 0.19. The average was 0.18 and we applied this to all dwellings with fewer monitoring locations. This approach was a compromise, and imperfect, but it was the best way to estimate uncertainty with limited data.

For each dwelling, with estimates at N locations and mean in-situ U-value Um, we calculated the 95% confidence ranges as $Um \pm 1.96 * sd/\sqrt{N}$

Where the lower bound was less than zero, we set it to zero because negative U-values are not possible. (This would imply heat gain from outside in winter.)

Appendix E: Analysis of cavity temperatures and air speed

For the regression of cavity air speed by environmental factors, the regression equation is:

cavity air speed = k0 + k1 x externalT + k2 x wind.speed

Cavity air speed and wind speed units are both m/s.

The results are shown in Table E.1 below. Wind is statistically significant but has a minor effect. There is only one case where the R-squared increased by more than 0.1 when wind is included: C27/low. This could be because of projecting elements on both sides at the back of the house – either side of the instrument location – which means the party wall was sheltered on three sides but not the fourth (the south).

Table E.1 Regression of cavity air speed by environmental factors, where wind improves regression by at least 1% (Increase in R-squared >-0.01). 'All directions' means that scalar wind speed – with no direction – was best.

House/location	Best wind angle	wind coefficient	R-squared	Increase in R-squared due to wind
C25/high/horiz.	All directions	-0.0021	0.46	0.07
C25/low/horiz.	All directions	-0.0069	0.36	0.04
C27/low/horiz	All directions	-0.0041	0.18	0.18
M57/Bed2botD/horiz.	All directions	-0.00047	0.05	0.04
M57/Bed2topA/vert.	190	0.00009	0.18	0.02
M57/Liv1botA/vert.	10	0.00036	0.27	0.01
M57/Stairs2Fbot/horiz	All directions	0.00008	0.18	0.03

Adding model parameters into the equation we used the following:

cavity air speed = k0 + k1 x externalT + k2 x mean.wall.T + k3 x flux.ext + k4 x wind.speed

where *mean.wall.T* is the average temperature over the two sides of the wall (modelled) and *flux.ext* is the modelled heat flux density from the two sides of the wall to the external environment.

This gives R-squared > 0.3 in about half of cases. The best is 0.63. The following table shows these results and also the T-values for some of the parameters. In most cases, high cavity air speed is associated with high modelled wall temperature and low external air temperature, which indicates large differences compared to outside. However, this is not consistent and heat flux can affect air speed either way. This suggests the processes driving cavity air movement are complex. They probably relate to temperature differences within the wall as well as to outside.

Table E.2 Regression of cavity air speed using model values, where R-squared > 0.3. T-value is a measure of the overall impact of that value on the regression (coefficient of the value / standard deviation of the value).

House/location	R-squared	Increase in R-squared due to wind	T-value externalT	T-value Wall meanT	T-value heat flux
C25/high/vert.	0.63	0.03	5.3	-6.1	5.4
C25/high/horiz.	0.48	0.07	-4.1	4.9	-1.3
C25/low/horiz.	0.47	0.02	-0.2	8.4	2.5
C27/low/vert.	0.32	0.15	-4.9	5.2	-4.9
C26/low/horiz.	0.39	0.00	-9.3	9.6	-9.2
M57/Bed2topA/vert.	0.34	0.02	-16.0	16.2	-15.9
M57/Liv1botA/vert.	0.32	0.00	2.9	-3.4	3.0

The same equation gives better results for cavity air temperature, though M57 is not as good as the others. It is noticeable from the T-values that for dwelling M57 the effect of external temperature is strongest at Bed2botD and Liv2topA, near the location of the known thermal bypass. However, wind is an important factor in most parts of the living room, with high winds leading to lower cavity temperatures. The only other case where there is the same combination of strongly negative T-value for wind and positive for external temperature is in C27 (low).

Table E.3 Regression of cavity air temperature using model values. T-values as above.

House/location	R-squared	Increase in R-squared due to wind	T-value Wind	T-value externalT	T-value Wall meanT	T-value heat flux
C25/high	0.98	0.00	11.3	18.4	-10.9	18.4
C25/low	0.96	0.00	2.0	12.8	-9.3	12.7
C27/low	0.90	0.05	-10.6	14.6	-13.0	14.5
C27/high	0.91	0.00	5.8	-1.5	2.4	-1.4
C26/high	0.94	0.00	4.3	-13.2	17.1	-13.3
C26/low	0.91	0.00	-12.8	-6.5	9.9	-6.4
M57/Stairs2Fbot	0.78	0.00	-1.8	-6.0	12.3	-1.6
M57/Bed2topA	0.83	0.00	-4.9	-1.5	15.8	-4.5
M57/Bed2botA	0.82	0.00	-7.7	-3.7	22.2	-2.9
M57/Bed2botD	0.73	0.03	-1.0	12.8	19.1	-5.5
M57/Liv1topA	0.87	0.02	-19.9	8.7	23.1	5.8
M57/Liv1topD	0.87	0.01	-17.7	4.3	21.7	2.1
M57/Liv1botA	0.85	0.01	-13.5	-3.4	12.0	1.8
M57/Liv1botD	0.80	0.00	-10.8	2.9	-3.4	-4.9

Appendix F: Validating methods

Back-to-back analysis

We installed flux plates on both sides of the same wall opposite each other in two homes, so that we could compare results. We also developed a variation on our model that uses heat flux and temperatures on both sides of the wall at once. For the two-sided model, we minimised the error calculated by summing abs(model-actual) for the flux plates on both sides. The R-squared is the average of the calculation on both sides.

Here there are three estimates of the U-value to compare:

One-sided model from the main house
One-sided model from neighbour
Two-sided model

Table F.1: In-situ U-values and R-squared for two homes with heat flux data for both sides of the wall.

House	Room	Main House U-value (r^2)	Neighbour U-value (r^2)	2-sided U-value (r^2)
C25	High back	0.25 (0.95)	0.33 (0.64)	0.26 (0.78)
	High front	0.31 (0.97)	0.41 (0.93)	0.38 (0.91)
	High middle	0.01(0.97)	0.03 (0.99)	0.07 (0.98)
C26	Downstairs back	0.25 (0.55)	0.93(0.63)	0.78 (0.55)
	Downstairs front	0.55 (0.37)	0.17 (0.61)	0.52 (0.52)
	Middle	0.03 (0.77)	0.05 (0.75)	0.03 (0.75)
	Upstairs back	0.00 (0.66)	0.19 (0.57)	0.25 (0.62)
	Upstairs front	0.14 (0.81)	0.04 (0.39)	0.14 (0.56)

The results are fairly consistent for C25 but less so for C26. We attribute this to poor model fit in C26, caused by greater heat transfer within the wall in the C26 case: the following charts show average temperature at each monitored location on the house side. For C25 the difference between the upper part of the wall and the lower part is 1.1˚C, whereas for C26 it is 3.3˚C. This may be partly explained by different building heights, with C25 only one storey.

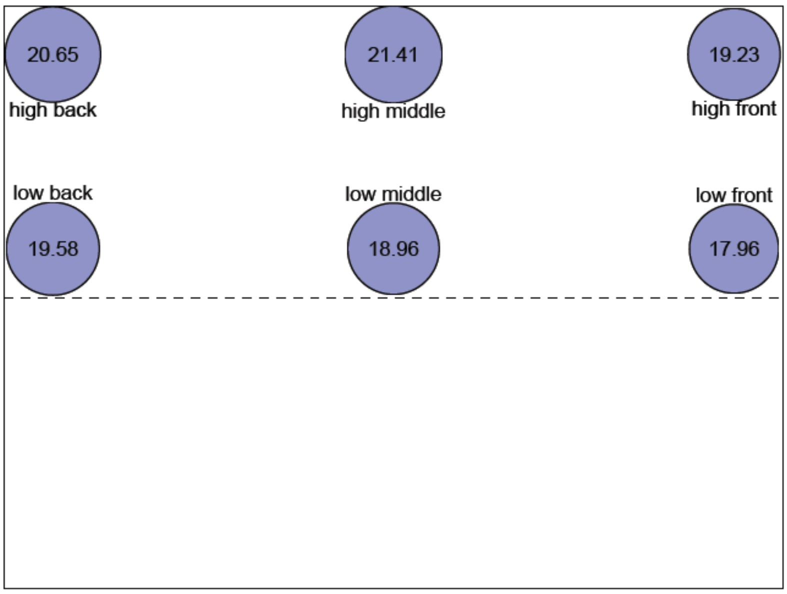

Figure F.1: Dwelling C25 wall surface temperature (˚C)

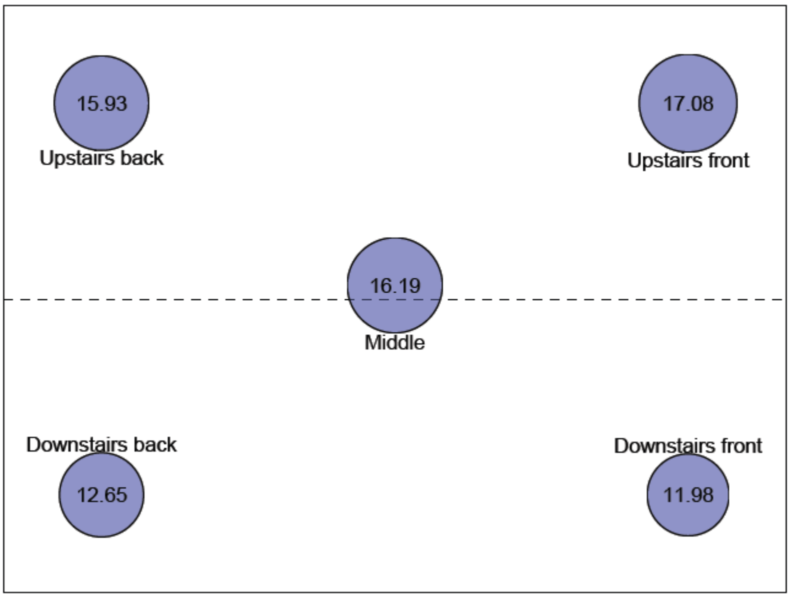

Figure F.2: Dwelling C26 wall surface temperature (˚C)

Steady temperatures, using regression

This method is an extension of the methods conventionally used to measure U-values in external walls. It relies on minimising the effect of thermal mass by doing the test under quasi steady-state conditions. This was possible only because the dwellings were unoccupied. Thermal mass effects were minimised by:

(a) maintaining room temperatures at a constant mean elevated temperature on both side of the cavity party wall.
(b) using average daily data so that the daily temperature swings were complete in each interval.

We can then use simple linear regression:

flux = k.u x (Twall.surface – Texternal) + k.n x (Twall.surface – Tneighbour)

where

k.u is the U-value describing heat loss to the outside that we wish to find
k.n is the U-value describing heat loss to the neighbour
Twall.surface, Texternal, Tneighbour are daily averages.
Also flux is the daily average heat flux density.

Note that in this regression there is no intercept. Flux must be zero when there is no temperature difference. We designate the results as 'good' if:

k.n is positive
k.u is significant at the 1% level (the p-value for this factor is < 0.01).

There are two dwellings where we were able to maintain temperatures sufficiently steady to run this analysis and compare results. These are described in the main body of the report.

We also tested adding wind speed into the regression analysis, but wind was not significant.

Appendix G: Analysis of in-situ U-value and location on the party wall

Figure G.1 below shows the relationship between the location of measurements and the in-situ U-values, for all homes with five or more measurements. Each dot represents one of the measurements on the five-on-a-dice houses (and the intensive or invasive studies). The dots are located in the corresponding positions on the party wall of each house (as a cross-section through the party wall), with small offsets so there are not dots on top of each other. The U-values are colour-coded so green is neutral (near the mean), blue is a high U-value, and red is a low U-value.

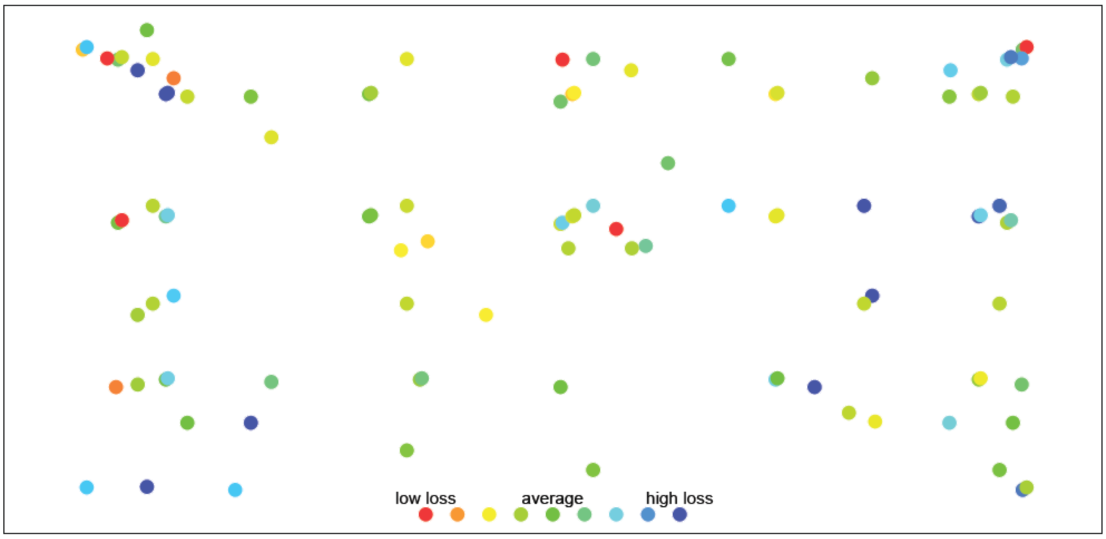

Figure G.1: Colour-coded U-values at different locations on the party wall (all homes with five measurements or more). Blue points are very high in-situ U-values, and red points are very low ones.

It is hard to draw clear conclusions from this spatial analysis, but none of the very low recorded in-situ U-values occur on the ground floor near the junction of the party wall and the floor. Conversely, the highest in-situ U-values usually occur near to the external walls, suggesting there is local heat loss from the party wall to the external cavity walls (thermal bridging). However, there are exceptions, with three cases of very low in-situ U-values even close to the external walls – possibly because these particular houses have a good thermal break between the party wall cavity and the external wall (for example, with an insulated external cavity and a cavity sock preventing communication between the party wall and the external wall).

Most measurements near the middle of the party wall, far away from external walls, have middling in-situ U-values, with two measurements showing very low U-values.