Heat-flow variability of suspended timber ground floors: implications for in-situ heat-flux measuring

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Abstract

Reducing space heating energy demand supports the UK's legislated carbon emission reduction targets and requires the effective characterisation of the UK's existing housing stock to facilitate retrofitting decision-making. Approximately 6.6 million UK dwellings pre-date 1919 and are predominantly of suspended timber ground floor construction, the thermal performance of which has not been extensively investigated. This paper examines suspended timber ground floor heat-flow by presenting high resolution in-situ heat-flux measurements undertaken in a case study house at 15 point locations on the floor. The results highlight significant variability in observed heat-flow: point U-values range from 0.56 ±0.05 to 1.18 ±0.11 $Wm^{-2}K^{-1}$. This highlights that observing only a few measurements is unlikely to be representative of the whole floor heat-flow and the extrapolation from such point values to whole floor U-value estimates could lead to its over- or under- estimation. Floor U-value models appear to underestimate the actual measured floor U-value in this case study. This paper highlights the care with which in-situ heat-flux measuring must be undertaken to enable comparison with models, literature and between studies and the findings support the unique, high-resolution in-situ monitoring methodology used in this study for further research in this area.

Keywords: *building performance; in-situ U-values; pre-1919 housing; retrofit; suspended timber ground floors; thermal performance*

Nomenclature	
U, U_{mean}, U_p, U_{wf},	Thermal transmittance or U-value, $Wm^{-2}K^{-1}$; U_{mean} is the estimated in-situ U-value obtained from a mean of ratios of point U-values (U_p). U_p is a point U-value and is the term used as a generic description of the small area-based in-situ U-value measurement on a certain location on the floor. U_{wf} is the in-situ estimated whole floor U-value derived from U_p-values.
HF1, HF2,…	Heat-flux sensor location 1, 2,…
T_{Si}, T_{ea}	Internal surface air temperature and external air temperature respectively
q	In-situ measured heat-flow rate, Wm^{-2}
R_{si}	Internal surface thermal resistance, taken to be 0.17 m^2KW^{-1} for downward heat-flow through floors

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1. Introduction

The UK has committed to reduce CO_2, or equivalent, emissions by 80% from 1990 levels by 2050 in the Climate Change Act 2008 [1]. Deep cuts in CO_2 emissions associated with the residential sector, which is responsible for approximately 30% of the UK's total emissions [2], are required. Reducing carbon emissions associated with domestic space heating, which accounts for around 13% of the UK's emissions [3], is a key aspect of the UK's planned transition to a low carbon economy [3, 4].

There are approximately 27 million dwellings in the UK, the majority of which are not well insulated [4]. An estimated 4.9 million dwellings were built pre-1919 in England alone [5] and 6.6 million in the UK [6]; seventy to eighty-five percent of existing UK housing is expected to still be in use in 2050 [7-9]. Dwellings of the pre-1919 period are predominantly of solid wall [10-12] and suspended timber floor construction [10]. They tend to have larger floor areas [5] and are predicted to have a 40% greater energy demand per metre floor area compared to newer dwellings built post-1990 [13]. A large proportion of this pre-1919 dwelling typology is also classified as hard to treat (HTT) [5, 6], due to the relatively high cost of retrofit options, disruption and difficulty to upgrade [14-16]. It is estimated that at least 50% of energy demand in pre-1919 housing is for space-heating [5, 17-19]; much of this heat is lost through un-insulated walls and insufficiently insulated roofs [20]. The proportion of total dwelling heat loss from un-insulated ground floors depends on the overall dwelling fabric efficiency standard and is estimated between 10% in un-insulated dwellings [20] and 25% in otherwise well insulated dwellings where the ground floor remains uninsulated [21]. Addressing this challenging typology presents an opportunity to deliver significant carbon reductions and increased occupant thermal comfort from improved building fabric performance [22, 23]. However, this carbon reduction challenge is intensified by the underperformance of many interventions [24-27] and the low rate of refurbishment [28-30]. Just four percent of solid walls in the UK's pre-1919 properties are insulated [31] and it is unknown how many pre-1919 ground floors are insulated.

Initiatives such as the UK government's Green Deal and Energy Company Obligations (ECO) policies, which were preceded by the Community Energy Saving Programme (CESP) and the Carbon Emissions Reduction Target (CERT), aimed to increase the rate of retrofit [32, 33]. One of several drivers for energy-efficiency measures is the cost-benefit of interventions [34]. The Green Deal for example allowed building occupants to take out a pay-as-you-save loan to finance certain energy efficiency improvements, assuming the loan could be paid back from the predicted energy savings [35, 36]. However, the actual carbon reductions and cost-effectiveness of retrofit interventions is contingent upon the delivered improvement in thermal performance.

Recently, potential disparities between predicted and actual performance of existing construction elements have been identified [37, 38]. For example, in-situ measurement of U-values in solid walls were found to be lower than those predicted [37, 39, 40], which affects the predicted energy savings and payback. However, while insulation of suspended timber ground floors was a Green Deal approved intervention measure [41], the heat-flow through this element, both uninsulated and insulated, is not well characterised at present, hindering retrofitting decision-making. Few in-situ measurements of floor heat loss have been undertaken and there is a need to understand the implications of the physical heat loss patterns on in-situ measuring methodology, such as location and spread of sensors across the floor, prior to undertaking larger scale field measurements.

This paper presents an investigation into the spatial variation in U-values derived from measurements at points on a suspended timber ground floor, and how this variation can affect the estimated whole floor U-value. This study presents the results of high-resolution in-situ measurements of the thermal characteristics of a suspended ground floor in a controlled environment in the Energy House (EH) a pre-1919 semi-detached house reconstructed in an environmental chamber at the University of Salford (UK). The potentially large variation in whole floor U-value estimates from low resolution measurement campaigns is illustrated and wider implications for the method of U-value estimation of floors are discussed.

Firstly, the research method is discussed, which includes a description of the Salford Energy House, instrumentation, in-situ measuring method and uncertainty. Subsequently, results and discussion are presented, focusing on wider applicability of implications arising from the findings, such as implications for future in-situ measuring techniques in the field and comparison difficulties with models and other published in-situ U-values.

2. Method

A 5-day monitoring programme was undertaken in the Salford Energy House (EH) in 2013. The EH is a reconstructed 1919 two bedroom semi-detached dwelling in a large environmental chamber at the University of Salford. The house is separated on one side with a solid brick party wall from another smaller house in the thermal chamber, referred to in this paper as the neighbouring house. The EH ground floor is of suspended timber construction, with timber floorboards in the living area and tiled floor finish in the kitchen. Its total ground floor measures 28m^2, with an exposed perimeter (measured externally) of 16m. The suspended floor is ventilated through air-bricks with a total ventilation opening area per metre of exposed perimeter of approximately 0.00077m^2/m (calculated in accordance with ISO 13370 [42]) excluding an airbrick opening to the neighbouring house. Given that the EH is a reconstructed dwelling there are some differences with an actual house: (a.) it sits on a 280mm thick concrete slab, which sits on top of an insulated ground floor slab (the slab of the building which houses the chamber) – collectively referred to as the concrete substructure; (b.) atypically, floor void ventilation occurs in between both houses and there are no airbricks on the back facade; (c.) joists run from gable wall to party wall and there is only a 50-70mm gap under the 190 mm joists and the concrete oversite slab, likely reducing free airflow in the void (see Fig. 2); (d.) the floor finish is tongued and grooved floorboards, apart from ten floorboards, which have gaps between them; this hybrid is atypical of floors of this kind.

While the EH structure and climatic conditions are a simulation of the actual environment, the EH can be used to investigate in detail some aspects of the variability of heat-flow across a construction element and report on the implications for in-situ measuring techniques of floors. For example, the EH enabled high-resolution monitoring (i.e. many points across the surface) and the control of the variables which actual houses are subject to in monitoring campaigns, such as the exclusion of occupant interference, a controlled internal and external environment and exclusion of solar gain and wind effects. Additionally, the steady-state conditions and isolation of dependent effects facilitated repeated measurement of the physical variables, leading to reduced measurement time and small instrument measurement uncertainties derived from statistical error propagation techniques. Further advantages of using the EH included monitoring under conditions which were not otherwise possible in occupied dwellings, such as heating the neighbouring house to a constant 18ºC and the ability to electrically space heat to control for the influence of uninsulated radiator pipes in the floor void affecting heat-flow measurements and instead enabling to study of the spatial variation of the floor heat-flow.

This research is based on in-situ measuring of a case-study floor and as such the numerical results are not representative of the wider pre-1919 housing population. However, as outlined above there are significant advantages of research in a controlled environment to isolate physical effects and the physical insight and qualitative results may be used to highlight potential trends and wider methodological implications [43]. This study aims to provide such broader insight, as undertaken elsewhere, such as the broadly applicable cavity wall heat loss mechanism identified by Lowe et al in a case study [44].

2.1. Instrumentation of the Salford EH

Variables measured were external environmental chamber air temperatures (T_{ea}, ºC), heat-flux (q, mV) and internal surface temperatures (T_{Si}, ºC) in 15 locations on the bare floorboards of the uninsulated floor of the living room, as shown in Fig. 1. One of the 15 locations was measured on a joist. Three sensor locations were near airbrick openings in the void below and <300mm from an external wall (locations 1, 9, 14); locations 10, 12 and 13 were more than 300mm and less than 1000mm away from an external wall; with locations 7 and 15 in the middle of the room and locations 2, 3, 4, 5, 6 and 8 ≥ 1250 mm from an external wall. The external chamber was held at ~5-6ºC and internal living spaces at ~18-20ºC during the monitoring campaign.

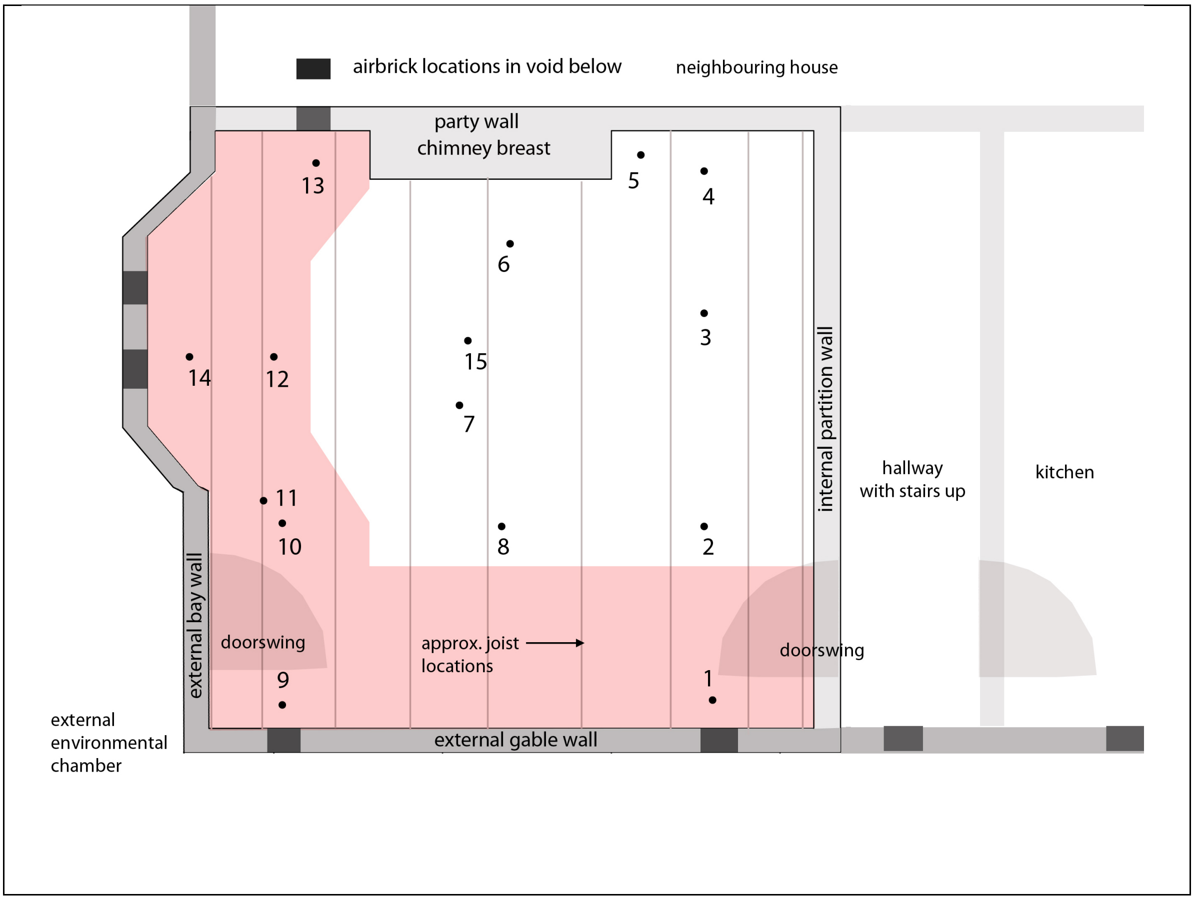

Fig. 1. Salford EH living room plan and in-situ point measurement locations; note that location 11 was taken on a joist; the shaded area signifies a 1 metre perimeter zone.

The Hukseflux HFP01 heat-flux sensors have instrument accuracy of ± 5% and each was located with a surface temperature sensor directly adjacent to each of them; sensors were fixed to the surface with a thin layer of Servisol heat-sink compound (thermal conductivity = 0.9 $Wm^{-1}K^{-1}$ [45]) to ensure good surface contact and were secured with masking tape in the middle of a floorboard. 110PV surface temperature thermistors with accuracy of ±0.2°C alongside type K thermocouples (±1.0ºC) were used to measure timber floor surface temperatures. Temperatures in the chamber, conditioned to external environmental conditions (T_{ea}, ºC), were measured with HOBO U12 (±0.35ºC) temperature sensors. Areas of floor were sought which broadly represented the conditions and structure of the floor, with minimal influence from local heat gains and other influences [46, 47]; floor joist locations were avoided apart from location 11. An infrared camera was used to aid sensor placement as recommended by for example ISO [47], ASTM [48] and McIntyre [49].

All measurements were recorded at 1 minute sequential intervals and averaged for hourly analysis. Outliers caused by researcher influence such as opening up floorboards to collect data for other research purposes were removed using Chauvenet's criterion [50]. This reduced the 120 hour data by three to seven hours depending on the sensor location. This process did not significantly change mean U-values and similar results were obtained with manual data removal. For instance, all mean U-values were within 0 to 1% from the data prior to quality control, though in location 1 and 9 this was 1.5% and 2.7% respectively.

2.2. Measurement uncertainty and data analysis method

In-situ U-value measurements were undertaken with the use of heat-flux (HF) monitoring equipment and by measuring representative and accurate temperatures on both sides of the construction. The measurements required for in-situ U-value estimation are subject to several identified uncertainties associated with instrumentation and measuring equipment set-up and the natural variability of U-values as an inherent characteristic under changing environmental conditions; see summary Table 1. As errors are assumed independent and random, the individual errors (*Eq.* (1), Table 1) are combined in the quadrature sum. ISO-9869 estimates the natural variability of U-values in the field as ±10% [51], leading to a total estimated error of ±14%, but this was significantly reduced when undertaking measurements in the steady-state environmental chamber in this study. The standard deviation (sd) of the data was therefore used in place of this variability error, leading to total estimated uncertainties of between ±9 and ±11% for each point location.

<table>
<tr><th>Instrument error</th><th colspan="2">Measuring equipment set-up errors</th><th>Natural variability U (not error)</th></tr>
<tr><td rowspan="3">± 5% (calibration heatflux and temperature sensors) [51]</td><td>Edge heat loss error [51]</td><td>±3%</td><td rowspan="3">±sd (%, hourly data for the environmental chamber); ISO 9869 [51] suggests this is ±10% in the field.</td></tr>
<tr><td>Contact error [51]</td><td>±5%</td></tr>
<tr><td>Temperature location measurement error [51]</td><td>±5%</td></tr>
<tr><td>Total ISO error</td><td colspan="3">$\geq \sqrt{5^2 + 3^2 + 5^2 + 5^2 + sd^2}$ (1)</td></tr>
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Table 1. Summary of estimated measurement uncertainties; adapted from ISO-9869 [51] and grouping by authors.

Unknown random or systematic researcher influence could also affect measurement, such as interference with instruments during data-collection; this was minimised during the duration of the study by taking prolonged measurements [52], by keeping the chamber at steady state conditions and by minimising access to the EH during the monitoring campaign. Nevertheless, the opening up of the floorboards to collect data in the floor void caused some outliers, which were removed as described in 2.1. Systematic errors that could affect each individual measurement location include calibration errors, thermal resistance of the heat-flux sensor itself and sensor placement errors. These errors were minimised by careful sensor placement with use of an infrared camera and by accounting for the thermal resistance of the heat-flux sensor in U-value calculations (~ 6.25×10^{-3} m^2K/W, [53]). A side by side 'calibration' test was carried out at the UCL thermal lab after the monitoring period, testing ~50% of the heat-flux sensors used (not all were available) in near-identical conditions. Heat-flow results indicated that the heat-flux sensors were within ±5% of the mean of the group of sensors and also between each other.

In-situ point U-values (U_p-values) were estimated according to the mean of ratios as per *Eq.*(2), instead of using the ISO-9869 'Average Method' [51]. This enabled the statistical treatment of random errors - see Eq (1) - as applied through *Eq.*(2); results in this paper are presented in accordance with *Eq.*(1) and *Eq.*(2), rounded to two decimal places. If surface temperatures are used, assumed surface resistances are added [37, 54, 55] to account for airflow and radiative effects at the surface:

$$U_{mean} = \frac{\mathbf{1}}{\mathbf{n}}\sum_{\mathbf{j=1}}^{\mathbf{n}} 1/(\frac{(Tsij - Teaj)}{qj} + R_{Si}) \qquad \text{(2) – Mean of ratios}$$

where U_{mean} is the final estimated in-situ U-value in Wm^2K^{-1}; q is the heat-flow rate (Wm^{-2}) which is inferred using each sensor's unique sensitivity (or calibration factor, *ESen* in mVm^2W^{-1}). where T_{Si} is the surface temperature of the floor in the room, T_{ea} is the external air temperature and R_{Si} is the internal surface thermal resistance, taken to be 0.17 m^2KW^{-1} in accordance with BSI [56]. Index j identifies individual measurements in the same location over time and n is the number of measurements taken sequentially. No external surface thermal resistance is added if external air temperatures (T_{ea}) are used instead of surface temperatures, as was the case in this study.

3. Results and discussion

3.1. Large spread of observed U_p-values across the floor surface

Fifteen locations on the floor were observed, as marked on Fig. 1. There was a large variation between the 15 U_p-values depending on where the point measurements were undertaken; as expected, nearer the exposed perimeter, the observed U_p-value was greater than that further away. U_p-values ranged from 0.56 ±0.05 $Wm^{-2}K^{-1}$ far from the external walls (location 5) to 1.18 ±0.11 $Wm^{-2}K^{-1}$ in the bay window area (location 14), see Table 2. Location 11 was measured on a joist and had an estimated U-value of 0.92 ±0.09 $Wm^{-2}K^{-1}$; a 21% relative change compared to the adjacent floor-board U-value of 1.16 ±0.11 $Wm^{-2}K^{-1}$in location 10.

Location on floor and distance to internal face of ***nearest*** external wall (mm)		**In-situ measured U-value ($Wm^{-2}K^{-1}$)**
HF1	185	0.73 ±0.08
HF2	1290	0.72 ±0.08
HF3	2500	0.66 ±0.06
HF4	2960	0.61 ±0.06
HF5	2589	0.56 ±0.05
HF6	2192	0.67 ±0.06
HF7	1880	0.77 ±0.07
HF8	1260	0.81 ±0.08
HF9	195	0.92 ±0.09
HF10	510	1.16 ±0.11
HF11	500	0.92 ±0.09
HF12	780	1.03 ±0.10
HF13	580	1.09 ±0.11
HF14	250	1.18 ±0.11
HF15	1912	0.70 ±0.07

Table 2. Results of estimated point U-values in accordance with *Eq.*(2) and total uncertainty in accordance with *Eq.*(1).

3.2. Causes for such large variability of U_p-values

The large variability in U_p-values is because the thermal path varies considerably across a floor, primarily because the ventilation rates in the void vary in addition to expected increases in the thermal resistance as the distance to the exterior wall changes, as also reported for solid ground floors [57-59], both factors lead to expected increased heat-flow near the perimeter. Conductive and convective heat-flow between a point on the floor and exterior air depends on a number of heat-flow paths, including through the exterior wall, through the ground and through the void air layer [21, 42, 60]. In one dimension, the latter two of these heat-flow paths may be simplified as inversely proportional to the distance between hot and cold points; in a real floor it is unlikely that this clear relationship would hold due to the complex three dimensional nature of heat-flow and ventilation. Additionally, ventilation rates vary considerably in the floor void [61], being notably higher in the proximity of airbricks or sources of ventilation, increasing the rate of heat-flow. This ventilative heat-flow will vary in accordance to this relationship and is likely to be higher in floor perimeter areas but is also likely to depend on airbrick locations and void obstructions such as joist locations and sleeper walls. Given that airbricks are located in exposed perimeter walls, the ventilative and exterior wall heat-flow factors are confounding variables and it is not possible to isolate the impact of these different heat-flow mechanisms; this observation suggests that these factors require further research.

Fig. 3 illustrates the increased heat-flow near the perimeter and plots U-values derived at each observed location as a function of their nearest distance to an exposed wall and Fig. 4 plots the U_p-values as a function of the distance to the bay wall. A simplified categorisation of estimated U_p-values in non-perimeter and perimeter zones was undertaken with a 1000 mm perimeter zone after Delsante [57] for solid ground floors. Distances are from the nearest internal surface of the external wall to the middle of the heat-flux sensor. In general and as expected, U_p-values are higher in the perimeter zone for the suspended timber ground floor. Statistically comparing the U_p-values within 1000 mm from the external wall (locations 1, 9, 10 and 12 to 14, Fig. 1, in red) with the non-perimeter zone of the floor (points in black), an unpaired Mann-Whitney U (Wilcoxon rank sum) test suggests that the observed U_p-values in the perimeter and non-perimeter zone differ significantly (Mann–Whitney $W = 46$, $n1 = 6$ $n2 = 8$,$P < 0.05$ (0.003), unpaired). The probability that there is a zero difference in heat-flow between the perimeter zone and the non-perimeter zone of the floor is negligible (0.003, or about three in 1000). Fig. 3 shows the expected relationship between heat-flow and distance to external walls; however as stated above, it is not possible to isolate the effect of the airbricks in the perimeter walls and further exploration would be required to isolate these variables. Fig. 3 also highlights that while the use of a perimeter zone provides a convenient measure, there is no clearly defined extent of the perimeter effect as there is no abrupt change after 1000mm, but a gradual reduction in U_p-values the further away from the external environment.

As illustrated in Fig. 3 and Fig. 4, in general, increased heat-flow in locations nearest to the external bay wall (10,12 to 14) is observed compared to locations near the gable wall (locations 1, 9); this is likely explained by the bay wall's two airbricks and its large exposed perimeter; though this observation is based on a few locations only. The joists run from gable wall to party wall with little space underneath them (50-70mm, see Fig. 2), likely preventing airflow from the bay wall airbricks into the rest of the void and vice versa. One would expect this to lead to an isolated area of low void and surface temperatures and hence increased heat-flow in the bay area with lower heat-flow in the middle of the floor due to the joist inhibiting the mixing of colder air further along the floor, leading to a more pronounced floor heat-flow effect in the bay-wall area.

Fig. 2 shows the limited space under the deep joists and location of the airbricks within the deep joist zone along the gable wall. This is likely to have channeled airflow between joists, with joists acting as obstructions to flow of air between different floor areas, in turn affecting heat flow patterns.

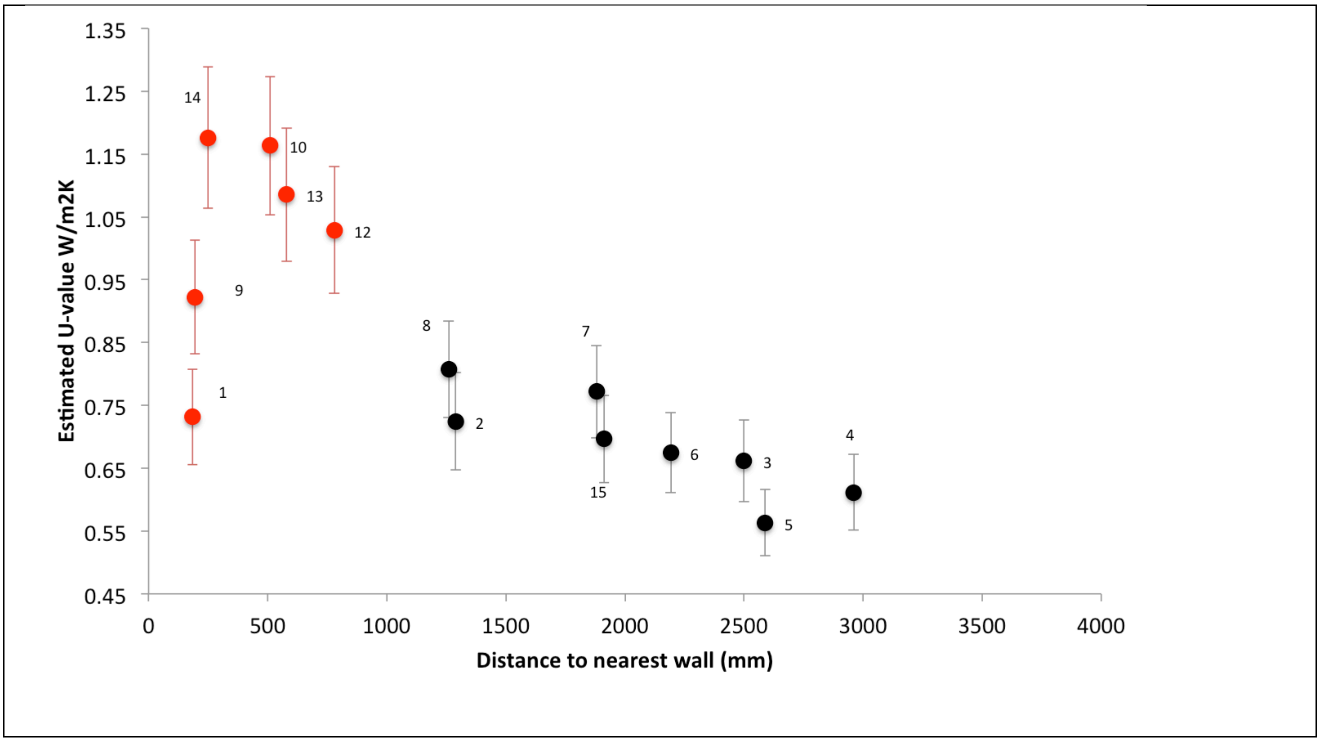

Fig. 3. In-situ estimated Salford EH suspended floor U_p-values as a function of nearest distance to exposed wall. Red data points are U_p-value point locations in the 1000 mm perimeter zone; while black data points are in the non-perimeter zone. Error margins are estimated as per *Eq.* (1).

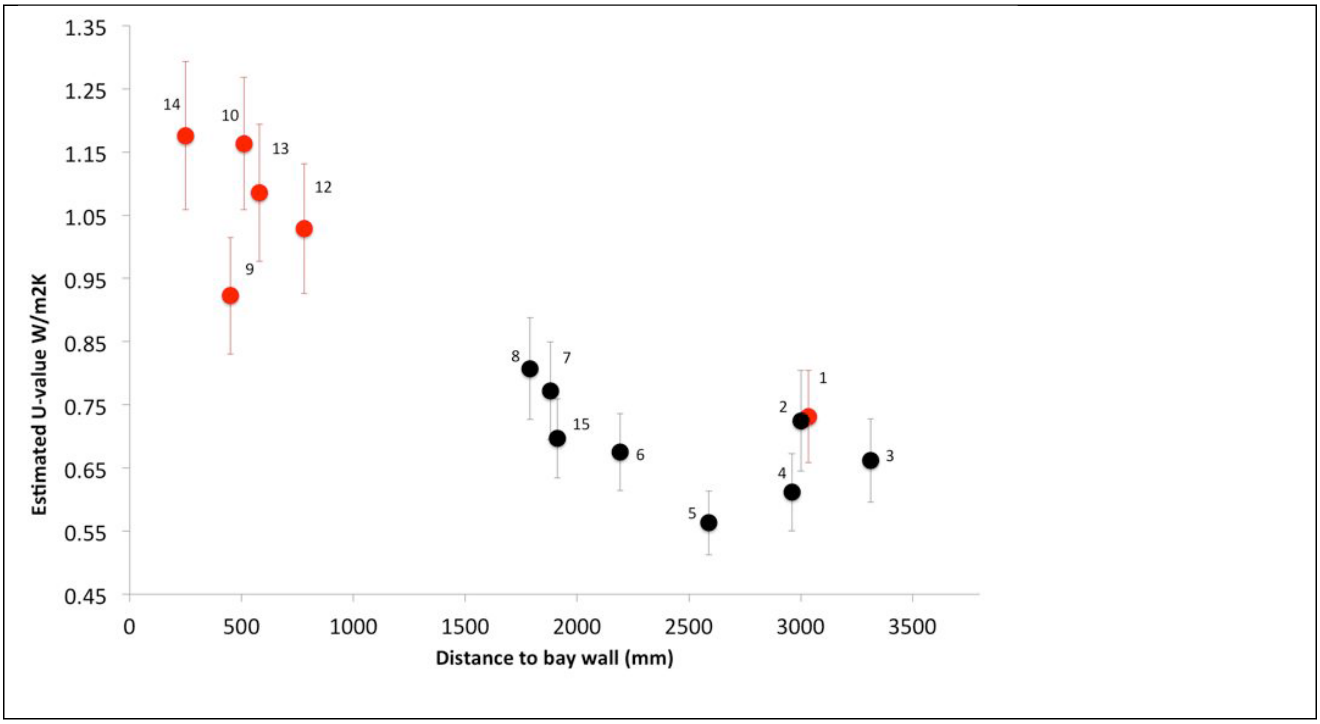

Fig. 4. In-situ estimated U_p-values as a function of external bay wall distance. Red data points are U_p-values in the perimeter zone; while black data points are in the non-perimeter zone. Error margins are estimated as per *Eq.* (1).

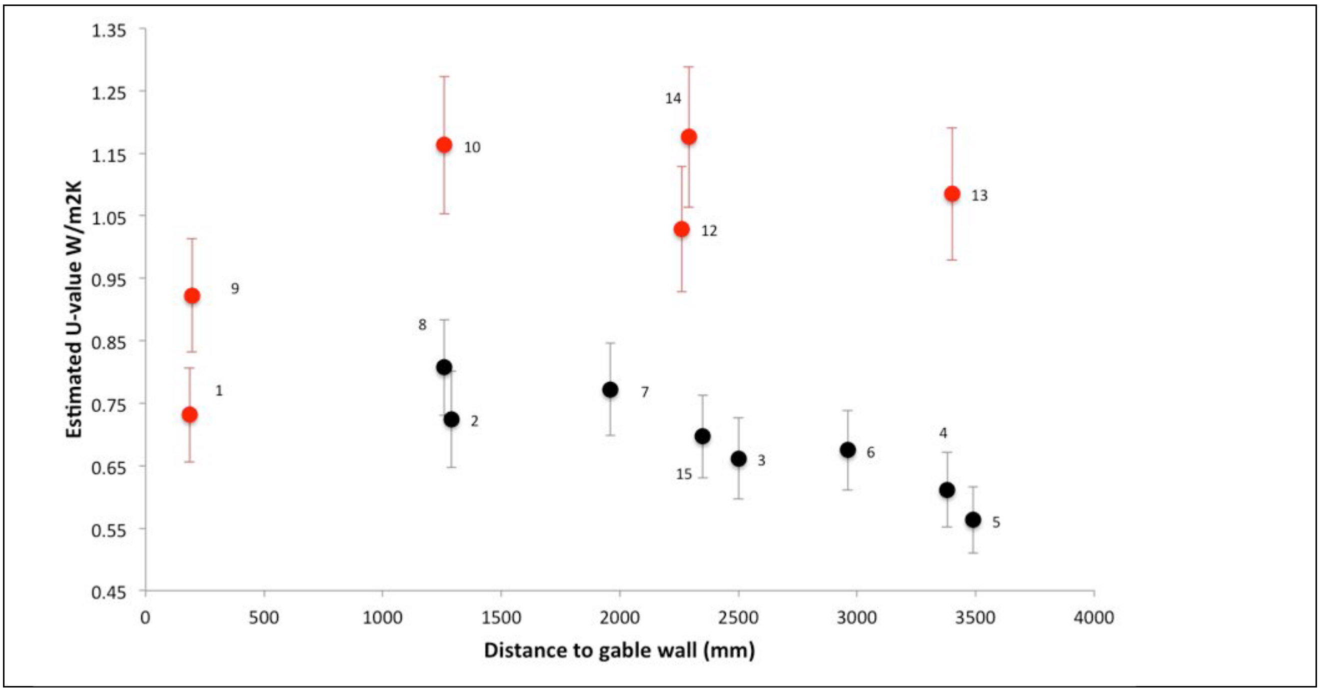

Fig. 5. In-situ estimated U_p-values estimated U-values as a function of external gable wall distance. Red data points are U_p-values in the perimeter zone; while black data points are in the non-perimeter zone. Error margins are estimated as per *Eq.* (1).

Fig. 5 plots the U_p-values as a function of the gable wall distance and shows asymmetric heat-flow, further confirming the above hypothesis. Below sensor locations 1 and 9, airbricks are located with clear airflow between joists, unlike in the bay void. This might explain the relatively low estimated U_p-values in location 1 and in 9, despite their proximity to airbricks and external walls as the cold incoming chamber air mixes with warmer void air in this floor void region. However, as both anomalies occur in the only two observed locations near the gable wall, further investigation and additional measurements such as void airflow would be required to determine the above hypothesis as to why the gable wall is less influential in heat-flow determination. After the monitoring period, builder's debris in the void, reducing airflow through the airbrick nearest to location 14, was discovered. This is likely to have affected perimeter heat-flow in location 14 and other nearby locations, possibly resulting in reduced U_p-values than if the airbrick had been fully clear.

Fig 6. illustrates the observed heat-flow as a function of the bay and gable wall distances, by linearly interpolating U_p-values between observed values. Fig. 6 aids visualisation of trends in floor heat-flow in the room and is not intended to provide an accurate prediction of U-values between measurement points; no account is taken of structural factors, such as floor joists. Fig. 6 highlights that heat-flow is generally increased near the perimeter of the floor; it illustrates the stronger relationship between heat-flow and distance to bay, compared to distance to gable.

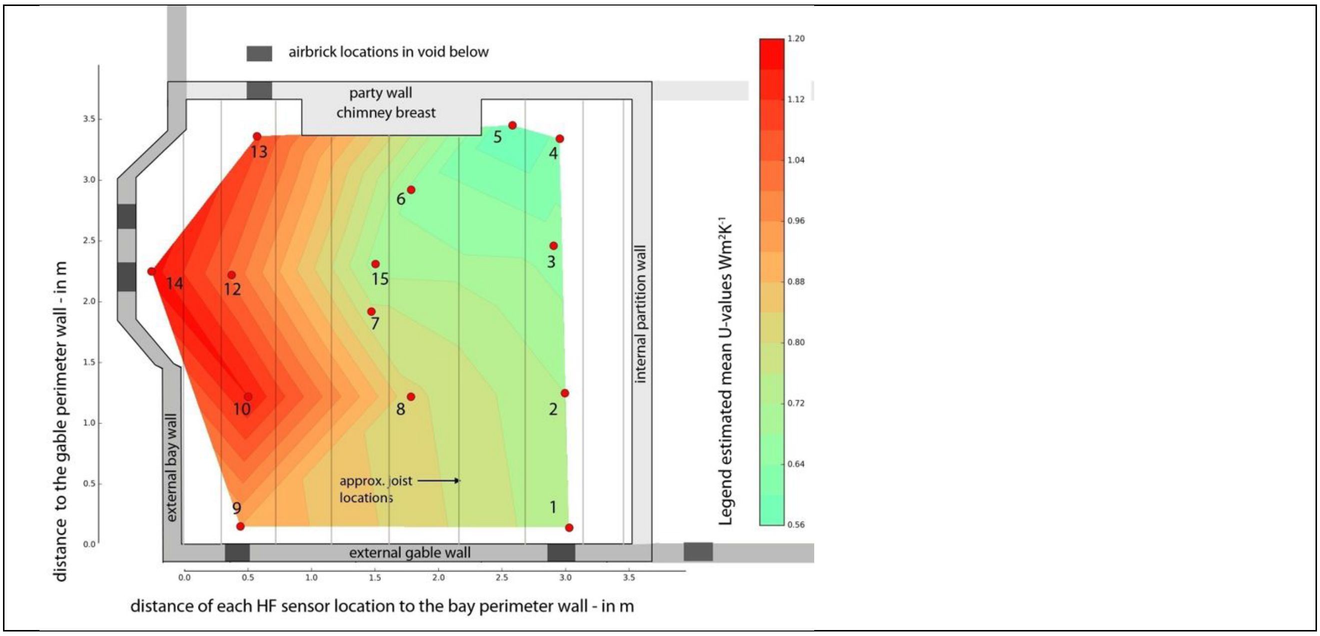

Fig. 6. Linear interpolated U_p-values as a function of both bay (X-axis) and gable (Y-axis) wall distances.

3.3. Obtaining a 'whole' floor U-value (U_{wf})

While U-values are usually used to characterise the thermal performance of a whole building element, in-situ 'point' U-values are estimated from measurements of heat-flux through a sensor area of 30mm diameter. Given the large spread of U_p-values across the surface, a single 'point' U-value is unlikely to be representative of the entire element, as illustrated by the above findings. However, the total thermal transmittance (or resistance) of the floor may be estimated from area-weighting [62]. A whole floor U-value (U_{wf}) was obtained by an area-weighted summation of each U_p-value multiplied by its representative floor area (A_j) as a proportion of the total floor – see *Eq.*(3):

$$U_{wf} = \sum_{j=1}^{n} \frac{Aj \times Upj}{Awf} \qquad (3)$$

where U_{wf} ($Wm^{-2}K^{-1}$) is the whole floor U-value; A_j in m^2 is the representative floor area assigned to each U-value point (U_{pj}) and A_{wf} is the whole floor area. Index *j* identifies individual point locations on the floor measured simultaneously and *n* is the number of point locations observed. Representative areas around sensors were identified via infrared thermography, helping to divide the floor surface in a grid in accordance with the location of sensors in these areas.

For the Salford EH, the whole floor U-value estimated by weighted summation is equal to the mean estimated floor U-value of 0.83 ± 0.08 $Wm^{-2}K^{-1}$; suggesting that a good spread of measurements was taken across the floor, though excluding reduced heat loss through the joists. Accounting for 12% joists and assuming that the heat-flow through joists is 21% less than through floorboards, as was found for location 11 in this study, for illustrative purposes this would give an adjusted whole floor U-value of 0.81 ±0.08 $Wm^{-2}K^{-1}$, so estimated to range from 0.73 to 0.89 $Wm^{-2}K^{-1}$. Where fewer or less well distributed U_p-values are obtained, it is highly unlikely that a simple averaging of these U_p-values is appropriate to obtain U_{wf} and hence an area-weighted summation is preferable for determining U_{wf}. This is illustrated by a hypothetical limited monitoring campaign using - as example - only U_p-values in locations 4 and 5 on the floor: the estimated U_{wf}-value would be 0.59 ±0.06 $Wm^{-2}K^{-1}$, excluding joist presence. This is much lower than the estimated whole floor U-value of 0.83 ±0.08 $Wm^{-2}K^{-1}$, based on the area-weighted summation of 14 observed U_p-values. Similarly, an overestimated U_{wf}-value of 1.10 ± 0.11 $Wm^{-2}K^{-1}$ would be estimated if just observing heat-flow in locations 10 and 12; both these estimates are outside the margins of error. Furthermore, about 70% of the estimated U_{wf}-values obtained from just two U_p-values would over-or under-estimate the case study floor U_{wf}-value as obtained from the 14 U_p-values; this is illustrated by Fig. 7. To obtain a larger surface area coverage, an alternative to point measurements might be the use of larger heat flux plates, however these instruments are not commercially available but were purpose made and used by for instance New Zealand researchers and were about 450mm wide and 600mm long (see for example Cox-Smith [63] and Isaacs [64]). Similar issues of placement and coverage still remain however.

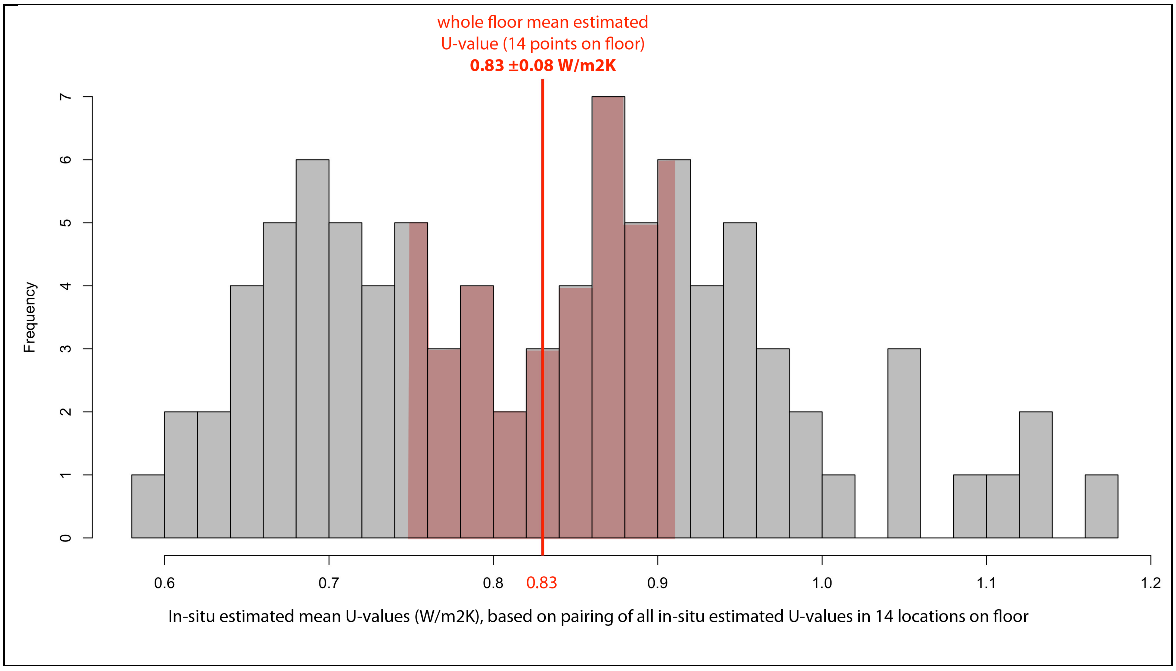

Fig. 7. 91 paired U-values for the Salford EH; only about 30% of the paired values are within the margins of error of the whole floor estimated U-value; the red line indicates the whole floor estimated U-value, while the red bars indicate the U-value distribution within the error margins of the whole floor U-value. This proportion increases to 43% with individual measurements falling within the margins of error of the whole floor U-value; measurement in location 8 is the closest to the estimated U_{wf}-value.

3.4. Salford Energy House: comparison of the in-situ U_{wf}-value estimate with model U-value estimates

Obtaining a 'whole' element U-value is needed for comparison with modelled U-values; which for the case-study floor is estimated at 0.58 to 0.71 $Wm^{-2}K^{-1}$ using ISO-13370 [42], CIBSE [65] Guide A and SAP [66] with the same input assumptions: assuming 12% joist presence and depending on assumed external wind speeds (0-5 m/s) and concrete ground conductivity of 1.3 to 1.9 $Wm^{-1}K^{-1}$ [65]. In this case the modelled U-value appears to underestimate the in-situ measured U_{wf}-value between 12% and 28%, based on the above model assumptions and outside the estimated margins of measurement error.

Floor U-value models are simplified and exclude several variables such as structural issues acting as void obstructions as described earlier. Models also exclude linear thermal bridging of the wall-floor as these are included in whole building heat loss models. However, in-situ measurements might be affected by the wall-floor junction heat-transfer – as expressed by the increased heat-flow in the perimeter areas. It is unclear whether models and in-situ measurements are directly comparable, and while such model exclusion might explain a disparity, a larger sample and measurement in actual floors in the field are required to investigate any potential deviation between modelled and measured U-values in the wider housing stock. This is especially important for the effective characterisation of the UK's existing housing stock to facilitate appropriate retrofitting decision-making based on the estimated payback of retrofit measures[1].

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1 This is illustrated with a simplified payback model for the case-study, based on West Pennines (15.5ºC) Heating Degree Days and floor insulation cost estimates of between £25 to £70/m^2 when professionally installed and between £100 DIY [67] and 4 pence per kWh gas-heating cost, excluding standing charges and insulation grants. The yearly estimated energy cost associated with uninsulated floors is just £35 to £43 according to the modelled value, compared to £49 for the in-situ measured value. The payback of insulating floors is thus long (between 3 and 99 years depending on cost), especially when based on modelled U-values and professionally installed: 25 to 99 years payback when insulated to 2015 Building Regulation standard (U=0.25 $Wm^{-2}K^{-1}$) compared to 21 to 58 years when based on the actual in-situ measured value. The payback of a DIY-insulated floor might be as low as 3 years based on in-situ measurements, while 4-5 years based on predictive models.

3.5. Comparison of Salford EH observed floor U-values with other in-situ measured sources

Few in-situ measured U-values have been published for suspended timber ground floors in the UK. For semi-detached dwellings, U_p-values estimated from in-situ measurements range from 0.69 to 2.4 $Wm^{-2}K^{-1}$, based on just 5 sources, as listed in Table 3. Baker [11] and Snow [68] observed heat-flow in one location on the floor; but their position relative to the perimeter is undisclosed. Stinson [69] measured one location on the floor in the perimeter area. Miles-Shenton [70] on the other hand undertook measurements at three locations, one in the perimeter/bay area and two in the central area of the uninsulated floor. The U_p-values presented by Miles-Shenton [70] are presented as a minimum to maximum range of instantaneous calculated U_p-values over the monitoring period rather than U-values derived by the ISO Average Method, as the other sources, or as a final mean U_p-value as was the case for the data presented here. Miles-Shenton's U_p-values indicate that as expected, the observed heat-flow in the bay was on average greater than when measured in the middle of the floor.

In-situ measured U_p-values of un-insulated suspended ground floor (point measurements, $Wm^{-2}K^{-1}$)	**Source & Notes**
1.19	Semi-detached house in Derbyshire, ~45m^2 ground floor with part of the floor in solid concrete [11].
2.4 ±0.2 (measured in perimeter zone)	Semi-detached house in Edinburgh, measured at the perimeter and floor surface to external environment [69, 71].
2.3	Scotstarvit Cottage, Fife; measured from air skirting level to external. No further details [68].
1.19 ~ 1.93 (measured in perimeter/bay zone)	Temple Avenue, York, 1930s house semi-detached; internal air to external environment; U-value ranges are based on calculated daily averages [70].
0.69 ~ 1.44 (measured in central floor zone)	

Table 3. In-situ measured U_p-values of un-insulated suspended ground floor (point measurements)

U_p-values listed in Table 3 highlight the wide variation of heat-flow observed for measurements taken on buildings in different locations, with some overlap with the findings here. However, the reported field studies appear to have higher estimated U_p-values, especially along the perimeter zone. The differences may relate to the differences in environmental conditions or physical form and materials and higher expected variations in the field; constraints associated with the use of the EH are discussed in section 2. Differences between the case-study buildings include the sub-floor material properties (concrete in the EH), ventilation rates, floor finishes, void depths, wall thermal performance and environmental conditions. These variables affect measured floor heat-flow differently, hence comparison between findings from different studies is challenging. Furthermore, the large spread of in-situ heat-flow observed across the floor in this case-study, highlights that using a few point measurements is unlikely to represent the entire floor's U_{wf}-value. Estimating the performance of the whole floor by measurements taken in one or two locations may systematically over- or under- estimate floor U_{wf}-values. As monitoring in perimeter locations is generally used in occupied dwellings for practical reasons, this could lead to over-estimation of U_{wf}-values. This raises a question about the estimation of U_{wf}-values from in-situ U_p-value measurements and its importance for comparison to literature and models, which are based on whole floor U-values, not point measurements. It is clearly important to undertake and interpret the results of in-situ monitoring campaigns with care and transparency. Moreover, differences in methods further challenge the comparison between estimated floor U-values presented in different sources. For example, placement of temperature sensors is not the same in each study; air temperatures in rooms are inhomogeneous, leading to vertical temperature gradients [51, 72, 73], affecting U-value estimates as they depend on the temperature gradient – more research is required.

4. Conclusions and further research

Suspended timber ground floors are the main floor construction in up to 10 million dwellings in the UK [16], and the upgrade of these floors could contribute to reduced energy use in the residential sector [8]. Insulating suspended timber ground floors was an approved measure under the Green Deal [41], yet currently their performance is not well characterised. This research undertook unique high-resolution floor U-value measurements in a controlled environment at the Salford Energy House. Our results highlight the value and necessity of high-resolution monitoring techniques compared to the generally available low resolution measurements on construction surfaces. This high-resolution monitoring in 15 floor locations produced a high variability of U_p-values between 0.56 ±0.05 and 1.18 ±0.11 $Wm^{-2} K^{-1}$, depending on location. In general, it was found that the observed U_p-values were greatest near the airbricks and along the exposed external wall perimeter, which reflects physical theory and solid ground floor research (see section 3.2.). Additionally, high resolution monitoring revealed that the thermal behaviour of floors is complex and affected by a number of environmental and structural factors (such as joist direction and depth affecting heat flow), which are excluded from predictive models and payback calculations.

The in-situ U-value of suspended timber ground floors in the wider population might be different from published or modelled values, as was observed for this case study: depending on input assumptions, the measured U_{wf}-value was 12% to 28% higher than the modelled U-values of 0.58 to 0.71 $Wm^{-2}K^{-1}$.. However, it is unclear how robust comparisons are between measured and modelled values and further research is required to determine whether the modelled underestimation of actual floor U-values is reflective of the wider stock. Our findings also highlighted that estimating and comparing representative U-values for suspended timber ground floors from just one or a few in-situ point measurements has significantly increased uncertainties: only 43% of the individual U-value point measurements and just 30% of paired U_p-values would give a whole floor in-situ estimated U-value (U_{wf}) within the margins of error of the floor's estimated U_{wf} of 0.83 ±0.08 $Wm^{-2} K^{-1}$ (excluding joist presence). This highlights the potential impact of heat-flux sensor location on U-value estimation. The observed large spread of floor U_p-values has significant implications for in-situ measuring techniques of these floors: where to take point measurements on the floor and how to average these point measurements to derive a representative 'whole floor' U-value? It also leads to comparison difficulties with predictive models and with other in-situ sources. Addressing these challenges needs to be a priority because validation of U-values is essential to confirm pay-back and carbon reduction estimations of intervention measures especially considering that for practical and resource reasons, in-situ measurements have been usually limited to just a few point measurements in occupied houses. Fabric-efficiency policies need to have a sound empirical validation to allow practical decision-making and to be successful. .

Nevertheless, these findings indicate that observing one or a few measurements are unlikely to be representative of the whole floor heat-flow while it could also lead to over-or underestimating the whole floor U-value if taken to be representative of the entire floor's heat-flow. Unless in-situ measuring was specifically set up to measure a sufficient and representative number of point measurements, a whole floor U-value, which might be obtained from an area-weighted summation as per *Eq.* (3), cannot be derived with confidence. Based on these findings, single point measurements in in-situ monitoring trials are likely to have a significant location bias and for suspended timber ground floors, high resolution measuring methods should be used to avoid such bias. In addition the issue of a low or high-resolution sampling strategy that we identified is likely to be also relevant for in-situ measurements of other elements and not just for floors. Improving the characterisation of the heat-flow and its variability through real floors from high-resolution in-situ measurements will facilitate a more accurate prediction of the current performance and support a more accurate prediction of the impact of interventions in support of carbon reductions in the housing stock.

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