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Suspended timber ground floors: Heat loss reduction potential of insulation interventions

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ABSTRACT

There are approximately 10 million suspended timber ground floor constructions in the UK and millions more globally. However, it is unknown how many of these floors are insulated and their performance has not been widely investigated. This study investigates the impact of retrofitting insulation on the thermal performance of suspended timber ground floors through the detailed investigation of a UK case study dwelling. Practical and buildable interventions were undertaken: fully-filling the floor void with EPS beads, and 100 mm woodfibre insulation between the joists. The performance of both interventions was monitored by high-resolution in-situ heat-flow monitoring in 27 floor locations, allowing for comparison with the uninsulated floor and with modelled results. While floors often remain uninsulated due to the disruption of retrospective works, this study highlighted potentially significant heat loss reductions: the mean whole floor U-value dropped by 65% for woodfibre insulation and 92% for bead-insulation which also benefited from sealed airbricks. A disparity between the in-situ measured and modelled performance was observed; this gap reduced the better insulated the floor was. The findings have implications for policy, retrofit decision-making and carbon emission reduction stock models, especially given the modelled underestimation of floor heat loss, impact of interventions and assumed financial payback for this study.

1. Introduction

Most of the UK's 27 million dwellings are not well insulated [1] and the UK's housing stock is responsible for approximately 30% of the UK's total emissions [2]. The majority of existing housing will still be in use in 2050 [3–5], hence one of the key strategies in the UK's carbon reduction targets set out in the Climate Change Act 2008 is increasing the energy efficiency of the domestic housing stock [1,6]. Shorrock [7] estimates that there are nearly 10 million uninsulated suspended timber ground floors in the UK, including the majority of buildings built pre-1940 [8]. Additionally, suspended ground floor constructions are also prevalent in other countries such as the USA, New Zealand, Australia (e.g. [9–12]) and other European countries [13]. While the exact number of such floor constructions is unknown, it is estimated that for example in France and Germany there are approximately 6.5 million and 4.5 million suspended ground floors respectively [14,15]. The proportion of total dwelling heat loss from uninsulated ground floors depends on the overall dwelling fabric efficiency standard and the proportion of exposed areas and has been estimated to be as little as 4% [16], 10–15% [17–19], and can be as much as 25%, if the rest of the building is well insulated [20]. This small assumed proportion of floor heat loss of the entire dwelling's heat loss, and the disruptive nature of insulating such floors, might contribute to the low priority of floor insulation in retrofitting and energy policy and might explain the slow uptake of floor insulation in both social and privately owned dwellings [16,21–23]. Furthermore, a survey of industry reported that floor insulation was found to be one of the least considered energy efficiency upgrades to conservation properties: just 9% to 18% of 118 respondents said floor insulation was considered in most or all projects respectively [24].

The proportion of insulated floors in the UK's pre-war housing stock is unknown [13,25], and there is also no robust data available on the thermal upgrade potential of such floors. Insulating the millions of uninsulated floors might lead to large carbon savings [4,7], supporting carbon reduction policies. Floor insulation was highlighted as a cost-effective carbon reduction measure by Shorrock [7] and total dwelling carbon reductions of 50–70% have been reported after insulating floors, walls, windows and lofts and installing new efficient boilers in existing housing [26]. Previous estimates suggest around 60% of the heat loss through suspended timber ground floors might be reduced by insulating them [27].

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Nomenclature

U, U_{mean}, U_p, U_{wf}, U_{avg} 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 area-weighted U_p-values. U_{avg} is the in-situ estimated whole floor U-value derived from a simple average of all U_p-values
HF1, HF2 Heat flux sensor location 1, 2
T_{Si}, T_{ea} Internal surface temperature and external air temperature respectively
q In-situ measured heat-flow rate, Wm^{-2}
R_{si} Internal surface thermal resistance, taken to be $0.17\,m^2\,KW^{-1}$ for downward heat-flow through floors
λ Conductivity, $Wm^{-1}\,K^{-1}$

Between January 2013 and June 2015, around 200,000 suspended ground floor insulation measures were recommended as part of the (now withdrawn) Green Deal assessments in the UK (this was nearly 12% of all recommended measures) [28]. However, in a similar time-frame, only 0.5% or approximately 9000 floors were actually insulated under the ECO-policy and Green Deal combined [29]. The proportion of uninsulated floors in several other EU countries is unknown [13], though it is estimated that in the Netherlands and Austria the proportion of uninsulated suspended ground floors might be as high as 57% and 70% respectively [13]. Despite thousands of floors being insulated, for example in the UK as part of the Green Deal and ECO-policy, the actual heat loss reduction impact of the insulation installations remains uncharacterised. An additional benefit of insulating floors might be increased dwelling airtightness as well as better occupant thermal comfort [30], but this remains uncharacterised at present.

To support retrofit policy and retrofit decision-making based on the financial payback of interventions, a better understanding of the thermal performance of these floors and the potential improvements from insulation interventions is required. The value of such studies has been highlighted by a reported underperformance of many interventions [31–34], raising questions about the achieved carbon savings, predicted cost-effectiveness of retrofit measures and assumed pay-back times, [35,36], all key factors in retrofit-decision making and to inform government policy [37]. The financial payback of retrofit interventions depends on the accurate estimation of the construction's performance and on the actual achieved improvement in thermal performance. In particular, recent research suggests that actual floor heat loss might be underestimated by models, which could underestimate the energy saving potential of measures affecting this building component [38,39].

This paper explores the efficacy of retrofit measures on a suspended timber ground floor in a pre-1919 terraced house in West-London, UK. The aim of the study was to investigate the heat loss reduction potential of two different insulation methods. In-situ heat flow was measured with heat flux sensors in 27 floor locations pre- and post-insulation interventions, allowing for comparison with modelled results. Firstly, the case study house and insulation interventions are discussed, followed by instrumentation and research and analysis methods. Subsequently, results are presented and discussed, focusing on the heat-loss reduction potential of the different interventions, impact on the variation of heat-flow across the floor and comparison between in-situ measured and modelled U-values. Finally, the policy implications arising from these findings are discussed.

2. Case study house, instrumentation, data and error analysis methods

The case study house was a pre-1919 solid wall terraced house located in a conservation area in London and the case study characteristics, alongside instrumentation of the uninsulated floor and research methods, are described in more detail in [38]. The $12.15\,m^2$ living room floor had a floor void depth of 250 mm below the 100 mm joists, with a 150 mm concrete oversite surface on the soil. Airbricks were located between the joists and three sleeper walls divided the void in four void sections, as described in [38]. A total of 27 heat flux sensors (Hukseflux HFP01, ±5% accuracy) were placed on the living-room floor surface, with one sensor on a joist, see Fig. 1. Nine sensors were located within a 1000 mm perimeter zone, with several sensors in line with airbricks below. Sensor placement was aided by the use of infrared images and sensors were affixed to the floor surface with a thin layer of heat-sink compound and duct tape along the edges and the first 100 mm of the lead. Direct solar gain was reduced by closing window blinds. External air temperatures (T_{ea}, ±0.4 °C accuracy) were measured with thermistors and a Stephenson screen to shield from solar radiation at the front of the house; internal floor surface temperatures were measured with thermistors (T_{Si}, ±0.1 °C accuracy), paired and located next to each heat flux sensor. Eltek Remote Sensor GENII data loggers or Squirrel 451L or 851L data loggers were used to collect all of the heat flux and temperature data described above. Radiant oil-filled electrical plug-in heaters were set to a daily heating schedule to reach 21 °C between 7–9 a.m. and 4 p.m.–11 p.m. in accordance with the BREDEM model [40], which is the basis for SAP models used for Building Regulations compliance and to compare pre-and post retrofit efficiency savings [41]. This dynamic heating pattern reflects heated and unheated periods in actual occupied houses.

2.1. Data and error analysis methods

All measurements were taken at 5 min sequential intervals and were analysed at daily intervals to estimate point U-values in accordance with Eq (1). and as per [38]:

$$U_{mean} = \frac{1}{\mathbf{n}}\sum_{\mathbf{j}=1}^{\mathbf{n}} 1\Big/\left(\frac{(Tsij - Teaj)}{qj} + R_{Si}\right) - \text{mean of ratios} \quad (1)$$

where U_{mean} is the final estimated in-situ U-value in $Wm^{-2}\,K^{-1}$; q is the heat-flow rate (Wm^{-2}); 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 $0.17\,m^2\,KW^{-1}$ in accordance with ISO 6946 [42]. Index j identifies individual measurements in the same location over time and n is the number of measurements taken sequentially. All estimates include adjustment for the thermal resistance of the heat flux sensor itself ($\sim 6.25 \times 10^{-3}\,m^2\,KW^{-1}$, [43]). This method of U-value estimation simplifies the heat flow path, and heat flow to and from the ground and other dynamic effects are considered accounted for during the monitoring campaign if measured over a sufficiently long enough time (and if the ISO-9869 test criteria are met). The U-values derived in this manner may be considered effective U-values, a result of definitional uncertainty and practical limitations for measurements in situ.

The first nine days of monitoring were used for data analysis, however for 9 point-locations on the bead insulated floor, shorter

Fig. 1. Floor plan with heat flux sensor locations (red circles and numbered); airbrick locations (blue), and sleeper walls (grey). Approximate joist locations are marked with a faint grey line and annotated with J1, J2 etc. Location 13j is the only location measured on a joist. Portable radiant oil-filled electrical plug-in heaters are marked on the plan. Note that the colours have no meaning other then each colour distinguishes one representative area around a HF sensor from another. Representative areas were derived from infrared images. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Monitoring period for U-value estimation for the point-locations on the bead-insulated floor and effect on U-vale estimation, based on meeting the ISO-9869 convergence tests. The effect on U-value estimation is within the estimated error margins (mean estimated uncertainty of around 30% for the bead insulated floor).

Point location	Monitoring period used for data analysis	U_p-value difference ($Wm^2 K^{-1}$) compared to the 9 day monitoring period (% difference in brackets)	% difference in *sd* of monitored period compared to 9 days
HF 24	5 days	0.01 $Wm^2 K^{-1}$ (17%)	0%
HF 5, HF15, HF16	6 days	0–0.01 $Wm^2 K^{-1}$ (0% to 11%)	0%
HF 21, HF 26	8 days	0.01–0.02 $Wm^2 K^{-1}$ (6% to 10%)	13% to 17%
HF 14, HF 23	12 days	0 to −0.02 $Wm^2 K^{-1}$ (0% to 15%)	0%
HF 13	15 days	0 $Wm^2 K^{-1}$ (0%)	17%
All other HF sensors:	9 days	–	–

periods were used (see Table 1)[1] to estimate mean U-values, to ensure that the three ISO-9869 criteria were met, which are (1.) monitoring in full 24 h periods for at least 3 days; (2.) the final U-value is within ±5% of the U-value obtained a full 24 hr prior and (3.) the final U-value obtained using the first 2/3rds of the data should be within ±5% of the U-value obtained after analysing the last 2/3rds of the data (based on full 24-hr periods) [44]. Using different time periods is not ideal, given the different environmental conditions over different monitoring periods, though they did not differ greatly during the monitoring periods. Hence in this case the final estimated U-values (and *sd*) did not significantly differ between different monitoring periods, neither did the use of different analysis periods affect the final whole floor U-value (i.e. all within the estimated error margins, see Table 1). The reasons for non-compliance of the three test criteria for some locations on the floor are unknown; further research is required. ISO-9869 esti-

[1] Note that all but location 6 did not meet ISO test 2 at any monitoring time, but was ±6% after 9 days of monitoring, hence data was analysed after 9 days. Additionally, locations 15 and 16 met ISO test 2 after 6 days of monitoring, though ISO test 1 was just outside the ±5% threshold.

Table 2
Identified errors and error propagation in this study, after ISO-9869 [44]; grouping by authors. Replacement of the ISO-9869 'natural variability error' of ±10% with the sd of daily U-values as described in 2.1.

Identified errors – (after ISO-9869) [44]	Applicable for each U_p-value, without comparison (after ISO-9869) [44]	Applicable when comparing uninsulated and EPS bead insulated floor	Applicable for comparisons with woodfibre insulated floor
Intrinsic: Instrument error (calibration heat flux and temperature sensors)	± 5%	–	–
Extrinsic: Measuring condition error – Edge heat-loss error	±3%	–	–
Extrinsic: Measuring condition error – Contact error	±5%	–	±5%
Extrinsic: Measuring condition error – Temperature location measurement error	±5%	±5%	±5%
Natural variability U (inherent property, not a measurement error) – *sd* of daily Umean	±sd	±sd	±sd
Final estimated error	$\sqrt{5^2+3^2+5^2+5^2+sd^2}$ Eq. (2).	$\sqrt{5^2+sd^2}$ Eq. (3).	$\sqrt{5^2+5^2+sd^2}$ Eq. (4).

mates the natural variability of in-situ U-values as ±10% [44], but the standard deviation (*sd*) of the daily estimated U_p-value was used instead of this variability factor, to reflect the actual variability of the daily estimated U-values during the monitoring period (see Table 2.), which was generally greater than the ±10% assumed by the ISO-9869 standard for the insulated floors.

2.2. Error analysis

The measurement uncertainty for the in-situ estimated U-values is estimated from Eq. (2). in Table 2, which is explained in detail in [38]. Sensors remained in place for the bead insulated floor and as such the contact, edge heat loss and instrument errors are identical before and after this intervention and may be excluded when comparing the relative U-values for the uninsulated and bead-insulated floor – see Eq. (3). However, sensors were removed and put back in the same location after the woodfibre insulation installation, so contact error is likely to apply in this case, as per Eq. (4).

The final estimated uncertainty for the uninsulated whole floor (area-weighted mean) was ±12% for the uninsulated floor and ±18% for the woodfibre insulated floor, while ±31% for the bead-insulated floor, which is large. However this larger proportional uncertainty generally represents only a small U-value range around the mean-point U-value – see Table 3.

3. Insulation interventions

In the UK, the building regulations recommend design U-values of maximum 0.25 $Wm^{-2}K^{-1}$ for the upgrade of existing ground floor structures when at least 50% of the floor surface is upgraded or replaced, or where 25% of the entire building envelope is renovated [45]. Relaxations exist for listed buildings and a maximum U-value of 0.70 $Wm^{-2}K^{-1}$ is permitted in specific cases, for example when payback is greater than 15 years [45].

Typically a flexible or fibrous insulation is installed in between the timber joists when insulating the floor, as was tested in one of the interventions in this study. This is a disruptive process, as this usually requires lifting of all of the floorboards, as often there is only limited access from below [16]. and working in confined spaces has associated health and safety risks. Placing insulation on top of the joists is another option and this reduces the joist thermal bridging effect after insulation, but this is also disruptive because door openings, skirting boards and electrical sockets will need adjusting [20] and it reduces floor to ceiling heights. Some alternative insulation methods have recently been developed, aiming to reduce disruption and installation time by insulating the floor without lifting all floorboards. This includes remote spraying of insulation to the underside of floorboards and joists [46,47] or full-filling the floor void with EPS bead insulation [48,49], as was the first intervention tested in this study. The second intervention was the placement of 100 mm woodfibre insulation in between the joists, as described below.

Fig. 2. The bead filled floor along the exposed perimeter wall.

3.1. Intervention 1: full-filling of the floor void with EPS beads

Loose graphite coated EPS beads (λ = 0.033 $Wm^{-1}K^{-1}$ [50]) were blown into the full depth of the four floor void sections, allowing the insulation of floors without the disruption of lifting and re-fitting all of the floorboards. As the entire floor void depth is filled with EPS beads, and to avoid beads spilling out, airbricks were sealed with airtightness tape and covered with waterproof plastic boxes on the outside and bubble wrap on the inside. However this is yet to be proven appropriate, as airbricks are in place to regulate moisture in the void [51–53]; the long-term impact of sealing airbricks remains uncharacterised at present. Four floorboards – one in each section – were lifted to fill the entire 250 mm floor void under the joists and in between and up to the top of the 100 mm joist height, using the same equipment as cavity blown EPS beaded insulation, without the binding agent to allow for later removal of the beads by vacuuming them out. After mechanical filing, beads were manually filled and smoothed to the top of the joists – see Figs. 2 and 3.

Fig. 3. Post-bead insulation with monitoring instruments in place.

Fig. 4. Installation of woodfibre insulation in between the joists, held in a breather membrane over and under joists.

Fig. 5. Close-up of the chamfered woodfibre insulation to enable airbrick airflow.

Fig. 6. A typical sleeper wall, showing also the openings between the joists, which were filled with insulation and hence leading to significantly reduced airflow between different floor sections.

3.2. Intervention 2: 100 mm woodfibre between the joists

After bead removal,[2] all instruments and floorboards (as illustrated in Fig. 3) were removed and 100 mm woodfibre insulation (λ=0.038 $Wm^{-1}K^{-1}$ [54]) was installed between the joists (see Fig. 4), held by a tightly stretched and stapled breather membrane suspended over and under the joists with taping of overlapping joints. This is a typical insulation solution, but generally the insulation is a more flexible product such as mineral wool, which can be more easily inserted between unevenly spaced floor joists and often installed DIY [55,56] and held in place by netting. Reduced insulation had to be fitted where radiator pipes and services encroached in the space between joists, as was the case near sensor locations 23–26. Near the airbricks, the insulation was also reduced by chamfering the edge to allow airflow underneath (see Fig. 5). Insulation was fitted tightly between the joists to minimise any air gaps which could lead to increased convective heat loss [57]. The airflow between sleeper wall sections was likely significantly reduced due to the insulation being installed between joists, which were the largest openings between floor void sections prior to insulation (see Fig. 6).

3.3. Environmental conditions pre/post insulation

In field studies, the environmental conditions are unpredictable and not the same over the monitoring period. For this reason, the interventions were undertaken in sequence and as close as possible together. Some additional environmental variables, such as wind-speed, were measured and a qualitative evaluation was undertaken of how the pre/post intervention measurements might have been affected by other external changing variables. However, it was not possible to ascertain the magnitude of these single or combined effects; additionally dynamic seasonal thermal mass ground effects were excluded.

In summary, higher mean wind-speeds were observed during the bead-intervention, which might have under-estimated the efficacy of the intervention, especially along the perimeter. However, this is likely to have had a minimal effect, as the bead intervention relied on sealed airbricks, though colder air may have infiltrated

[2] After the removal of beads with an industrial hoover, floor boards were removed to install woodfibre insulation. Prior to this, the floor was inspected to ensure bead removal around joist ends etc.

through gaps and cracks in the foundation wall. Additionally, the pre-insulation mean external air temperature was slightly warmer than the mean external temperature during bead-intervention ($\Delta T = 0.8\,°C \pm 0.14\,°C$); however any impact on estimated U-values is likely to be negligible (i.e. within the margins of error) due to the measuring duration (accounting for thermal mass time lag and measuring in full 24 h periods) and by meeting the ISO-9869 test criteria as explained in 2.1. For the woodfibre insulated floor, the pre-intervention period was colder ($6.2 \pm 0.1\,°C$) than the mean external temperature during the woodfibre intervention ($7.9 \pm 0.1\,°C$); the effect on U-value determination is unknown but is likely to be small given the measured heat flux is proportional to ΔT and ISO 9869-tests were met. There was also significantly increased mean external windspeed (0.79 ± 0.2 m/s) compared to the pre-insulation period (0.41 ± 0.2 m/s) and this might lead to under-estimation of the woodfibre efficacy due to potentially increased U_p-value estimates along the perimeter.

4. Results, analysis and discussion

The uninsulated floor point U-values (U_p) were estimated between $0.54 \pm 0.09\,Wm^{-2}\,K^{-1}$ further away from the exposed environment, to as much as $2.04 \pm 0.21\,Wm^{-2}\,K^{-1}$ near the perimeter wall and airbricks (location 6) – as reported in [38]. This large spread of U_p-values and reduced U_p-values with increased distance from the perimeter wall was as expected and as also observed across the floor in a thermal chamber [58]. The same studies also highlighted that models might underestimate suspended timber ground floor heat loss; in the case of the field study, the in-situ measured whole floor U-value (U_{wf}) was estimated to be $1.04 \pm 0.12\,W/m^2\,K$, nearly double model estimates [38].

4.1. Heat-flow reduction of the insulation interventions

As expected, for the bead-insulated floor, there was a significantly reduced spread of U_p-values, ranging from $0.02 \pm 0.01\,Wm^{-2}\,K^{-1}$ (location 9 and 19) to $0.58 \pm 0.24\,Wm^{-2}\,K^{-1}$ (location 6) near the external perimeter and the middle airbrick– see Table 3. For the woodfibre insulated floor, there was still a large spread of U_p-values, ranging between $0.18 \pm 0.04\,Wm^{-2}\,K^{-1}$ (location 4) to $1.89 \pm 0.22\,Wm^{-2}\,K^{-1}$ near the perimeter and above the middle airbrick in location 6 –see Table 3. A reduction in heat-flow associated with the interventions is highly statistically significant (Mann–Whitney $W = 351$, $n1 = n2 = 26$, $P < 0.05$ (0.00000003,

Table 3
Presents the estimated point U-values with the total estimated uncertainty and percentage reduction after woodfibre insulation and bead-insulation compared to the pre-insulated floor; error margins in accordance with Eq. (2). For wood fibre insulation only, small U_p-value reductions were achieved in locations 3, 6, 14 and an increase in U_p-value was observed in location 21, though within the estimated margins of error, all highlighted in shaded areas. This is likely due to installation quality issues – see 4.3. As expected, the joist U-value (13j) is similar pre/post intervention as this remained uninsulated in the woodfibre intervention, though is reduced after EPS bead-filling given the void was bead-filled under the observed joist location.

Sensor location on the floor (P = perimeter location)	Uninsulated floor- mean U-value ($Wm^{-2}K^{-1}$)			Woodfibre insulated floor- mean U ($Wm^{-2}K^{-1}$)			% reduction from uninsulated	bead insulated floor- mean U ($Wm^{-2}K^{-1}$)			% reduction from uninsulated
HF1 (P)	1.74	±	0.18	0.55	±	0.11	**68**	0.25	±	0.07	**86**
HF2 (P)	1.62	±	0.18	0.32	±	0.06	**80**	0.09	±	0.02	**94**
HF3	1.25	±	0.14	1.19	±	0.16	**5**	0.08	±	0.02	**93**
HF4	0.66	±	0.09	0.18	±	0.04	**72**	0.07	±	0.01	**89**
HF5	0.54	±	0.09	0.22	±	0.04	**60**	0.10	±	0.02	**82**
HF6 (P)	2.04	±	0.21	1.89	±	0.22	**7**	0.58	±	0.24	**71**
HF7 (P)	1.62	±	0.19	0.31	±	0.07	**81**	0.07	±	0.03	**95**
HF8 (P)	*1.37*	±	*0.16*	0.41	±	0.07	**70**	0.08	±	0.02	**94**
HF9	***1.11***	**±**	***0.14***	0.27	±	0.06	**75**	0.02	±	0.01	**98**
HF10	***0.99***	**±**	***0.13***	0.28	±	0.06	**72**	0.06	±	0.02	**94**
HF11	0.78	±	0.10	0.23	±	0.05	**70**	0.04	±	0.01	**95**
HF12	0.69	±	0.09	0.20	±	0.04	**71**	0.06	±	0.01	**91**
HF13	0.60	±	0.09	0.25	±	0.05	**58**	0.17	±	0.06	**72**
HF14 (P)	***1.14***	**±**	***0.12***	0.99	±	0.17	**13**	0.15	±	0.05	**87**
HF15 (P)	1.21	±	0.12	0.36	±	0.06	**70**	0.09	±	0.03	**93**
HF16 (P)	***1.13***	**±**	***0.11***	0.27	±	0.05	**76**	0.08	±	0.02	**93**

Table 3 (*Continued*)

HF17	***0.99***	**±**	***0.11***	0.31	±	0.05	**68**	0.04	±	0.01	**95**
HF18	***1.01***	**±**	***0.11***	0.26	±	0.04	**74**	0.07	±	0.01	**93**
HF19	0.90	±	0.11	0.21	±	0.04	**77**	0.02	±	0.01	**98**
HF20	0.80	±	0.09	0.25	±	0.05	**69**	0.06	±	0.01	**92**
HF21	0.60	±	0.09	0.70	±	0.10	**-17**	0.17	±	0.05	**71**
HF22 (P)	1.99	±	0.21	0.66	±	0.18	**67**	0.25	±	0.10	**87**
HF23	1.21	±	0.14	0.36	±	0.06	**70**	0.06	±	0.03	**95**
HF24	***0.96***	**±**	***0.11***	0.27	±	0.05	**72**	0.05	±	0.02	**95**
HF25	0.75	±	0.10	0.23	±	0.04	**70**	0.06	±	0.01	**92**
HF26	0.66	±	0.10	0.22	±	0.04	**67**	0.18	±	0.07	**73**
HF_Joist_13 j	0.51	±	0.07	0.51	±	0.08	**0**	0.18	±	0.05	**64**
U_{avg} (excluding joist presence)	1.11	±	0.13	0.45	±	0.08	**60%**	0.11	±	0.04	**90%**
U_{wf} (area-weighted, excluding joist presence)	1.04	±	±0.12	0.36	±	0.07	**65%**	0.09		0.03	**92%**

paired) for the bead insulated floor and Mann–Whitney W = 349, n1 = n2 = 26, $P < 0.05$ (0.00000009, paired) for the woodfibre insulated floor).

An area weighted U-value (U_{wf}) was obtained by defining areas (as shown in Fig. 1) around each heat flux sensor for the uninsulated floor, for which its measured per unit area heat flux was considered the most representative available. This was achieved by detailed thermography, whereby surface temperatures were inspected and areas of similar surface temperature around heat flux plates identified. This informed method of area selection around each sensor ensures that construction-specific heat flow characteristics can be identified (such as near the perimeter and airbricks) and area-weighted to reflect the extent of these effects. This method reduces spatial uncertainty associated with sensor placement, which would not be accounted for in simple averaging. Instead the U_{wf}-value reflects the whole floor heat loss more accurately, and any differences were within the error margin when compared to simple averaging (U_{avg}) – see Table 3. Slightly different configurations of the areas made no significant difference on the final estimated U_{wf}-value. Generally lower U_{wf}-values were obtained compared to U_{avg}-values, but still within the margins of error, due to a slight bias towards a proportionally larger number of perimeter sensor locations given their limited effect. Each sensor's individual estimated error is combined in a similar manner to obtain the whole floor estimated error margin. The estimated whole floor U-value for the woodfibre insulated floor is $0.36 \pm 0.07\,Wm^{-2}\,K^{-1}$, which is a mean U_{wf} –value reduction of 65% compared to the uninsulated floor. As expected, the bead insulated floor had a low estimated whole floor U-value ($0.09 \pm 0.03\,Wm^{-2}\,K^{-1}$), due to both the $\sim 3.6\,m^3$ of beads in the void, but also the sealing of airbricks, leading to a 92% U_{wf}-value reduction for the bead insulated floor – see also Table 4.

The above U_{wf}-values exclude joist presence adjustments. Only one measurement was undertaken on a joist ($0.51 \pm 0.07\,Wm^{-2}\,K^{-1}$), which represents a 15% reduction compared to the nearby floorboard measurement and within the margins of error. The uninsulated U_{wf}-value adjusted with this 15% joist presence reduction was within the margins of measurement error: U_{wf}-value of $1.04 \pm 0.12\,Wm^{-2}\,K^{-1}$ without joist adjustment compared to $1.02 \pm 0.12\,Wm^{-2}\,K^{-1}$ with joist adjustment. While in an uninsulated floor the presence of joists leads to slightly increased thermal resistance, for the insulated floors the joists became thermal bridges and are areas of reduced thermal resistance [59]. For the bead insulated floor, the U-value was increased by about 6% in the joist location (with 250 mm EPS underneath) compared to the better insulated location nearby – but again within the estimated error margins and this makes negligible difference to the bead insulated U_{wf}-value. For the woodfibre intervention, the joists remained uninsulated with only the addition of a thin breather-membrane. Hence as expected, the joist U-value remained the same in the woodfibre insulated floor ($0.51 \pm 0.08\,Wm^{-2}\,K^{-1}$ pre-insulation and $0.51 \pm 0.07\,Wm^{-2}\,K^{-1}$ post-insulation; the similarity of the joist U_p-value pre-and post woodfibre insulation also suggests that different environmental variables did not have a significant impact on measured U-values. However, the uninsulated joist has now become a thermal bridge in the woodfibre insulated joist, with an observed increased heat loss of 50%, compared to the insulated floorboards nearby, leading to an estimated U_{wf} –value of $0.40 \pm 0.08\,Wm^{-2}\,K^{-1}$ after joist adjustment. However this is based on the assumption that the

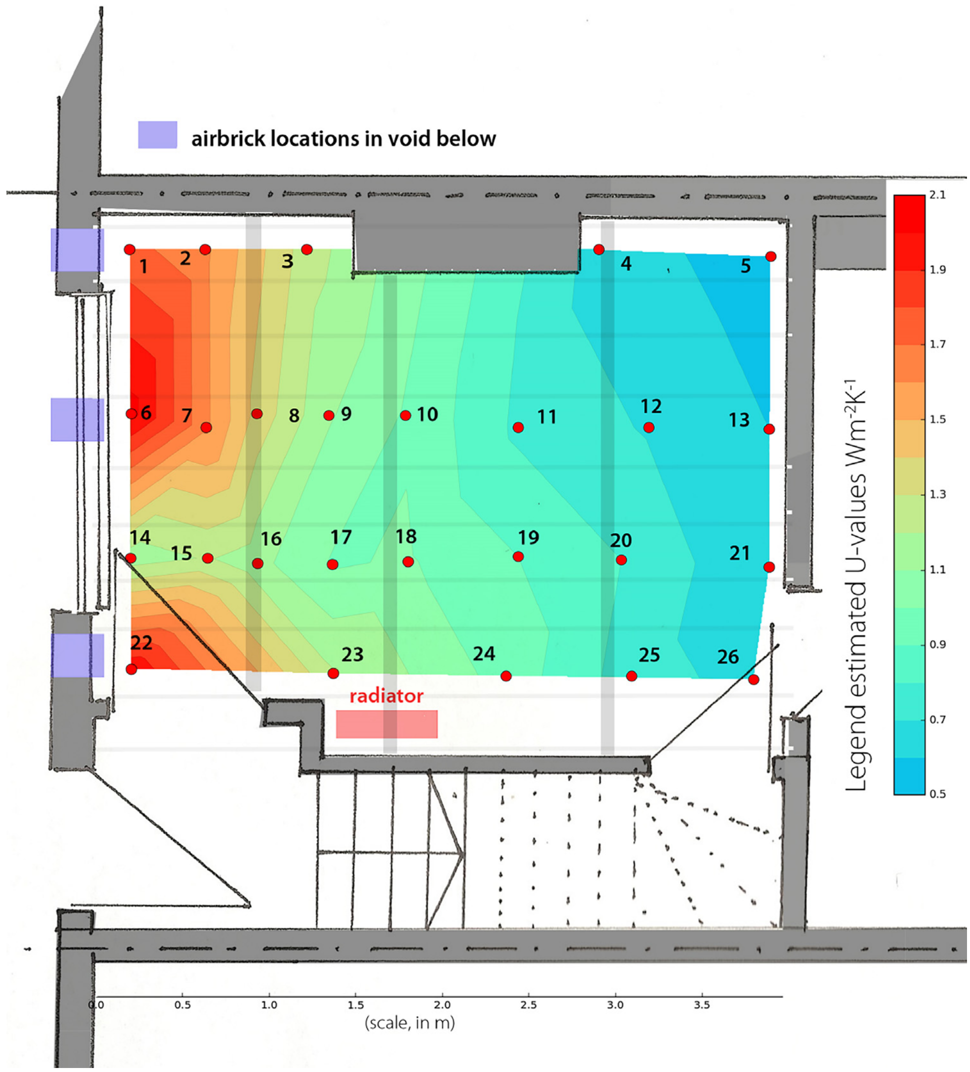

Fig. 7. Presents linearly interpolated U_p-values as a heat map between observed point U-value locations for the uninsulated floor; point locations are marked with a round dot and numbers; sleeper wall locations are indicated in light grey shade. Note that the map only shows interpolated values between points, with no values between the walls and the points (hence the white zone). Joist presence is not accounted for.

Table 4
Presents comparison of whole floor U-values and proportional U-value reduction based on in-situ measured values. Error margins estimated in accordance with Eq. (2).

	uninsulated floor	woodfibre insulated floor	bead insulated floor
whole floor U-value, U_{wf} ($Wm^{-2}K^{-1}$)	1.04 ± 0.12	0.36 ± 0.07	0.09 ± 0.03
% reduction compared to uninsulated	65%		92%
% Reduction when taking Min and Max U into account	54–75%		88–95%

proportional joist impact is the same across the floor for each intervention and given the spread of heatloss across the floor this is highly unlikely the case. Additionally, given that the joist U_{wf}-values are all within the margins of error of the U_{wf}-values without joist adjustment, there was no strong evidence to justify any adjustment due to joist presence. Hence for comparison purposes, joist presence was also excluded in predictive U-value models.

Few in-situ measurements have been published for insulated floors and for pre/post floor insulation studies for comparison purposes. Given the different variables, including different insulation materials, insulation depth and material conductivities and floor characteristics, direct comparison between floor insulation studies is challenging. For example, Harris [20] reported around a 50% suspended timber ground floor U-value reduction in a test cell after the introduction of 30 mm EPS insulation (with similar thermal conductivity as woodfibre insulation). This is a significant U-value reduction given the small depth of insulation, however due to the test-cell nature, comparison with in-situ field study results are difficult. Currie [60] reported a 71% point U-value reduction (from 2.4 $Wm^{-2}K^{-1}$ to 0.70 $Wm^{-2}K^{-1}$) after 80 mm woodfibre insulation installation of the suspended timber ground floor of a detached cottage in Scotland. This is a slightly better improvement than the mean 65% reduction observed in this study with 100 mm woodfibre insulation installation, though within the experimental error estimate of 54%–75% heat loss reduction for this case study in different locations when woodfibre insulated. Moreover, he study presented here is based on the whole floor U-value reduction of 26 measurement points pre/post insulation; while the Currie [60] study

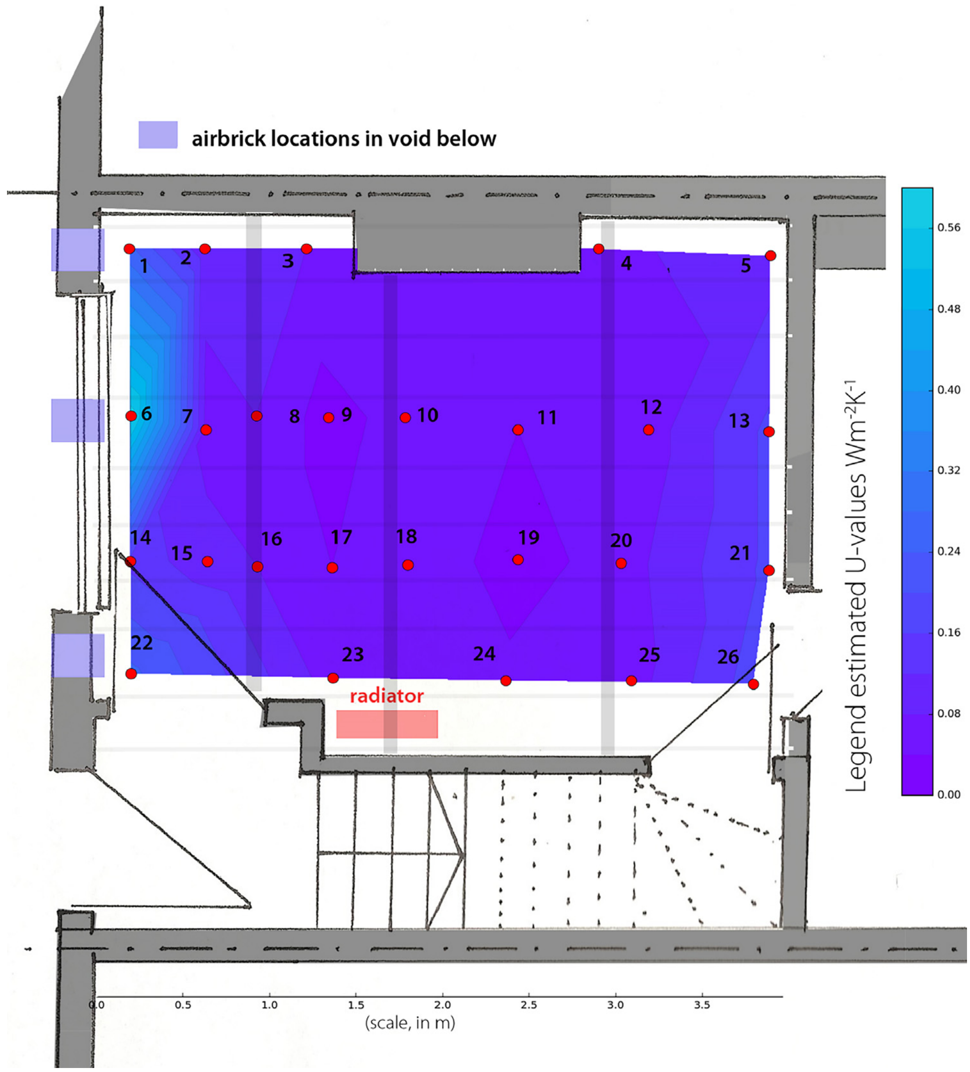

Fig. 8. Linearly interpolated U_p-values as a heat map between observed point U-value locations for the bead insulated floor, with the same scale used for the colour legend as in Fig. 7. An overall significantly reduced heat loss is observed post-insulation, with a reduced perimeter effect (though still present) and a more even spread of U_p-values across the floor.

was based on observation of one point measurement located in the exposed perimeter zone (and unknown how close to airbricks).

4.2. Perimeter effect and spread of U_p-values post-insulation

For the uninsulated floor, there is a clear association between the measured U_p-value and distance to the external perimeter walls [38,58], see Fig. 7. However, the relationship between the distance from the observed location to the exposed wall was significantly reduced once insulated, though there were still increased U_p-values in the perimeter zone – see Figs. 8 and 9. U_p-values near the perimeter were considerably lower for the bead insulated floor compared to the uninsulated floor, explained by the sealed airbricks and large amount of insulation – see Fig. 8. However, as illustrated in Fig. 9. for the woodfibre insulated floor, a larger perimeter effect was still observed due to insulation installation quality issues, as described in section 4.3. Due to this, only small heat-flow reductions were observed in locations 6 and 14 near the exposed perimeter, while an increase in U_p-value was observed in location 21 further away from the perimeter and only a small reduction in location 3 (all were within the margins of error) – see Table 3 and section 4.3.

The spread of heat loss across the floor surface has implications for in-situ measurement. Similarly to other findings [38,58], measuring in just a few point locations on a construction element with a large variability of heat flow would highly likely lead to significant over-or underestimation of the whole floor U-value. Additionally, Figs. 7–12 and Table 3 also indicate that if relying on one or a few point measurements only, and depending on location and installation quality issues, different conclusions could be drawn with regards to the performance of the insulation; this could lead to over- or underestimation of insulation efficacy. This would be especially pronounced for the woodfibre insulated floor, due to the significant spread of U_p-values across the floor (see Fig. 9).

The increased U_p-values in the perimeter zone were statistically significant for both insulated floors (Mann–Whitney ($W = 127$, $n1 = 9$; $n2 = 17$, $P < 0.05$ (0.005, unpaired)) for the bead insulated floor and Mann–Whitney ($W = 130$, $n1 = 9$; $n2 = 17$, $P < 0.05$ (0.003, unpaired)) for the woodfibre insulated floor). For the bead insulated floor, the estimated mean of the perimeter U-values was $0.18 \pm 0.08\,Wm^{-2}\,K^{-1}$ compared to $0.08 \pm 0.02\,Wm^{-2}\,K^{-1}$ for locations >1000 mm away from the perimeter (after [58]). For the woodfibre insulated floor, the mean perimeter zone U-value was $0.64 \pm 0.11\,Wm^{-2}\,K^{-1}$ compared to $0.33 \pm 0.06\,Wm^{-2}\,K^{-1}$ in the non-perimeter zone. In both cases, locations near the airbricks (sealed for the bead intervention) were generally outside the margins of error of other estimated point U-values and the pre/post

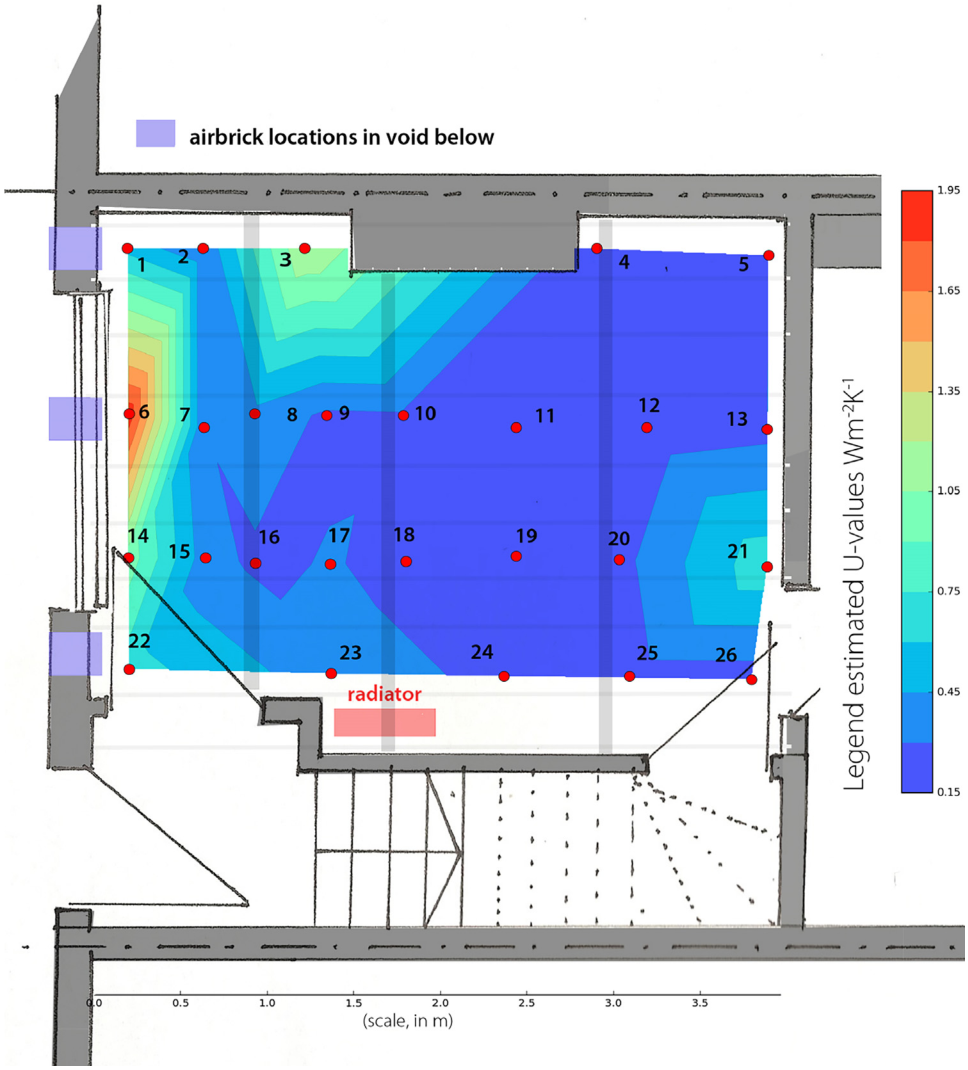

Fig. 9. Linearly interpolated U_p-values as a heat map between observed point U-value locations for the woodfibre insulated floor with the same scale used for the colour legend as in Figs. 7 and 8. An overall significantly reduced heat loss is observed post-insulation, though as expected not as much as the bead-insulated floor. There is still a significant perimeter effect and also a large spread of U_p-values across the floor.

U_p-values were also generally outside the estimated margins of error (see Figs. 10 and 11).

U_p-values (outline data points) as a function of distance to the exposed wall. Red data points are located in the 1000 mm perimeter zone; black-data points are >1000 mm away from the external perimeter wall. Error margins are as per Eq (3).; pre/post insulated point U-values are outside the estimated margins of error. Significant U_p-value reductions are observed after insulation.

U_p-values (outline data points) as a function of distance to the exposed wall; significant U_p-value reductions are observed after insulation. Red data points are located in the 1000 mm perimeter zone; black-data points are >1000 mm away from the external perimeter wall. Error margins are as per Eq. (4); pre/post insulated point U-values are generally outside the estimated margins of error, although U_p-values in locations 3, 6, 14 and 21 (in blue) are within the margins of errors, likely due to installation quality issues – see 4.3.

4.3. Impact of installation quality on intervention efficacy

Generally, U_p-values for the woodfibre insulated floor were between 58%–81% lower than the uninsulated values, depending on where measurements were taken (see Table 3). Use of the thermal camera, combined with the high-resolution measuring technique and post-measurement lifting of floorboards to visually assess the installation fit and quality, allowed for the identification of local installation issues, caused by insufficiently tight-fitting insulation in some areas. For example, insulation in locations 6 and 14 was ill-fitting against the perimeter foundation wall, in addition to reduced insulation from chamfered edges in location 6 (see Fig. 5), leading to reduced heat loss savings post-insulation – see Fig. 9 and thermal image Fig. 12. Such installation issues are likely to have contributed to an increased perimeter effect; this might also have occurred in other non-observed locations. Similarly, installation issues were identified in the other outliers (see Table 3): ill-fitting insulation and gaps in floorboards and membrane in Location 3 and a 15–20 mm gap between a bent floorboard and the insulation below in location 21, a likely source of a thermal bypass.

It might be argued that the observed installation quality issues have led to an underestimation of the efficacy of the insulation in this case study. However, insulation installs elsewhere are likely to have similar installation issues, especially where airbricks are located in between the joists. Further studies are required to investigate typical occurring installation quality issues in other floor insulation projects.

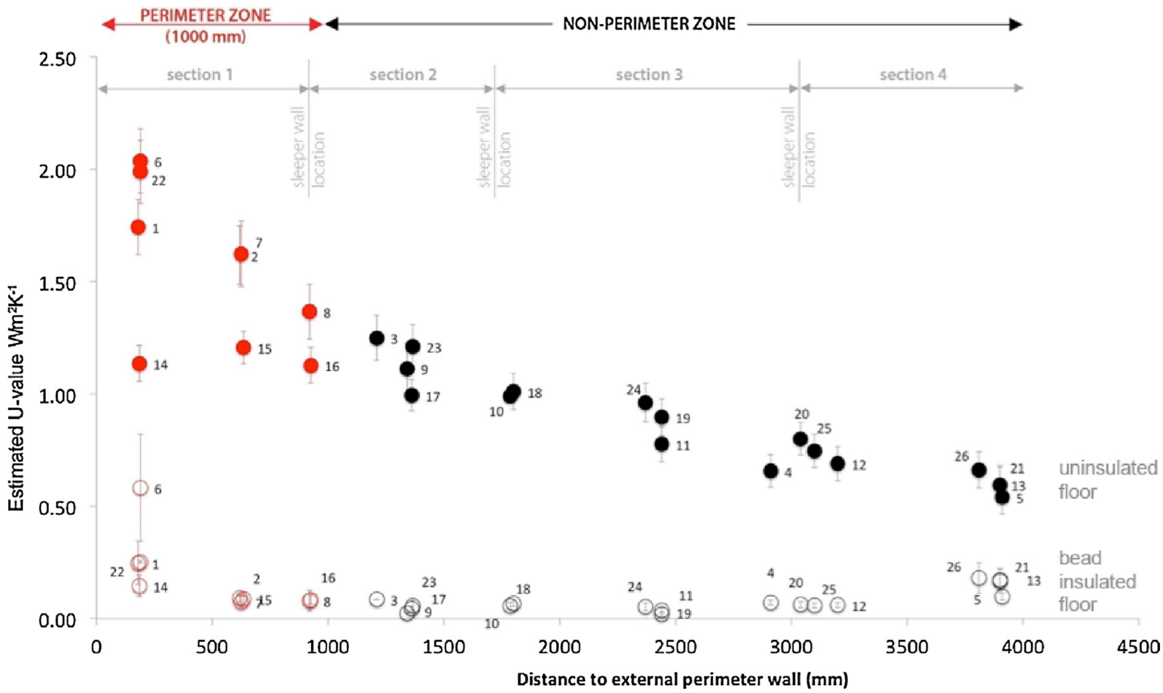

Fig. 10. Plots the uninsulated U_p-values (solid data points) compared to bead-insulated U_p-values (outline data points) as a function of distance to the exposed wall. Red data points are located in the 1000 mm perimeter zone; black-data points are > 1000 mm away from the external perimeter wall. Error margins are as per Eq. (3).; pre/post insulated point U-values are outside the estimated margins of error. Significant U_p-value reductions are observed after insulation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

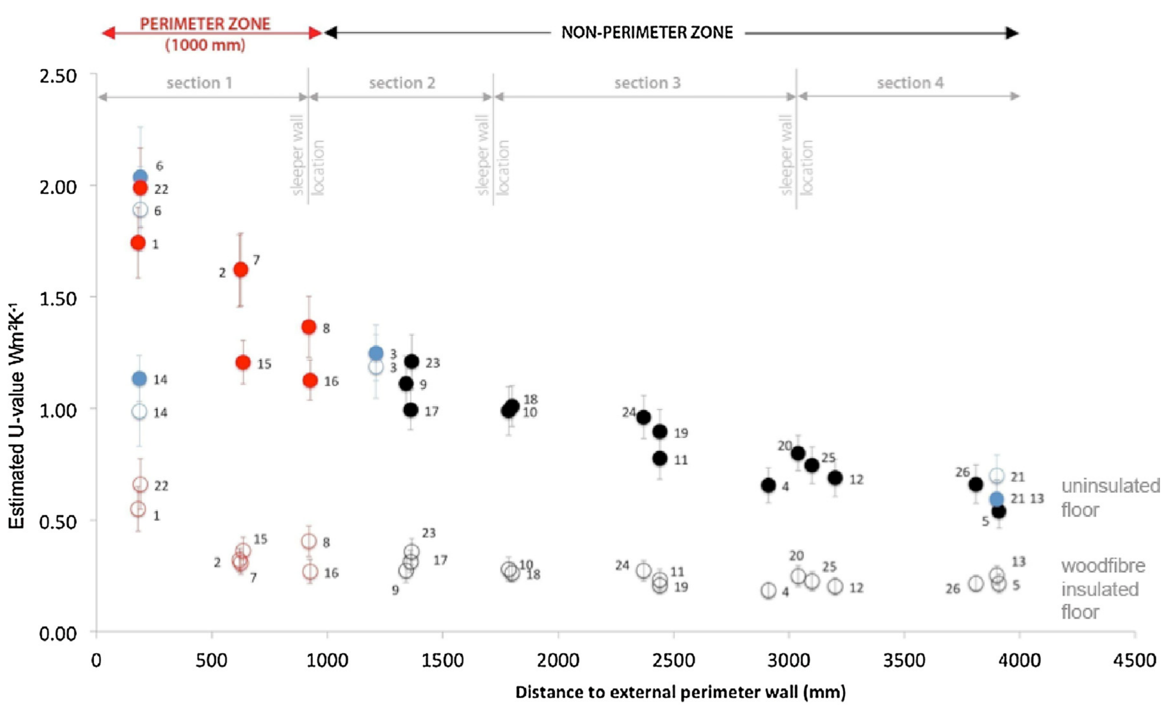

Fig. 11. Plots the uninsulated U_p-values (solid data points) compared to woodfibre-insulated U_p-values (outline data points) as a function of distance to the exposed wall; significant U_p-value reductions are observed after insulation. Red data points are located in the 1000 mm perimeter zone; black-data points are > 1000 mm away from the external perimeter wall. Error margins are as per Eq. (4); pre/post insulated point U-values are generally outside the estimated margins of error, although U_p-values in locations 3, 6, 14 and 21 (in blue) are within the margins of errors, likely due to installation quality issues – see 4.3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.4. Comparison to models

The floor U-value of the field study house was estimated using several models: the ISO-13370 model as described in [61], RdSAP [62], the 2015 CIBSE [63] model, and the superseded CIBSE-1986 model [64]. Case study site survey data was used to inform model inputs, or where not available, typical input assumptions were used – see [38]. The predicted U-value model estimate for the

Table 5
Different modelled outputs compared to each other and to in-situ measured U_{wf}-values; based on site-survey and actual interventions taken place; 5 m/s windspeed at 10 m high; with no airbrick ventilation for the EPS bead insulated floor. Joist presence excluded for all modelled and in-situ measured estimates.

Input assumptions based on survey, unless stated otherwise; joist presence excluded U-value outputs, $Wm^{-2} K^{-1}$, assumed 5 m/s wind-speed as per RdSAP recommendation.	ISO-13370	RdSAP	CIBSE 2015	CIBSE 1986	In-situ measured U_{wf}-value $Wm^{-2} K^{-1}$
Uninsulated floor [38],	0.57	0.51	0.52	1.34	1.04 ±0.12
Woodfibre insulated floor 100 mm (Pavaflex; λ = 0.038 $Wm^{-1} K^{-1}$ [54]	0.23	0.22	0.22	0.30	0.36 ± 0.07
Bead insulated floor (Warmfill Silver beads; λ = 0.033 $Wm^{-1} K^{-1}$	0.08	0.08	0.08	0.09	0.09 ± 0.03
Woodfibre insulated floor; installation issues taken into account (in accordance with ISO-9646).	0.25			0.33	0.36 ± 0.07
Woodfibre insulated floor; 15% "in-use" factor applied without/with observed installation issues accounted for	0.26/0.29			0.35/0.38	

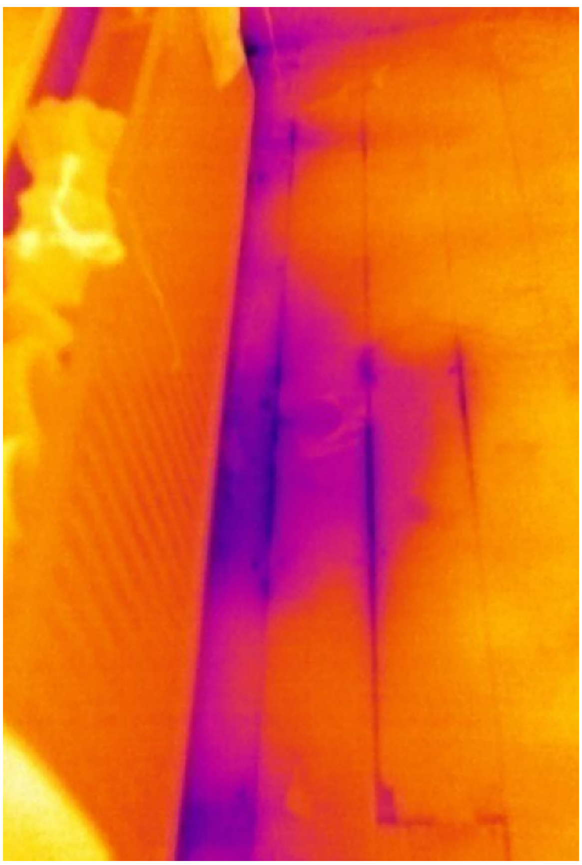

Fig. 12. Shows a thermal image of woodfibre insulated floor and the ineffective fitting of insulation in location 6 along the perimeter.

bead insulated floor was 0.08 $Wm^{-2} K^{-1}$ for all current models (and 0.09 $Wm^{-2} K^{-1}$ for the CIBSE-1986 model). The predicted U-value model estimate for the woodfibre insulated floor was between 0.22 and 0.23 $Wm^{-2} K^{-1}$ for the current models and 0.30 $Wm^{-2} K^{-1}$ for the superseded CIBSE-1986 model- see Table 5.

Table 5 highlights that the majority of the models appear to underestimate the in-situ measured U_{wf}-value of the uninsulated floor– as found previously [38]. However, the superseded CIBSE-1986 model appears to overestimate the in-situ measured U_{wf}-value of the uninsulated floor [38]. According to the modelled U-value outputs, bead-insulating the floor would reduce the floor U-value by 86% and by 60% when woodfibre insulated. These are slightly underestimated improvements compared to the actual mean observed reductions achieved: 92% (88%–95%) for the bead insulated floor and 65% (54%–75%) for the woodfibre insulated floor.

This slight underestimation might be mainly associated with the initial underestimation of the U-value of the uninsulated floor, which was nearly twice as much as modelled. There is closer alignment between the superseded CIBSE-1986 model and in-situ measured U_{wf}-values: an overestimation of the uninsulated U_{wf}-value of about 30% and an underestimation of about 16% of the U_{wf}-value of the woodfibre insulated floor, though within the margins of measurement error, while predicting the same value as measured for the bead-insulated floor. It is unclear if this is due to the ability of the CIBSE-1986 model to better reflect actual floor heat loss or due to other factors specific to this case study; further research in a larger sample is required to investigate if this would be the case for other in-situ measured case-studies.

Table 5 also highlights that for this study, the observed difference between modelled and in-situ measured U-values reduced the better insulated the floor was, as also noted by Cox-Smith [12]. This is likely to be because as insulation, of relatively well characterised thermal performance, is added to the floor, it starts to dominate the total thermal resistance. In addition, for the bead-insulated floor, there might be fewer confounding (or assumed) variables: sealed airbricks removed ventilation inputs from both the in-situ measurements and the model. The bead insulated floor had a similar floor U-value whether in-situ measured (0.09 ± 0.03 $Wm^{-2} K^{-1}$) or modelled (0.08–0.09 $Wm^{-2} K^{-1}$) for current and superseded models. In contrast to the bead insulated floor and disregarding the superseded CIBSE-1986 model, the U-values estimated from in-situ measurements and modelling were outside the margins of error for both the uninsulated and wood fibre insulated floor. The in-situ measured uninsulated floor U-value was about twice that derived from modelling [38]. For woodfibre insulation, the in-situ measured whole floor U-value estimate (0.36 ± 0.07 $Wm^{-2} K^{-1}$) was about 35% higher than current model outputs.

ISO-9869 [44] states that >20% differences between modelled and in-situ measured values should be considered significant, which is the case here for the uninsulated and woodfibre insulated floor. This divergence between modelled and measured values might be due to any or a combination of (a.) inaccurate model inputs such as wind-speed, wind-shielding factors, material and ground conductivities and excluded variables; (b.) installation quality issues (such as chamfered edges, ill-fitting insulation, bent floorboards etc.) are not taken account in models: generally perfect insulation fit is assumed, but this might be difficult to achieve in reality; (c.) measured results might not be directly comparable to modelled results due to conceptual differences between measured and modelled U-values. While the models are steady-state predictions assuming thermal mass equilibrium [44], field measurements are subject to dynamic conditions yet longer term seasonal effects outside the monitoring period are excluded. Additionally, the floor U-value models exclude the linear thermal bridging of the wall-floor junction, though this likely affected in-situ measurements, as discussed in [38].

Adjusting models for installation quality issues can only be undertaken upon in-situ measurement and detailed knowledge of the installation undertaken in each case, requiring observations to be made of this process. Allowing for localised chamfered insulation installation in locations 1, 6 and 22, and a 10% air-gap correction factor[3] (both as per ISO-9646 [42]), lead to slightly increased predicted U-values for the woodfibre insulated floor: 0.25 $Wm^{-2} K^{-1}$ for the current models and 0.33 $Wm^{-2} K^{-1}$ for the superseded CIBSE-1986 model, converging with the in-situ measured value of 0.36 ± 0.07 $Wm^{-2} K^{-1}$. At present, UK ECO-policy uses a 15% 'in-use' factor for floor insulation for ECO-funded insulation installations [65], further converging model outputs of insulated floors with in-situ measurements (Table 5). It is unknown if the in-use factor reflects realistic installation quality issues. Evidently, further research is required to understand which parameters and assumptions contribute to the disparity between measured and modelled results, and study in a larger, international floor sample is needed to confirm these findings for other in-situ measured case-studies in the UK and elsewhere.

5. Regulations, payback and implications for retrofit decision-making

The bead-filled floor void meets current maximum regional regulatory requirements of 0.25 $Wm^{-2} K^{-1}$ when both modelled and measured in-situ, however it is unclear whether Building Regulations Part C, which stipulates a ventilated floor void [66] would be satisfied. Contrary to this, the woodfibre insulated in-situ measured U_{wf}-value fails to meet the building regulation requirement by about 30%, although the modelled U-values meet the regulations (with exception of the superseded CIBSE-1986 model output). Additionally, the presence of services and installation quality issues associated with airbrick locations and ill-fitting floorboards are excluded from models, but are likely to be practical issues present in other interventions, preventing 'perfect insulation' installation.

Furthermore, airbrick locations and joist depth will limit the depth of insulation that can practically be fitted without blocking the airbricks along the perimeter, as was the case in this study. The RdSAP model, used for regulatory compliance in building upgrades in the UK, assumes a default 150 mm insulation installation between the joists [67], however this was not practically possible in this case study with joists of depth 100 mm. Using a different material with lower thermal conductivity should lead to a better in-situ thermal performance; however, lower conductivity insulation might be limited to those (vapour-impermeable) materials not recommended for suspended ground floors [59]. This raises questions about the practicalities of achieving the UK regulatory recommended design floor U-values, though some exemptions are permitted in the UK if it "*is not technically, functionally or economically feasible*" and instead to upgrade to "*the best standard that is technically and functionally feasible and delivers a simple payback period of 15 years or less*" [45].

The UK building regulations also state that "*where the existing floor U-value is greater than* 0.70 $Wm^{-2} K^{-1}$, *then the addition of insulation is likely to be cost-effective*" [45]. In this study, the recommended threshold of 0.70 $Wm^{-2} K^{-1}$ for floor insulation was not met according to the modelled outputs from current models (0.51–0.57 $Wm^{-2} K^{-1}$). Yet, the in-situ measured floor U-value in this study was found to be nearly twice as high as the modelled value and greater than the recommended threshold to install floor insulation. For this case study – and if confirmed in the wider housing stock – this might have implications for retrofit decision-making and regulatory requirements: current models may suggest it is not cost-effective to upgrade the floor and may lead to regulatory exemptions if the payback exceeds 15 years, leaving the floor uninsulated. In reality the floor U-value may be significantly greater than predicted by the current models, and hence lead to greater cost-effectiveness to insulate.

Calculated payback times will differ depending on the extent of exposed perimeter and whether the installation is DIY or carried out by professionals. UK Payback times were quoted as little as 2 years [68], 3–8 years [69], 30 years at a cost of £1000 [22], and 4–46 years if the building is gas-centrally heated and depending on insulation method (based on £25/m^2 and £70/m^2 [70]). Shorrock [7] states a floor insulation cost of between £50–£1000 per dwelling, stating no payback times. In this case study, the yearly estimated energy cost associated with uninsulated floors is just £28[4] according to the modelled U-value, but £51 compared to the in-situ measured value. A simplified payback model[5] indicates that the payback of insulating floors is very long, especially when based on modelled U-values. For example, the payback of the bead-insulated floor might be as low as 15 years based on in-situ measurements, while double that based on predictive models. For woodfibre insulation, a payback of 42–117 years is estimated from models. However, this reduced to 21–58 years when based on in-situ measured heat flow. Despite reduced payback based on in-situ measured heat loss estimates, payback is still large and indicates that further research into actual space-heating energy use associated with floor heat loss would be beneficial, in addition to more cost-effective floor insulation methods.

The energy and cost savings associated with fabric upgrades are currently estimated from modelling; as highlighted above, in this case study such estimates significantly underestimate the efficacy of interventions. If, as expected, this is replicated more widely in the stock, this is likely to be a significant contributor to the low uptake of floor insulation compared to roof and wall insulation and opportunities to reduce energy use may be missed. Furthermore, in some low-carbon retrofits, such modelling results led to the suspended ground floor remaining uninsulated, off-setting its predicted heat-transfer with increased insulation elsewhere [71]. This could lead to a significant performance gap for the whole house performance if the models do not capture the true floor heat loss well in those studies.

Finally, it might be that U-values higher than those recommended in the UK regulations might help prevent void conditions becoming ideal for mould growth, as reported by Airaksinen [72] in Finland. Hence, undertaking floor upgrades needs to be carefully balanced with the effect this might have on floor void conditions to protect occupant health and the building fabric, though at present these considerations are poorly characterised and further research is required.

6. Conclusion

Two floor insulation interventions were undertaken in an unoccupied field study house: 100 mm woodfibre insulation

[3] The air-gap correction was only possible from in-situ observations, though it is still unclear if this also affected other locations than those observed – hence assumption of 10% occurrence was assumed in accordance with ISO-6946.

[4] Estimates based 4 p/kWh gas-heating cost (Npower, July 2016), excluding standing charges.

[5] Estimates based on London Heating Degree Days and EH (2013) floor insulation cost estimates of £25/m^2–£70/m^2; 4 p/kWh gas-heating cost (Npower, July 2016), excluding standing charges. Impact of draughts and any energy compensating behaviour associated with floor heat loss, financial incentives (ECO-funding) or DIY options are also excluded.

between joists and bead-filling the void (alongside sealing airbricks). High resolution in-situ heat-flow measurements were undertaken and pre/post U-values were compared. Statistically significant reductions in in-situ measured U-values for the insulated floors were observed: 65% for the woodfibre insulated floor ($U_{wf} = 0.36 \pm 0.07\,Wm^{-2}\,K^{-1}$) and 92% for the bead insulated floor ($U_{wf} = 0.09 \pm 0.03\,Wm^{-2}\,K^{-1}$). Even with the presence of insulation, the observed U_p-values in the 1000 mm perimeter zone were (statistically) significantly larger compared to the non-perimeter zone, though significantly reduced for the bead-insulated floor which also had a reduced spread of point U-values. However, this reduced variability in heat flow was not observed in the woodfibre insulated floor due to insulation installation inhomogeneity.

In this study, it was found that the discrepancy between modelled and in-situ estimated U-values reduced the better insulated the floor was, while the in-situ measured uninsulated floor U_{wf}-value was nearly twice modelled values, this gap reduced to 35% for the woodfibre insulated floor, with no divergence between modelled or in-situ measured for the bead-insulated floor. The superseded CIBSE-1986 model outputs appeared to align more closely with in-situ measured values, however further research is required in a larger sample to investigate whether this is circumstantial or due to it representing the heat loss of floors better than current models. Despite current model outputs predicting that the woodfibre insulated floor would meet the regulatory recommended maximum U-values ($0.25\,Wm^{-2}\,K^{-1}$), the in-situ estimated U_{wf}-value fell short of these recommended design values. Adjusting the woodfibre insulated floor model to take account of installation quality issues after in-situ observations and/or applying the 15% ‘in-use’ ECO factor, reduced the divergence between modelled and in-situ U-values. This highlights the value of detailed site specific information to improve the accuracy of modelling. Additionally, this study reiterated the value of high-resolution in-situ monitoring to derive the whole floor U-value: using just one or two point measurements in in-situ pre/post studies is likely to over- or under- estimate the (un)insulated floor U-value and the insulation efficacy, depending on the observed locations. The greater the spread of heat-flow across the element, the greater the risk of significant error in whole element values from just a few point measurements.

It was also found in this study, and likely to occur in other buildings, that good installation quality is important to maximise heat-flow reductions, such as a tight fit between insulation material and joists and floorboards and special attention along the perimeter walls and near airbricks. However, models do not reflect installation quality issues. In addition, RdSAP assumes a default 150 mm insulation in between joists, which is unlikely to be practically achievable in many floors, which typically have 100 mm joist depth, as in this case study.

The case-study illustrated that the estimated in-situ floor U-value might be significantly greater than assumed and modelled at present. As a consequence, the benefits of insulating the ground floor might be underestimated. If these observations are more broadly confirmed in the UK housing stock and in a larger international sample of suspended floors, it would have significant implications for policy and retrofit decision-making nationally and internationally. For example, given the disruption involved in insulating ground floors, they might be left uninsulated if U-values are underestimated by models and if proportional U-value reductions due to interventions are also underestimated, as was the case here. Additionally, the estimated pay-back of upgrade measures on which decisions are based, are likely to exceed the $\leq$15 year guideline, meaning that there would be reduced incentives to insulate floors, when in fact the potential space-heating energy reductions might be much greater than assumed, with faster payback. Furthermore, if stock-models are based on underestimated floor heat loss assumptions and regulatory standards for the upgrade of floors, the heat loss reduction potential might be underestimated, leading to uncertainty in energy and carbon emission models and associated policy-making. Ground floors might be left uninsulated, bypassing a significant reduction potential in space-heating energy.

The significant floor U-value reductions achieved through retrofitting with floor insulation in this field study suggest that, if reflective of the wider suspended ground floor population, a significant energy reduction potential is available. Improved in-situ characterisation of floor U-values and their likely variation in a larger and diverse sample, alongside studies of the impact of interventions both in the UK and elsewhere, would confirm any implications for carbon reduction policies and support sound retrofit decision-making in the national and international building stock.

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